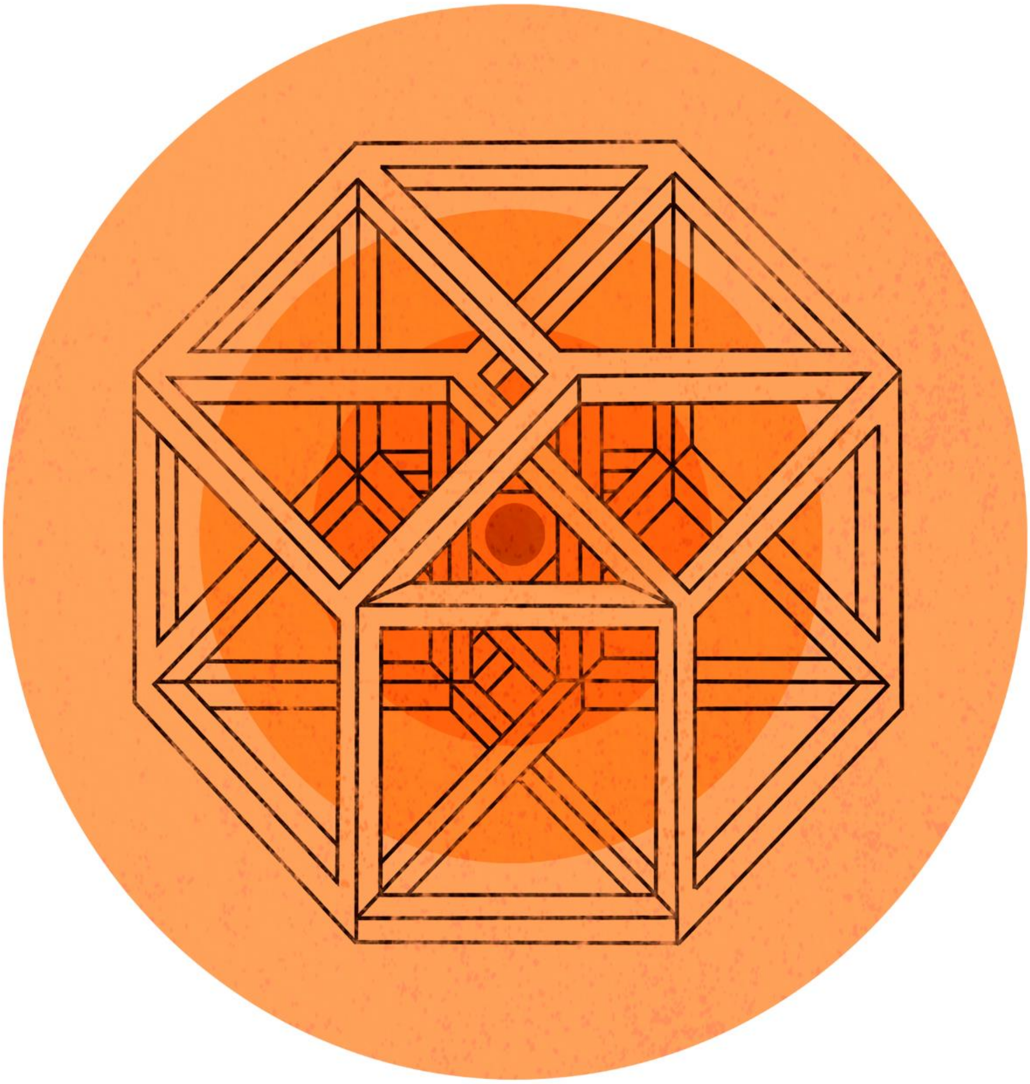
THERMOECONOMICS

a tool for energy and economic evaluation
of building thermal systems



2018

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for Mikel & Irene
for Irene & Mikel

Nahiz ez sinetsi hiruki baten
barruan dagon begian,
gezur guztitan dago egi bat
eta gezur bat egian.
Naufragatuta baldin bazaude
itsasoraren erdian
errezazazu tarteka baina
segi zazu igerian

("Although not believing
in the eye inside a triangle,
in all the lies
there is a truth
and there is a lie
within the truth.
If you have been shipwrecked
in the middle of the sea
pray from time to time
but do not stop swimming")

Jon Martin Bertso berriak itxaropenari jarriak

ACKNOWLEDGEMENTS

I want to express my gratitude to all those people who, in these days or in one moment or another, helped making this thesis a reality.

First of all, I would like to acknowledge Pr. José María Sala Lizarraga for offering me the opportunity to do the thesis, for his confidence and for his permanent supervision. Since, without a doubt, this work is unfeasible without his enormous knowledge, motivation and interest.

I want also to recognize the guidance received during the stances of three months each. The first one in the Institute for Energy Engineering at the TU Berlin, under the supervision of Pr. George Tsatsaronis, who has focused and expanded my knowledge thanks to his extensive experience and dedication in the development of Advanced Exergy Analysis.

The second in the DEIM at the University of Palermo, where the dedication and guidance of Pr. Antonio Piacentino were essential for the analysis of cooling and air conditioning systems; I want to thank him also for the opportunity given to collaborate with his research group.

The third one in the Department of Industrial Engineering at the University of Padova, under the continuous direction of Pr. Andrea Lazzaretto, who organized my ideas, motivated the reflection and inspired the structure of the thesis.

I want to recognize the help offered by Pr. Miguel Ángel Lozano and Pr. Luís Serra from the University of Zaragoza, who prompted the improvement of the research.

The Laboratory for the Quality Control of Buildings (LCCE) of the Basque Government must be mentioned too, referencing particularly to the Head of the Laboratory D. Agustin de Lorenzo that allowed the testing essays of the research. I do not want to forget, of course, the people working at the Thermal Area of the LCCE: Iván Flores, César Escudero, Imanol Ruiz de Vergara, Eider Iribar, Carlos García, Daniel Pérez, who facilitated unselfishly the improvement of the thesis.

The Saincal Group, especially José Luis Cortijo, for giving realism and practicality to the theory.

Naturally, the colleagues and friends of the universities: Irati, Cata, Niko and Erik, for their talks and rewarding breaks in Bilbao. Saeed and Mathyas, for their help and for their time; as well as Andreas and Elisa, for their positive energy and good humour, giving colour to the grey days of Berlin. Pietro, for listening to me, forcing me to think and making me laugh in Palermo. Nico, for his enthusiasm and Gianluca for taking me hiking to disconnect from the landscape of Padova.

The girls of the “kuadrilla”, being there when I need them and "los truchas", since they brighten my days; and all those people who have made the research an adventure that is worth living.

Ama, Aita, Laura and Maria, because they are the most wonderful people I know.

Mikel and Irene, wherever they are, because a piece of their lives is inside myself.

ALL CHAPTERS

ACRONYMS

AHU	Ain Handling Unit
Col.	Collector
COP	Coefficient of Performance
DAEA	Dynamic Advanced Exergy Analysis
DHW	Domestic Hot Water
Dist.	Heat Distribution and DHW Primary Circuit
ECT	Exergy Cost Theory
EEA	Exergy Economics Approach
EED	Energy Efficiency Directive
EFA	Engineering Functional Analysis
Emis.	Heating Emission and DHW Supply
Env.	Envelop
EPBD	Energy Performance of Buildings Directive
FEA	First Exergoeoconomic Approach
Gen.	Heat Generation
HVAC&R	Heating, Ventilation and Air Conditioning & Refrigeration
IAQ	Indoor Air Quality
LIFOA	Last-In-First-Out Approach
LQCB	Laboratory for the Quality Control in Buildings
MS	Member States
nZEB	nearly Zero Energy Buildings
P.E.	Primary Energy
R.A.	Room Air
SPECO	Specific Exergy Costing
ST	Symbolic Thermoeconomic
Stor.	Heat Distribution and DHW Storage System
TADEUS	Thermoeconomic Approach to the Diagnosis of Energy Utility Systems
TFA	Thermoeconomic Functional Analysis,
Trnsys	Transient System Simulation Tool

BASIC MATHEMATICS

ΔY	Increment of variable Y
$\dot{Y}$	Y variable per unit of time
$\mathbf{Y}$	Vector or matrix of variable Y
$\mathbf{Y_D}$	Diagonal matrix of variable Y
$^{\mathbf{T}}\mathbf{Y}$	Transposed $\mathbf{Y}$ matrix
Y_{ij}	Component of i row and j column of $\mathbf{Y}$ matrix
$\mathbf{u}$	Unitary vector
$\mathbf{U_D}$	Identity matrix

RESEARCH ABSTRACT

One of the current main objectives of the European Union is focused on primary energy conservation, as a consequence of the enduring climate change the world is undergoing. Buildings are responsible for almost 40 % of the final energy used in the EU while in Spain, the built environment accounts for 28 % of the final energy consumption. Therefore, such sector plays an important role in the total energy consumption and many specialists are working for the improvement of buildings energetic efficiency.

The benefits obtained through the application of *exergy* concept in buildings are currently known, since they contribute to the proper use of energy as well as to a better adequacy of the different energy qualities taking part in a facility. This is especially useful in buildings where low quality energy demands are required, such as heating, cooling and domestic hot water.

The aim of **Chapter A** is to show the enormous possibilities for the energy efficiency improvement that still exist, which cannot be assessed through a common energetic analysis; in both, new and retrofit buildings.

Because buildings are permanently changing over the time, *dynamic models* are imperative. In **Chapter B** two innovative methods are developed for their transient representations.

Besides, an exergy analysis supports the identification of the economic cost formation in every phase of the energy transformation chain, which is, precisely, the objective of **Chapter C**. Such study is the base of *Thermoeconomics* that, among other applications, enables the exergetic and exergoeconomic costs of all the flows along the system. For that, Symbolic Thermoeconomic is used to obtain general equations, which relate the thermoeconomic variables of every component. The pioneering point is related to the dynamism incorporation, which is, in addition, seconded by a ground breaking dynamic software in the **Annex**.

Furthermore, *thermoeconomic diagnosis* attempts to identify the components affected by any anomaly by analyzing its symptoms according to the exergetic efficiency variations and quantifying the energy recovery potential; unfortunately, it limps in certain aspects. **Chapter D** overcomes the essential issues of the application and succeed in the direct dynamic diagnosis problem resolution.

In **Chapter E**, by contrast, a *Dynamic Advanced Exergy Analysis* is applied for the first time in buildings. Therefore, the corresponding dynamic challenges are solved.

The overall research purpose it to stand out the advantages and disadvantages of the Second Law analyses in buildings dynamic systems. After all, a critical judgment is the base of any application and the only way forward to achieve the goal of energy and economic savings in buildings.

CHAPTER A

Required energy savings in buildings

CHAPTER A

SUBSCRIPTS

DHW	Domestic hot water
$Heat$	Heating
TOT	Total
0	Ambient
op	Operative
$trans$	Transmission
$vent$	Ventilation
inf	Infiltration
g_{solar}	Solar gains
g_{int}	Internal gains

SYMBOLS

T	[ºC]	Temperature
c_P	[kJ/kg·K]	Heat capacity
$\dot{m}$	[kg/s]	Mass flow rate
$\dot{Q}$	[kJ/s]	Heat flow
$\dot{E}$	[kJ/s]	Exergy flow
η	[%]	Energy efficiency
ε	[%]	Exergy efficiency

CHAPTER A: REQUIRED ENERGY SAVINGS IN BUILDINGS

A.0. ABSTRACT

This introductory chapter justifies the motivation of the research in Thermoeconomic implementation in buildings energy systems. For that, a brief explanation of the objectives and methodology followed along the thesis is first given. After that, the current state of art of energy in buildings is shortly explained and exergy is later introduced.

After all, although buildings are big energy consumers, their energy saving potential is extremely high. That is the reason why European Directives are boosting to create nearly Zero Energy Buildings (nZEB) or to promote refurbishments in the existing ones.

Unfortunately, the enhancements cannot be fostered by using only energy parameter; exergy must be used instead since it considers not only the quantity but also the energy quality. The buildings exergetic analysis should be applied over the completely energetic transformation chain (i.e. from the energy generation until the energy consumption). Therefore, some key aspects of exergy demand calculation are given.

The main idea of this chapter, apart from synthetizing the thesis structure, is to show the energy saving potential of buildings and the improvements obtained through the exergy application. Therefore, two examples are developed: the first one reflects the constraints encountered with the pure energy analysis in a nZEB and the way to solve them. Conversely, the second one justifies the method of exergy demand calculation and explains the utility of exergy for the comparison of systems in rehabilitation.

A.1. OBJECTIVES & METHODOLOGY

The opening issue is to justify the use of *exergy* in building thermal facilities. Even being a powerful tool for analyzing the weaknesses of energy systems, the exergetic analysis seldom was applied in the building sector, even less the more useful *Second Law* (or *Thermoeconomic*) *applications*, i.e. thermoeconomic cost accounting and diagnosis.

One of the main purposes of the thesis is to connect thermoeconomic analyses with buildings (by solving, therefore, the encountered problems as well as enhancing their outcomes) in order to create a pioneering guideline that covers any further complex implementation. The key feature is related to the dynamism of the approach.

As predictable, this introductory **Chapter A** deals with the benefits and justification of applying exergy in buildings but it is simply the previous step for the following Second Law applications, which are in turn the objective of the thesis. Indeed, these are the proposed steps for the Second Law applications, see Figure A. 1:

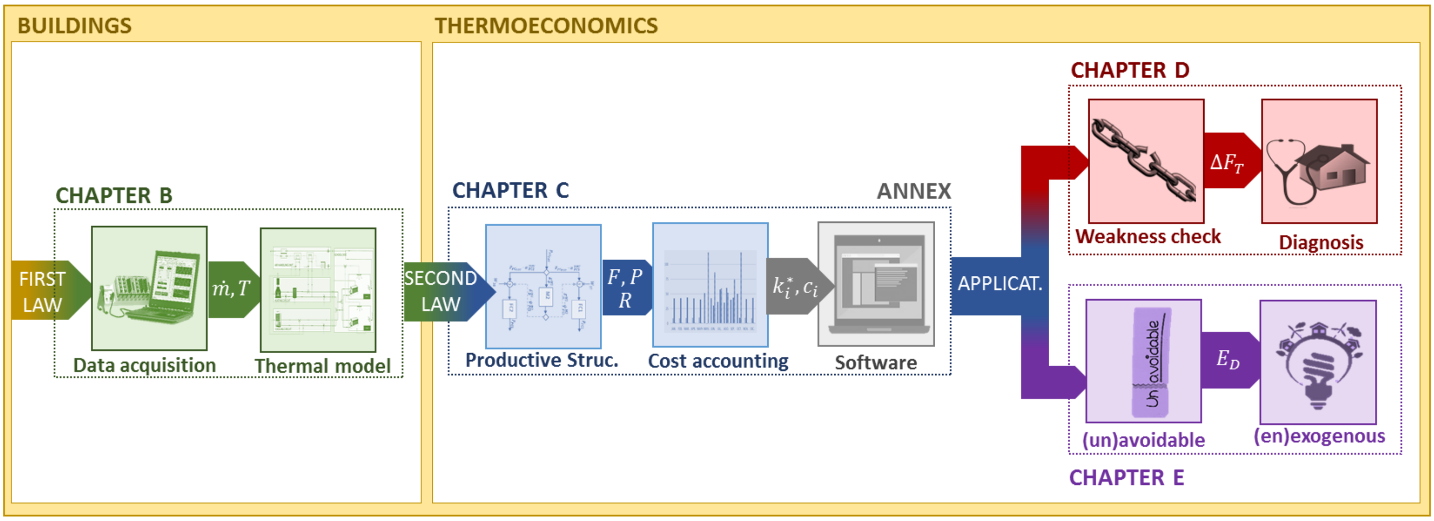


Figure A. 1 Steps for thermoeconomics application in buildings

✓ **CHAPTER B**. First law approach

1. *Data acquisition.* Previous step deals with thermodynamic variable obtainment; such us environment conditions or building/facility requirements.
2. *Thermal model*. According to the mass and energy balances, two simple methodologies for dynamic thermodynamic representation of each component and the system as a whole are proposed to extract the data for every exergy flow calculation.

✓ **CHAPTER C** / **ANNEX**. Second law approach

3. *Productive structure*. A critical analysis of the thermal system must be made, which may be proficiently carried out by applying a cost accounting method (or Second Law Approach). For that, exergy flows and components need to be classified.
4. *Cost accounting*. An implementation of a cost accounting method based on exergy derives on unit exergetic costs and other useful results. In addition, a pioneering dynamic super-structure based on ST permits general equations to determine systems internal connections.
5. *Software*. A novel dynamic program collects all the introduced enhancements and implements the cost accounting in real systems. Accordingly, a critical analysis of results highlight the most critical processes to be enhanced in further applications.

✓ **CHAPTER D** / **CHAPTER. E**. Applications

6. *Weakness check*. One of the outcomes taken from exergy analysis is the location and quantification of exergy destruction across the energy chain, which should be minimized as much as possible.
7. *Diagnosis*. For the first time Thermodynamic Diagnosis direct problem is solved and applied to detect anomalies as well as the produced effects. Besides, by solving the anomalies and reducing exergy destruction, optimization and/or rehabilitation in building systems can be implemented.

8. *(un)Avoidable*. Application of Advanced Exergy Analysis helps to detect which part of the exergy degradation can be prevented and which is limited because of technical constraints.
9. *(en)Exogenous*. Moreover, the effects related to the component behavior itself and those coming from the outside are accounted. Once more, the groundbreaking input concerns with the introduction of dynamics in the approach.

All that theory is seconded by seven case studies thoroughly defined and developed.

- (i) nZEB Building Case Study
- (ii) Building Retrofit Case Study
- (iii) School's AHU Case Study
- (iv) Simple DHW facility
- (v) Solar Energy Building System Case Study
- (vi) Heating & DHW System Case Study
- (vii) Stirling and Condensing Boiler Case Study

Consequently, for the first occasion dynamism is considered inside thermoeconomic approaches. What is more, a critical analysis of the ins and outs of each theory is given by successfully solving the vulnerable points.

As a result, Thermoeconomics is validated as a suitable tool for the common worldwide objective of energy savings, economic reduction and environment sustainability in buildings.

A.2. INTRODUCTION

As mentioned, the aim of this introductory chapter is to justify the use of exergy in buildings and to underline the incongruences that may arise with the simple energy analysis. Indeed, energy saving is a worldwide scope and exergy is a suitable tool for achieving such goal.

A.2.1. Required Energy Savings

Human activity is possible thanks to the utilization of natural resources. Unfortunately, the depletion of non-renewable resources is hard to avoid and it implies an important danger for the future of the living beings. Therefore, the minimization of the consumption is a vital task in the design and operation of production processes. However, according to the high level of comfort humans have accustomed to, the reconciliation between exploitation rate and resource regeneration is a challenging assignment; even further considering that the requirements of the increasing population can lead to unsustainable situations.

Thereby, the worldwide awareness for reducing energy demand is well known. Moreover, one of the current main objectives of the European Union is focused on primary energy conservation and the reduction of CO_2 emissions, because of the enduring climate change the world is undergoing. As reported in [1], if the current trend in energy use remains the same, the demand for oil from 2007 to 2035 is expected to grow by 30 % and for coal and natural gas by 50 %.

Furthermore, the energy consumption in buildings has increased rapidly in recent years, among other things, due to the rise in population, higher requirements of healthy, comfortable indoor environments and so on. The situation in Europe indicates that tertiary buildings (residential and services) are responsible for 40 % of the final energy consumption and for the 50 % of the CO_2 emissions [2]. In Spain, these buildings account for a smaller 28 % of the national global consumption, being 18 % used in dwellings and the remainder 10 % in services, [3]. Unfortunately, the current trend is moving towards the raise of these percentages in a very alarming way. Therefore, there is some urgency for lowering the energy consumption, mainly in Heating, Ventilation and Air Conditioning & Refrigeration (HVAC&R) systems [4].

In any case, great amount of energy is used along the life cycle of buildings (construction, usage and demolition) to provide them with the necessary services and to furnish the energy contained in the construction materials. In consequence, there is still a great potential for energy improvement to be attained in the upcoming years. This context encouraged new European energy saving policies such as the Energy Efficiency Directives (EED) and the Energy Performance of Buildings Directives (EPBD). The last update of the EPBD established that, from 2020 onwards, all new buildings must be nearly Zero Energy Buildings (nZEB), which is the first step towards positive energy buildings. Thus, development of energy efficient facilities represents a great concern and has become the focus of many research activities [5].

On the one hand, great advances have been made in the recent years for the application of new materials, new façades and roofs and big improvements have been achieved in the energy supply systems; particularly with the integration of renewable energies in the hybrid installations.

Against this background, the Passivhaus standard encompasses a very low energy demand construction often used as a reference for nZEB buildings. It is based on an exhaustive procedure, during the project design and construction, which procures buildings with a thoroughly low energy requirement.

On the other hand, there is a great potential to make the investments in rehabilitation economically attractive (in both, the residential and the tertiary sector), although only about 1 % of the existing surface is annually renewed. Faced with this reality, the EU has tried to increase energy efficiency measures in existing buildings through a series of directives.

Nevertheless, energy is used as the base parameter of building analysis and design and, as it will be justified later on, some incongruences can arise within such perspective. Indeed, most of the energy systems analyses in the built environment are based on the first law of thermodynamics, i.e. they are performed according to the energy efficiencies and based on the primary energy input and CO_2 emissions, as in [6]. They do not consider the different qualities of the energies and they only assume as losses those flows of energy which are not used, generally heat flows, without considering the irreversibilities related to equipment imperfections as additional losses.

In order to obtain more useful information from a system, an *exergy analysis* should be conducted in addition to a conventional *energy analysis*, since the former measures the maximum theoretical useful work which can be obtained [7] by accounting not only for the quantity of energy but also for its quality [8]. Exergy, unlike energy, does not satisfy a conservation law, but it is destroyed when the quality of energy is degraded because of the irreversibilities within different processes [9]. In other words, the idea that something can be destroyed through a process is very useful in the design, analysis and optimization of building energy systems. An energy balance fails to identify the true thermodynamic inefficiencies, and thereby, an evaluation based exclusively on the energy concept might be misleading.

A.2.2. Exergy Analysis

The problem of minimizing the consumption of natural resources can be handled by taking into account the *useful work* or transformability that can be obtained from an energy.

As it is well-known, different types of energy have diverse abilities to transform into other forms. The quality of energy identifies the idea of convertibility disparity and, because of that, reflects that the same amount of energy can have different quality according to its ability to be transformed into other forms. In general, among all possible forms of energy the common reference is *useful work*, in other words, the quality of energy is expressed by its ability to become useful work measured by *exergy* [7].

Some energy forms can be completely converted into work (for example, electrical energy); consequently, energy is identified with exergy. However, there are other forms of energy (for instance, heat) that only a part of it can be converted into work; therefore, only a fraction is an exergy flow.

Exergy considers the First and the Second Law of thermodynamics as it includes the inefficiencies due to irreversibilities [10]. Consequently, it allows detecting the degradation of energy [11] and represents a synthesis of thermodynamic information; hence, it is useful for describing the components technical behavior [12] and facilitates the comparison between different systems. Besides, labor and capital can be converted in exergetic terms and their equivalent can be included by extended exergy methods [13].

Nevertheless, exergy is meaningless without a reference state or "dead state" which shows the capability or limit for the useful work; hence, relativity is the main feature of exergy analysis [11]. Moreover, as exergy variables are a combination of several physical variables, some information is lost when converting physical magnitudes to exergetic parameters. Consequently, Second Law does not explain the "meaning" of the efficiency (physics or even geometric parameters need to be included instead). In any case, although exergy is built by a set of dependent variables of the thermodynamic model [14] it gives a relevant information for any energy system design, optimization or maintenance.

These advantages enabled the exergy analysis to become the ideal tool to guide efforts related to the improvement of energy efficiency, by reducing irreversibilities. It is a widely used tool at the industry level, so there are numerous references applied to the analysis of industrial processes and power plants such as in PEM fuel cells [15], in a sugar plant [16] or in a drying plant [17]. However, in the building sector the use of exergy analysis is less common although several publications have appeared in recent years and concepts associated with exergy are becoming known, i.e. low-ex buildings.

For instance, some exergetic studies using air-ground source heat pumps can be found in Refs. [18],[19] as well as publications referring to solar thermal collectors [20]. Likewise, work analysing the exergetic performance and implementing it in simulation methodologies have been published, as in the case of a hospital trigeneration system in [21].

The possible causes that can explain the difficulties for exergy use in buildings can be the following ones:

- In systems far from environmental conditions, such as in many industrial applications, fixed standard environmental conditions can be considered without significant loss of accuracy. This is not the case of building services, which operate at relatively near environmental conditions and it is thus essential to consider the effect of changes in those environmental conditions. Therefore, the exergy fluctuates according to the environmental temperature variation as it was analysed in several studies, such as in building services [22], [23], [24] or in a ground-coupled heat pump [25].

- Furthermore, exergy analysis shows the extremely low exergetic efficiencies building services usually have. For instance, a DHW production can have an exergetic efficiency of 3.2-10.8 % [26]; a heating system ranges from 2.5 to 7.4 % [27] or a common air conditioning system is about 3.4 % [28] and that can be considered as bad publicity.

(More information of building systems exergetic particularities is found in [29]).

A.3. ENERGY QUALITY IN BUILDINGS

In buildings, the energy demands have different qualities and the resources to supply them are manifold. Electricity is used for lighting and appliances, whereas other types of high-quality energy are used for indoor heating, cooling and Domestic Hot Water (DHW), such as natural gas or fossil fuels. The electric demand is a high-quality energy in contrast with the heating, cooling and DHW demands. These last ones are low-quality demands because their objective is to keep the indoor air temperature few degrees above or below the ambient temperature. Accordingly, there is not matching between the generation energy quality and the one for conditioning, as clearly exposed in [30]. Consequently, important exergy destructions (quality losses) take place, which are much higher than the energy losses. The Figure A. 2 illustrates the proper way to use energy according to the supplying source.

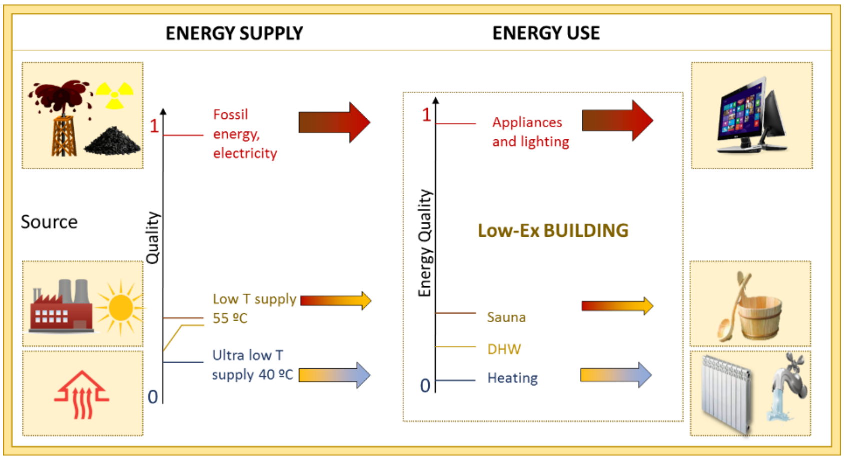


Figure A. 2 Proper use of energy related to the energy supply

The Low-ex building, in contrast to nZEB, takes advantage of the different energy qualities for the different types of energy demands. These buildings reduce the energy losses and exergy destructions. Thus, an increase of the system efficiency means reducing irreversible losses so, ultimately, using energy more efficiently. A work based on building systems exergetic performance is found in [31].

Although the energetic analysis is much common in housing field, exergetic application must be used instead. Such analysis should be carried out for both, building envelope and its facilities. The objective must be to optimize all the stages of the process: starting from the building design, proceeding with the construction and commissioning phases and improving the control and even the maintenance.

A.3.1. Heating and DHW Demands

Over the last several years, the efforts to enhance the energetic performance have been targeted in two main directions: on the one side, the envelope elements are improved (façade, windows, roofs, etc.) while, on the other side, the facilities are upgraded (heating, cooling, ventilation and lighting). However, examining the components individually may reveal not sufficient: the buildings are complex systems that operate as a whole in an integrate manner with the facility, the envelope and the environment.

Managing a facility which supplies energy services for a building (either in the form ventilation, cooling, heating and/or domestic hot water) requires a preliminary assessment of energy loads. Depending on the building type, different specifications should be assured [32], like thermal comfort [2] and indoor air quality (IAQ) [33].

Therefore, the *energy demand* highly depends on the building characteristics, the users' patterns and the local climate. Highly irregular load profiles usually result from the imbalance between energy losses and energy gains [34]. HVAC&R systems aim to encompass those requirements by means of several energy transformation processes. External energy resources are consumed as inputs to the plant, whose amount and related emissions should be limited or, preferably, minimized.

Thereby, the heating energy demand, $\dot{Q}_{heat}$, is the required amount of energy in order to keep the indoor environment in thermal comfort conditions for the users and it is calculated following the ISO 13790 (2008). Referring to the heating period, the total demand is equal to the total losses (transmission through the inertial walls, ventilation and infiltration) minus the gains (solar and internal):

$$\dot{Q}_{heat} = \left(\dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{inf}\right) - \left(\dot{Q}_{g_{solar}} + \dot{Q}_{g_{int}}\right) \tag{A. 1}$$

This balance is accomplished in every building zone and gathered afterwards for the whole building demand calculation. The balance of those thermal zones includes flows of heat and matter, such as ventilation and infiltration, but neither humidification nor dehumidification are regarded.

The exergy demand for heating ($\dot{E}_{heat}$) is calculated on the basis of the heating energy demand and can be defined as the exergy content of this energy, i.e. the minimum amount of work needed to maintain the place in comfort conditions. Accordingly, any excess of exergy supplied will result in utility losses, exergy destructions, between the heating (or cooling) facility and the demand point.

There are two methods for $\dot{E}_{heat}$ calculation: simplified and detailed. Although the first one is mostly utilized, as in [35], the second one will be used instead (and justified with a case study). Both of them are extensively described in Annex 49 [36]. The detailed differs from the simplified one basically because it separates the exergy demand associated with ventilation from the rest. None of them takes into account the chemical exergy and neither considers the small differences between the heat convection exergy and the radiation exergy exchanged between surfaces with small temperature differences.

The main idea of the detailed method is that the quality factor (the relationship between exergy and energy, E/Q) of the *internal energy* of a system at operation temperature (T_{op}) is smaller than the quality factor associated with *heat energy* at the same temperature T_{op}. In this way, in order to determine the exergy demand, it will be necessary to evaluate, first of all, which part of the demand is needed to warm up (or cool down) the ventilation air and, after that, provide the remaining heat in form of heat at the operating temperature.

To sum up, in order to calculate the exergy demand with the detailed method, it should be separated into two components: firstly, the required exergy to temperate the ventilation air coming from the outside and mixed with the inside ($\dot{E}_{vent}$) should be accounted; and secondly, if more exergy demand exists, that quantity must be supplied as heat ($\dot{E}_{heat}$) at the operating temperature (T_{op}). Therefore, the heat demand is split into two separate inputs: one input refers to the preconditioned outside air and the other one to the heat (or cold).

Nevertheless, in any methodology, the exergy demand is verified to be about 10 % of the energy demand, which obviously depends on ambient temperature (T_0) and T_{op}.

The energy demand for DHW supply $\dot{Q}_{DHW}$ is evaluated as a function of the required set-point temperature for DHW use and the demanded mass flow. Likewise, the exergy demand for DHW is evaluated as a function of the required set point temperature and the demanded mass flow, when using the appropriate equation.

A.3.2. Building Thermal Facility for Demand Coverage

The energy supply chain in a building is decomposed in a set of subsystems. Starting from the coverage until the generation, the chain begins with the envelope of the building, continues with the terminal elements, the energy distribution and storage systems, the generation equipment and ends with the energy vectors (fuel, electricity, thermal energy, etc.). The aim is to satisfy the previously calculated comfort demands by transforming the primary, renewable and fossil energy, through the stages of its corresponding energy chain until the indoor requirements are fulfilled, see Figure A. 3.

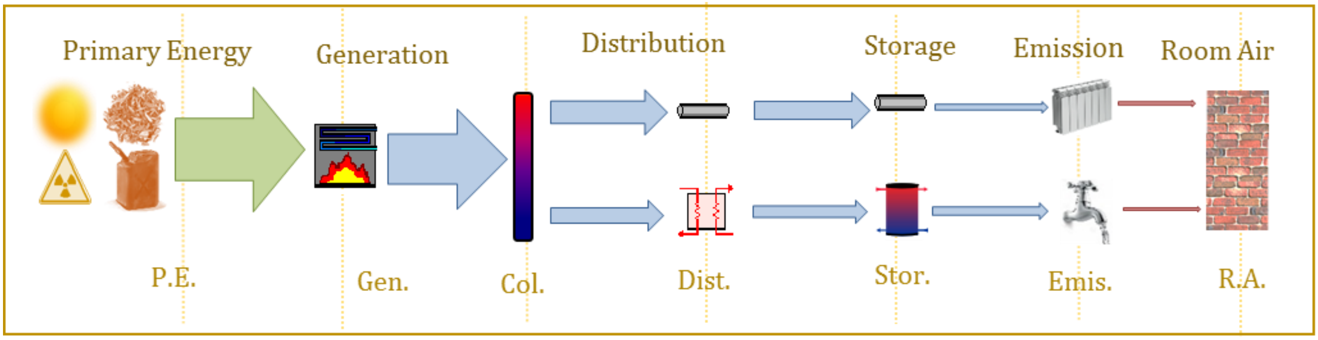


Figure A. 3 Generic energy chain for demand coverage

A.4. CASE STUDY

In order to understand better the benefits and potential of the exergy application, two examples are developed.

The aim of the first one is to show the differences between the energy and exergy performance of the whole energy supply chain of buildings. For that, the whole structure from the primary energy until the demand covering is considered. In this regard, energy and exergy analysis are performed to a recognized nZEB situated in Álava, Spain, (with the Passivhaus certificate) following the First and the Second Law of Thermodynamics trough a yearly dynamic analysis. Some remarks about nZEB shortcomings are also given.

The aim of the second example is to show the improvement in the performance of the whole energy supply chain in a retrofitted heating and DHW facility, by means of exergy analysis. The renovation was only implemented in the thermal facility so that the building energy demands are the same in the old and the new circumstances. The comparison between simplified and detailed exergy method is done too, where detailed one is chosen as the most accurate.

A.4.1. (i) nZEB Building Case Study

The theory was applied to an nZEB to understand better the exergy use in buildings. It is a single-family dwelling with 176 m^2 of net floor area, located in Álava (northern Spain), in a D1 climatic zone. The annual heating demand is less than the limit so it has the Passivhaus certification [37], see Figure A. 4.

Figure A. 4 Single-family house located in Álava

A.4.1.1. Energy and exergy demands

First, a dynamic thermal modelling of the single-family house was performed using the EnergyPlus software and was calibrated with one-year monitoring data [38]. Solar gains, ventilation and transmission losses were adjusted by comparing the results of the model and the monitored data. In this way, the heating demand was hourly obtained according to the balance represented in Eq.(A. 1) where the incoming flows are compensated with the outgoing flows.

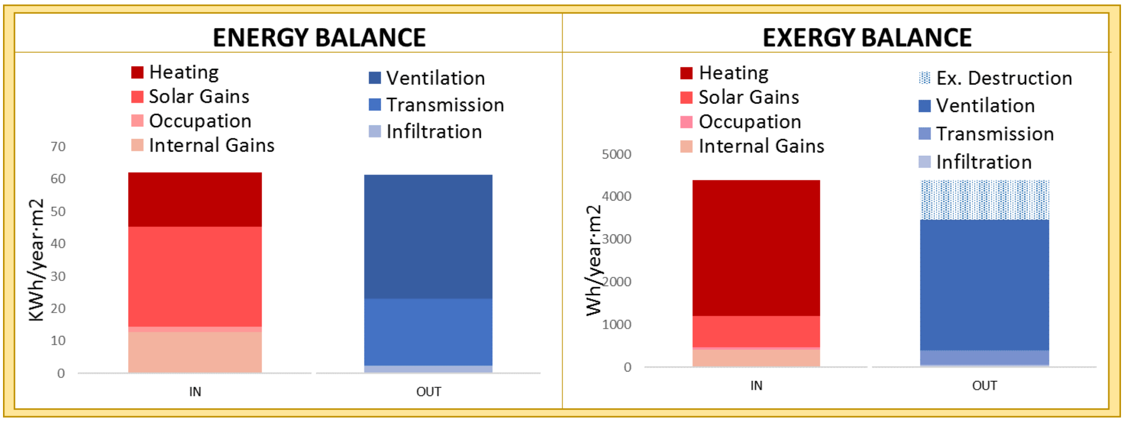


Figure A. 5 (a) Energetic balance of the building. (b) Exergetic balance of the building

The exergy heating demand was calculated following the detailed exergy demand calculation method. Figure A. 5 (a) shows the accumulated annual energy balance per m² and, in contrast, Figure A. 5 (b) depicts the exergy balance.

It is worth noting the enormous difference among those values, as well as the fact that the exergy destruction term is about the 21 % of the total exergy demand. Therefore, considerable improvements can be done to avoid those destructions.

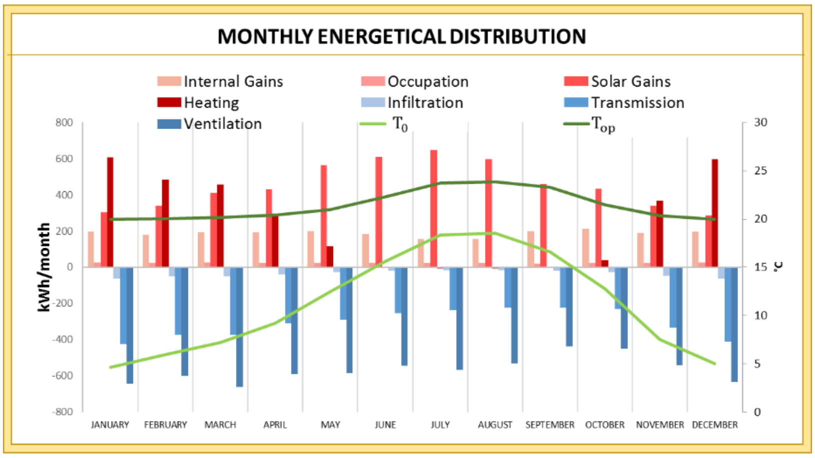


Figure A. 6 Exergy gains and losses every month

In addition to all that, Figure A. 6 shows the monthly energy gains and losses while Figure A. 7 presents those gains and losses in exergy values. In both cases, the outdoor air temperature (T_0) and the indoor operative temperature (T_{op}) profiles were added so that the profile of the demand could be better understood.

It should be noted that the scale of the kWh/month in the exergy graph is 5 times smaller.

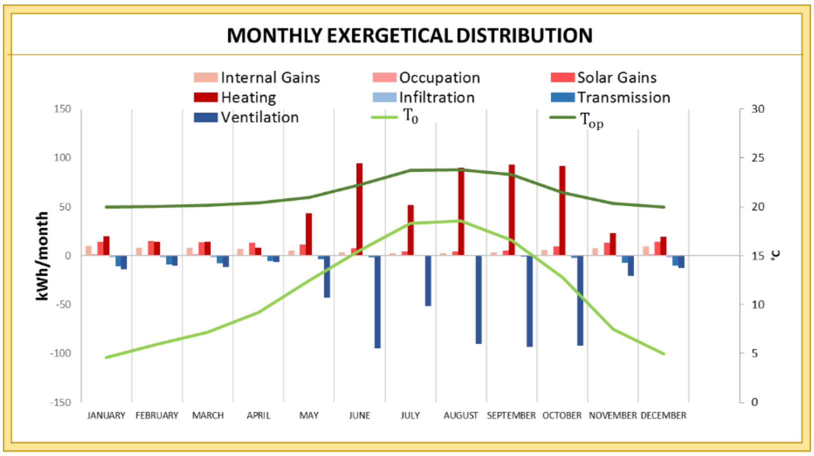


Figure A. 7 Exergy gains and losses every month

In order to show the hourly behaviour, in Figure A. 8 (a) the heating energy and exergy demands are hourly presented. A typical winter day was chosen, namely, February the 15th. In this plot, T_0 as well as the quality factor (the ratio between the exergy and the energy heating demand) were added.

In a similar way, the DHW demand is obtained based on a standard hourly profile defined by IEA-SHC Task26 software [39]. The annual DHW energy demand is 459 kWh/y·pers and the exergy demand is 46 kWh/y·pers. Then, in Figure A. 8 (b) represents the energy and exergy DHW demands for the same day February the 15th as well as the external temperature and the quality factor for DHW.

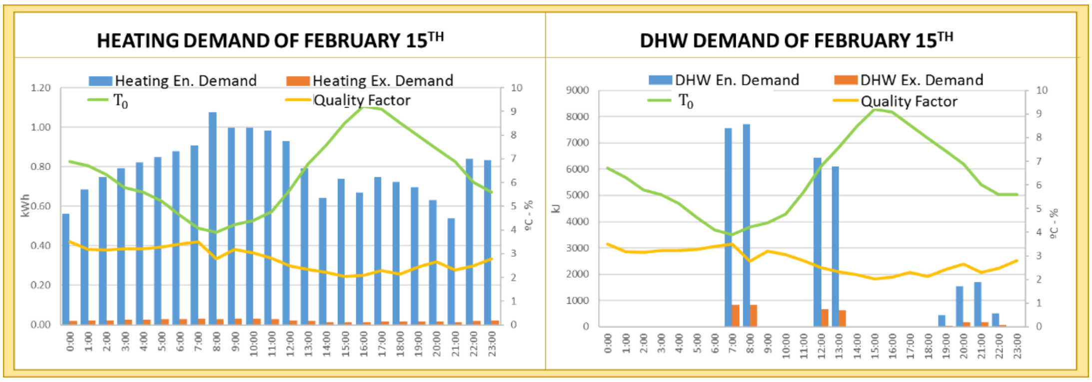


Figure A. 8 (a) heating and (b) DHW Q and E demand for winter typical day

A.4.1.2. Building Thermal Facility for Demand Coverage

The thermal facility consists of a biomass stove (2.4 - 9 kW) for the heating coverage. The domestic hot water (DHW) is obtained by the combination of a solar panel (with a 2.3 m² module and a tank for the solar income) that preheats the water and an air-water heat pump

(3.6 kW) with an internal 300 l DHW storage, see Figure A. 9. The house includes ventilation with heat recovery system and summer bypass and there is no active cooling.

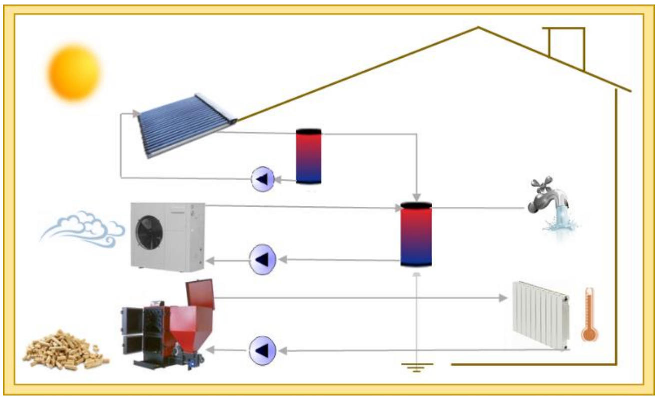


Figure A. 9 Heating and DHW facility of the case study

A.4.1.1. Energy and Exergy Analysis of the Facility

The facility was simulated by means of Trnsys v17 [40]. The various components appearing in the case study were simulated using simplified models available in the software library, which try to represent their real performance as faithfully as possible. In addition, the calculated DHW and the real heating demands were simultaneously inserted. The modelling was implemented for a period of a year with one hour time-step.

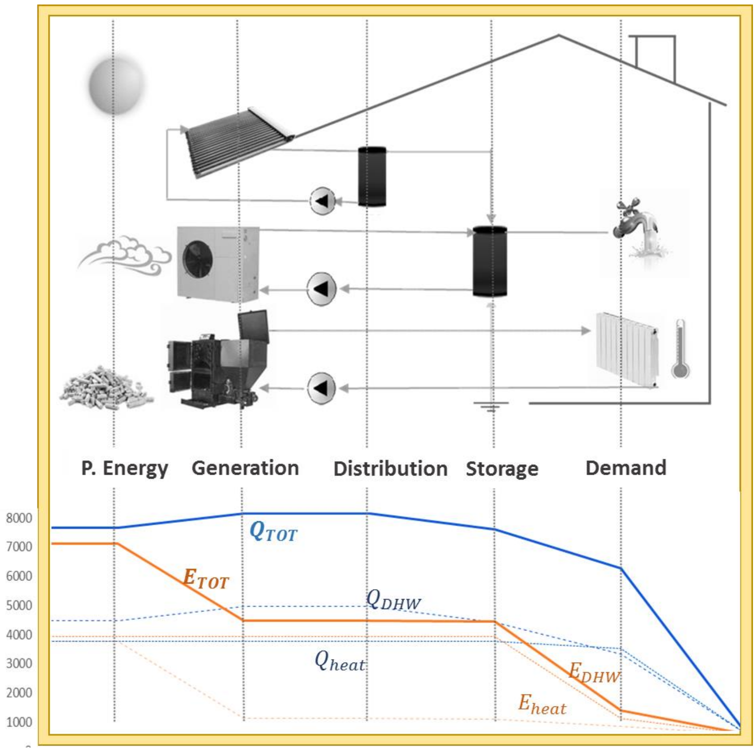


Figure A. 10 Energy and Exergy transformation chain during the thermal facility

After performing the simulation, the thermodynamic data of every flow was extracted and the energy and exergy hourly values were registered. Hence, considering the Q and E yearly accumulated values Figure A. 10 was constructed where five stages were taken into account, moving on from the resource acquisition to the product fulfilling: primary energy, generation, distribution, storage and demand.

The blue line of Figure A. 10 illustrates the energy transformation chain whereas the orange one symbolized the exergetic one. Likewise, the full lines allude to the total results (Q_{TOT} and E_{TOT}), the dotted lines represent the DHW (Q_{DHW} and E_{DHW}) circuit, while the blinking ones refer to the heating branch (Q_{heat} and E_{heat}). This is a decisive graph in order to understand the quality of the energy used to provide the demand; as it can be observed, the exergy curve is notably lower than the energy one.

It may appear strange the opposite direction the Q_{TOT} and E_{TOT} lines have between the Primary Energy and Generation transformation phase, as the first one goes upwards and the second's tencency is downward. This is because, in this stage, the heat pump's coefficient of performance (COP) is considered. That value is determined by the ratio between the heat extracted from the condenser of the unit and the energy usage of the compressor. For instance, a COP value of 3 means that the consumption of 1 kW of electrical energy releases 3 kW of heat at the condensor. Therefore, it is always a factor higher than the unit.

However, if the quality factor of the energy is considered (that is, the exergy amount), the value would radically decrease. This happens because electricity is pure exergy and only a part of heat energy can become in useful work, so that, by definition, the exergetic efficiency will be always less than one. In this example, whereas the yearly average COP of the heat pump is 2.85, the exergetic efficiency is $\varepsilon_{HP} = 0.28$.

Something similar occurs with storage units: as the only losses considered in energy analysis are the thermal losses, their efficiencies are close to the ideality of 100 % (as it is the case of adiabatic tanks). Nevertheless, the irreversibilities occurring due to the mixing of flows at different temperatures are not contemplated there, as it happens in the cases of cold water flow mixing with the tank's hot water. In this example, the yearly average energy efficiency of the DHW storage tank is $\eta_{T1} = 81$ % and the exergetic efficiency is $\varepsilon_{T1} = 54$ %.

Likewise, the simple observation of the exergy profile E_{TOT} indicates where the greatest exergy destructions occur: during the transformation from primary energy to the warming up of the circuit and from the tank output to user's final demand. Similarly, the large-scale differences between exergy and energy are shown.

A.4.1.2. Results Discussion

The yearly heating demand amounts $Q_{heat} = 2.96\ GWh/y$ and the yearly DHW demand is $Q_{DHW} = 2.76\ GWh/y$. Translated into exergy values those demands are $E_{heat} = 0.56\ GWh/y$ and $E_{DHW} = 0.27\ GWh/y$ respectively, being evident the low quality factor of both. The energetic performance of the heating circuit is $\eta_{heat} = 93$ % and the exergetic efficiency $\varepsilon_{heat} = 17$ %. Meanwhile, the DHW generation circuit efficiencies are $\eta_{DHW} = 71$ % and $\varepsilon_{DHW} = 9$ %.

All in all, the overall energy performance of the whole facility is $\eta_{TOT} = 81$ %, whereas the exergetic efficiency is $\varepsilon_{TOT} = 13$ % as the energy conversion irreversibilities are now accounted.

As a result, even being a nZEB, energy saving enhancements can be accomplished as long as the energy quality is considered in both, the building thermal envelope and the thermal facility. A reduction of the exergy resource consumption implies that less high quality energy is needed and, thus, low quality energy sources can be used instead (such as residual heat) to cover the demand. Such information can only be acquired through Second Law application.

A.4.2. (ii) Building Retrofit Case Study

This second case study refers to four dwelling blocks with a common heating and DHW supply system. Those blocks located in northern Spain, Bilbao, were built in the 70s; one block (I) has 190 residents, two of them (identified as II and III) have 108 residents each and the fourth one (block IV) has 160, see Figure A. 11. The energy supply system has been recently retrofitted and the boilers and circulating pumps have been removed as it is explained later on.

Figure A. 11 Four blocks case study

The four buildings have the same structural characteristics, see Table A. 1.

Table A. 1 Structural characteristics for the blocks

STRUCTURAL CHARACTERISTICS		
Group	**Description**	**Transmittance**
Façades	Double brick walls with no insulation	1.68 W/m^2K
Flat roof	Treated with thermal insulation & protected with waterproof cement mortar	1.51 W/m^2K
Windows	Original outside frames were wooden made & windows were monolithic. Over time some were replaced with better thermal performance ones	2.89 W/m^2K

The energy performance of the buildings has been analysed by means of the dynamic simulation tool Trnsys v17. The building model is based on the multi-zone building component with energy balance in each zone; all the architectural properties and thermal characteristics of materials can be faithfully represented. More details can be found in the Trnsys User Manual where a mathematical description of the models and the energy balances are presented.

The weather data were introduced on an hourly basis in the simulation so the heating demand is also calculated hourly. Bilbao's weather data were taken from Meteonorm software [41] which provides the yearly data based on the last 30 years of weather data averages. To define the simulation condition (ventilation, infiltrations and thermal gains), the values of Appendix C of the Technical Building Code HE1 were adopted [42]. A 20 °C thermal comfort temperature was considered and the night setback was regarded from 11 p.m. to 6 a.m. allowing a temperature drop of 4°C during those hours. The heating timetable is from November 1st up to April 30th and the heating is turned on when the outside temperature is below 15 °C or when the average temperature of the last eighteen hours is less than 15 °C. Consequently, the heating demand follows a typical profile of Northern Spain dwellings [43].

DHWcalc tool was used for the calculation of the DHW [l/h] demand. The program distributes DHW draw-offs throughout the year by statistical means. Thus, considering the number of dwellings in every block and therefore the number of inhabitants, the DHW demand profile for an entire year was hourly extracted, being the DHW provided at 55 °C. Figure A. 12 represents the annual demand for heating and DHW.

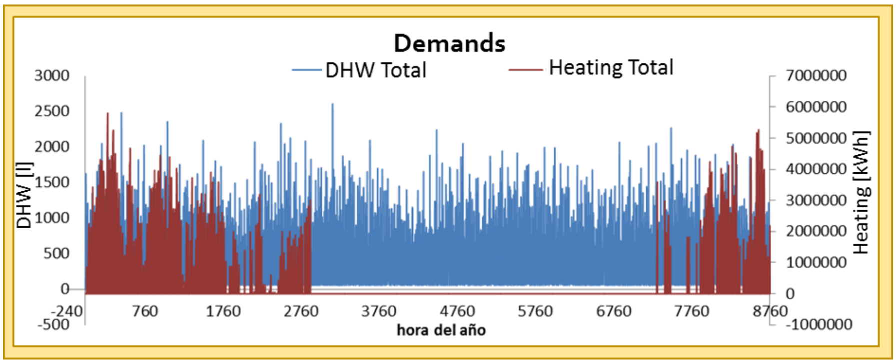


Figure A. 12 Total heating demand [kJ/h] and DHW demand [l/h] during the year

A.4.2.1. Energy and exergy demands

The yearly energy balance is depicted in Figure A. 13. Losses, represented in the right column, are heat transfer from the building envelope, $\dot{Q}_{trans}$ ($965\ MWh$); sensible heat losses from ventilation air, $\dot{Q}_{vent}$ ($410\ MWh$) and losses owed to uncontrolled flow of air through cracks in the building $\dot{Q}_{inf}$ ($332\ \ MWh$). Conversely, the gains are due to solar gains $\dot{Q}_{sol}$ ($386\ MWh$) and internal gains $\dot{Q}_{int}$ ($312\ MWh$), which are depicted in the left part of Figure A. 13. Additionally, the vertical green arrow stands for the required yearly heating demand ($1{,}009\ MWh$).

Once the heating demand has been calculated, the exergy demand ($\dot{E}_{heat}$) is obtained according to the simplified and the detailed approach. The results obtained by both methods are shown in Figure A. 14. As recommended in [36] the surrounding outdoor air has being taken as the reference environment (T_0).

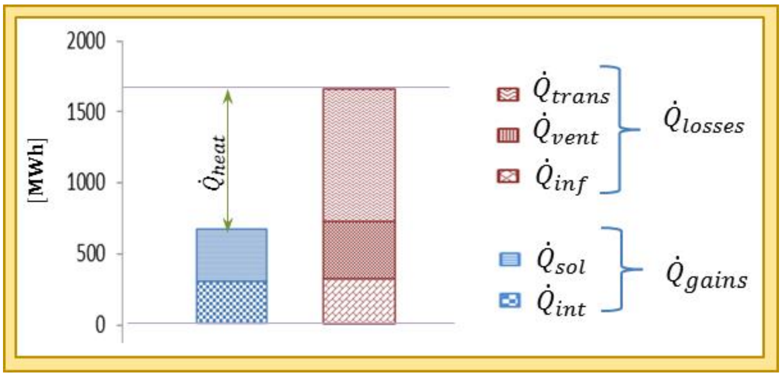


Figure A. 13 Energy balance

The yearly exergy demand obtained by the detailed approach (26,804 kWh) is significantly lower than the value obtained by the simplified approach (33,074 kWh). This is explained as ventilation and infiltration losses are larger than the net heat demand, due to solar and internal gains, and as a result, ventilation air does not need to be preheated to the interior temperature but to a lower temperature that varies according to each hourly thermodynamic characteristic.

Besides that, as justified in [36], the closer the operative temperature (T_{op}) is to the environment's temperature the bigger the difference is between the simplified and detailed approach. Consequently, the detailed method is applied from now on in the research.

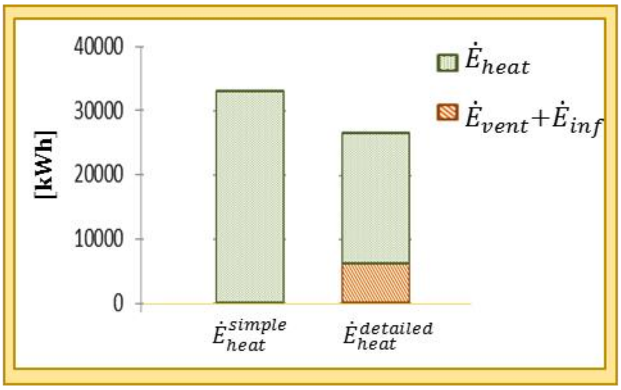


Figure A. 14 Exergy balance

In Table A. 2 the yearly heating and DHW demands in energy and exergy terms are presented. As shown in energy terms, DHW represents 28.1 % of the heating demand, whereas in exergy terms that percentage increases to 69.2 %.

Table A. 2 Yearly energy and exergy DHW and heating demands

	DEMAND $[MWh/y]$	
	DHW	HEATING
Energy	284	1,009
Exergy	18	26

A.4.2.2. Building Thermal Facility for Demand Coverage

Driven by current building regulations, building energy retrofit is largely reliant on maximizing thermal efficiency of the building's envelope before heating system improvements are introduced.

During this case study, conversely, due to the problems of the old heating installation and the lack of resources, the neighbourhood community decided to proceed with the heating installation improvements first. For this reason, as the envelope was not enhanced, the heating and DHW demands remained the same while the energy supply system was renovated. The changes done are described below.

① There were three *fuel oil* boilers in the old facility, two 2325 kW boilers and one of 1162 kW. Those boilers have been replaced with natural gas boilers, two low-temperature boilers of 1900 kW each and a 1150 kW condensing boiler ② provided with a heat recovery heat exchanger that condenses the combustion exhaust gases.

The hydraulic circuit of both facilities, the old and the retrofitted one, is the same. The boilers are connected to the distribution circuit by means of a hydraulic collector whose aim is to separate the heating and the DHW circuits. The heating distribution is branched into four hydraulic circuits, one for covering the heating demand of each block. The DHW distribution is split into two branches: one goes to the lower floors and the other one supplies the DHW demand to the higher floors. Likewise, the lower floor's circuit contains two 3500 l storage tanks and the higher floors have one 4000 l storage tank.

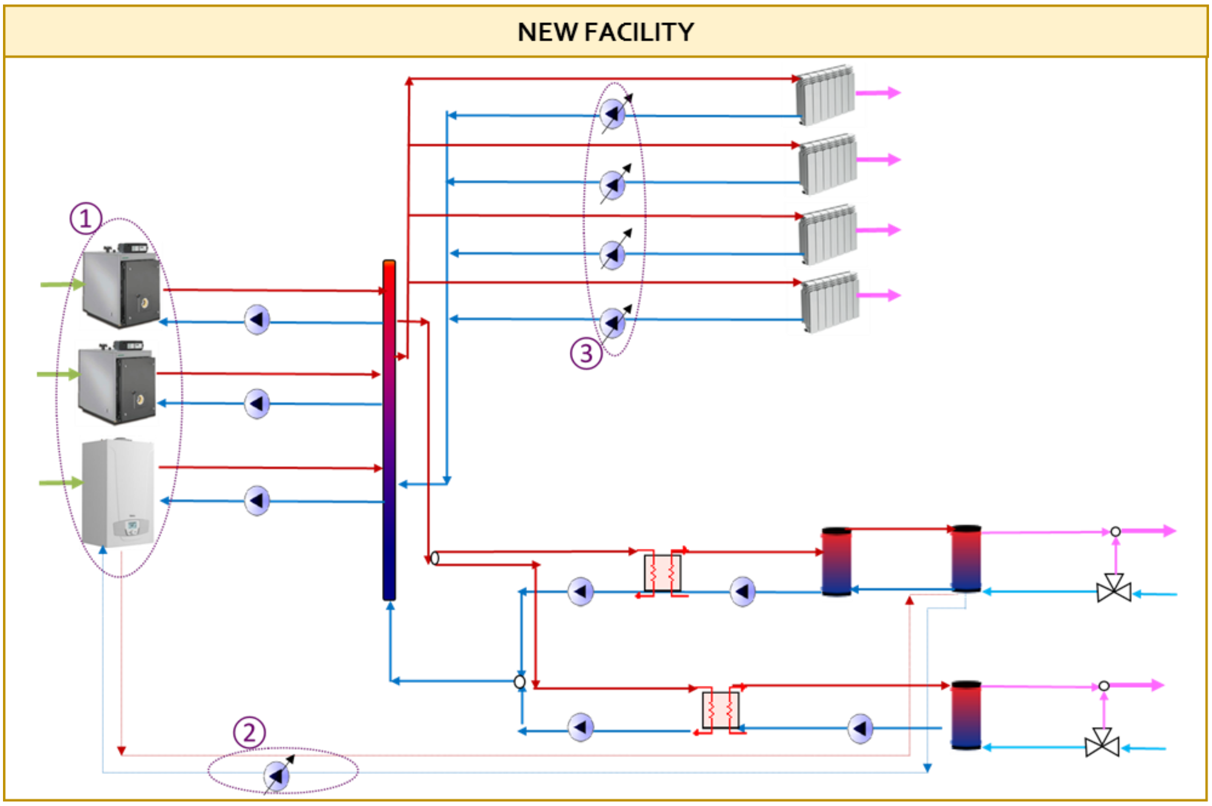
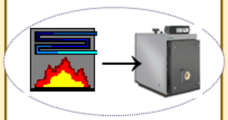
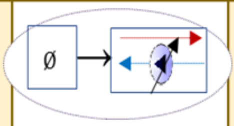
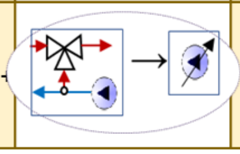


Figure A. 15 Scheme of the New facility. Renovations are highlighted with purple circles

③ The circulating pumps in the old circuit were constant flow pumps while the new ones are variable speed pumps. This means that the old heating circuit branches were provided with 3-way valves in order to match the heating temperature to the requested set point. The retrofitted facility takes advantage of the new pumps variability so the 3-way valves are avoided.

Figure A. 15 depicts the new facility where, additionally, the renovations are highlighted with purple dotted circles, besides Table A. 3 summarizes the enhancements from the old one.

Table A. 3 Summary of the renovations

	RENOVATIONS IN THE FACILITY		
	OLD		NEW
①	Fuel Oil boilers		Gas Natura Boilers
②	Ø		Heat Recovery HX
③	Constant flow pumps for heating + V3V		Variable speed pumps

The master control of the facility can be outlined as follows: DHW takes precedence over heating and DHW is enabled during the whole year whilst heating is turned on during the heating period. The storage tanks are continuously monitored to be at a temperature beyond 60 °C in order to avoid legionella. If during the heating season the temperature in the collector is lower than 60 °C, the boilers are switched on following a cascade control.

The conventional energy transformation phases in the building facility are graphically depicted above in Figure A. 3 of **Section A**.3.2. As can be seen, it is divided into the following layers: primary energy (P.E.); heat generation (Gen.); collector (Col.); heat distribution and DHW primary circuit (Dist.); heat distribution and DHW storage system (Stor.); heating emission and DHW supply (Emis.); room air (R.A.) and envelop (Env.).

A.4.2.3. Energy and Exergy Analysis of Both Facilities

The two facilities have been simulated during a year with a 0.5 h time-step, according to the demand calculated in the previous section, $\dot{Q}_{TOT} = \dot{Q}_{heat} + \dot{Q}_{DHW}$. Those simulations enable the gathering of the thermodynamic parameters needed to calculate the energy and exergy of all flows.

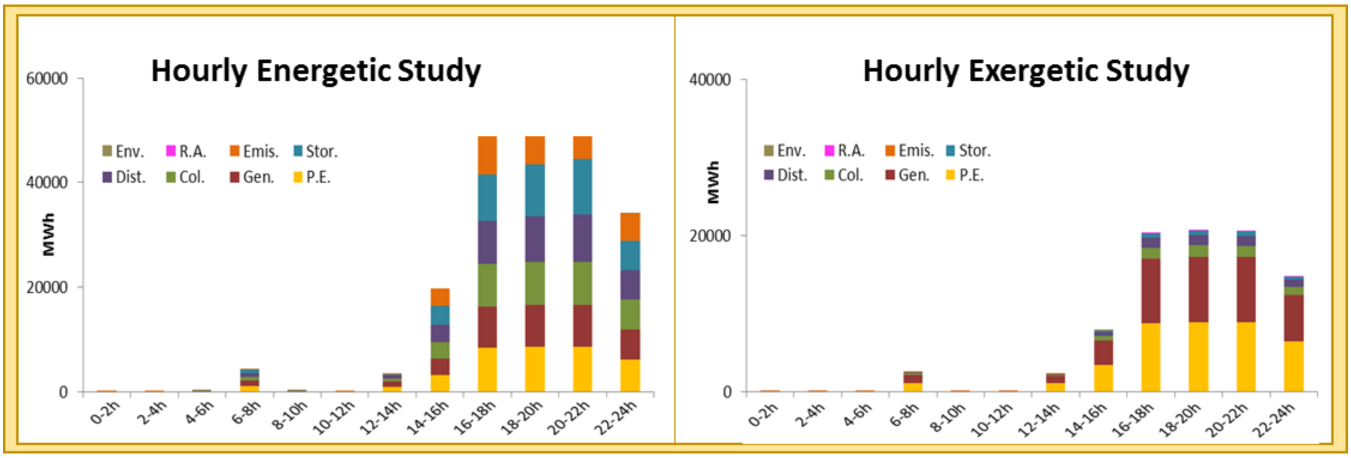


Figure A. 16 Hourly study of February the 5th of (a) energetic transformation chain & (b) exergetic transformation chain

The study has been dynamically processed and afterwards the annual values were accumulated. Owing to the huge number of data, only the hourly energetic and exergetic study corresponding to the 5th of February has been depicted in Figure A. 16 following the same layer structure as the rest of the graphics.

In Table A. 4 (a), the annual energy and exergy values of primary resource input, the energy and exergy inputs and outputs and the efficiencies of the main sections as well as the constituent components are displayed for the old facility, whereas in Table A. 4 (b) those values refer to the new facility. Both tables are subdivided in the layers represented in Figure A. 3, and the highlighted box in new facility reflects the extra input coming from the condensing boiler recovery system. The coefficients used to obtain the primary energy are 1.12 for fuel oil and 1.07 for natural gas, whereas the quality factor coefficients are 1.07 and 1.04 respectively.

Likewise, Figure A. 17 has been built in order to pictorially summarize all the information. This is an overview which allows both the comparison between energy and the exergy conversions and the distinctiveness among the old and the new facility. These graphs are divided into the same layers as the above tables and Figure A. 3.

By contrasting the energy behaviour of the old and the new facility the following can be concluded:

- A 35 % primary energy savings has been reached with the refurbishment, not only because the natural gas has replaced the fuel oil, but also because the new boilers have a better energy performance. Moreover, contrary to the oversized old facility, where the second boiler was always turned off, the three boilers now intervene in heat production (see *P.E.* row in Tables).
- In the heat distribution system, higher losses appear in the old facility (see their *Dist. Heat* performance in Table A. 4 (a)). This is because 3-way valves are modulating when following the demand, instead of the variable flow pumps which are in the new facility.
- The DHW tank's performance is also enhanced due to the extra heat inserted by the HR (see the highlighted box in Table A. 4 (b)) and the arrow in Figure A. 17).

Table A. 4 Annual energy and exergy values of the (a) old and (b) new facility

		(A) OLD FACILITY					
		ENERGY [kWh]			EXERGY [kWh]		
		Q_{out}	Q_{in}	η %	E_{out}	E_{in}	ψ %
P.E.	B1	2108	2361	-	2255	2526	-
	B2	-	-	-	0	0	-
	B3	89	99	-	95	106	-
Gen.	B1	1791	2108	85	334	2255	15
	B2	-	-	-	0	0	-
	B3	75	89	85	13	95	14
Col.	C	1858	1867	100	313	347	90
Dist. Heat	H1 br.	398	581	68	16	96	16
	H2 br.	142	205	69	6	34	16
	H3 br.	122	206	59	5	34	14
	H4 br.	408	546	75	16	90	18
Dist. DHW	HX1	185	185	100	26	33	80
	HX2	134	134	100	23	26	90
Stor.	T1+T2	166	185	90	14	624	2
	T3	125	134	93	12	23	52
Emis. Heat	H1	386	398	95	13	16	80
	H2	135	142	95	4	6	77
	H3	116	122	95	4	5	78
	H4	388	408	95	13	16	79
Emis. DHW	DHW L	164	166	99	10	14	74
	DHW H	120	125	97	8	12	64
R.A.	Block I	386	386	100	10	13	83
	Block II	129	135	96	3	4	76
	Block III	111	116	95	3	4	74
	Block IV	383	388	99	10	13	83
Env.	Heat	698	1009	69	0	27	-

		(B) NEW FACILITY					
		ENERGY [kWh]			EXERGY [kWh]		
		Q_{out}	Q_{in}	η %	E_{out}	E_{in}	ψ %
P.E.	B1	271	290	-	282	302	-
	B2	124	133	-	129	138	-
	B3	1041	1113	-	1082	1158	-
Gen.	B1	255	271	94	42	282	15
	B2	117	124	94	20	129	16
	B3	1032	1041	99	174	1082	16
Col.	C	1344	1347	100	199	226	88
Dist. Heat	H1 br.	411	412	100	17	60	29
	H2 br.	142	142	100	6	21	29
	H3 br.	122	123	100	5	18	29
	H4 br.	408	408	100	17	59	29
Dist. DHW	HX1	127	127	100	17	19	89
	HX2	129	130	99	20	21	92
Stor.	T1+T2	164	184	89	13	28	49
	T3	121	129	94	10	20	52
Emis. Heat	H1	391	411	95	13	17	73
	H2	135	142	95	4	6	71
	H3	116	122	95	4	5	71
	H4	388	408	95	13	17	73
Emis. DHW	DHW L	164	164	100	10	13	77
	DHW H	120	121	100	8	10	75
R.A.	Block I	386	386	99	10	13	83
	Block II	129	135	96	3	4	76
	Block III	111	116	95	3	4	74
	Block IV	383	388	99	10	13	83
Env.	Heat	698	1009	69	0	27	-

By contrasting the exergy behaviour of both facilities, the following comments can be made:

- Huge irreversibilities are encountered in the heating production system (see the low exergetic performance of boilers in tables and the low value of the *Gen.* layer in Figure A. 17). This emphasises the idea of the strong irreversibilities that take place in the mixing, combustion and heat transfer processes in the boilers.
- Even if the heating radiators' system has an energy efficiency of almost 95 %, its exergetic efficiency is substantially lower (~71 %). There are also big exergy destructions in the air room (~77 %) because the operating temperature is sensibly lower than the average surface temperature of the radiators' system.
- The exergetic performance reduction in DHW tanks is also remarkable because not only the exergy losses associated to heat losses are considered but the irreversibilities arising from flow mixtures inside the tanks as well (see the exergetic efficiency in *Stor.* box in Table A. 4 (a) and (b)).

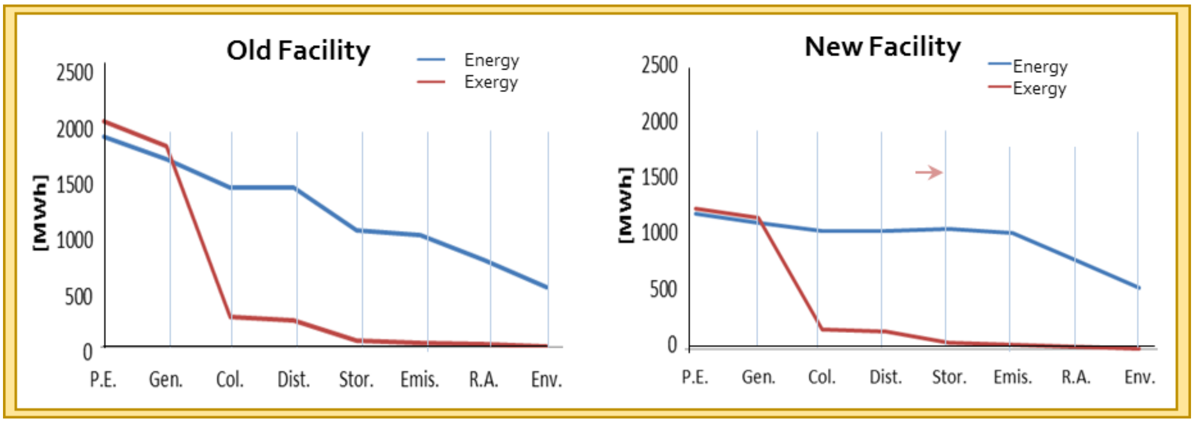


Figure A. 17 Energy and exergy flow diagram in the old and the new facility

A.4.2.4. Results Discussion

The heating and DHW energetic and exergetic demands have been calculated, having identified the detailed exergetic demand method as more appropriate than the simple one due to the big losses associated with ventilation and infiltration.

The exergy analysis shows the improvement achieved with retrofitting, going from a 2.55 % yearly average exergy efficiency of the old facility to a 4.01 % value for the retrofitted one (the energy performance raises from 59.90 % to 91.64 %). As expected, the biggest irreversibilities are encountered in the boilers that account for 81 % of the total exergy destruction. The heating distribution and emitters also have high irreversibilities and they amount to 11 %.

Therefore, even having acquired some enhancements through rehabilitation and according to the low exergy efficiency, there are still great improvement possibilities: better connection should be done between the generation and demand energy quality. Such information is revealed thanks to the Second Law application.

A.5. CONCLUSIONS

The building sector is responsible for almost a third of the total energy consumption over the world and this justifies the great concern for the improvement of their energetic efficiency. For this reason, great advances have been prompted in energy regulations during the last decade; moreover, the Directive 2010/31/UE already lays down a broad definition of a nZEB and establishes the 31st of December of 2020 as the deadline for making all new buildings nZEB. Nevertheless, it allows the Member States (MS) to draw up national plans for increasing the number of nZEB and, undoubtedly, this is the first step towards the positive energy building.

Besides that, the EED 2012/27 /EU establishes the exemplariness of public buildings. Therefore, from 1st of January 2014, the 3 % of the heated and refrigerated surface of occupied public buildings must be renewed each year, so that the rehabilitated buildings meet at least the minimum efficiency required by each MS.

In that context, many authors have worked in the optimization and design of thermal systems for buildings but, unfortunately, most of them were done from a purely energetic point of view.

The conventional energy studies are based on the First Law of Thermodynamics. This type of analysis is confined to a simple energy accounting, which quantifies the energy inputs and outputs of a system and particularly of a building. In this way, the energy given to the processes through fuels, electricity, flows of matter, and so on, must appear into the final products or by-products. Under this perspective, energy losses are simply the not used heat flows. Thus, the analysis based on the First Law suggests that the loss of efficiency of an equipment or a process is a consequence of those waste heats.

There are currently different ways to state the energetic efficiency of a system or component based in this First Law and none of them takes into account the quality of energy. Thus, with those efficiency definitions the same weight can be assigned to different forms of energy, regardless of their quality. Correspondingly, this conveys some drawbacks, for example, the fact that the performance of the Carnot engine is the Carnot-factor instead of the unit (which is what one expects for the perfect engine); or even the point that the heat pumps efficiency is expressed through the COP (an index always greater than unity), and so on. Furthermore, large thermoelectric plants, which are regarded among the most efficient energy conversion systems, have low performances (between ~40-55 %); while typical individual hot water boilers, which are thermodynamically much less efficient devices, appear to have higher performances (~90 %), a fact that seems contradictory.

By contrast, the exergy based efficiencies describe better the way in which the resources are used and provide a clearer guidance about the possible improvements. Both, the exergy destruction and the entropy production, are valid measures for the irreversibility of a process. However, the use of entropy makes difficult to assign a meaning to the loss due to the encountered irreversibilities. On the other side, the exergy method allows assessing directly the real losses of a process, that is, it evaluates the decrease in the available work because of the process transformation irreversibilities and it serves as a key tool for systems comparison. Accordingly, the irreversibilities measure the system inefficiency and the exergy method quantifies them and identifies their location, either for system synthesis or for rehabilitation.

Thus, according to the benefits coming from exergy application, such analysis is justified as a useful tool for achieving the required energy savings in buildings. Moreover, and considering the goal of this thesis, the deeper analyses based on exergy (Thermoeconomic cost accounting and diagnosis) facilitate to allocate the weaknesses points and to improve the proper use of energy in order to decrease not only the consumption but also the economic costs and emissions to the environment.

That is, in fact, the motivation for applying for the first time an accurate Thermoeconomic dynamic analysis in buildings energy systems.

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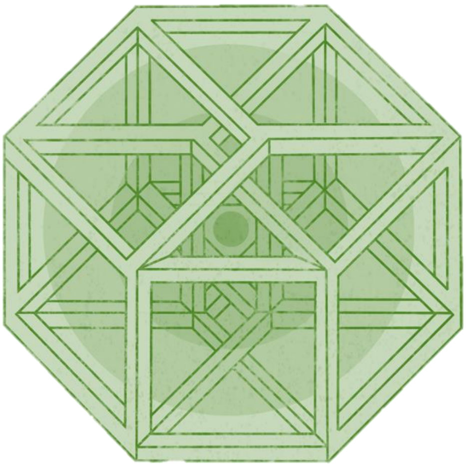


CHAPTER B

Building dynamic representation

CHAPTER B

SUBSCRIPTS	
DHW	Domestic hot water
$Heat$	Heating
TOT	Total
0	Ambient
lat	Latent
Dep	Dependent
Ind	Independent

SUPERSCRIPTS	
Tr	Trnsys
Re	Real
$Calc$	Calculated

SYMBOLS		
T	[ºC]	Temperature
$\dot{m}$	[kg/s]	Mass flow rate
RH	[%]	Relative humidity
$\dot{Q}$	[kJ/s]	Heat flow
LL	[*][1]	Low limit
HL	[*]	High limit
η	[%]	Energy efficiency
$\bar{x}$	[*]	Operation variables
$\bar{\tau}$	[*]	Design variables

[1] [*] = units of the corresponding variable

CHAPTER B: BUILDING DYNAMIC REPRESENTATION

B.0. ABSTRACT

This is a short chapter based on energy system modelling. Even not requiring exergetic point of view, the thermal model is the essential former stage for any Second Law application, since all the results depend on the quality of such representation.

Because buildings are permanently changing over the time, dynamic models are imperative. Two innovative methods are developed in order to overcome two typical situations: the first one refers to the thermal system virtual construction according to the building requirements; in other words, the building exist but not the facility (or its data is not available). The second one, by contrast, is associated with the system modelling in reference with the tested registered data. Both methodologies are outlined by means of examples.

B.1. INTRODUCTION

It is commonly known that the thermodynamic behavior of a system is represented by the so called thermal model acquired merely from the mass and energy balances. That representation is a key step since it is not only the basis for any thermodynamic study but also the route for exergetic cost accounting as well as the previous step for diagnosis implementation.

Since the behavior of HVAC&R systems is not stationary, it is necessary to use dynamic models to get reliable results. This requirement is particularly important in systems using renewable energies where storage capacities are necessary to guarantee the user's needs when the source is not available. Besides, the system configuration (the activation and deactivation of components) is continuously changing due to different user's needs because of the permanently variable ambient conditions.

Among others, two main situations can emerge: (1) the energy supply system does not exist (or data is not available) so its design and corresponding model have to be constructed for covering the dynamic demands of a specific building or (2) the facility exists and (some) dynamic data can be extracted from the monitored system. The first case needs a dynamic simulation while the second one requires a dynamic characterization. As said, the result of both cases ends with the thermal model representation in order to acquire, in each time-step, the proper thermodynamic data.

B.2. BUILDING DYNAMIC SIMULATION

This first part explains the dynamic assessment procedure when the building energy supply system needs to be virtually designed and also its corresponding model. It is a simple alternative since system *design* is a large field which is not the aim of this research.

B.2.1. Methodology for the simulation

Figure B. 1 depicts the workflow for the application that it is here bellow detailed:

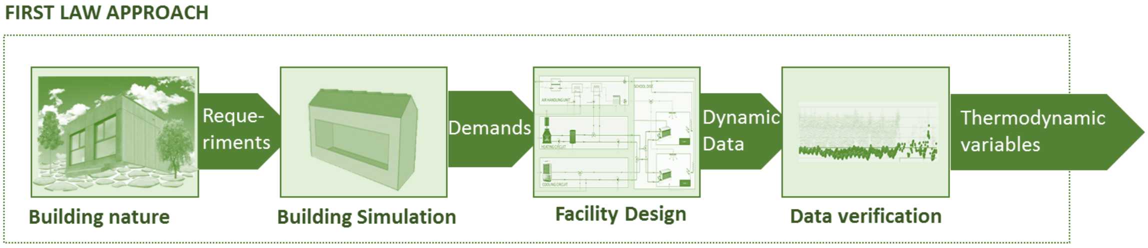


Figure B. 1 Workflow for dynamic simulation in buildings

1. *Building nature*. An accurate design of HVAC&R facilities in buildings requires the preliminary collection of details about area, climate, building type, envelope, occupant's behavior, etc.
2. *Building simulation*. Such a set of data enables the analyst to develop a dynamic simulation model of the building to obtain the demands.
3. *Facility design*. After that, a design of a HVAC&R configuration capable to supply the required energy services can be assessed by defining technical features and control strategy (including set points adopted for space heating, cooling and ventilation).
4. *Data verification*. By developing a Trnsys model and simulating it, data can be extracted and validated (i.e. checking the control performance, confirming set-points adjustment and comfort conditions, etc.).

The proposed methodology will be applied in a public construction in order to consider the restrictive heat, DHW and cold demands to maintain the air indoor quality (IAQ). In such way, the validity of the method is verified.

B.2.2. (iii) School's AHU Case Study

The building corresponds to a school in Palermo (Italy) and is constituted by 6 classrooms, all of them gathered in the ground level, see Figure B. 2. Being a state educational structure, the IAQ must be verified as well as indoor comfort temperature and humidity. To ascertain those requirements, an air-handling unit supported by fan-coils additional terminals is created.

Figure B. 2 Picture of the case study building

B.2.2.1.1. Building nature

As mentioned, the first step deals with an exhaustive analysis of the building requirements to select the suitable equipment for comfort supply.

Consequently, the building structural characteristics and environment features were defined in Trnsys ([1] Transient System Simulation Tool) TRNBuild interface. Having a symmetric architecture, the school was divided into two thermal zones: each of them contains three classrooms, holds 6300 m^3 of the total volume and has a capacitance of $7560 kJ/K$. Besides, one window is disposed in every zone; the first one is oriented to south face while the second one is directed to the north. In Table B. 1 the main physical and thermal characteristics of the different walls and window designs are specified.

Table B. 1 Thermal and structural characteristics of building walls and windows

WALL TYPE	LAYER	THICKNESS	
IntWall	gypsum	0.012	m
	insulation	0.05	m
	gypsum	0.012	m
	U-value	0.652	W/m²K
	Surface	210	m²
OutWall	brick	0.24	m
	insulation	0.1	m
	plaster	0.015	m
	U-value	0.339	W/m²K
	Surface	210	m²
Roof	Concrete	0.24	m
	insulation	0.16	m
	U-value	0.233	W/m²K
	Surface	900	m²

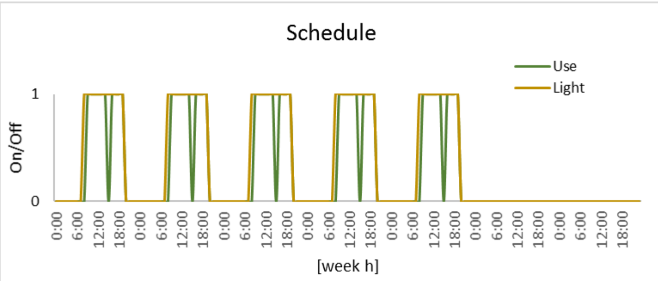
WALL TYPE	LAYER	THICKNESS	
Ground	floor	0.05	m
	stone	0.06	m
	silence	0.04	m
	concrete	0.24	m
	insulation	0.08	m
	U-value	0.313	W/m²K
	Surface	900	m²
IntFloor	floor	0.05	m
	stone	0.06	m
	silence	0.04	m
	concrete	0.24	m
	U-value	0.834	W/m²K
	Surface	900	m²

WINDOW	LAYER	THICKNESS	
Double	Zone 1	NORTH	
	Zone 2	SOUTH	
	U -value	0.4	W/m²K
	Surface	105	m²

The internal gains were inserted according to the building usage: lighting is turned on during the weekdays from 8 a.m. until 7 p.m.; students (25 per classroom) arrive at 9 a.m., have lunch from 2-3 p.m. and finish lessons at 7 p.m.; computer (1 per room, 6 in total) are switched on while people are inside; such information is outlined in Table B. 2.

Table B. 2 Internal gain type and schedule

INTERNAL GAINS	TYPE	SCHEDULE
People	ISO 7730	75 · USE
	Seated, light work, typing	
Computer	140 W PC + monitor	3· USE
Light	Artificial	75·LIGHT



A Weather Data Processor introduced Palermo's weather data taken from Meteonorm [2]. Figure B. 3 depicts the temperature (T) and relative humidity (RH) of the city according to the typical meteorological year; nevertheless, only the operating-time data are there shown, i.e. night or weekend values are not reveal.

Accordingly, the outside average temperature and relative humidity during the turn on period of heating time (1st Nov.-15th May) is 14 ºC and 68 % and of cooling time (16th May-31th Oct.) is 23 ºC and 76 %.

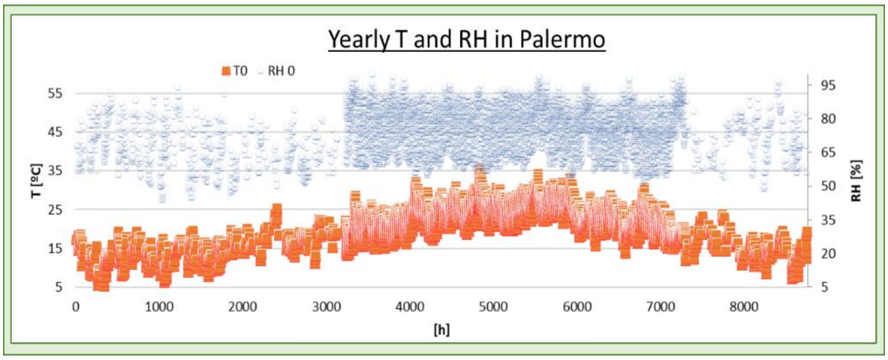


Figure B. 3 Palermo's yearly temperature and Relative Humidity (Meteonorm data)

B.2.2.2. Demand accounting

Before inserting any facility, equipment or control, the building demands must be estimated. To begin with, thermal comfort requirements (only temperature and humidity constrains) were firstly obtained and, after, in a second simulation, the air quality requisite was implemented (i.e. the minimum ventilation rate).

As a result of the first stage, Figure B. 4 (a) shows the assumed heating (HeatingDemand) and cooling (CoolingDemand) monthly demands to maintain the indoor temperature at 21 ºC on winter time and 25 ºC on summer period. Monthly average outside temperature (To) and zone mean temperature (Tzone) are also displayed. Likewise, monthly latent demand (LatentDemand) is plotted in Figure B. 4 (b), which corresponds to the amount of latent heat required to overcome only the internal gains to maintain at 60 % the indoor relative humidity (HRzone); outside monthly average relative humidity is represented (HRo) too.

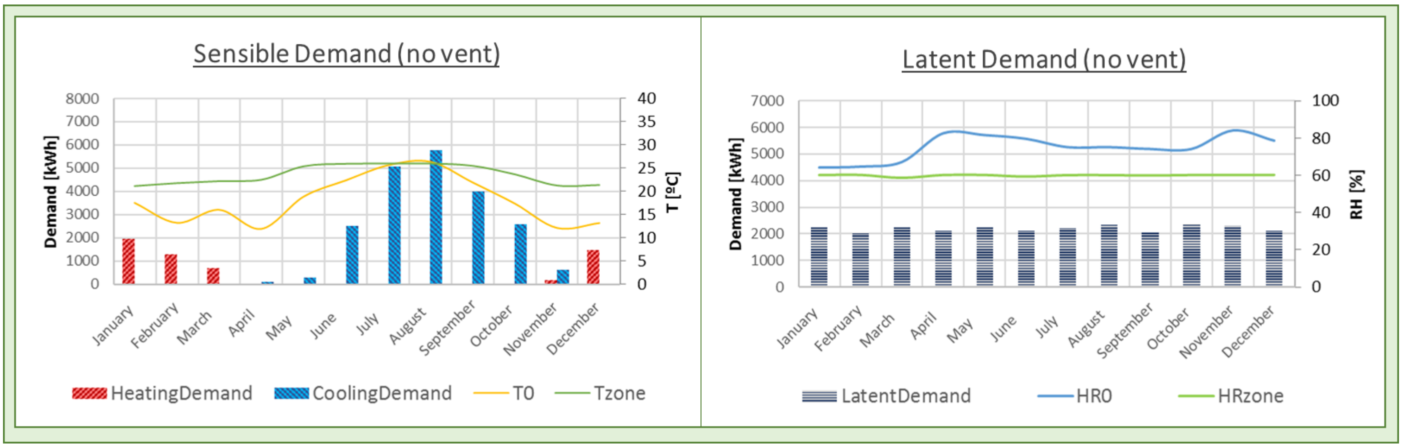


Figure B. 4 School's (a) sensible latent average heating and cooling demands and (b) latent average monthly demand for indoor set temperature (no ventilation minimum rate is provided)

In accordance with those results, by considering a chiller with $COP = 4$ and a boiler of $\eta = 90\%$, the maximum nominal power the chiller needs to support is $14\ kW$ and the boiler $44\ kW$; additionally, the maximum latent heat of one zone is $\dot{Q}_{zone_M}^{lat} = 66700\ kJ/h$.

The second step covers the indoor air quality (IAQ) requirement. The quality is mainly defined by specifying the wanted level of ventilation in air changes per hour or the outside air supply rate [3]. Two criteria were chosen depending on the school usage: if people are in, the minimum ventilation rate is enforced to be 12,5 $l/s \cdot person$; if there is nobody but, however, the use is turned on, the rate should be higher than 0,83 $l/s \cdot m^2$.

Pursuant to that necessity, the next simulation calculates the demand by also including the minimum amount of outside rate for pollutants removal, see Figure B. 5.

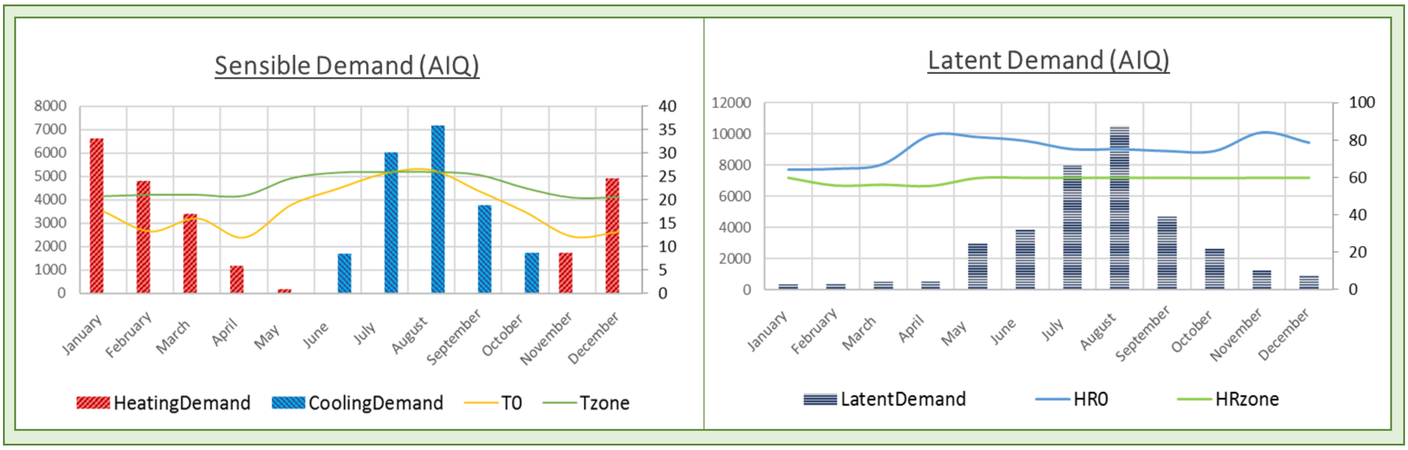


Figure B. 5(a) School's heating and cooling average monthly demand for indoor set temperature; (b) latent demand for indoor set humidity

Hence, in such situation the minimum power of the chiller should be set to 50 kW and 77 kW for boiler.

B.2.2.3. Facility design

Table a.A. 3 Label and brief description of facility components

LABEL		DESCRIPTION	LABEL		DESCRIPTION
1	B	Boiler	9	H	Humidifier
2	Ch	Chiller	10	Mc	V3V of Cooling Coil
3	T	Storage tank	11	Mh	V3V of Heating Coil
4	FC1	Fan Coil zone1	12	M1	V3V of H/C FC
5	FC2	Fan Coil zone2	13	M2	V3V of FC1/FC2
6	CC	Cooling Coil	14	M3	Mixer of Exhaust air
7	HC	Heating Coil	15	D	Diverter ventilation
8	HR	Heat Recovery	16	Bc	Boiler Chimney

The selected facility consists of an air-handling unit (AHU) assisted by two fan-coil terminals, see Figure B. 6; the components are numbered and briefly explained in Table a.A. 3.

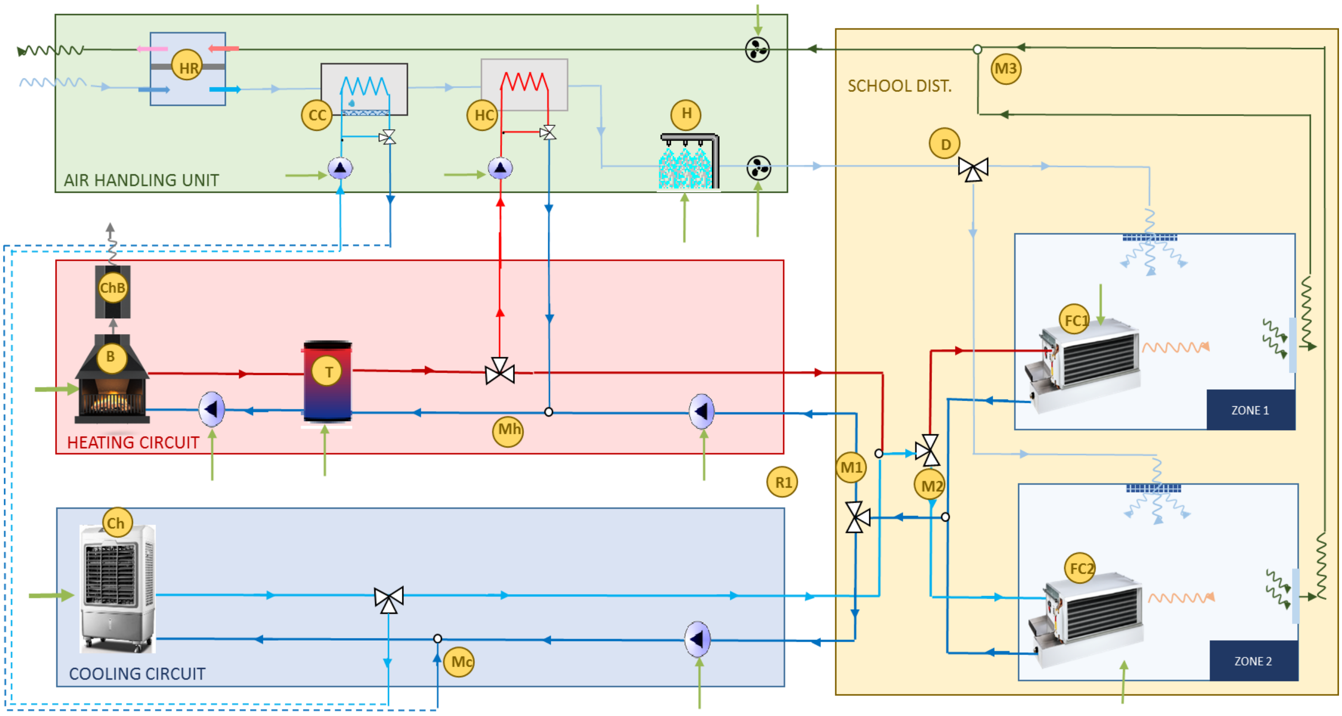


Figure B. 6 Physical scheme of the system facility

As shown in the principal scheme, the AHU is composed by the following units: air heat recovery (HR); cooling coil (CC) and a heating coil (HC) fueled respectively by the chiller and the boiler; humidification system (H) and zone distribution equipment (D and M3).

Furthermore, two circuits fed zones fan coils (FC1 and FC2) for cooling or heating purpose depending on the demand period of the year.

On the one side, the warm circuit entails a boiler of 80 kW (B) together with a thermal storage tank of 2500 l (T). That hot water is supplied to the AHU either to FC by means of modulating 3-way valve (Mh); on the other side, the cold circuit is related to a 100 kW chiller (CH) and its respective delivery equipment (Mc). Both circuits are connected to the terminals through hydronic components (M1 and M2).

B.2.2.3.1. Facility control

The building's yearly main set points are listed in Table B. 4 while each equipment operation is hereafter exposed:

Table B. 4 Main yearly set points and schedules

$\checkmark \textit{Yearly Schedule} = \begin{cases} \textit{Winter} & (1^{st}\ Nov. - 15^{th}\ May) \\ \textit{Summer} & (16^{th}\ May - 31^{st}\ Oct.) \end{cases}$ $\checkmark \textit{Vent.Schedule} = \{ \geq \dot{m}_{vent}^{min} \quad (1^{st} Jan. - 31^{st} Dic.)$ $\checkmark \textit{Generators Set T} = \begin{cases} T_B^{out} = 60\ °C \\ T_{CH}^{out} = 7\ °C \end{cases}$	$\checkmark \textit{Indoor Set T} = \begin{cases} \textit{Winter}\ 19\ °C < T_{Zone}^{i} \leq 25\ °C \\ \textit{Summer}\ 22\ °C < T_{Zone}^{i} \leq 27\ °C \end{cases}$ $\checkmark \textit{Indoor Set RH} = \begin{cases} \textit{Winter}\ 50\% < RH_{Zone}^{i} \leq 60\ \% \\ \textit{Summer}\ 45\% < RH_{Zone}^{i} \leq 60\ \% \end{cases}$

- ✓ The ventilation mass flowrate crosses over the AHU for the air treatment. The target is to meet the IAQ as well as the control of latent load, so, it is subject to the demand period:
  - On *summer time*, both the CC and the HC are simultaneously operating and the humidifier H is always switched off. The amount of treated air is the minimum required and CC is devoted to its dehumidification; afterwards, the HC heats the air up to 14 °C to ensure the correct inside air distribution.
  - On *wintertime*, the CC is always turned off and the HC is operating (and, therefore the B) as H seldom turns on. The ventilation air controls the indoor relative humidity requirement. In turn, the HC output temperature is controlled to provide comfort set conditions.
- ✓ All over the time, the exhausted air and the clean air go across a sensible air-to-air heat recovery system (HR).
- ✓ Fan coils are auxiliary elements that cover the remainder sensible heating demand.
- ✓ On *summer time*, the chiller provides the cool for comfort conditions while on *winter time*, the heating circuit is used instead; in heating circuit the boiler operates according to the tank T set points.

B.2.2.3.2. Data verification

All these systems and control were implemented in the Trnsys Simulation Studio interface and the simulation was performed for 8760 hours using a 3 minutes time-step.

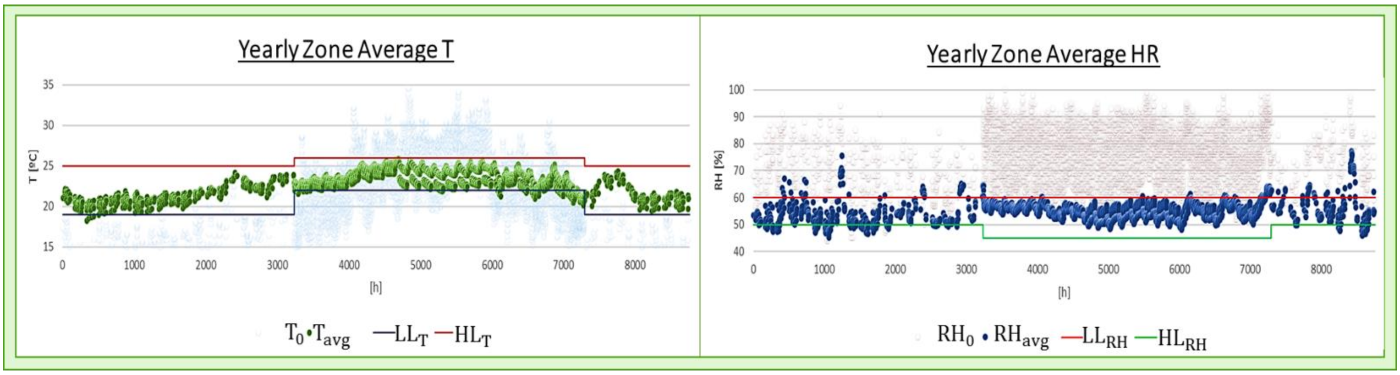


Figure B. 7(a) Yearly zone average temperature, outside temperature and comfort temperature range; (b) average RH, outside RH and comfort RH

Figure B. 7 (a) shows the average temperature and (b) RH of both zones all over the year. Besides, the outside conditions and the comfort stated range are also included (trough a blurred cloud); only the operating-period data are shown and the non-operating period (nights, weekends, etc.) are removed. As it can be seen, 94 % of indoor zone temperature values are inside the low and high limits (LL, HL) as well as 93 % of the RH. Correspondingly, the control is well adapted to the purpose.

Figure B. 8 represents the heating and cooling consumption of CC (Ch_{CC}), HC (B_{HC}) and both FCs (B_{FC} and Ch_{FC}) over the year according to the feeding generator (B or Ch). As reflected, there is not cooling consumption during the heating period and little heat is used during cooling time to ensure the indoor air distribution at 14 °C; almost all the heat is used in CC and HC since the FCs are the supporting secondary components.

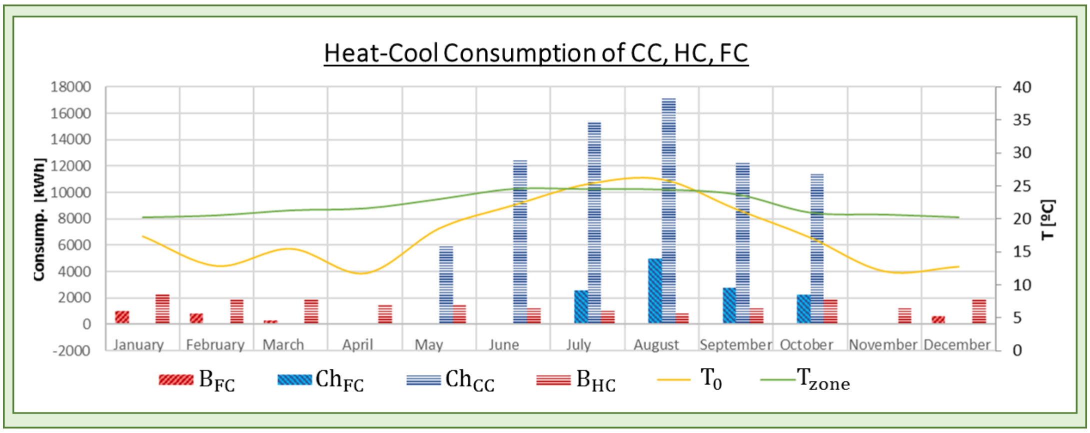


Figure B. 8 Monthly heat and cool consumption of CC, HC, FCs and outside and inside average temperatures

Inasmuch as monthly values are not representative but hourly (or even lower) periods are better to depict the utilization of the school, Figure B. 9 and Figure B. 10 were included. A representative winter week (1st of January) and summer week (1st of August) are there pictured.

Figure B. 9 follows hourly the description of Figure B. 8 while the next graphic shows the hourly zone and outside temperature and humidity with respect to the usage turn on period.

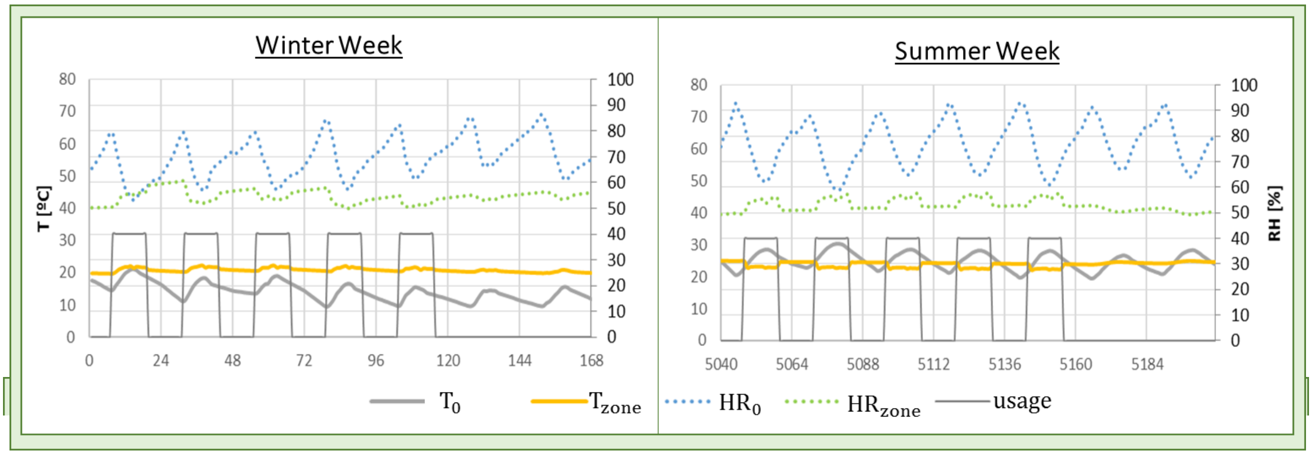


Figure B. 10 Output and indoor temperature and RH according to the usage during a week of (a) January and (b) August

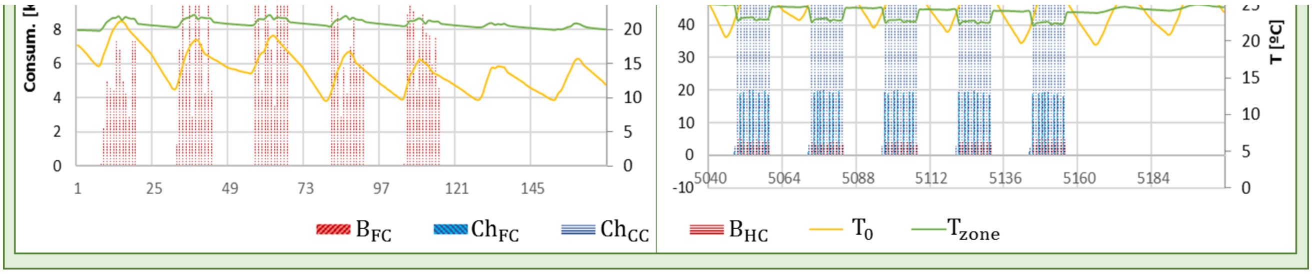


Figure B. 9 CC,HC, and FCs hourly consumption; output and indoor temperature during a week of (a) January and a week of (b) August

Henceforth, by noticing the difference scale among heating and cooling consumption, one can think that a cooling inertia system (such as a buffer) should be required in order to prevent the number of switching on and turning off of the chiller; this number is much smaller in the boiler as there is an inertial storage tank in the heating circuit. Considering the 3-minute time-step, the generators can be deeply reviewed and the functioning mode can be extracted. In that way, if the quantity of turn-on over an hour results higher than 8 times, an inertial system should be incorporated.

Figure B. 11 (a) outlines the maximum activation amount of the boiler and the chiller during the 8760 hours of the year; Figure B. 11 (b), instead, shows the number of operation hours over a day during the 365 days of the year.

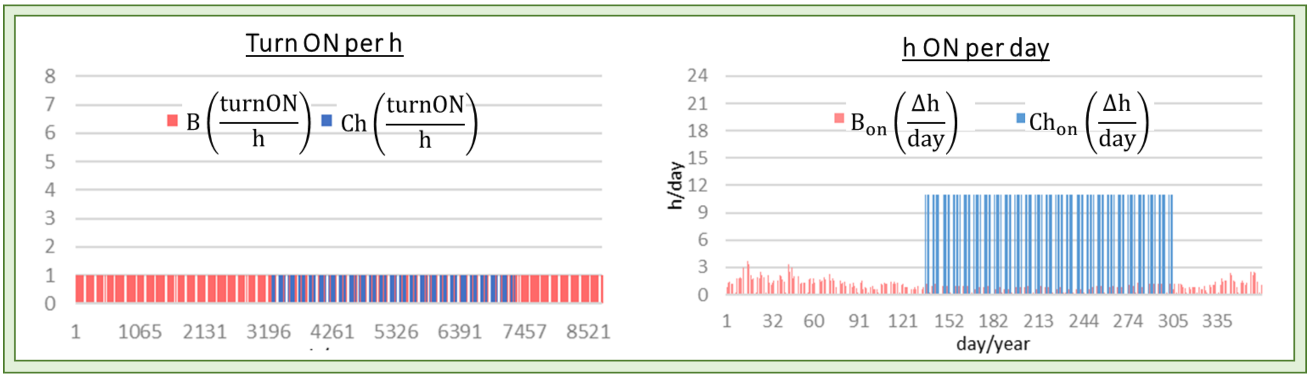


Figure B. 11 Generation units (a) Number of activation and deactivation during the year (b) Working hours of day during the year

As discussed, no extra inertia system is required because even the B or the Ch maximum hourly switching-on is 1. Moreover, as reflected in the (b) section, the chiller is activated for 11 hours during a cooling period day.

Accordingly, the proposed facility covers perfectly the yearly dynamic necessities of the school.

B.3. BUILDING DYNAMIC CHARACTERIZATION

The second situation addresses the required dynamic characterization when the system is monitored and real data can be extracted.

That is required for making the leap from the experimental data to the mathematical thermodynamic model. Every component taking part on the facility must be precisely and dynamically represented in order to represent the reality as accurately as possible according to the registered data.

One of the problems with the detailed energy simulation of a building facility is the fact that they require many inputs for model definition [4]. In practice, some of these inputs are simply unattainable or may not be practicably measurable. So, the characterization strongly depends on the availability of the experimental data.

According to Ref. [5], two types of models can be defined depending on the gathered data: (1) the *law-driven* models are based on the physical laws such as gravity or heat transfer laws; these are often over-parameterized, since they require more inputs than the available experimental data. Conversely, (2) the *data-driven* models require prior data knowledge and use the system behavior to predict system properties; generally, these models require a minimal set of adjustable inputs to describe a system.

The cases studied along this research follows the second model characteristics, since the data are taken from a limited number of sensors and monitoring devices in the system. The developed model is built based on a new *grey-box* modelling approach, which is well-proven as a comprehensive and accurate method for modelling dynamic systems [6] through identification of certain key parameters using a physical system model. There are some building transient simulation tools based on these premises, such as Trnsys, which implements a component-based simulation approach through a modular structure.

Likewise, system identification can be used for parameter estimation in a dynamic model representation. It is used for building models based on the observed behavior of the system, so variables like thermal inertia can be reflected. Consequently, the characterization of the facility under study and the parameter adjustments are achieved by combining Trnsys software specific components together with the Matlab System Identification Toolbox [7].

The representation of complex systems through essential simplifications and simulation constraints can be questioned inasmuch as some information could be lost within that transition. The uncertainties founded need to, henceforth, be mentioned. As listed in Ref. [8], various sources of uncertainty can be found in the system identification, the modelling, the numerical processing, and the scenario itself. Besides, in any modelling environment, the quality of the outputs can only be as good as the quality of the available inputs.

B.3.1. Methodology for the characterization

Figure B. 12 depicts the workflow for the application of any dynamic study in buildings and is hereafter explained:

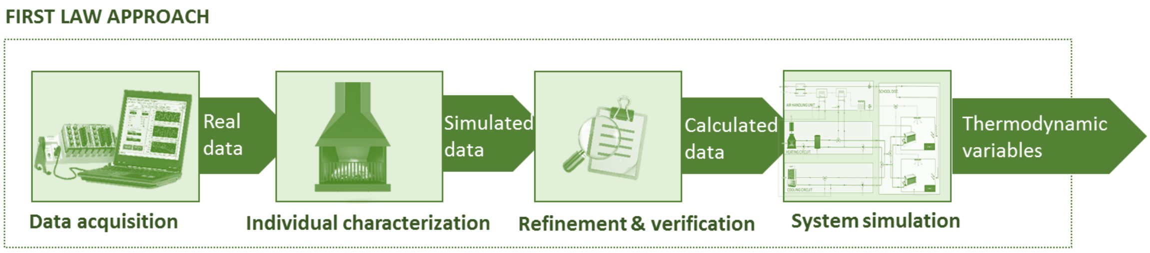


Figure B. 12 Workflow for dynamic characterization in buildings

1. *Data acquisition*. An accurate design of every system component requires the preliminary collection of monitored data (mass flow rates, temperatures, pressures, etc.) and component specific characteristics (capacity, volume, heat transfer coefficient, etc.).
2. *Individual characterization*. Such a set of data enables the analyst to select and adapt a model from Trnsys library.
3. *Refinement & characterization*. After that, comparing the output of Trnsys with the real data, Matlab is used for upgrading the component in order to incorporate the real particular behavior. This step is repeated as many times needed until the convergence or tolerance with the real data is achieved.
4. *System simulation*. All the individual component models are linked together and the control is implemented. Therefore, data can be extracted and verified.

Hence, a new methodology for system real characterization is proposed that will be deeply developed. Considering the complexities of the Trnsys and Matlab mathematical internal models, only an easy example of a collector will be shown.

B.3.1.1. Characterization model

As stated above, the modelling of every component relied on Trnsys inasmuch as it includes the transient mathematical models of the different components by integrating the mass and energy balance equations ($\sum_k m_k = 0$ and $\sum_k m_k \cdot h(\bar{x}) = 0$). Operation variables ($\bar{x}$), instead of design variables ($\bar{\tau}$), are used as independent variables since the system is already fixed (accordingly, the physical characteristics are determined too).

Thus, after collecting real data from the test, the Type that best fits the real equipment is chosen from the Trnsys library and an individual simulation is done; the input *independent* (operation) variables required from the Type are directly taken from the real values of the essay. The outputs of the simulation, which are the *dependent* variables, are every time-step contrasted with the corresponding experimental values to be refined; in that manner the simulated output is readjusted by incorporating the real inefficiencies. In other words, the variable $\left(T_{i_{Dep}}^{Tr}\right)$ obtained from Trnsys simulation and the real values measured in the tested essay $\left(T_{i_{Dep}}^{Re}\right)$ might have a deviation, because Trnsys does not consider the additional inertia encountered in the components of the experimental facility. The refinement is performed using the Matlab System Identification Toolbox, by incorporating that inertia and the consequent real behavior to adapt the outputs of Trnsys to the reality $\left(T_{i_{Dep}}^{Calc}\right)$.

Figure B.13 shows the procedure of the boiler characterization where the schematic connections between real data, Trnsys simulation and Matlab are depicted. Conversely, Figure B. 14 explains how the individual characterizations of the supply and return collectors (C) and heat exchanger (HX) were programmed in the interface Simulation Studio of Trnsys.

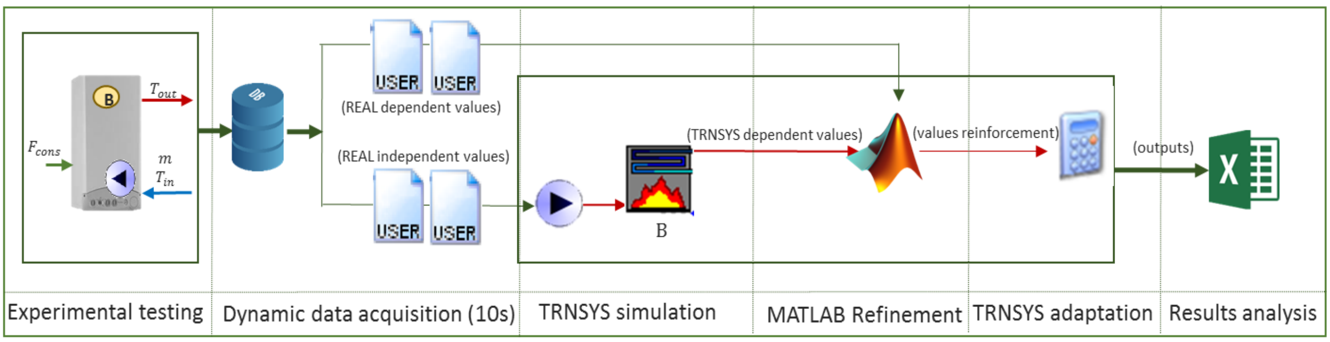


Figure B.13 Scheme of acquirement of boiler simulation model

As displayed in Figure B. 14, different modules take part in the adaptation and improvement of the models as explained below:

- The component itself, chosen from the Trnsys library, is located in the middle (C or HX). First, the Type needs to be chosen and then adapted to the characteristics of the real facility. That is done by changing the parameters of the selected Trnsys Type.
- The *User* Types, which appear in the component's surrounding (labelled as T_i^{Re}), correspond to the external data readers containing the experimental values. Here, the monitored data from the real facility needs to be inserted according to the chosen time-step. The number of the User Types is equal to the number of recorded variables from the sensors.
- There are two types of User variables: independents $\left(T_{i_{Ind}}^{Re}\right)$ and dependents $\left(T_{i_{Dep}}^{Re/Tr/Calc}\right)$, denoted by the subscripts *"Ind"* and *"Dep"*, respectively. The independent variables correspond to the inputs of the component being analyzed and

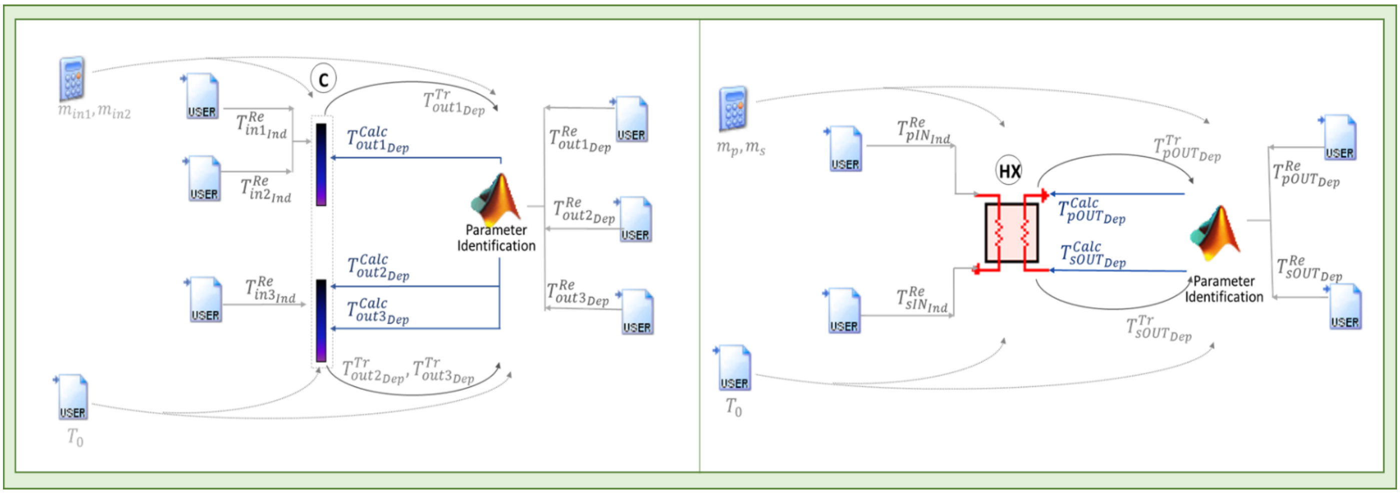


Figure B. 14 Representative image for the C and HX characterization through the Simulation Studio interface of Trnsys

are located in the left side of the component in Figure B. 14, while the dependent User variables that are the actual measured values taken from the test facility are placed on the right side. These dependent variables should be compared to other dependent variables resulted from the Trnsys simulation to obtain a model to describe the real behavior of the component. To sum up, there are three different *dependent* variables: those acquired from the Trnsys simulation $\left(T_{i_{Dep}}^{Tr}\right)$, the real ones provided by the sensors in the experimental facility $\left(T_{i_{Dep}}^{Re}\right)$, and the ones calculated in Matlab $\left(T_{i_{Dep}}^{Calc}\right)$. Since the first two values are not the same $\left(T_{i_{Dep}}^{Tr} \neq T_{i_{Dep}}^{Re}\right)$, the aim is to find a mathematical relationship between the independent values $\left(\sum_j T_{j_{Ind}}^{Re}\right)$ and the dependent ones in order to represent the reality (see Eq.(B. 1)). This final step is completely done in Matlab System Identification Toolbox.

$$T_{i_{Dep}}^{Calc} = f\left(T_{i_{Dep}}^{Tr}, \sum_{j} T_{j_{Ind}}^{Re}\right) = T_{i_{Dep}}^{Re} + error \quad \text{(B. 1)}$$

- For the reason mentioned above, $T_{i_{Dep}}^{Re}$ and $T_{i_{Dep}}^{Tr}$ are connected to the MatLab Type in Figure B. 14 (with *Parameter Identification* tag). This Type refers to the interconnection between both software where the adjustment of dependent variables is carried out. To achieve that, the experimental data have been compared to the values obtained from Trnsys, so that the new output from Matlab is adjusted to the reality.

In this way, a mathematical model of every component of the system can be developed, and later on, implemented in the simulation of the entire facility according to the programed control.

B.3.2. Collector Case Study

As an example, the dynamic characterization of the collector (C) tested during 4-day essay on the Laboratory for the Quality Control in Buildings (LQCB) from the Basque Government is shown. Such was monitored together with the rest of the components in order to provide the real data of the whole system behavior and its interconnections.

Considering the naming of Figure B. 14 the registered data for the C characterization were: the mixing mass flow rates (m_{in1}, m_{in2}), the incoming temperatures ($T_{in1_{ind}}^{Re}, T_{in2_{ind}}^{Re}, T_{in3_{ind}}^{Re}$) as well as the outgoing ($T_{out1_{dep}}^{Re}$) and mixed ($T_{out2_{dep}}^{Re}, T_{out2_{dep}}^{Re}$) ones. Therefore, the refined variables are: $T_{out1_{Dep}}^{Calc}, T_{out2_{Dep}}^{Calc}, T_{out2_{Dep}}^{Calc}$.

Hence, the variables obtained as Trnsys outputs $\left(T_{i_{Dep}}^{Tr}\right)$ were corrected according to the actual experimental facility measurements by means of the Matlab System Identification Toolbox, which becomes:

$$T_{out1_{Dep}}^{Calc}(t) = \frac{\dot{m}_{in1}(t) \cdot T_{in1_{Ind}}^{Re}(t) + \dot{m}_{in2}(t) \cdot T_{in2_{Ind}}^{Re}(t)}{\dot{m}_{in1}(t) + \dot{m}_{in2}} \quad \text{(B. 2)}$$

$$T_{out2_{Dep}}^{Calc}(t) = T_{in3_{Ind}}^{Re}(t) \quad \text{(B. 3)}$$

$$T_{out3_{Dep}}^{Calc}(t) = \begin{cases} T_{in3_{Ind}}^{Re}(t) \cdot 0.9649 & \dot{m}_{in2} = 0 \\ T_{out3_{Dep}}^{Tr}(t) & \dot{m}_{in2} \geq 0 \end{cases} \quad \text{(B. 4)}$$

As mentioned, the effects of the activation and deactivation of the pumps and the components inertias are taken into account (see the condition on $\dot{m}_{in2}$ in the Eq.(B. 4)).

The relative error between the experimental data and the simulation results, that is, the difference among the real dependent values and the dependent values calculated from Trnsys and Matlab combination $\left(T_{i_{Dep}}^{Calc} - T_{i_{Dep}}^{Re}\right)$ is less that $\pm 3\%$.

Consequently, the proposed technique ideally serves for the building real system characterization.

B.4. CONCLUSIONS

One of the main features of a building energy supply system is associated with the dynamism, since a steady state can never be related to the building demands neither to the energy supply facilities. Therefore, before any calculation, the development of a reliable thermodynamic model of every component and the facility as a whole is of crucial importance.

Among others, two situations can be encountered: the first one is associated with the facility creation in order to cover the necessities of a specific building. It is demonstrated that, even with very complex requirements, the proposed methodology gives satisfactory results.

The second one is related to the system dynamic representation by means of registered real data. This is achieved on the basis of the grey-box modelling, by the combination of Trnsys models and Matlab for the parameter adjustment. This innovative proposal brings also successful outcomes.

The result of both methodologies brings the required thermodynamic variables of each system flow.

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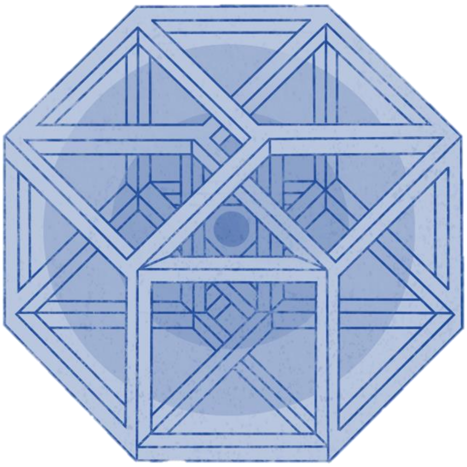

CHAPTER C

Thermoeconomic analysis in buildings

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CHAPTER C

SUPERSCRIPT	
0	Reference state, environment
T	Total
in	Input
out	Output
n	Number of system component
m	Number of system flows
e	System incomings
x	System bifurcations
r	System recirculations
F	Fuel
P	Product
R	Residue

SUBSCRIPT	
e	Useful product
r	Useful residue
z	Fixed costs
Fix	Fixed values

SYMBOLS		
$\mathbf{E}$	[kJ]	Flow exergy vector $(m, 1)$
$\mathbf{E_D}$	[kJ]	Exergy destruction vector $(m, 1)$
$\mathbf{F}^*$	[kJ]	Exergy cost of fuel $(n, 1)$
$\mathbf{P}^*$	[kJ]	Exergy cost of product $(n, 1)$
$\mathbf{R}^*$	[kJ]	Exergy cost of residue $(n, 1)$
$\mathbf{k}_\mathbf{F}^*$	[kJ/kJ]	Unit exergy cost of fuel $(n, 1)$
$\mathbf{k}_\mathbf{P}^*$	[kJ/kJ]	Unit exergy cost of product $(n, 1)$
$\mathbf{C}$	[€]	Exergoeconomic cost of flow $(m, 1)$,
$\mathbf{C_F}$	[€]	Exergoeconomic cost of fuel $(n, 1)$
$\mathbf{C_P}$	[€]	Exergoeconomic cost of product $(n, 1)$
$\mathbf{Z_e}$	[€]	Equipment investment, amortization and maintenance cost $(n, 1)$
$\mathbf{J}$	[-]	Matrix of exergetic balance (n, m)
$\boldsymbol{\alpha}_\mathbf{s}$	[-]	Output flow matrix (s, m)
$\boldsymbol{\alpha}_\mathbf{r}$	[-]	Recirculation matrix $(m - n - s, m)$
$\mathbb{F}_\mathrm{r}$	[kJ]	Extended fuel vector $(m, 1)$
$\mathbb{Y}_\mathrm{s}$	[-]	Extended output vector $(m, 1)$
$\mathbb{J}_\mathrm{r}$	[kJ]	Extended matrix of $\mathbf{J_r}$ (m, m)
k_j	[kJ/kJ]	*j* component unit exergy consumption
α_{ij}	[-]	Bifurcation parameters, *FP* representation
r_{ij}	[-]	Recirculation parameters, *PF* representation
ψ_{ir}	[-]	Residue distribution parameters, *FP* representation
ω_{ej}	[kJ]	*j* component external resources, *FP* representation
ω_{sj}	[kJ]	*j* component output product, *PF* representation
$\langle\mathbf{FP}\rangle$	[-]	Dependent matrix of x_{ij} (n, n) distribution parameters, *FP* rep.
$\langle\mathbf{PF}\rangle$	[-]	Dependent matrix of r_{ij} (n, n) distribution parameters, *PF* rep.
$\langle\mathbf{KP}\rangle$	[-]	Dependent matrix of distribution unit consumption (n, n), *PF* rep.
${}^t\langle\mathbf{F_T F}\rangle$	[-]	Portion of each component external fuel vector $(1, n)$
$\lvert\mathbf{F}\rangle$	[-]	Matrix operator (n, n), *PF* representation
$\lvert\mathbf{P}\rangle$	[-]	Matrix operator (n, n), *PF* representation
$\lvert\mathbf{I}\rangle$	[-]	Matrix operator (n, n), *PF* representation
$\lvert\tilde{\mathbf{P}}\rangle$	[-]	Matrix operator with residues (n, n), *PFR* representation
$\lvert\tilde{\mathbf{R}}\rangle$	[-]	Matrix operator with residues (n, n), *PFR* representation

QF	[-]	Quality factor
$\bar{\tau}$	[*][2]	Design parameters

[2] [*] = units of the corresponding variable

CHAPTER C: THERMOECONOMIC ANALYSIS IN BUILDINGS

C.0. ABSTRACT

Thermoeconomics connects the physics and economics of energy conversion processes through the Second Law of Thermodynamics. A limited number of thermoeconomic applications in buildings have been proposed, due to the difficulties in dealing with very irregular energy load profiles and unsteady plant operating conditions, which require the use of dynamic approaches that increase the complexity of the method.

By means of the historical development overview and a summary of the Symbolic Thermoeconomic (ST) application, the first part of the present chapter highlights the potential of thermoeconomics as a support for decision making, due to the capability to identify trade-offs between cost and efficiency. Two case studies serve for the better insight of the ST application.

The second part aims to improve the application in buildings energy systems, so a new methodology for dynamic implementation is developed. Some key aspects for productive structure settings are solved, particularly those related to the commonly used 3-way valves and inertial components. The role of dissipative components is also explored by means of case studies.

All in all, this chapter underscores not only the strengths but also the weaknesses of the thermoeconomic application and serves as a guide for building enforcement.

C.1. INTRODUCTION

Second Law analyses of energy systems started having reasonable impact in the middle of the 60's and, therefrom, great improvements have been pursued until current days. One of the major achievements of exergy method implementation, developed in the 80's, was the *exergy cost accounting*, included on the science of Thermoeconomics, which allocates the cost of flows according to the process irreversibilities. Thermoeconomics combines economic and thermodynamic analyses and can be applied for the assessment of rational prices of system products, detection of inefficiencies and calculation of their economic effects, evaluation of various design alternatives, optimization of specific process unit variables, and so on [1]. Because the lack of a unique method, the different techniques were compared and tried to unify through the CGAM problem (C. Frangopoulos, G. Tsatsaronis, A. Valero and M. von Spakovsky) in the 90's, where the idea was to share a common path for the exergy cost allocation.

Accordingly, the cost is allocated in proportion to exergy, searching a proportional behaviour depending on the energy process irreversibilities. In particular, exergetic cost accounts for the amount of exergy units required to produce a given product and for its calculation three conditions need to be fulfilled: (1) system boundaries are previously defined, (2) interconnections between components are known (*thermodynamic model*) and (3) each component production purpose is defined (*Productive Structure*) [2].

The thermodynamic model is used to determine simply the entering and outgoing flows of a component while, conversely, the functional productive model classifies them among fuel (*F*), product (*P*) and residues (*R*) [3].

Therefore, not only exergy balance is needed but also economic purpose must be detailed in every component. Indeed, although the exergy of a flow is a thermodynamic property that depends on its state and composition, the cost is a function of the specific process followed by the production of that flow. Consequently, the same flow can have different exergy costs according to the procedure used for its creation [4]. In such case, exergetic cost contains the information of the accumulated irreversibilities until the specific point of the energy chain. Consequently, this parameter shows the direct and indirect influence of the equipment interconnections as well as the justification of different costs in each flow. Furthermore, the average, structural and marginal costs follow an analogous mathematical formulae [5] (according to Ref. [6] the only difference between marginal and average costs is due to the amortization capital cost terms).

Besides, the exergetic cost is an alternative to evaluate the thermodynamic performance and cost effectiveness of each plant component as well as the whole system interactions. The determination of the intermediate and product costs is useful to make trade-off economic analyses of the subsystem components.

Notwithstanding all those advantages, the value of costs depends on the chosen limits of the system and on the purpose; therefore, it is relative to the engineer objective and understanding.

For that reason and bearing in mind the complexity of some energy systems, various propositions were developed for the mechanization and fining of the technique. Among others, *Exergy Economics Approach* (EEA), [7]; *First Exergoeconomic Approach* (FEA), [8]; *Thermoeconomic Functional Analysis*, (TFA), [9]; *Engineering Functional Analysis* (EFA), [10]; *Last-In-First-Out Approach* (LIFOA), [11]; *Structural Theory*, [12]; *Specific Exergy Costing* (SPECO), [13]; etc. can be listed. In this chapter *Symbolic Thermoeconomic* (ST) [14] is developed, which gives generic matrix equations for cost accounting resolutions; while in **Chapter E**, however, *Advanced Exergy Analysis* (AEA) [15] is studied, which focuses the analysis based on another perspective.

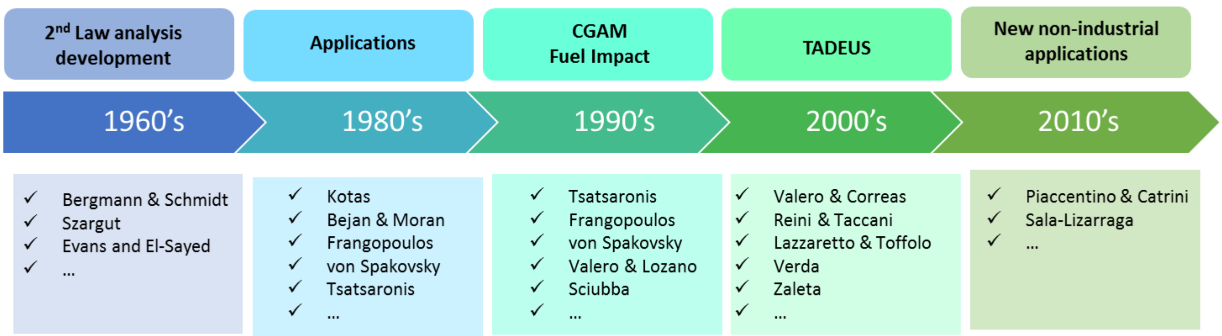


Figure C. 1 Scheme of Second Law Analysis development

In the latter 2000's, thermoeconomics was implemented for *diagnosis* objectives and TADEUS research field (Thermoeconomic Approach to the Diagnosis of Energy Utility Systems) was created. For author's best knowledge, diagnosis applications in non-industrial areas (such as residential energy supply systems) were not explored until the 2010's, see Figure C. 1. Full detailed bibliography revision appears in [16] and [6].

The reasons for being thermoeconomics widely used on an industrial level [17] but less frequently in the building environment are, for instance, the fact that the energy flows are much lower than those of thermal power plants or those of many industrial processes. In addition, the analysis uses many concepts and definitions originated in the electrical power and chemical industries, and then, a procedure is required to establish the applicability of those concepts to the building environment. What is more, thermal levels are so low that the choice of environmental conditions significantly impacts the exergy values [18]. However, work based on building systems are rapidly increasing [19], [20].

Moreover, its application is starting to become a key stage for building thermal systems design (e.g. solar energy based heating systems [21], HVAC systems [22], air conditioning systems [23], [24], absorption cooling systems [25], ground-source systems [26], etc.) or for particular individual component characterization (namely, micro-trigeneration machines [27], ground and air source heat pumps [28],[29], heat exchangers [30], thermal energy storage modules [19] and so on). In addition to these, it was also integrated into building energy retrofit design (for example, in the renovation of a natural-gas cogeneration system [31] or to compare different building energy retrofit designs).

C.2. SYMBOLIC THERMOECONOMICS

C.2.1. Symbolic Thermoeconomic Analysis in Buildings

Symbolic Thermoeconomics (ST) is a methodology for the analysis of the *productive structure* and the natural resources consumption to identify the causes of the cost formation. Based on the Exergy Cost Theory (ECT), it allows obtaining general equations, which relate the overall efficiency of an energy system and other thermoeconomic variables such as fuel, exergy cost, etc., with the efficiency of each component that forms it. After all, cost accounting methodologies (as the ECT) are numerical techniques that enable accurate calculation of costs by resolving linear equations systems, but do not allow identifying the causes of the cost formation process. By bringing together ECT and Symbolic Computation (using symbolic computation packages, like *Mathematica* or *Matlab*) it is possible to obtain general formulae of any energy system, see Figure C. 2.

The ST target is to describe relationship between components in order to expound the production process by means of fuel-product representation. For that, each system element,

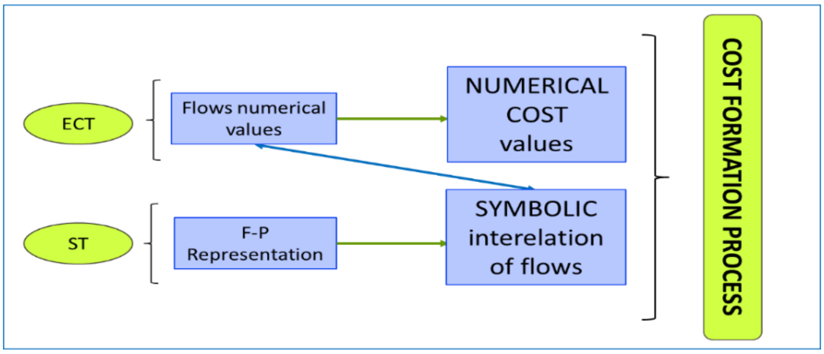


Figure C. 2 General description of method considered as a black box, is defined by an input-output parameter, known as Fuel or Product. Such representation permits appreciating how any variation in a component can affect the overall plant. Moreover, the analytical expressions relating the costs with the free parameters of the plant are acquired. For that reason, the general solutions obtained by ST are valid for any state of the system.

In short, working with general equations allows obtaining general solutions to general problems. Thus, ST is a powerful tool for cost accounting.

Whilst the application of ST to industrial processes and thermal plants is well-known and there are several papers, [32], the literature on ST applied to buildings and building services is really scarce. Nevertheless, in recent years some works have been published as in the control strategies study of an airport HVAC system [33], the analysis of co-generation with gas expansion system [34], the ST theory application in a conventional refrigeration plant [35], etc. The latter puts in evidence the simplicity of the thermoeconomic methodology, which does not require the use of sophisticated mathematical tools, as only some metrical treatment is needed.

When working with ST two different situations can emerge, see Figure C. 3. In some cases, the consumption of resources is established (F_{IN}^{fix}) so that the obtained product varies depending on the plant structure, described through distribution coefficients (α_{ij}), the efficiency of its components, or its inverse, the exergetic consumption (k_i), and the entrance characteristic (ω_{in}): $P = P(\alpha_{ij}, k_i, \omega_{in})$. This situation is known as FP formulation or supply-driven model.

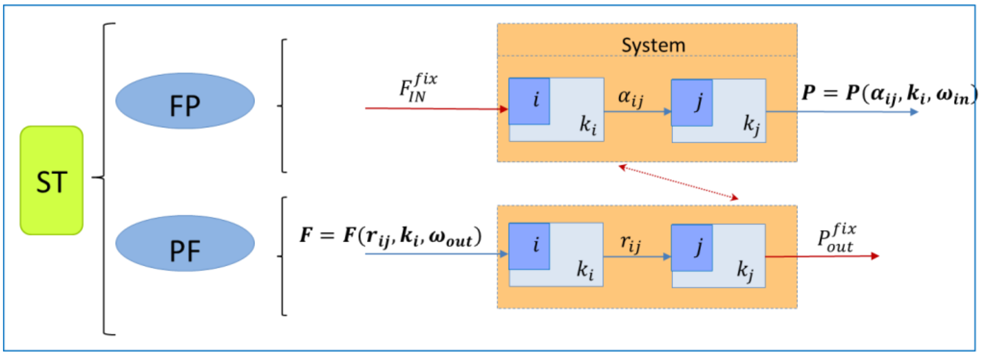


Figure C. 3 Supply driven model and Demand-driven model scheme

Conversely, there are other situations in which the product of the plant is established (P_{OUT}^{fix}). Thus, a heating and DHW system has to supply the demand for heating and DHW, an air conditioning system must supply the demand for cooling, etc. Hence, the needed resource varies depending on the plant structure, described in this case through junction coefficients (r_{ij}), the exergetic consumption (k_i) and the output characteristic (ω_{out}): $F = F(r_{ij}, k_i, \omega_{out})$. This formulation is known as PF or demand-driven model.

ST enables to obtain the thermoeconomic properties, like exergy and costs as a function of the canonical variables in the two structural representations. Obviously, both representations are closely linked and it is possible to switch from one to another. ST is a valuable tool in the design of energy systems and complements conventional optimization or simulation techniques of complex systems.

C.2.1.1. Summary of ST in the demand-driven model

The resources required by the system to supply the demand will be symbolically obtained (PF model). Therefore, those inputs depends on the plant structure, which is described through the *junction coefficients*, the *exergetic consumption* of each unit and the final *output production*.

C.2.1.1.1. Physical Structure

Let us consider an energy system, which is formed by a number n of units and m mass and/or energy flows which are interrelated. The relationship between flows and components is determined by the incidence matrix $\mathrm{A}\ (n, m)$. The incidence matrix allows expressing the mass, energy, exergy and costing balances in matrix form. The lower the level of aggregation considered the more detailed the incidence matrix is, which means better definition of costs and inefficiencies, but in turn, it requires a larger amount of data and, therefore, greater quantity of instrumentation.

Once the physical structure is defined, the second step is the determination of the productive structure which indicates the products and resources of each subsystem. This requires the association of flows and the definition of those that are the fuel in each component and those that constitute the product. In this way, the fuel incidence matrix A_F and the product one A_P can be built. Calling $\mathbf{k_D}$ to the diagonal matrix (n, n) which contains the components unitary consumption, and according to the exergy balance in each component, next equation can be written:

$$(\mathbf{A_F} - \mathbf{k_D} \cdot \mathbf{A_P}) \cdot \mathbf{E} = \mathbf{0} \tag{C. 1}$$

were $(\mathbf{A_F} - \mathbf{k_D} \cdot \mathbf{A_P})$ is named as $\mathbf{J}$.

With ECT prepositions, $(m - n)$ additional equations can be constructed. If s is the number of final products, s extra equations would correspond to those outgoing flows, $\boldsymbol{\alpha}_\mathbf{s} \cdot \mathbf{E} = \mathbf{E_s}$ and $(m - n - s)$ would correspond to recirculation equations, $\boldsymbol{\alpha}_\mathbf{r} \cdot \mathbf{E} = \mathbf{0}$. Thereby, extended $\mathbb{J}_\mathrm{r}$ matrix (m, m) and extended $\mathbb{F}_\mathrm{r}$ vector $(m, 1)$ can be constructed. This last vector contains the exergy flows of the total products, $[\mathbf{0}_{(n,1)}; \mathbf{E_s}_{(s,1)}; \mathbf{0}_{(r,1)}]$, verifying the matrix equation:

$$\mathbb{J}_\mathrm{r} \cdot \mathbf{E} = \mathbb{F}_\mathrm{r} \tag{C. 2}$$

$\mathbb{J}_\mathrm{r}$ is a regular matrix, so its inverse matrix can be obtained. In this way, the expressions for the exergy $\mathbf{E}$ of the flows are obtained as functions of the canonical variables of this representation, that is, depending on the unitary exergetic consumption, junction coefficients and external plant products.

C.2.1.1.2. Productive Structure

Although the ECT could be used to obtain the expressions for the costs of the flows and the costs of fuels and products, Fuel-Product representation allows more direct the expressions. The productive structure can be represented by a Fuel/Product table or diagram and this productive structure identification is closely related to Leontief´s input-output economic analysis but, in this case, all the flows are measured in exergy. Accordingly, each component is represent as a black box with an incoming F and outgoing P. Some virtual components are inserted to consider the junctions (circumferences) and splitters (diamonds).

Let´s define the junction coefficients r_{ij} as the portion of the resources of the component *j* (F_j), coming from the product i:

$$r_{ij} = \frac{E_{ij}}{F_j} \tag{C. 3}$$

The production of one component is used as fuel of another component (E_{ij}) or as part of the total production of the plant ($E_{i,e}$) so we have:

$$P_i = E_{i,e} + \sum_{j=1}^{n} r_{ij} \cdot F_j \quad , \quad i = 1,\ldots,n \tag{C. 4}$$

and the total fuel of the plant is**:**

$$F_T = \sum_{j=1}^{n} r_{e,j} \cdot F_j \tag{C. 5}$$

The Eq(C. 4) could be written in matrix form as:

$$\mathbf{P} = \mathbf{P_s} + \langle \mathbf{PF} \rangle \cdot \mathbf{F} \tag{C. 6}$$

The vector $\mathbf{P_s}$ contains the exergy values of the final product obtained in each unit and $\langle \mathbf{PF} \rangle$ is a (n, n) matrix whose elements are the junction coefficients (r_{ij}). If $\kappa_{i,j}$ corresponds to the marginal exergy consumptions, as the amount of resources coming from the component i (E_{ij}) required to obtain a unit of the product of the component *j* (P_j) and being k_j the unitary exergy consumption of component *j*:

$$\kappa_{i,j} = \frac{E_{i,j}}{P_j} = \frac{r_{i,j}.F_j}{P_j} = r_{i,j} \cdot k_j \tag{C. 7}$$

It is verified that the sum of marginal exergy consumptions for all the components is equal to the unitary exergy consumption:

$$\sum_{i=0}^{n} \kappa_{i,j} = k_j \tag{C. 8}$$

$\langle \mathbf{F_T F} \rangle$ is a $(1, n)$ vector that indicates the portion of fuel of each component coming from the external resources.

$$^{\mathbf{T}}\langle \mathbf{F_T F} \rangle = {}^{\mathbf{T}}\mathbf{u} \cdot (\mathbf{U_D} - \langle \mathbf{PF} \rangle) \tag{C. 9}$$

Let's define a new $\langle \mathbf{KP} \rangle$ matrix whose elements are $\kappa_{i,j}$ and then:

$$\langle \mathbf{KP} \rangle = \langle \mathbf{PF} \rangle \cdot \mathbf{k_D} \tag{C. 10}$$

where, as we said above, $\mathbf{k_D}$ is a diagonal matrix containing the efficiency of each component.

In this way the fuel, product and irreversibility of every component are

$$\mathbf{P} = |\mathbf{P}\rangle \cdot \mathbf{P_s} \quad , \quad |\mathbf{P}\rangle = (\mathbf{U_D} - \mathbf{KP})^{-1} \tag{C. 11}$$

$$\mathbf{F} = |\mathbf{F}\rangle \cdot \mathbf{P_s} \quad , \quad |\mathbf{F}\rangle = \mathbf{k_D} \cdot |\mathbf{P}\rangle = \mathbf{k_D} \cdot (\mathbf{U_D} - \mathbf{KP})^{-1} \tag{C. 12}$$

$$\mathbf{I} = |\mathbf{I}\rangle \cdot \mathbf{P_s} \quad , \quad |\mathbf{I}\rangle = (\mathbf{k_D} - \mathbf{U_D}) \cdot |\mathbf{P}\rangle = (\mathbf{k_D} - \mathbf{U_D}) \cdot (\mathbf{U_D} - \mathbf{KP})^{-1} \tag{C. 13}$$

The total resources of the plant may be obtained as:

$$F_T = \sum_{j=1}^{n} \kappa_{ej} P_j \tag{C. 14}$$

and in matrix form:

$$\mathbf{F_T} = {}^{\mathbf{T}}\mathbf{k_e} \cdot |\mathbf{P}\rangle \cdot \mathbf{P_s} \tag{C. 15}$$

where ${}^{\mathbf{t}}\mathbf{k_e} = (\kappa_{e1}, \kappa_{e2}, \dots, \kappa_{en})$ is a $(n, 1)$ vector containing the marginal exergy consumptions of the input resources to the system.

$$\mathbf{k_e} = \langle \mathbf{F_T F} \rangle \cdot \mathbf{k_D} \tag{C. 16}$$

Then the universal formula of the unitary exergy consumption of the system (just the inverse of the efficiency), no matter how complex, is:

$$k_T = \frac{F_T}{P_T} = \frac{{}^{\mathbf{T}}\mathbf{k_e} \cdot |\mathbf{P}\rangle \cdot \mathbf{P_s}}{{}^{\mathbf{t}}\mathbf{u}\ \mathbf{P_s}} \tag{C. 17}$$

C.2.1.1.3. Cost accounting

Let´s now obtain the equations for exergy costs and the exergoeconomic costs of the fuel and product of every component. An equivalent equation to Eq(C. 4) can be applied to exergy costs and, considering the cost assessment rules of ECT, the following equation for the unit exergy costs is obtained:

$$k_{P_i}^* - \sum_{j=1}^{n} \kappa_{ji} \cdot k_{P_j}^* = k_{e_i}^* \qquad , \qquad i = 1, \dots, n \tag{C. 18}$$

This equation relates the unitary exergy cost of the products ($k_{P_i}^*$) with the marginal exergy consumption of each component ($\kappa_{ji} \cdot k_{P_j}^*$) and in matrix form:

$$\mathbf{k_P^*} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{k_e^*} \tag{C. 19}$$

It is easy to observe that the unitary exergetic cost of the external resources is $\mathbf{k_e^*} = \langle \mathbf{F_T F} \rangle$.

The cost of fuel of each component can be obtained as:

$$k_{F_i}^* = r_{ei} + \sum_{j=1}^{n} r_{ji} \cdot k_{P_j}^* \tag{C. 20}$$

and in matrix form:

$$\mathbf{k_F^*} = \mathbf{k_e^*} + \ ^{\mathbf{T}}\langle\mathbf{PF}\rangle \cdot \mathbf{k_P}^* \tag{C. 21}$$

Taking into account the equation $\mathbf{k_F^*} = \mathbf{H_D} \cdot \mathbf{k_P^*}$ where $\mathbf{H_D}$ is the diagonal matrix containing the elements efficiency, a lineal operator can be defined:

$$|\mathbf{k_F^*}\rangle = (\mathbf{U_D} - \ ^{\mathbf{t}}\langle\mathbf{PF}\rangle \cdot \mathbf{k_D})^{-\mathbf{1}} \tag{C. 22}$$

Then an equation that relates the unitary exergy costs of fuels with the portion of external resources is written bellow:

$$\mathbf{k_F^*} = |\mathbf{k_F^*}\rangle \cdot \mathbf{k_e^*} \tag{C. 23}$$

The exergy cost of a flow is defined as the resources needed to obtain it and then it has not sense to express it as a function of the plant production. Similarly for the products of the components:

$$\mathbf{k_P^*} = |\mathbf{k_P^*}\rangle \cdot \mathbf{k_e^*} \tag{C. 24}$$

where the operator $|\mathbf{k_P^*}\rangle$ is

$$|\mathbf{k_P^*}\rangle = (\mathbf{H_D} - \ ^{\mathbf{T}}\langle\mathbf{PF}\rangle)^{-\mathbf{1}} \tag{C. 25}$$

Let´s refer now to the exergoeconomic costs. In a similar way to Eq(C. 22) it can be said that:

$$\mathbf{c_F} = \mathbf{c_e} + \ ^{\mathbf{T}}\langle\mathbf{PF}\rangle \cdot \mathbf{c_P} \tag{C. 26}$$

where $c_{e,i}$ is the unitary cost of the external resources applied to element i. From the above equation and as:

$$\mathbf{c_F} = \mathbf{H_D} \cdot (\mathbf{c_P} - \mathbf{z_p}) \tag{C. 27}$$

where $\mathbf{z_P}$ is a $(n, 1)$ vector whose elements contain the amortization, maintenance and other operating costs per unit of product, one has

$$\mathbf{c_F} = |\mathbf{k_F^*}\rangle \cdot \mathbf{c_e} + (|\mathbf{k_F^*}\rangle - \mathbf{U_D}) \cdot \mathbf{z_F} \tag{C. 28}$$

and then

$$\mathbf{c_P} = |\mathbf{k_P^*}\rangle \cdot \mathbf{c_e} + (|\mathbf{k_F^*}\rangle - \mathbf{U_D}) \cdot \mathbf{z_P} \tag{C. 29}$$

These operators allow relating the unitary exergetic costs of fuel and product with the unitary exergetic costs of the external resources. As it can be seen, the exergoeconomic costs of products are shaped with two components, one related to the unitary cost of external resources ($|\mathbf{k_P^*}\rangle \cdot \mathbf{c_e}$) and the other with the unitary amortization costs, ($(|\mathbf{k_F^*}\rangle - \mathbf{U_D}) \cdot \mathbf{z_P}$).

C.2.1.2. Residues Incorporation

Up to this moment in this brief summary of the ST, flows that either are fuel or product have been considered. But in any productive process, along with those flows there will appear unintended remaining flows of matter or energy which are called residues. They do not have utility concerning the productive structure but require extra energetic expenditure for reduce their impact. In any energy system, in the same way that there are productive components also dissipative components exists whose purpose is to partially or totally eliminate the undesirable flows.

The residue cost allocation is a complex problem since it depends on the nature of such flows and the way in which were formed. There are different ways to resolve the problem of allocating the costs of residues [36], [37], [38]. During the research, the method developed by Ref.[39] will be used where a mathematical structure to calculate the cost of residues and its effect on the cost of products is developed.

The cost of the exergy contained in the residues (its formation cost) and the cost of resources employed in its treatment (the abatement cost) must be allocated to the productive units that have generated them and then to the final products according to the productive structure of the plant. After identifying all the residues, the formation process of each residue needs to be trade to locate its origin.

Let´s refer to the exergoeconomic costs. If the residue dissipated in the component r has its origin in several components, the cost of the residue is divided into several costs, one for each component that has generated it:

$$P_r^* = \sum_{i \epsilon produc} P_{r,i}^* \qquad \text{(C. 30)}$$

Therefore, the cost of the residues charged to the productive component i is given by:

$$R_i^* = \sum_{\substack{r \epsilon dissipative \\ i \epsilon productive}} P_{r,i}^* \qquad \text{(C. 31)}$$

and then:

$$P_i^* = F_i^* + R_i^* \qquad \text{(C. 32)}$$

and in this way the cost of the residues produced in the dissipative units are allocated to the productive components that have generated them.

In order to determine the $P_{r,i}^*$ values, a cost distribution ratio must be define ($\psi_{i,r}$), such as:

$$P_{r,i}^* = \psi_{i,r} \cdot P_{r,e}^* \quad , \quad \sum \psi_{i,r} = 1 \qquad \text{(C. 33)}$$

This allocation can be made in several ways, depending on the type and nature of residue and there is no a general criterion. As the cost in the r dissipative unit is:

$$P_r^* = E_{e,r} + \sum_{i=1}^{n} k_{P_i}^* \cdot E_{i,r} \qquad \text{(C. 34)}$$

The cost of waste allocated to the productive unit *i* is:

$$\psi_{i,r} = \frac{k_{P_i}^* \cdot E_{i,r}}{k_{P_r}^* - k_{e,r}^*} \qquad \text{(C. 35)}$$

A new $\langle \mathbf{KR} \rangle$ (n, n) matrix is introduced whose elements are $\rho_{r,i}$ and then:

$$\rho_{r,i} = \frac{k_{P,i}^{e*} \cdot \kappa_{i,r}}{k_{P,r}^{e*} - k_{e,r}^{*}} \cdot \frac{P_r}{P_i} \qquad , \qquad i \in produc\ ; \ r \in dissipa \tag{C. 36}$$

This allocation only considers a short path of waste contribution. A more complex method considers the complete chain of production cost [37].

Accordingly, unitary exergetic costs can be decomposed into contributions associated with external resources ($\mathbf{k_P}^{\mathbf{e},*}$) and those associated with residues ($\mathbf{k_P}^{\mathbf{r},*}$). So that:

$$\mathbf{k_P}^{*} = \mathbf{k_P}^{\mathbf{e}*} + \mathbf{k_P}^{\mathbf{r}*} \tag{C. 37}$$

$$\mathbf{k_P^{e,*}} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{k_e^*} \quad , \quad |\mathbf{P}\rangle = (\mathbf{U_D} - \mathbf{KP})^{-1} \tag{C. 38}$$

$$\mathbf{k_P^{r,*}} = {}^{\mathbf{T}}\big|\widetilde{\mathbf{R}}\big\rangle \cdot \mathbf{k_p^{e,*}} \quad , \quad \big|\widetilde{\mathbf{R}}\big\rangle = (\mathbf{U_D} - |\mathbf{R}\rangle)^{-1} - \mathbf{U_D} \quad , \quad |\mathbf{R}\rangle = \langle\mathbf{KR}\rangle \cdot |\mathbf{P}\rangle \tag{C. 39}$$

$$\mathbf{k_P}^{*} = {}^{\mathbf{T}}\big|\widetilde{\mathbf{P}}\big\rangle \cdot \mathbf{k_e^*} \quad , \quad \big|\widetilde{\mathbf{P}}\big\rangle = (\mathbf{U_D} - \langle\mathbf{KP}\rangle - \langle\mathbf{KR}\rangle)^{-1} \tag{C. 40}$$

Let´s refer now to the exergoeconomic costs. In a similar way to Eq(C. 37) it is easy to realize that the production costs could be decomposed into the different contributions due to external resources costs ($\mathbf{c_P^e}$), equipment investment costs ($\mathbf{c_P^z}$) and waste generation costs ($\mathbf{c_P^r}$). The production costs could be expressed as:

$$\mathbf{c_P} = \mathbf{c_P^e} + \boldsymbol{c}_\mathbf{P}^\mathbf{z} + \boldsymbol{c}_\mathbf{P}^\mathbf{r} \tag{C. 41}$$

$$\mathbf{c_P^e} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{c_e} \tag{C. 42}$$

$$\mathbf{c_P^z} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{z_p} \tag{C. 43}$$

$$\mathbf{c_P^r} = {}^{\mathbf{T}}\big|\widetilde{\mathbf{R}}\big\rangle \cdot \mathbf{c_P^e} \tag{C. 44}$$

Once the production costs are calculated the costs of fuel could be worked out as follows:

$$\mathbf{c_F} = \mathbf{c_e} + {}^{\mathbf{T}}\langle\mathbf{PF}\rangle \cdot \mathbf{c_P} \tag{C. 45}$$

Considering the versatility of ST, the cost formation accuracy raises as the number of the facility's subsystems increases. In other words, with a more detailed definition of the subsystems a greater understanding for the cost formation process is achieved.

C.2.2. Case study

To deepen the previous theory two examples will be develop:

The aim of the first example is to present the ST methodology as a compact and brief summary, by introducing the general expressions for the thermoeconomic variables as function of the component unit consumption, the outputs and the junction coefficients, in the demand-driven model. Searching for the simplicity, a basic DHW facility is used as a case study.

The objective of the second example is to emphasize the versatility and coverage of ST tool for cost accounting. Following the previously defined (ii) Retrofit Case Study of **Chapter A**, two thermal system are compared and the economic benefits acquired through system renovation are highlighted.

C.2.2.1. (iv) Simple DHW facility

The considered energy supply system covers the DHW demand of 20-householder multi-family flat, located in Bilbao (Spain), through a natural gas condensing boiler with a rated power of 28 kW. The system consists of a hydraulic compensator, a three way valve which acts according to demand, a heat exchanger and a DHW tank. In addition, there are two circulation pumps, both in the primary and in the secondary circuit (see Figure C. 4). 7 components and 15 flows were considered for the analysis (see Figure C. 5).

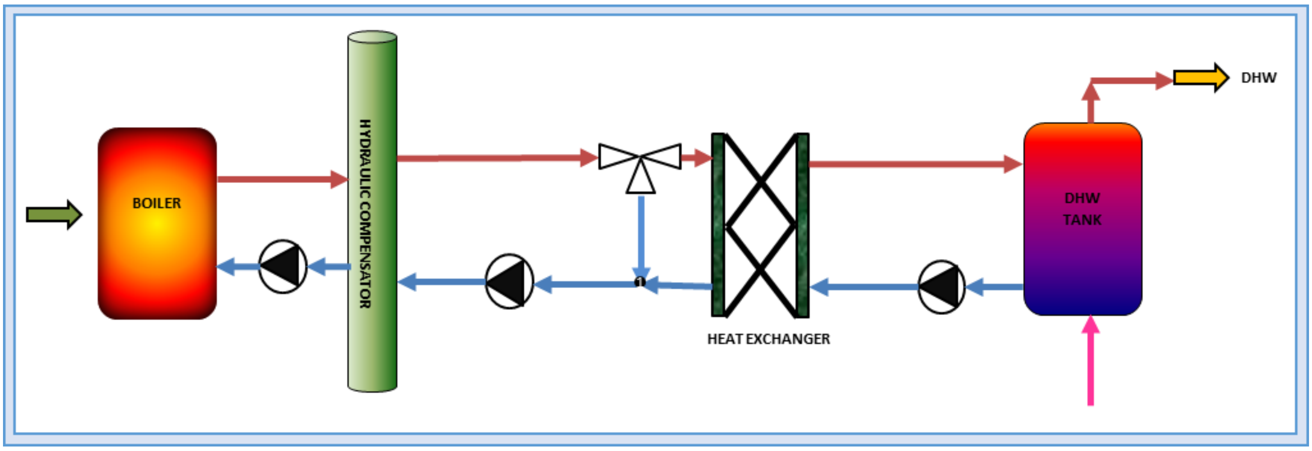


Figure C. 4 Scheme of the facility for the production of DHW

As it can be seen a dissipative component was regarded, which is the chimney (the flows related to it are highlighted in red). Besides, the two circulation pumps have not been taken into

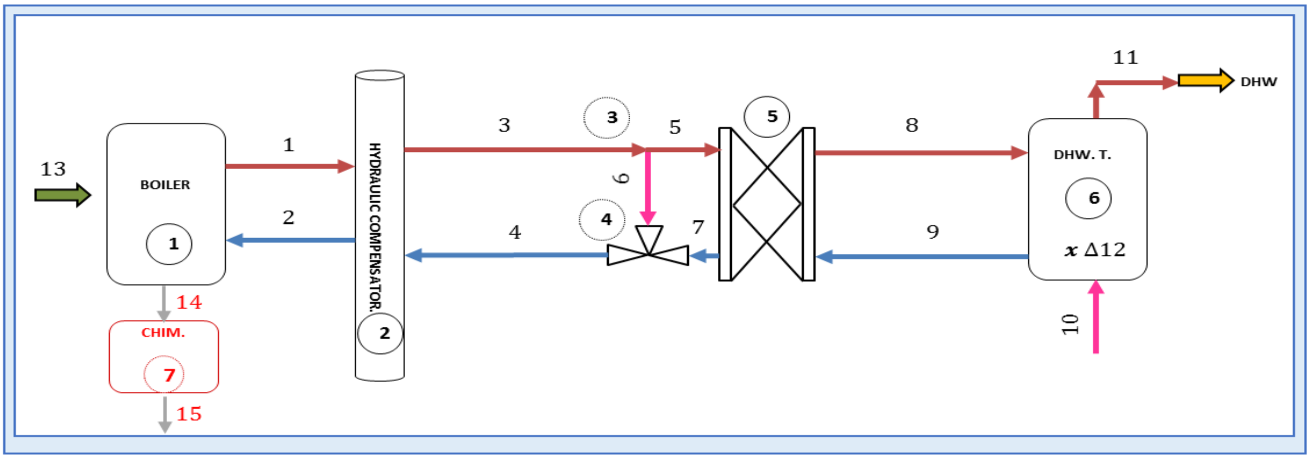


Figure C. 5 Physical Structure of the facility consideration. This is due to the small power of those elements. Therefore, the calculations do not contain the effect of pressure on the values of physical exergy of the water flow.

C.2.2.1.1. Symbolic expressions

In Table C. 1 (a) the results of the structural analysis are collected. In this table the Fuel and Product of each component, the unit exergy consumption, the external product of the plant and the residues appear[3]. Only the flow 14 is a residue which is associated with the combustion gases exiting the chimney of the boiler, so that 15 is the same waste flow with a lower temperature.

Table C. 1 (a) F/P/R Table and exergy unitary consumption of each device (b) Junction ratios

	n	FUEL	PROD.	RESID.	k	P_s	R_s
①	Boiler	$\dot{E}_{13}$	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_{14}$	$\frac{(\dot{E}_1 - \dot{E}_2) + \dot{E}_{14}}{\dot{E}_{13}}$	0	-
②	Hidraulic Comp.	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_3 - \dot{E}_4$	-	$\frac{\dot{E}_3 - \dot{E}_4}{\dot{E}_1 - \dot{E}_2}$	0	-
③	Diverter	$\dot{E}_3$	$\dot{E}_5 + \dot{E}_6$	-	$\frac{\dot{E}_5 + \dot{E}_6}{\dot{E}_3}$	0	-
④	V3V	$\dot{E}_6 + \dot{E}_7$	$\dot{E}_4$	-	$\frac{\dot{E}_4}{\dot{E}_6 + \dot{E}_7}$	0	-
⑤	HX	$\dot{E}_5 - \dot{E}_7$	$\dot{E}_8 - \dot{E}_9$	-	$\frac{\dot{E}_8 - \dot{E}_9}{\dot{E}_5 - \dot{E}_7}$	0	-
⑥	Tank	$(\dot{E}_8 - \dot{E}_9) + \Delta\dot{E}_{12}$	$\dot{E}_{11} - \dot{E}_{10}$	-	$\frac{\dot{E}_{11} - \dot{E}_{10}}{(\dot{E}_8 - \dot{E}_9) + \Delta\dot{E}_{12}}$	$\dot{E}_{11}$	-
⑦	Chimney	$\dot{E}_{14}$	$\dot{E}_{15}$	-	$\frac{\dot{E}_{15}}{\dot{E}_{14}}$	0	$\dot{E}_{15}$

n	JUNTION RATIOS	α_r
①	$r_1 = \frac{\dot{E}_2}{\dot{E}_1}$	$\dot{E}_2 - \dot{E}_1 \cdot r_1 = 0$
②	$r_2 = \frac{\dot{E}_4}{\dot{E}_3}$	$\dot{E}_4 - \dot{E}_3 \cdot r_2 = 0$
③	$r_3 = \frac{\dot{E}_7}{\dot{E}_6}$	$\dot{E}_7 - \dot{E}_6 \cdot r_3 = 0$
④	$r_4 = \frac{\dot{E}_9}{\dot{E}_8}$	$\dot{E}_9 - \dot{E}_8 \cdot r_4 = 0$
⑤	$r_5 = \frac{\dot{E}_{10}}{\dot{E}_{11}}$	$\dot{E}_{10} - \dot{E}_{11} \cdot r_5 = 0$
⑥	$r_6 = \frac{\dot{E}_8 - \dot{E}_9}{\Delta\dot{E}_{12}}$	$(\dot{E}_8 - \dot{E}_9) - \Delta\dot{E}_{12} \cdot r_6 = 0$

From this table the Fuel A_F and Product A_P matrixes are immediately constructed. Note that for DHW tank the increasing exergy produced in the simulation period of time, $\Delta\dot{E}_{12}$, was considered as an additional Fuel.

In Table C. 1 (b) junction equations used for the development of α_r matrix are presented. Since the products of the plant are two, α_s (2,7) matrix can be built.

[3] All the E_i exergy flows, along this work, should be regarded as dependent aggregated variables $E_i(\bar{x})$, where $\bar{x}$ are composed by extensive (m) and intensive $(\gamma, T, \ldots)$ variables. Because of space reasons E_i is used instead of $E_i(\bar{x})$.

Finally, $\mathbb{J}_r$ matrix (which constitute the extended matrix resulting from joining the $\mathbf{J} \equiv \mathbf{A_F} - \mathbf{k_D} \cdot \mathbf{A_P}$, $\boldsymbol{\alpha}_s$ and $\boldsymbol{\alpha}_r$ matrixes) and the $\mathbb{Y}_S$ extended vector are constructed. See Table C. 2.

Table C. 2 J_R and Y_s extended matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
***J*=**	$-k_1$	k_1	0	0	0	0	0	0	0	0	0	0	1	$-k_1$	0
	1	-1	$-k_2$	k_2	0	0	0	0	0	0	0	0	0	0	0
	0	0	1	0	$-k_3$	$-k_3$	0	0	0	0	0	0	0	0	0
	0	0	0	$-k_4$	0	1	1	0	0	0	0	0	0	0	0
	0	0	0	0	1	0	-1	$-k_5$	k_5	0	0	0	0	0	0
	0	0	0	0	0	0	0	1	-1	k_6	$-k_6$	1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	1	$-k_7$
α_s=	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
α_r=	$-\frac{\dot{E}_2}{\dot{E}_1}$	1	0	0	0	0	0	0	0	0	0	0	0	1	0
	0	0	$-\frac{\dot{E}_4}{\dot{E}_3}$	1	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	$-\frac{\dot{E}_7}{\dot{E}_6}$	1	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	$-\frac{\dot{E}_9}{\dot{E}_8}$	1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	1	$-\frac{\dot{E}_{10}}{\dot{E}_{11}}$	0	0	0	0
	0	0	0	0	0	0	0	1	-1	0	0	$-\frac{(\dot{E}_8-\dot{E}_9)}{\Delta\dot{E}_{12}}$	0	0	0
${}^t\mathbb{Y}_s$=	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1

Solving the matrix Eq(C. 2) and after finding the inverse of the expanded matrix $\mathbf{J_r}$, symbolic expressions of each flow of the plant are obtained, depending on the unitary exergy consumption, junction ratios and plant outputs, see Table C. 3.

The total unitary exergy consumption of the plant (the inverse of the total exergy performance) becomes: $k_T = \frac{F_T}{P_T} = \frac{\Delta\dot{E}_{12}+\dot{E}_{13}}{(\dot{E}_{11}-\dot{E}_{10})} = \frac{k_1 \cdot k_7 \cdot \dot{E}_{S_{15}} + k_6 \cdot \frac{\dot{E}_{S_{11}}}{1+r_6} \cdot \left[1 + r_6 \cdot k_1 \cdot k_5 \cdot \frac{k_2 \cdot k_3 \cdot (1-r_2)}{(1-k_3 \cdot k_4 \cdot r_2)}\right]}{\dot{E}_{S_{11}}}$

This formula allows relating the unit consumption of the plant with the unitary exergy consumption of the elements that compose it, through the junction parameters that reflect the physical structure and through the external products. It is a universal formula, so that for different values of these coefficients and for different consumption values, the whole unit consumption of the plant can be obtained.

Table C. 3 Symbolic expressions of every flow

	SYMBOLIC EXPRESIONS OF FLOWS
1.	$\dot{E}_1 = r_6 \cdot k_2 \cdot k_3 \cdot \frac{(1-r_2)}{(1-r_1)} \cdot \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
2.	$\dot{E}_2 = r_1 \cdot r_6 \cdot k_2 \cdot k_3 \cdot \frac{(1-r_2)}{(1-r_1)} \cdot \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
3.	$\dot{E}_3 = r_6 \cdot k_3 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
4.	$\dot{E}_4 = r_2 \cdot r_6 \cdot k_3 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
5.	$\dot{E}_5 = r_5 \cdot \frac{[k_3 \cdot k_4 \cdot r_2 - (1+r_3)] \cdot k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_3) \cdot (1+r_6)}$
6.	$\dot{E}_6 = r_2 \cdot r_6 \cdot k_3 \cdot k_4 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_3) \cdot (1+r_6)}$
7.	$\dot{E}_7 = r_3 \cdot r_2 \cdot r_6 \cdot k_3 \cdot k_4 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_3) \cdot (1+r_6)}$
8.	$\dot{E}_8 = r_6 \cdot k_6 \cdot \frac{\dot{E}_{s_{11}}}{(1-r_4) \cdot (1+r_6)}$
9.	$\dot{E}_9 = r_4 \cdot k_6 \cdot \frac{\dot{E}_{s_{11}}}{(1-r_4) \cdot (1+r_6)}$
10.	$\dot{E}_{10} = r_5 \cdot \frac{\dot{E}_{s_{11}}}{1-r_5}$
11.	$\dot{E}_{11} = \frac{\dot{E}_{s_{11}}}{1-r_5}$
12.	$\Delta\dot{E}_{12} = k_6 \cdot \frac{\dot{E}_{s_{11}}}{1+r_6}$
13.	$\dot{E}_{13} = k_1 \cdot k_7 \cdot \dot{E}_{s_{15}} + r_6 \cdot k_1 \cdot \kappa_5 \cdot k_6 \cdot \frac{k_2 \cdot k_3 \cdot (1-r_2)}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
14.	$\dot{E}_{14} = k_7 \cdot \dot{E}_{s_{15}}$
15.	$\dot{E}_{15} = \dot{E}_{s_{15}}$

C.2.2.1.1.1. Exergetic Cost

In order to calculate the cost of fuels and products of each unit, $\langle \mathbf{FP} \rangle$, $\langle \mathbf{KP} \rangle$ and $\langle \mathbf{KR} \rangle$ matrixes are previously required, according to Eq (C. 7), (C. 10) and (C. 36) respectively. The results obtained are shown in Table C. 4.

Table C. 4 $\langle \mathbf{FP} \rangle$, $\langle \mathbf{KR} \rangle$, $\langle \mathbf{KR} \rangle$matrices depending on the junction ratios

${}^{t}\langle \mathbf{F_T F} \rangle =$	1	0	0	0	0	$\frac{1}{1+r_6}$	0
$\langle \mathbf{FP} \rangle =$	0	1	0	0	0	0	1
	0	0	$1-r_2$	0	0	0	0
	0	0	0	1	1	0	0
	0	0	r_2	0	0	0	0
	0	0	0	0	0	$\frac{r_6}{(1+r_6)}$	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

$\mathbf{k_e}^{\mathbf{T}} =$	k_1	0	0	0	0	$\frac{k_6}{1+r_6}$	0
$\langle \mathbf{KP} \rangle =$	0	k_2	0	0	0	0	κ_7
	0	0	$k_3 \cdot (1-r_2)$	0	0	0	0
	0	0	0	k_4	k_5	0	0
	0	0	$k_3 \cdot r_2$	0	0	0	0
	0	0	0	0	0	$\frac{k_6 \cdot r_6}{(1+r_6)}$	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

$\langle \mathbf{KR} \rangle =$	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	$\frac{\dot{E}_{15}}{(\dot{E}_1 - \dot{E}_2) + \dot{E}_{14}}$	0	0	0	0	0	0

Once these matrices are obtained, the exergetic costs of products are calculated by applying Eq.(C. 38) and (C. 39), see Table C. 5.

Table C. 5 Unitary exergetic cost of fuels associated with (a) external resources and (b) residues

	P UNIT EXERGETIC COST RELATED TO EXTERNAL RESOURCES
①	$k_{p_1}^{e,*} = k_1$
②	$k_{p_2}^{e,*} = k_2 \cdot k_1$
③	$k_{p_3}^{e,*} = \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1$
④	$k_{p_4}^{e,*} = k_4 \cdot \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1$
⑤	$k_{p_5}^{e,*} = k_5 \cdot \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1$
⑥	$k_{p_6}^{e,*} = \frac{k_6 \cdot r_6}{(1+r_6)} \cdot k_5 \cdot \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1 + \frac{k_6}{(1+r_6)}$
⑦	$k_{p_7}^{e,*} = k_7 \cdot k_1$

	PRODUCT UNIT EXERGETIC COST RELATED TO RESIDUES
①	$k_{p_1}^{r,*} = \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
②	$k_{p_2}^{r,*} = k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
③	$k_{p_3}^{r,*} = \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
④	$k_{p_4}^{r,*} = k_4 \cdot \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
⑤	$k_{p_5}^{r,*} = k_5 \cdot \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
⑥	$k_{p_6}^{r,*} = \frac{k_6 \cdot r_6}{(1+r_6)} \cdot k_5 \cdot \frac{(1-r_2)\cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
⑦	$k_{p_7}^{r,*} = \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$

So, obviously the total unitary cost of products is: $\mathbf{k_P}^{*} = \mathbf{k_P}^{\mathbf{e}*} + \mathbf{k_P}^{\mathbf{r}*}$ Eq.(C. 37).

Regarding the unitary costs of fuels for each component, Eq.(C. 21) is applied, appearing the results in Table C. 6.

Table C. 6 Unitary exergetic cost of fuels

	FUEL UNIT EXERGETIC COST
①	$k^*_{F_1} = 1$
②	$k^*_{F_2} = \frac{k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
③	$k^*_{F_3} = \frac{(1-r_2)}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
④	$k^*_{F_4} = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
⑤	$k^*_{F_5} = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
⑥	$k^*_{F_6} = 1-\frac{k_6\cdot r_6}{(1+r_6)}-\frac{k_6\cdot r_6}{(1+r_6)}\cdot\frac{(1-r_2)\cdot k_3\cdot k_5}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
⑦	$k^*_{F_7} = \frac{k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$

Table C. 7 Exergoeconomic costs of products and fuels

	PRODUCT UNIT EXERGOECOMIC COST RELATED TO EXTERNAL COSTS
①	$c^z_{p_1} = z_1$
②	$c^z_{p_2} = k_2\cdot z_1 + z_2$
③	$c^z_{p_3} = \frac{z_3 + k_3\cdot(1-r_2)\cdot(k_2\cdot z_1 + z_2 + r_2\cdot z_4)}{(1-k_3\cdot k_4\cdot r_2)}$
④	$c^z_{p_4} = \frac{z_4 + k_4\cdot(1-r_2)\cdot(k_2\cdot k_3\cdot z_1 + k_3\cdot z_2 + z_3)}{(1-k_3\cdot k_4\cdot r_2)}$
⑤	$c^z_{p_5} = z_5 + \frac{\kappa_5\cdot(1-r_2)\cdot(\kappa_2\cdot\kappa_3\cdot z_1 + \kappa_3\cdot z_2 + z_3 + r_2\cdot\kappa_3\cdot z_4)}{(1-k_3\cdot k_4\cdot r_2)}$
⑥	$c^z_{p_6} = z_6 + \frac{\kappa_6\cdot r_6}{(1+r_6)}\cdot\frac{z_5 + \kappa_{d5}\cdot(1-r_2)\cdot(\kappa_2\cdot\kappa_3\cdot z_1 + \kappa_3\cdot z_2 + z_3 + r_2\cdot\kappa_3\cdot z_4)}{(1-k_3\cdot k_4\cdot r_2)}$
⑦	$c^z_{p_7} = \kappa_7\cdot z_1$

	PRODUCT UNIT EXERGOECOMIC COST RELATED TO RESIDUES
①	$c^r_{p_1} = \frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
②	$c^r_{p_2} = k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
③	$c^r_{p_3} = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
④	$c^r_{p_4} = k_4\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
⑤	$c^r_{p_5} = k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
⑥	$c^r_{p_6} = \frac{k_6\cdot r_6}{(1+r_6)}\cdot k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
⑦	$c^r_{p_7} = \frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot\kappa_7)}\cdot k_1\cdot c_{NG}$

	PRODUCT UNIT EXERGOECOMIC COST RELATED TO EXTERNAL RESOURCES
①	$c^e_{p_1} = k_1\cdot c_{NG}$
②	$c^e_{p_2} = k_2\cdot k_1\cdot c_{NG}$
③	$c^e_{p_3} = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG}$
④	$c^e_{p_4} = k_4\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG}$
⑤	$c^e_{p_5} = k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG}$
⑥	$c^e_{p_6} = \frac{k_6\cdot r_6}{(1+r_6)}\cdot k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG} + \frac{k_6}{(1+r_6)}\cdot c_w$
⑦	$c^e_{p_7} = k_7\cdot k_1\cdot c_{NG}$

	FUEL UNIT EXERGOECOMIC COST
①	$c_{F_1} = c_{NG}$
②	$c_{F_2} = c_{P_1}$
③	$c_{F_3} = (1-r_2)\cdot c_{P_2} + r_2\cdot c_{P_4}$
④	$c_{F_4} = c_{P_3}$
⑤	$c_{F_5} = c_{F_3}$
⑥	$c_{F_6} = \frac{1}{(1+r_6)}\cdot c_w + \frac{r_6}{(1+r_6)}\cdot c_{P_5}$
⑦	$c_{F_7} = c_{P_1}$

C.2.2.1.1.2. Exergoeconomic Cost

Concerning the exergoeconomic costs, three components are differentiated: one is associated with external resources, another one is related to the amortization and maintenance of the units and the third one is connected with the residues. By Eq(C. 42), (C. 43) and (C. 44) cost of products are obtained and gathered in Table C. 7. According to external cost of products, z_i refers to the amortization and maintenance cost per unit of exergy produced in each component, that is to say, $z_1 = \frac{Z_1}{P_1} = \frac{Z_1}{(\dot{E}_1 - \dot{E}_2) + \dot{E}_{14}}$ and so on. Moreover, c_{NG} reflects the natural gas exergetic unitary cost, whereas c_w is the unitary cost of the mains water.

So, the total unitary economic cost of products is: $\mathbf{c_P} = \mathbf{c_P}^{\mathbf{e}} + \mathbf{c_P}^{\mathbf{z}} + \mathbf{c_P}^{\mathbf{r}}$, Eq.(C. 41).

Once the costs of products are obtained, the costs of fuels are derived by applying Eq.(C. 45). The results obtained also appear in Table C. 7.

C.2.2.1.2. Numerical results

The thermal model required for extracting the thermodynamic variables is obtained by means of Trnsys dynamic simulation. As it is known, it does not only consider the building residents and its usage, but also the localization, climate and cold water feed temperatures according to the positioning [40]. DHW demand is obtained following the standard distribution probability based on Gaussian and step functions [41]. Net water temperature and DHW demand profile are depicted in Figure C. 6 for the three days simulation period.

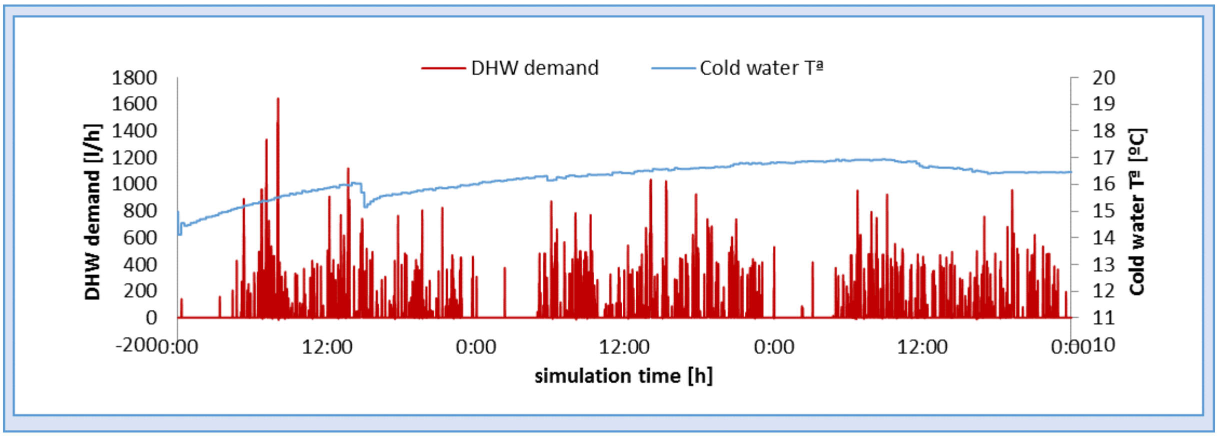


Figure C. 6 DHW and Cold water temperature profile

Table C. 8 shows the accumulated exergy for each flow at the end of a three-day period.

Table C. 8 Accumulated Exergy in each flow at the end of a three- day period

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\frac{kW.h}{3\ days}$	109.07	72.19	112.80	83.12	91.42	21.38	61.73	106.73	82.02	0	18.50	3.30	293.72	1.11	1.11

In Table C. 9 Fuel, Product and Residue values are collected. The unitary exergy consumption and the total production accumulated during the three-day period are also displayed.

Table C. 9 F/P/R accumulated values during three days of simulation

		FUEL	PRODUCT	RESIDUE	k	P_s
①	Boiler	293.72	36.88	1.1	7.96	-
②	H.Comp	36.88	29.69	-	1.24	-
③	V3V	112.80	112.80	-	1	-
④	T	83.12	83.12	-	1	-
⑤	HX	29.69	24.71	-	1.20	-
⑥	Tank	28.01	18.50	-	1.51	18.5
⑦	Chim.	1.11	1.11	-	1	1.1

C.2.2.1.2.1. Exergetic Cost

Once the values of the $\langle \mathbf{FP} \rangle$, $\langle \mathbf{KP} \rangle$ and $\langle \mathbf{KR} \rangle$ matrixes are obtained, the unit exergetic costs of the products of each component have been calculated. Table C. 10 (a) reflects those values partitioned into its two components ($k_{P_i}^{e,*}, k_{P_i}^{r,*}$) while Table C. 10 (b) displays the values of unitary exergetic cost of fuel and product of each component ($k_{F_i}^{*}, k_{P_i}^{*}$) and therefore the unitary cost of DHW.

Table C. 10 (a) Disaggregated unitary costs (b) Fuel and Product unitary

	$k_p^{e,*}$	$k_p^{r,*}$
Bolier	7.73	0.23
Comp	9.61	0.29
V3V	9.61	0.29
T	9.61	0.29
HX	11.54	0.35
Tank	15.59	0.46
Chim	7.73	0.23

	k_f^*	k_p^*
Bolier	1	7.96
Comp	7.96	9.89
V3V	9.89	9.89
T	9.89	9.89
HX	9.89	11.72
Tank	10.60	17.46
Chim	7.96	7.96

C.2.2.1.2.2. Exergoeconomic Cost

The information needed in order to calculate the exergoeconomic costs are the amortization and maintenance costs in the period of three days as well as the natural gas and the mains water unitary costs. Such information is shown in Table C. 11.

Table C. 11 Needed data to calculate the exergoeconomic costs

		Adquisition Cost (I_i) [€]	Yearly Fixed Cost (CF_i) [€/ year]	Operation Time [min/ 3days]	Yearly Op. Time (OP_{year}) [h/year]	$Z_i = \frac{CF_i}{OP_{year}}$ [€/h]	Z_i [€/3days]
①	Boiler	1100	152.14	748	1516.78	0.10	7.22
②	H.Comp	900	124.48	748	1516.78	0.08	5.91
③	V3V	-	-	748	1516.78	-	-
④	T	100	13.83	748	1516.78	0.01	0.66
⑤	HX	795	109.96	1112	2254.89	0.05	3.51
⑥	Tank	1200	165.97	1663	3372.19	0.05	3.54
⑦	Chim.	-	-	-	-	-	-

Global info.	
Total investment (I_T)	4095
Maintainance & Operation (MO)	300

Useful Formulas	
Facility's useful life (n)	30 years
Annual (i)	0.05
$FR = i \cdot (1+i)^n$	0.07
Total Fixed Cost (CF_T)	$(MO + I_T \cdot FR)$
Yearly Fixed Cost (CF_i)	$\frac{CF_T}{I_T} \cdot I_i$

Unitary Inputs Costs	
$c_{NG} \left[\frac{€}{kWh_{ex}}\right]$	0.05
$c_w \left[\frac{€}{kWh_{ex}}\right]$	0.12

Finally, Table C. 12 (a) contains the unitary exergoeconomic costs of products broken down into its three components ($c^e_{P_i}, c^r_{P_i}, c^z_{P_i}$) and Table C. 12 (b) shows the unitary exergoeconomic costs of fuel and product of each component (c_{F_i}, c_{P_i}).

Table C. 12 (a) Unitary exergoeconomic costs of P split into its three components (b) Unitary exergoeconomic P

	c^e_P [€/kWh_{ex}]	c^r_P [€/kWh_{ex}]	c^z_P [€/kWh_{ex}]
Boiler	0.42	0.01	0.19
Comp	0.53	0.02	0.44
V3V	0.53	0.02	0.46
T	0.53	0.02	0.47
HX	0.63	0.02	0.69
Tank	0.87	0.03	1.12
Chim	0.42	0.01	0.19

	c_F [€/kWh_{ex}]	c_P [€/kWh_{ex}]
Boiler	0.05	0.63
Comp	0.63	0.98
V3V	1.00	1.00
T	1.00	1.00
HX	1.00	1.34
Tank	1.20	2.01
Chim	0.63	0.63

Expressions can also be displayed as function of energy by multiplying them by the energy/exergy coefficient of each product. Table C. 13 contains the unitary costs of products for each component and the total costs after three days (c_{P_i}, C_{P_i}).

Table C. 13 Unitary energetic costs of products and total cost for each component

	c_P $[€/kWh_{en}]$	C_P $[€/3days]$
Boiler	0.06	23.80
Comp	0.07	29.02
V3V	0.03	112.76
T	0.03	83.74
HX	0.03	33.19
Tank	0.07	37.12
Chim	0.06	0.69

C.2.2.1.3. Results Discussion

The extra insight over basic Thermoeconomics, and also the main objective of the methodology, is the obtainment of cost formation process. Thanks to ST tool, the interrelations between components, based on the productive structure of the system, are symbolically displayed. So it is easily seen how the whole plant efficiency changes when the efficiency of any component varies. As it is joined together with ECT, the change in cost when a parameter varies is checked too.

ST allows obtaining general expressions that can be used later to obtain the numerical values of fuels, products, costs, and so on, for different operating conditions of the plant. Therefore, to give values to those formulae, some data of the flows are needed. Pressure, temperature, mass flow values must be collected from the thermal model and then the numerical values for the thermoeconomic variables can be obtained for every state of the plant.

The results bring to light that in some units, such as in the boiler the cost associated with fuel is the most important component (0.42 $[\frac{€}{kWh_{ex}}]$); while it is the cost associated with the maintenance and amortization the more important component in other units, as for example, in the tank (1.12 $[\frac{€}{kWh_{ex}}]$).

The complex problem related to the residue cost allocation has also been considered. The cost of the residue (flue gases) has been allocated just to the component that generates it, by using the criteria of distributing that cost among the components involved in its generation. It can be seen that in some components, such in the boiler, the effect in the total cost of the product due to the residue is very small (0.01 $[\frac{€}{kWh_{ex}}]$); whereas in other components, such in the tank, that effect triples due to its position in the productive structure chain (0.03 $[\frac{€}{kWh_{ex}}]$).

C.2.2.2. (ii) Building Retrofit Case Study

This example is the continuation of the case study (ii) of **Chapter A**, where the energy facility of an old and a retrofitted building are compared. Therefore, there are two facilities with different productive structures. As previously mentioned, the accuracy of the cost formation process directly depends on the chosen groups.

The old facility is specified by 27 subsystems, 70 flows and 7 outputs (4 heating outlets and 2 DHW exits; the selected components are represented in Figure C. 7) whereas the new facility contains 20 subsystems, 62 flows and 7 outputs.

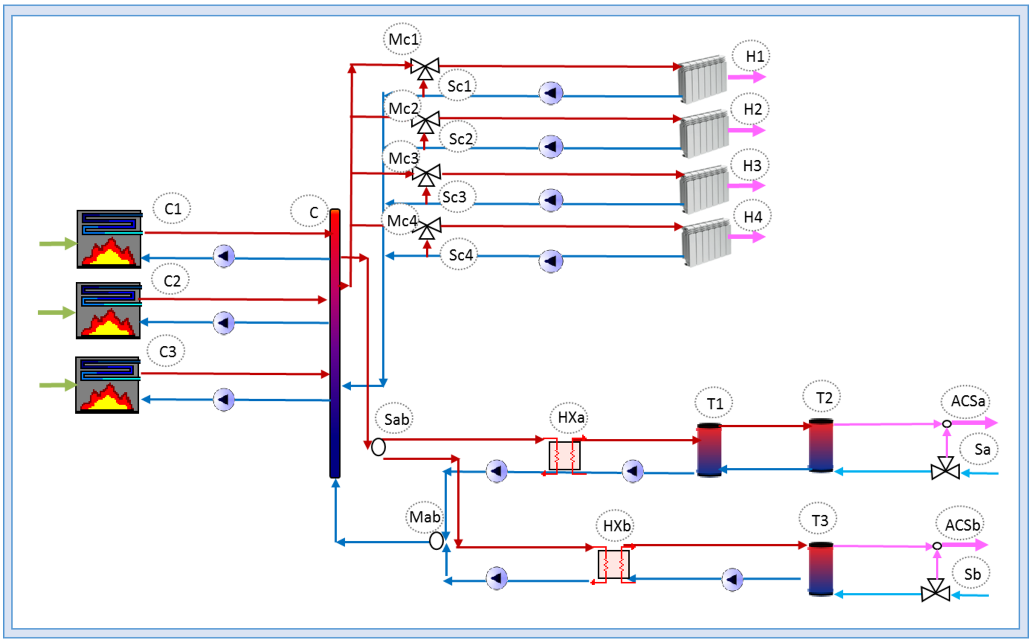


Figure C. 7 Selection of components in the old facility

Although having different symbolic structures, the subsystems were later on combined into specific groups to make possible the comparison between both facilities. The list of the particular groups used for both analyses is given in Table C. 14 where a key naming and a brief description of each component are represented.

Table C. 14 Old and new facility common groups for analogous ST application

FACILITY's COMMON GROUPS			
Group	**Description**	**Group**	**Description**
B1	Boiler 1+ Boiler Pump 1	T1	Tank 1+ low DHW Pump 6
B2	Boiler 2+ Boiler Pump 2	T2	Tank 2+ (recovery Pump 7)
B3	Boiler 3+ Boiler Pump 3	T3	Tank 3+ high DHW Pump 8
C	Collector	DHW L	DHW in low floors
H1 br.	Heating branch Distrib. I	DHW H	DHW in high floors
H2 br.	Heating branch Distrib. II	H1	Emission system of Block I + BI Pump 9
H3 br.	Heating branch Distrib. III	H2	Emission system of Block II+ BII Pump 10
H4 br.	Heating branch Distrib. IV	H3	Emission system of Block III+ BIII Pump 11
HX1	Low HX+ low HX Pump 4	H4	Emission system of Block IV+ BIV Pump 12
HX2	High HX+ high HX Pump 5		

The productive model, which is common for both facilities, is graphically depicted in Figure C. 8. The red arrows highlight the system production that goes inside the room (R.A.) while the green arrows represent the incoming resources, i.e. combustibles for boilers (continued lines), electricity input for pumps (dotted lines) and cold water for DHW circuit (grated lines). Additionally, there is also a dotted red arrow to represent the extra input coming from the condensing boiler recovery system of the new facility. As can be seen, a simple input-output analysis typical for a sequential system could be used for everything except for the 3-way valves

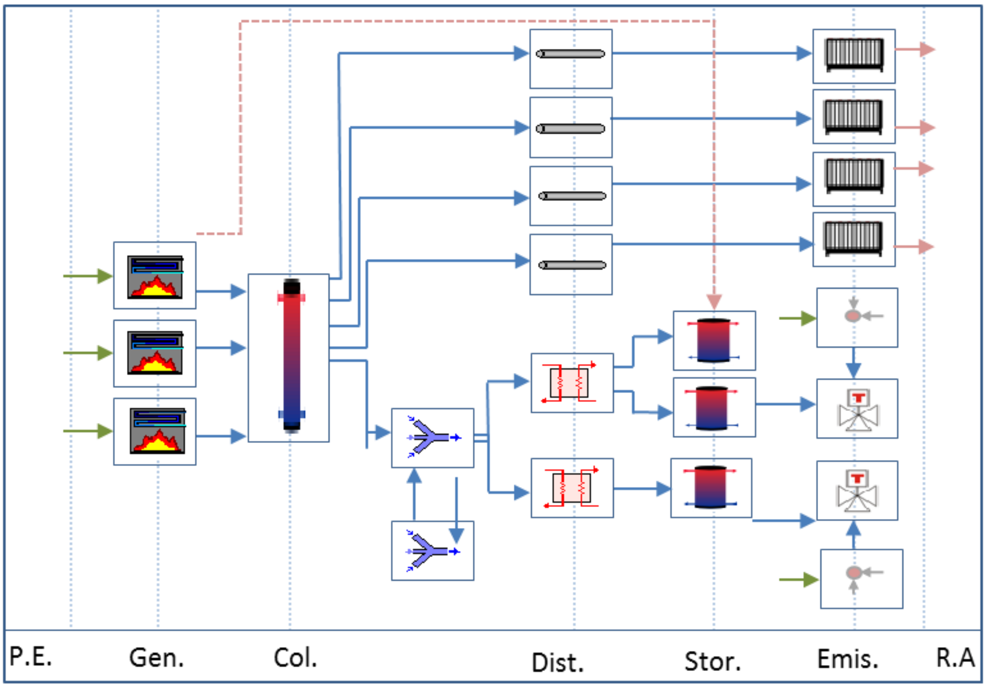


Figure C. 8 Productive model of both facilities

in the old facility and the DHW (this matter will be afterwards developed).

C.2.2.2.1.1. Exergetic Cost

The unit exergetic costs of fuels and products, $\mathbf{k}_{\mathbf{F}}^{*}$ and $\mathbf{k}_{\mathbf{P}}^{*}$, of every subsystem have been calculated and collected according to the common groups. The following Table C. 15 contains the unit exergy cost values for the old and retrofitted facility respectively. Every subsystem's irreversibility is pointed out through the increment of the unit exergy cost emerged from its fuel consumption to its product.

The highlighted blue boxes in the tables indicate the unit exergetic cost of DHW in the low and in the high dwellings circuit. Equally, the emphasized red boxes show the unit exergetic costs in each block heating circuit. As heating demands are at the end of the energy conversion chain, they display the bigger values since they incorporate all the exergy destructions picked up along the way.

If the old and new facility values are contrasted, important exergy savings can be noticed either in heating or DHW. Whereas in the old facility, the heating average unit exergetic cost is 47.8, in the new one it is 25.3. In the same way, the DHW average unit exergetic cost in the old facility is 22.7 whereas in the new one it is 20.2. Note that in Table C. 15 (b) the cost saving emerged from the heat recovery in T2 $\mathrm{k}_{\mathrm{F_{T2}}}^{*,\mathrm{new}} = 7.02$ is lower than $\mathrm{k}_{\mathrm{F_{T2}}}^{*,\mathrm{old}} = 9.46$ due to the new input of the condensing boiler.

Table C. 15 Unit exergy costs of F and P of the (a) old and the (b) new facility

OLD FACILITY [-]					
n	k_F^*	k_P^*	n	k_F^*	k_P^*
B1	1	6.76	T1	9.19	14.72
B2	-	-	T2	9.46	19.88
B3	1	7.20	T3	8.27	16.30
C	6.77	7.50	DHW L	17.48	22.34
H1 br.	22.37	23.12	DHW H	16.17	22.97
H2 br.	22.87	23.36	H1	23.12	46.22
H3 br.	26.64	27.36	H2	23.36	46.63
H4 br.	21.26	21.98	H3	27.36	55.24
HX1	7.45	9.46	H4	21.98	43.07
HX2	7.36	8.40			

NEW FACILITY [-]					
n	k_F^*	k_P^*	n	k_F^*	k_P^*
B1	1.00	6.69	T1	7.66	12.69
B2	1.00	6.36	T2	7.02	17.26
B3	1.00	6.23	T3	7.74	15.44
C	6.33	7.20	DHW L	15.56	20.15
H1 br.	6.74	6.74	DHW H	15.30	20.27
H2 br.	6.43	6.43	H1	6.74	25.41
H3 br.	6.33	6.33	H2	6.43	25.19
H4 br.	6.73	6.73	H3	6.33	25.20
HX1	6.93	8.25	H4	6.73	25.37
HX2	6.89	7.99			

C.2.2.2.1.2. Exergoeconomic Cost

Two components intervene in the exergoeconomic costs: one is associated to external resources (c_e) and the other one to the amortization and maintenance costs of the units (z_i). The exergoeconomic costs associated with the external fuels are obtained from their market prices whose values are $c_{e_{FO}}^{old} = 8.52\ c€/kWh_{ex}$ for the fuel oil, $c_{e_{NG}}^{new} = 4.75\ c€/kWh_{ex}$ for the natural gas and $c_{e_{elec}} = 12.21\ c€/kWh_{ex}$ for the electricity. The main water stream is a non-exergy-related cost that affects the total cost, being that cost equal to $51.97 c€/m^3$.

In order to compare the costs of both facilities, only the external resource costs are taken into account. The values related with the system main products (DHW and heating) are depicted in Table C. 16.

Table C. 16 Unit exergy costs of final products in the (a) old and the (b) new facility

OLD FACILITY $[c€/kWh_{ex}]$	
n	c_P
DHW L	190.87
DHW H	196.47
H1	395.22
H2	399.73
H3	473.44
H4	368.45

NEW FACILITY $[c€/kWh_{ex}]$	
n	c_P
DHW L	98.35
DHW H	99.04
H1	123.55
H2	124.08
H3	124.63
H4	123.43

As can be seen, due to the different prices of the fuels used and mostly thanks to the reduction of irreversibilities achieved through more efficient components, the economic saving in the retrofitted facility is quite relevant (admittedly, without considering the equipment investment). The unit exergoeconomic heating cost in the new facility is almost 69 % lower than in the old one (see red boxes) whereas the unit exergoeconomic DHW cost has practically been cut in half (see blue boxes).

The remaining results of the rest of the energy chain are graphically outlined in Figure C. 9 in order to visualize the cost tendency. Besides the unit exergoeconomic cost, the cumulative exergy destruction has also been portrayed for the old and new facility.

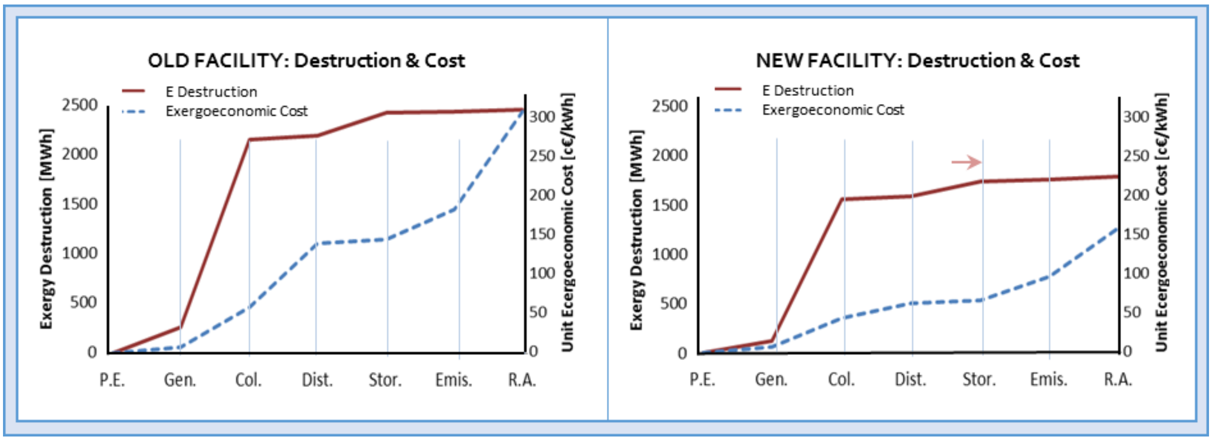


Figure C. 9 Exergy destruction and unit exergoeconomic cost in the old and new facility

C.2.2.2.2. Results Discussion

The exergetic analysis enables homogenizing the flows in terms of energy quality and making the comparison between components and systems more reliable. That is the reason why it is a key tool for analyzing the enhancements in energy systems refurbishment. Besides, exergy is the base variable for thermoeconomic cost allocation as the cost is assigned according to the encountered irreversibilities until arriving at such point of the system. If exergy cost is combined with ST, a versatile mechanic method is achieved.

This example aims the comparison of the old and the new retrofired building energy systems. Hence, after defining the productive structures of the facilities and relating them in same subgroups, the exergetic and exergoeconomic costs of every flow were calculated. Referring to the final products of the old and retrofitted facility, the values obtained are 47.8 and 25.3 for heating and 22.7 and 20.2 for DHW respectively. These values show the big improvement achieved through the refurbishment. Similarly, the values obtained for the unit exergoeconomic costs (not including the investment costs) are 15.93 $c€/kWh_{en}$ and 5.21 $c€/kWh_{en}$ for heating and 10.04 $c€/kWh_{en}$ and 4.87 $c€/kWh_{en}$ for DHW, highlighting once again the big savings in fuel costs achieved with the new facility.

C.3. ST IN DYNAMIC BUILDING SYSTEMS

As mentioned in **Chapter B**, buildings requirements change uninterruptedly due to the users demand and the tight connection with the environmental conditions. Therefore, buildings thermal facilities continuously modify their functioning mode (switching on, turning off and modulating) to adapt to the consumer claims. Because of that, as the physical configuration and the productive structure are being altered, the system can be assumed as a global super-structure composed by the linkages among components (i, j) and environment (e).

Considering the dynamic behavior of building facilities (therefore, dynamic productive structure), ST approach can be selected to systematically program a generic method for exergetic cost accounting resolution.

The idea is to create a generic super-structure that collects all the possible configurations. In such case, a specific productive structure will be each time-step derived to perfectly adapt to the particular conditions. Admittedly, every super-structure sub-combination would have different formation cost since diverse components are taken into account.

The novelty of the contribution given in this section lies in the highly innovative application of thermoeconomic cost accounting to a facility under dynamic operating conditions. The complexity of the proposed approach is related to the highly dynamic behavior of building systems, which makes trade-offs between capital cost and efficiency more difficult to identify.

Besides, because of their recursive usefulness, two specific components would be hereafter insightfully studied, which correspond to 3-way valves and inertial storages.

C.3.1. Deepening in components productive model

Being the productive structure already deeply studied in many other works, this section focuses on the 3-way valve (V3V) and inertial component thermoeconomic representation; after all, those are essential components in HVAC&R systems and require a meticulous analysis. Both of them need to be considered as dynamic components that change their productive structure according to the system requirements.

C.3.1.1. V3V dynamic structure

The V3V productive model can be in different ways interpreted; generally, the issue is connected with the mixing part since an exergetic destruction occurs due to the mixing of flows at different temperatures.

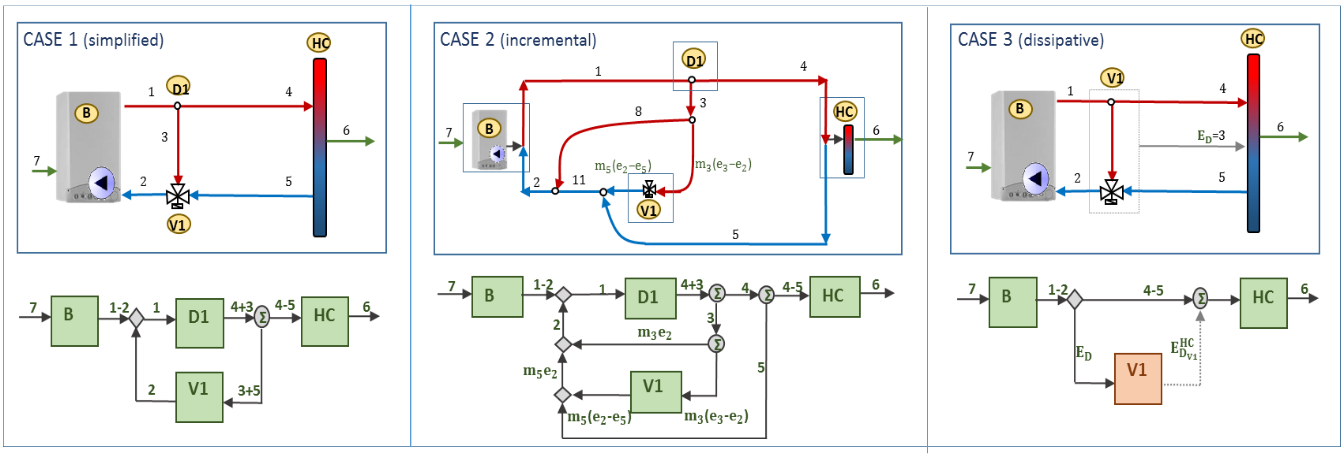


Figure C. 10 Different thermoeconomic interpretations for V3V

Figure C. 10 represents the frequent simple case in a building consisting of a boiler (B) that feeds a hydraulic compensator (HC) and is modulated by a 3-way valve. Three possible productive structures are analyzed and related to different productive perspectives; they are tagged as: *simplified*, *incremental* and *dissipative* (to facilitate the comprehension, the main product is considered as one unique flow 6). Each component F and P are defined according to the numbering in the lower part of Figure C. 10.

The first case corresponds to the simple case where the 3-way valve is split into its diverter (D1) and mixer (V1) components and the fuel and product correspond to the pertinent entering and outgoing exergetic flow, as done in [42]. In the second case, fuel and product of the V1 are related to the exergetic increment between the warmer fluid and the mixed one and the decrease between the output and cold flow [13]. The last case considers the V3V in a compact way and treats it as a dissipative component; that is to say, it is regarded as a component that has not any productive purpose (but destroys exergy) required for the proper operation of the system. In such case, the exergetic destruction is allocated to the productive component serving to [37].

If an exergetic balance in each component is defined and the F and P propositions are included, unit costs of every flow can be obtained; the balances, application of propositions and results are in Figure C. 11. Predictably, the cost of product c_6 in all cases is the same and equal to E_7/E_6; the intermediate flow cost values of case 1 and 2 slightly vary and are different in case 3.

CASE 1	CASE 2	CASE 3
BALANCE • $c_7E_7 + c_2E_2 = c_1E_1$ → $c_7 = 1$ • $c_1E_1 = c_3E_3 + c_4E_4$ → $c_3 = c_4$ • $c_3E_3 + c_5E_5 = c_2E_2$ • $c_4E_4 = c_5E_5 + c_6E_6$ → $c_4 = c_5$	**BALANCE** • $c_7E_7 + c_2E_2 = c_1E_1$ → $c_7 = 1$ • $c_1E_1 = c_3E_3 + c_4E_4$ → $c_3 = c_4$ • $c_4E_4 = c_5E_5 + c_6E_6$ → $c_4 = c_5$ • $c_5E_5 + c_{10}E_{10} = c_{11}E_{11}$ • $c_3E_3 = c_8E_8 + c_9E_9$ → $c_8 = c_9$ • $c_8E_8 + c_{11}E_{11} = c_2E_2$ • $c_9E_9 + c_{10}E_{10}$	**BALANCE** • $c_7E_7 + c_2E_2 = c_1E_1$ → $c_7 = 1$ • $c_1E_1 + c_5E_5 = c_2E_2 + c_3E_3 + c_4E_4$ → $c_3 = \frac{c_4(E_4-E_5)}{E_3}$ • $c_4E_4 + c_3E_3 = c_5E_5 + c_6E_6$ → $c_4 = c_5$
UNIT COSTS ✓ $c_1 = \frac{E_7(E_3+E_4)}{E_1(E_4-E_5)}$ ✓ $c_2 = \frac{-E_7(E_3+E_5)}{E_2(E_4-E_5)}$ ✓ $c_3 = \frac{E_7}{E_4-E_5} = c_4 = c_5$ ✓ $c_6 = \frac{E_7}{E_6}$ ✓ $c_7 = 1$	**UNIT COSTS** ✓ $c_1 = \frac{E_7(E_3+E_4)}{E_1(E_4-E_5)}$ ✓ $c_2 = \frac{-E_7(E_3+E_5)}{E_2(E_4-E_5)}$ ✓ $c_3 = \frac{E_7}{E_4-E_5} = c_4 = c_5$ ✓ $c_6 = \frac{E_7}{E_6}$ ✓ $c_7 = 1$ ✓ $c_8 = \frac{E_7E_3}{(E_8+E_9)(E_4-E_5)} = c_9$ ✓ $c_{10} = \frac{E_7E_3E_9}{E_{10}(E_8+E_9)(E_4-E_5)}$ ✓ $c_{11} = \frac{E_3E_9+E_5(E_8+E_9)}{E_{11}(E_8+E_9)(E_4-E_5)}$	**UNIT COSTS** ✓ $c_1 = \frac{E_7}{(E_1-E_2)} = c_2$ ✓ $c_3 = \frac{E_7}{2E_3}$ ✓ $c_4 = \frac{E_7}{2(E_4-E_5)} = c_5$ ✓ $c_6 = \frac{E_7}{E_6}$ ✓ $c_7 = 1$

Figure C. 11 Corresponding exergoeconomic cost balances and unit costs results

C.3.1.2. Inertial tanks dynamic structure

Inertial components can bring controversy due to their dynamic behavior. As depicted in Figure C. 12, different products and fuels can be defined for the tank (T1) depending on the primary and secondary mass flow rates conditions ($\dot{m}_p, \dot{m}_s$). In the example, $\Delta E_p, \Delta E_s$ and ΔE_{disc} were used to refer the incoming primary exergy, outgoing exergy and discharged exergy of the tank during the studied time-step.

Accordingly, in order to globally consider all the possibilities in a generic productive structure, i_{st} and o_{st} flows are incorporated (see right part of Figure C. 12 where the definition of those flows is given).

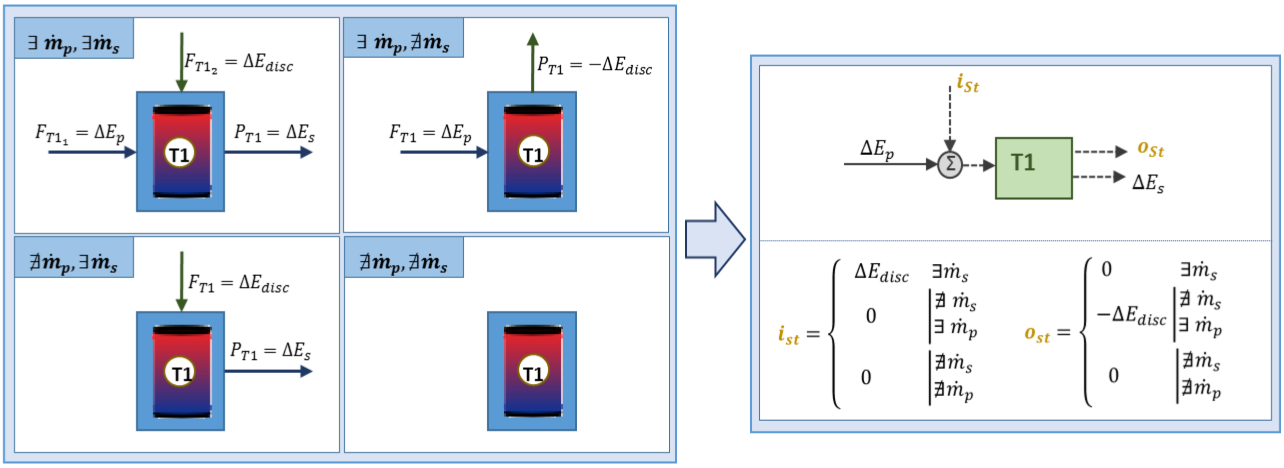


Figure C. 12 Possible configurations of T1 according to mass flow rates and generic productive structure

C.3.2. Case study

Two case studies will be developed to strengthen the previous ideas:

The first one corresponds to a building facility supported by solar energy collectors. The dynamic productive structure is gradually explained and the case 1 and 2 of V3V representation are there used. The thermoeconomic analysis is dynamically depicted.

The second example deals with the (iii) *School's AHU Case Study* exposed in **Chapter B**. The aim is to perform a detailed exergy and thermoeconomic application for a complex system covering the IAQ and thermal comfort. According to the ventilation purpose, dissipative components are regarded as key elements; besides, case 3 of V3V representation is used. Indeed, for author's best knowledge, no air handling unit AHU facility thermoeconomic analysis has being done so far.

C.3.2.1. (v) Solar Energy Building System Case Study

A facility was customized in the experimental facility of the Laboratory for the Quality Control in Buildings (LQCB) from the Basque Government providing the DHW and heating demand referred to a multifamily house.

It consists of a boiler, with 28 kW thermal energy and a manufacturer energetic efficiency (based on the lower heating value) of 97 % and an auxiliary solar collector system formed by two 2.5 m² panels connected in series. The solar circuit is equipped with a Roca 500-E 500-litter thermal storage, containing a 2.8 kW electrical resistance, providing the required inertia to maintain constant the entering water temperature in solar modules. The DHW is also supported by a 95 cm diameter and 2.25 m high 1000-litter storage tank. The heat dissipation is conducted by a 5RYardi HP 250 fan coil battery and 2-pipe system. Besides, intermediate three way-valves, heat exchangers and hydraulic compensator systems are used for the heat distribution.

The control acts in such way that boiler is turned on when heating is demanded or DHW storage tank goes beneath 62 ºC in order to avoid legionella proliferation. In such case, the DHW tank is filled if the difference between the primary incoming temperature of the heat exchanger and the tank average temperature is higher than 7 ºC. Solar storage, similarly, is activated whenever the variation of outgoing temperature of solar panels and solar tank average temperature is higher than 7 ºC.

A three-day essay was performed and data were acquired every 10 seconds thanks to the detailed monitorization and control implementation performed by the more than 120 sensors distributed along the facility. Figure C. 13 depicts the principal scheme and the different sensors allocated along the system.

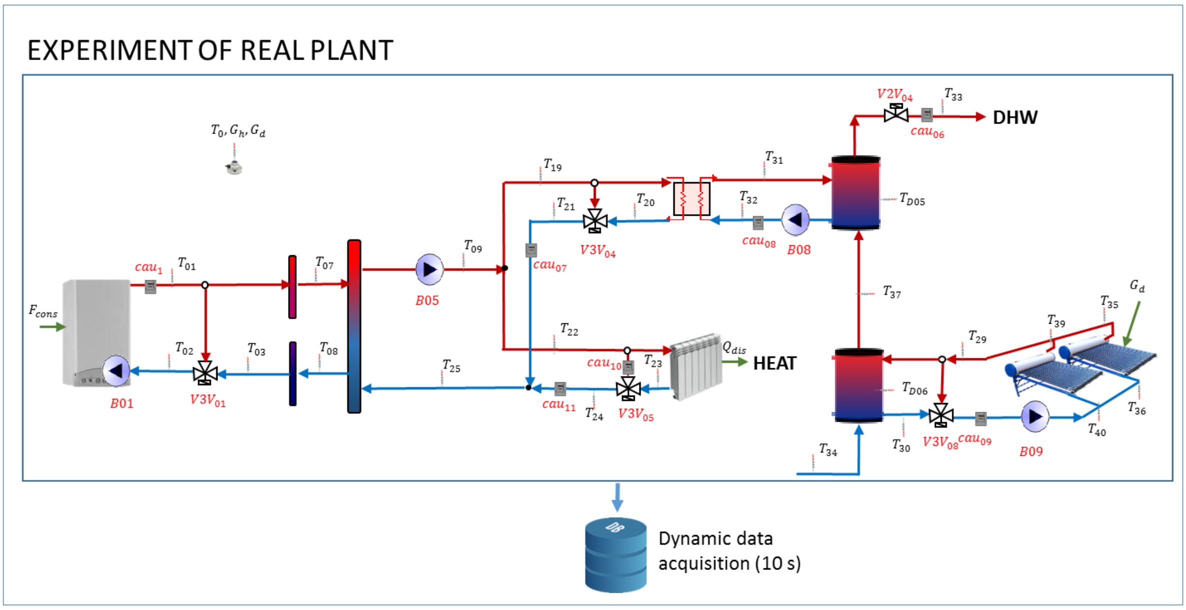


Figure C. 13 Heating and DHW system principal scheme and spread sensors

Distribution 3-way valves (V3V) have different behaviour according to their aim: the one located in the heating system modulates to cover the users heat demand. The one above the heat exchanger is an all-or-nothing valve, so all the flow is crossing or bypassing. The boiler and solar V3V are inserted for safety reasons (and for other operation mode combination) so they do not change their state.

C.3.2.1.1. Real behaviour characterization

As mentioned in **Chapter B**, the system thermal model representation is a key step. The system modelling starts with an individual characterization of the components, according to the experimental data, using Matlab [43] and Trnsys [40] combination. Once the simulation model of each component was obtained, the linkage and the specific control was implemented. Consequently, the dynamic simulation was pursued every 10 second with regard to the registered real data.

C.3.2.1.2. Thermoeconomic dynamic model

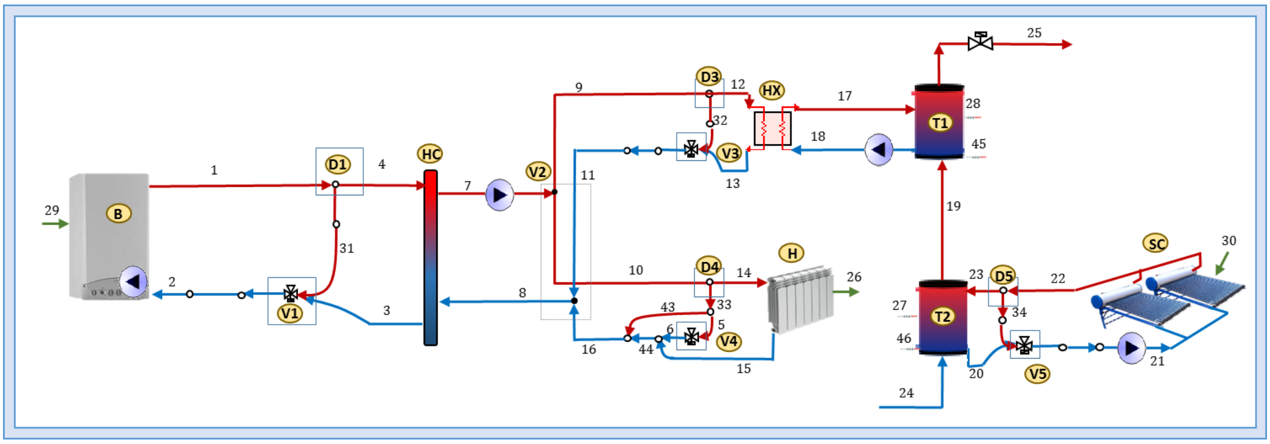


Figure C. 14 Description of the facility with V3V productive structure specific consideration

Figure C. 14 shows the numbering and nomenclature that will be used from now on. As it can be seen, according to the V3V different representations, the case 1 and 2 were chosen: the first one correspond to the all-or-nothing V3V (V1,V2,V3,V5) and the second one to the modulating one (V4). In addition, the storage tanks (T1 and T2) were globally described by considering all the possible configurations (see the i_{st}=E_{27}, $E_{28}$and o_{st}=E_{45}, E_{46} virtual flows in Figure C. 14).

Table C. 17 Generic equations and productive structure for "static" overall thermoeconomic model

		GENERIC EQUATIONS		PRODUCTIVE STRUCTURE	
		COST BALANCES	PROPOSITIONS	FUEL	PRODUCT
①	B	$c_{29}E_{29} + c_2E_2 = c_1E_1$	$c_{29} = 1$	E_{29}	$E_1 - E_2$
②	D1	$c_1E_1 + c_{31}E_{31} = c_4E_4$	$c_4 = c_{31}$	E_1	$E_4 + E_{31}$
③	V1	$c_{31}E_{31} + c_3E_3 = c_2E_2$		$E_{31} + E_3$	E_2
④	HC	$c_4E_4 + c_8E_8 = c_3E_3 + c_7E_7$	$c_4 = c_3$	$E_4 - E_3$ or E_8	$E_7 - E_8$ or E_7
⑤	V2	$c_7E_7 + c_{11}E_{11} + c_{16}E_{16} = c_8E_8 + c_9E_9 + c_{10}E_{10}$	$c_7 = c_8$; $\frac{E_9^* - E_{11}^*}{E_9 - E_{11}} = \frac{E_{10}^* - E_{16}^*}{E_{10} - E_{16}}$	$E_7 - E_8$	$E_{10} - E_{16} + E_9 - E_{11}$
⑥	V3	$c_{13}E_{13} + c_{32}E_{32} = c_{11}E_{11}$		$E_{13} + E_{32}$	E_{11}
⑦	D3	$c_9E_9 = c_{12}E_{12} + c_{32}E_{32}$	$c_{12} = c_{32}$	E_9	$E_{12} + E_{32}$
⑧	V4	$c_5E_5 = c_6E_6$		E_5	E_6
⑨	D4	$c_{10}E_{10} = c_{14}E_{14} + c_{33}E_{33}$	$c_{14} = c_{33}$	E_{10}	$E_{14} + E_{33}$
⑩	HX	$c_{12}E_{12} + c_{18}E_{18} = c_{13}E_{13} + c_{17}E_{17}$	$c_{12} = c_{13}$	$E_{12} - E_{13}$	$E_{17} - E_{18}$
⑪	H	$c_{14}E_{14} = c_{15}E_{15} + c_{26}E_{26}$	$c_{15} = c_{14}$	$E_{14} - E_{15}$	E_{26}
⑫	T1	$c_{17}E_{17} + c_{19}E_{19} + c_{28}E_{28} = c_{18}E_{18} + c_{25}E_{25} + c_{45}E_{45}$	$c_{28} = 1$. $c_{17} = c_{18}$; $\frac{E_{25}^* - E_{19}^*}{E_{25} - E_{19}} = c_{45}$	$E_{28} + E_{17} - E_{18} + E_{19} - E_{24}$	$E_{45} + E_{25} - E_{19}$
⑬	T2	$c_{24}E_{24} + c_{27}E_{27} + c_{20}E_{20} = c_{19}E_{19} + c_{23}E_{23} + c_{46}E_{46}$	$c_{27} = 1$. $c_{23} = c_{20}$; $\frac{E_{19}^* - E_{24}^*}{E_{19} - E_{24}} = c_{46}$	$E_{27} + E_{23} - E_{20}$	$E_{46} + E_{19} - E_{24}$
⑭	V5	$c_{20}E_{20} + c_{34}E_{34} = c_{21}E_{21}$		$E_{34} + E_{20}$	E_{21}
⑮	D5	$c_{22}E_{22} = c_{23}E_{23} + c_{34}E_{34}$	$c_{23} = c_{34}$	E_{22}	$E_{34} + E_{23}$
⑯	SC	$c_{30}E_{30} + c_{21}E_{21} = c_{22}E_{22}$	$c_{30} = 1$	E_{30}	$E_{22} - E_{21}$

Consequently, an overall "static" thermoeconomic model was built to contemplate all the possible dynamic conditions. Every main component cost balance and corresponding auxiliary equations are collected in the left part of Table C. 17. Right part of Table C. 17 describes each component fuel and product; the naming is the one of Figure C. 14. Moreover, the external global inputs are the entering natural gas and irradiation exergy (E_{29}, E_{30}) and tank discharge (E_{27}, E_{28}) while the outgoing total outputs are DHW and heating exergy demands ($E_{25} - E_{29}, E_{26}$) and tanks storage when $\dot{m}_s$ does not exist (E_{45}, E_{46}).

Figure C. 15 shows the productive structure (Fuel/Product diagram) that contemplates all the possibilities; thus, it is easy to program.

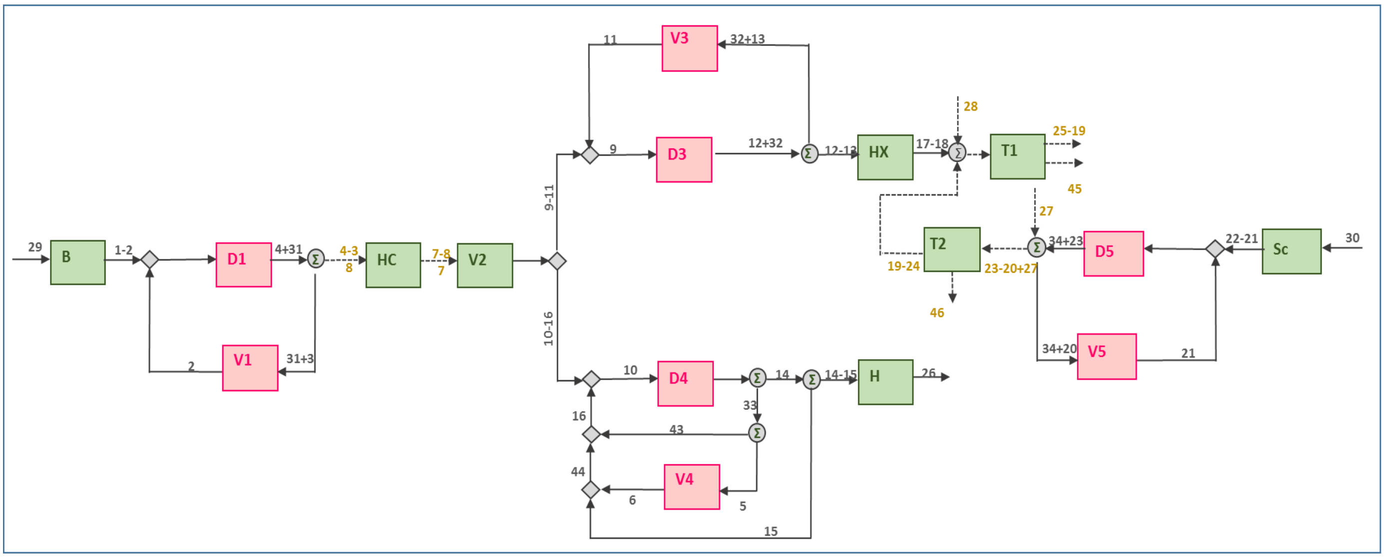


Figure C. 15 Generic Productive Structure of the facility

Correspondingly, the dynamic productive structure is extracted each time-step merely multiplying by zero the non-participating flows; Figure C. 16 shows two different cases in time-step t_1 and t_2. In the first one, $E_5, E_6, E_{10}, E_{14}, E_{15}, E_{16}$, E_{26}, E_{31}, E_{32}, $E_{33}, E_{34}, E_{43}, E_{44}, E_{45}, E_{46}$ flows are equal to 0 while E_1, E_2, E_4, $E_3, E_{20}, E_{21}, E_{22}, E_{23}, E_{29}, E_{30}, E_{31}, E_{32}$, E_{34}, E_{45}, E_{46} are in the second one nullified. Their corresponding equations and productive structure are located in Figure C. 17 - Table C. 18 and Figure C. 18 - Table C. 19.

By extension, thermoeconomic analysis of the system is performed every time step; hence, the dynamic cost accounting first objective is accomplished.

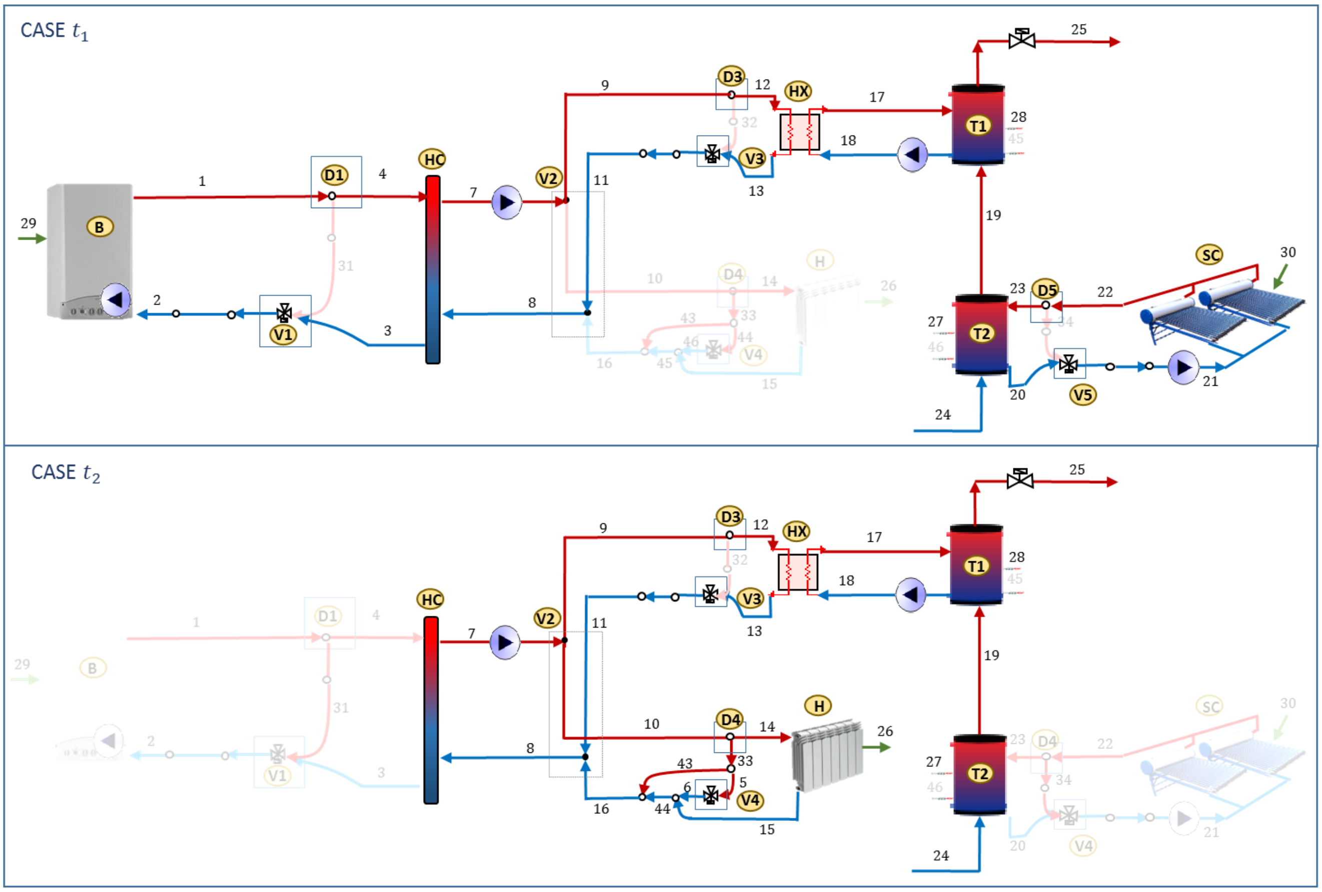


Figure C. 16 Two functioning possible cases according to time-step t_1 and t_2

Table C. 18 Equations and productive structure for the thermoeconomic model of case t_1

		DYNAMIC CASE t_1			
		GENERIC EQUATIONS		PRODUCTIVE STRUCTURE	
		COST BALANCES	PROPOSITIONS	FUEL	PRODUCT
①	B	$c_{29}E_{29} + c_2E_2 = c_1E_1$	$c_{29} = 1$	E_{29}	$E_1 - E_2$
②	D1	c_1E_1 ~~$+ c_{31}E_{31}$~~ $= c_4E_4$	~~$c_4 = c_{31}$~~	E_1	E_4 ~~$+ E_{31}$~~
③	V1	~~$c_{31}E_{31} +$~~ $c_3E_3 = c_2E_2$		~~$E_{31} +$~~ E_3	E_2
④	HC	$c_4E_4 + c_8E_8 = c_3E_3 + c_7E_7$	$c_4 = c_3$	$E_4 - E_3$ ~~or E_8~~	$E_7 - E_8$ ~~or E_7~~
⑤	V2	$c_7E_7 + c_{11}E_{11}$ ~~$+ c_{16}E_{16}$~~ $= c_8E_8 + c_9E_9$ ~~$+ c_{10}E_{10}$~~	$c_7 = c_8$ ~~$\frac{E_9^* - E_{11}^*}{E_9 - E_{11}} = \frac{E_{10}^* - E_{16}^*}{E_{10} - E_{16}}$~~	$E_7 - E_8$	~~$E_{10} - E_{16} +$~~ $E_9 - E_{11}$
⑥	V3	$c_{13}E_{13}$ ~~$+ c_{32}E_{32}$~~ $= c_{11}E_{11}$		E_{13} ~~$+ E_{32}$~~	E_{11}
⑦	D3	$c_9E_9 = c_{12}E_{12}$ ~~$+ c_{32}E_{32}$~~	~~$c_{12} = c_{32}$~~	E_9	E_{12} ~~$+ E_{32}$~~
⑧	V4	~~$c_5E_5 = c_6E_6$~~		~~E_5~~	~~E_6~~
⑨	D4	~~$c_{10}E_{10} = c_{14}E_{14} + c_{33}E_{33}$~~	~~$c_{14} = c_{33}$~~	~~E_{10}~~	~~$E_{14} + E_{33}$~~
⑩	HX	$c_{12}E_{12} + c_{18}E_{18} = c_{13}E_{13} + c_{17}E_{17}$	$c_{12} = c_{13}$	$E_{12} - E_{13}$	$E_{17} - E_{18}$
⑪	H	~~$c_{14}E_{14} = c_{15}E_{15} + c_{26}E_{26}$~~	~~$c_{15} = c_{14}$~~	~~$E_{14} - E_{15}$~~	~~E_{26}~~
⑫	T1	$c_{17}E_{17} + c_{19}E_{19} + c_{28}E_{28} = c_{18}E_{18} + c_{25}E_{25}$ ~~$+ c_{45}E_{45}$~~	$c_{28} = 1, c_{17} = c_{18}$ ~~$\frac{E_{25}^* - E_{19}^*}{E_{25} - E_{19}} = c_{45}$~~	$E_{28} + E_{17} - E_{18} + E_{19} - E_{24}$	~~$E_{45} +$~~ $E_{25} - E_{19}$
⑬	T2	$c_{24}E_{24} + c_{27}E_{27} + c_{20}E_{20} = c_{19}E_{19} + c_{23}E_{23}$ ~~$+ c_{46}E_{46}$~~	$c_{27} = 1, c_{23} = c_{20}$ ~~$\frac{E_{19}^* - E_{24}^*}{E_{19} - E_{24}} = c_{46}$~~	$E_{27} + E_{23} - E_{20}$	~~$E_{46} +$~~ $E_{19} - E_{24}$
⑭	V5	$c_{20}E_{20}$ ~~$+ c_{34}E_{34}$~~ $= c_{21}E_{21}$		~~$E_{34} +$~~ E_{20}	E_{21}
⑮	D5	$c_{22}E_{22} = c_{23}E_{23}$ ~~$+ c_{34}E_{34}$~~	~~$c_{23} = c_{34}$~~	E_{22}	~~$E_{34} +$~~ E_{23}
⑯	SC	$c_{30}E_{30} + c_{21}E_{21} = c_{22}E_{22}$	$c_{30} = 1$	E_{30}	$E_{22} - E_{21}$

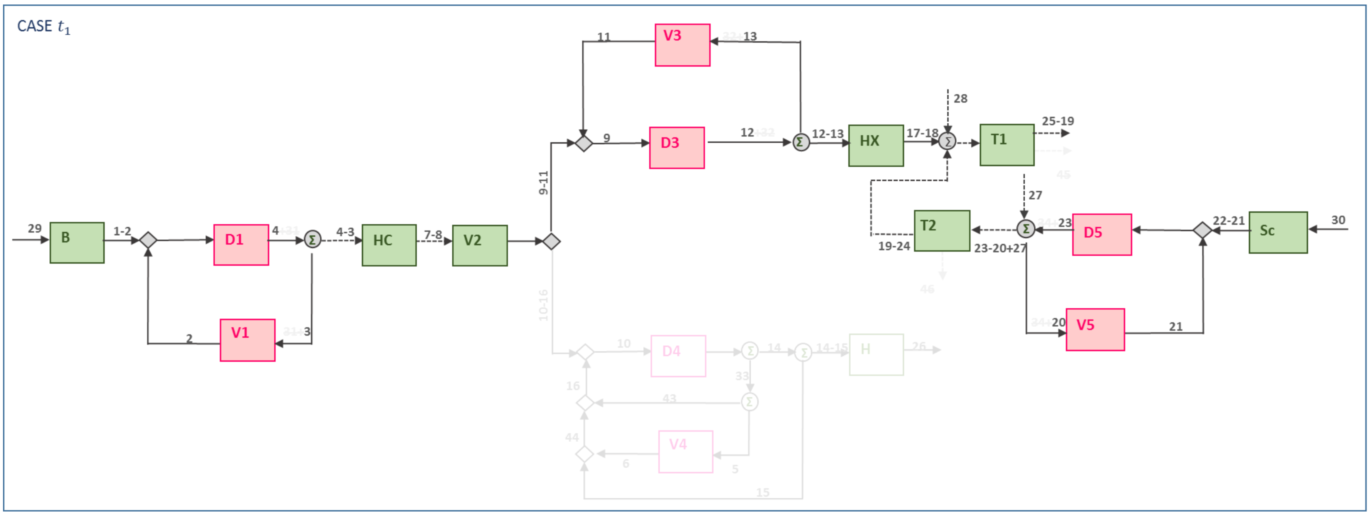


Figure C. 17 Productive Structure of the facility in case t_1

Table C. 19 Equations and productive structure for the thermoeconomic model of case t_2

		DYNAMIC CASE t_2			
		GENERIC EQUATIONS		PRODUCTIVE STRUCTURE	
		COST BALANCES	PROPOSITIONS	FUEL	PRODUCT
①	B	~~$c_{29}E_{29} + c_2E_2 = c_1E_1$~~	~~$c_{29} = 1$~~	~~E_{29}~~	~~$E_1 - E_2$~~
②	D1	~~$c_1E_1 + c_{31}E_{31} = c_4E_4$~~	~~$c_4 = c_{31}$~~	~~E_1~~	~~$E_4 + E_{31}$~~
③	V1	~~$c_{31}E_{31} + c_3E_3 = c_2E_2$~~		~~$E_{31} + E_3$~~	~~E_2~~
④	HC	~~$c_4E_4 +$~~ $c_8E_8 =$ ~~$c_3E_3 +$~~ c_7E_7	~~$c_4 = c_3$~~	~~$E_4 - E_3$ or~~ E_8	~~$E_7 - E_8$ or~~ E_7
⑤	V2	$c_7E_7 + c_{11}E_{11} + c_{16}E_{16} = c_8E_8 + c_9E_9 + c_{10}E_{10}$	$c_7 = c_8$ $\frac{E_9^* - E_{11}^*}{E_9 - E_{11}} = \frac{E_{10}^* - E_{16}^*}{E_{10} - E_{16}}$	$E_7 - E_8$	$E_{10} - E_{16} + E_9 - E_{11}$
⑥	V3	$c_{13}E_{13}$ ~~$+ c_{32}E_{32}$~~ $= c_{11}E_{11}$		$E_{13} + E_{32}$	E_{11}
⑦	D3	$c_9E_9 = c_{12}E_{12}$ ~~$+ c_{32}E_{32}$~~	~~$c_{12} = c_{32}$~~	E_9	E_{12} ~~$+ E_{32}$~~
⑧	V4	$c_5E_5 = c_6E_6$		E_5	E_6
⑨	D4	$c_{10}E_{10} = c_{14}E_{14} + c_{33}E_{33}$	$c_{14} = c_{33}$	E_{10}	$E_{14} + E_{33}$
⑩	HX	$c_{12}E_{12} + c_{18}E_{18} = c_{13}E_{13} + c_{17}E_{17}$	$c_{12} = c_{13}$	$E_{12} - E_{13}$	$E_{17} - E_{18}$
⑪	H	$c_{14}E_{14} = c_{15}E_{15} + c_{26}E_{26}$	$c_{15} = c_{14}$	$E_{14} - E_{15}$	E_{26}
⑫	T1	$c_{17}E_{17} + c_{19}E_{19} + c_{28}E_{28} = c_{18}E_{18} + c_{25}E_{25}$ ~~$+ c_{45}E_{45}$~~	$c_{28} = 1$; $c_{17} = c_{18}$ ~~$\frac{E_{25}^* - E_{19}^*}{E_{25} - E_{19}} = c_{45}$~~	$E_{28} + E_{17} - E_{18} + E_{19} - E_{24}$	~~$E_{45} +$~~ $E_{25} - E_{19}$
⑬	T2	$c_{24}E_{24} + c_{27}E_{27}$ ~~$+ c_{20}E_{20}$~~ $= c_{19}E_{19}$ ~~$+ c_{23}E_{23} + c_{46}E_{46}$~~	$c_{27} = 1$ ~~; $c_{23} = c_{20}$~~ ~~$\frac{E_{19}^* - E_{24}^*}{E_{19} - E_{24}} = c_{46}$~~	E_{27} ~~$+ E_{23} - E_{20}$~~	~~$E_{46} +$~~ $E_{19} - E_{24}$
⑭	V5	~~$c_{20}E_{20} + c_{34}E_{34} = c_{21}E_{21}$~~		~~$E_{34} + E_{20}$~~	~~E_{21}~~
⑮	D5	~~$c_{22}E_{22} = c_{23}E_{23} + c_{34}E_{34}$~~	~~$c_{23} = c_{34}$~~	~~E_{22}~~	~~$E_{34} + E_{23}$~~
⑯	SC	~~$c_{30}E_{30} + c_{21}E_{21} = c_{22}E_{22}$~~	~~$c_{30} = 1$~~	~~E_{30}~~	~~$E_{22} - E_{21}$~~

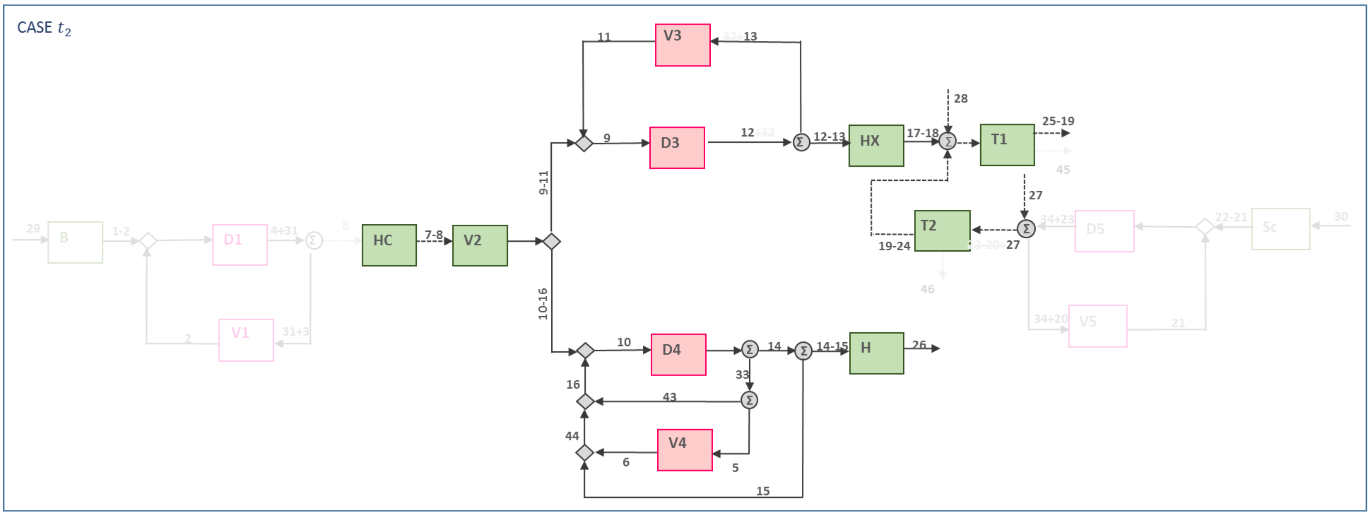


Figure C. 18 Productive Structure of the facility in case t_2

C.3.2.1.3. Numerical results

As previously mentioned, a 3-day test was carried out in the LQCB experimental facility. 30 thermocouples were used with $\pm 0.15°C$ uncertainty and 7 electromagnetic flowmeters with $\pm 0.1\%$ accuracy; moreover, 1 Class 1.5 meter measured the fuel consumption of the boiler and 3 pyranometers were used to measure the diffuse and global horizontal radiation and vertical global radiation. Data were registered every 10 seconds.

C.3.2.1.3.1. Test performed and data obtained

Figure C. 19 shows the corresponding data of incident irradiation, gas natural consumption, heating and DHW demand.

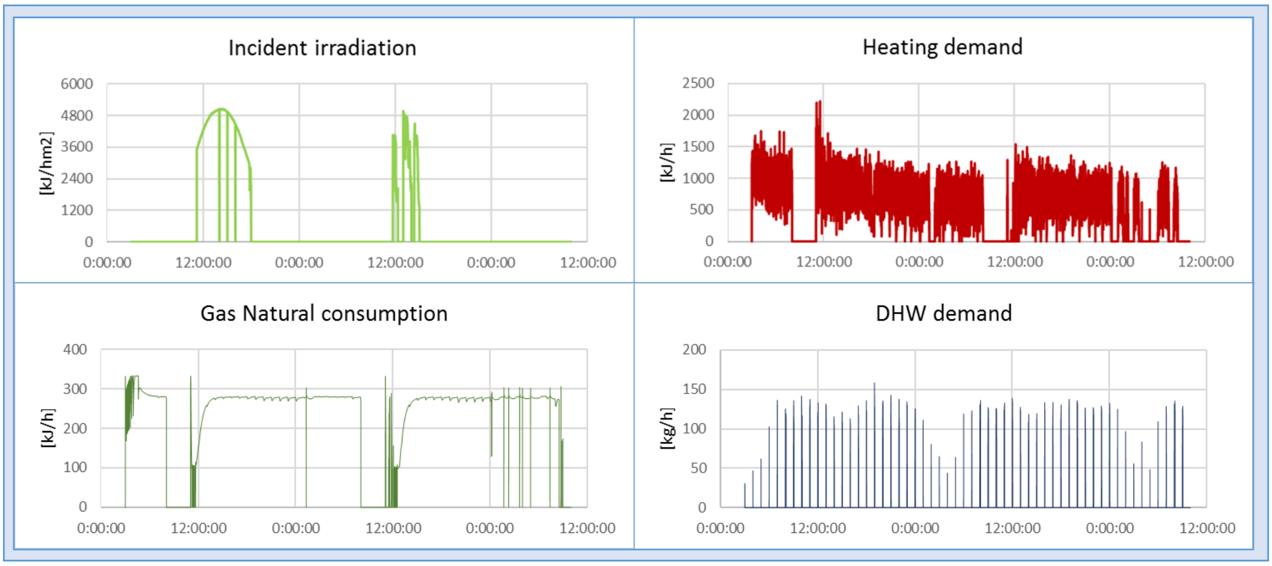


Figure C. 19 Registered irradiation, gas consumption, heating and DHW demand during the experimental essay

As explained, the first step deals with the individual mathematical characterization of the real components in order to build their thermal model. After that, components were interconnected and the control was implemented in the Simulation Studio interface of Trnsys. Thus, the dynamic model of the facility was obtained.

From there, thermodynamic variables (mass flow rates, temperatures, etc.) of every flow of Figure C. 14 were obtained every 10 seconds and each flow exergetic value was calculated according to the appropriate formulae [7].

C.3.2.1.3.2. Thermoeconomic analysis

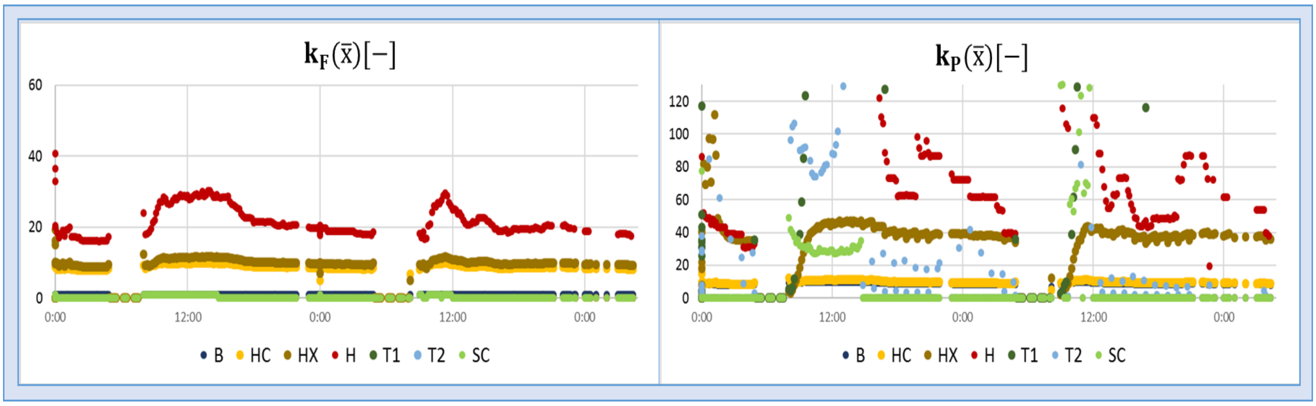


Figure C. 20 Main components dynamic fuel and product unit exergy consumption

Thermoeconomic dynamic analysis was performed once each flow thermodynamic values (and, therefore, exergy) were known. The generic equations of Table C. 17 were programmed and costs were calculated considering a cumulated time step of 10 minutes. The variable unit exergy consumption of each main component fuel and product are shown in Figure C. 20 while Table C. 20 contains the average values of unit exergetic costs on the studied period (admittedly, average costs cannot be benchmark values since cost varies according to the activated and disabled components but serve as a baseline).

Table C. 20 Average unit exergy consumption values

	$k_F^*(\bar{x})[-]$	$k_P^*(\bar{x})[-]$		$k_F^*(\bar{x})[-]$	$k_P^*(\bar{x})[-]$
B	1.00	8.78	**D4**	21.52	21.52
D1	8.78	8.78	**HX**	10.10	38.22
V1	8.78	8.78	**H**	21.55	112.02
HC	8.78	9.75	**T1**	36.87	107.72
V2	9.75	10.10	**T2**	21.57	55.39
V3	10.10	10.10	**V5**	47.45	47.45
D3	10.10	10.10	**D5**	50.70	50.70
V4	21.44	45.97	**SC**	1.00	30.94

The thermoeconomic analysis gives a picture of cost allocation along the system. The difference between the unit exergetic cost of the product and fuel of each component ($k_{p,i}^*(\bar{x}) - k_{F,i}^*(\bar{x})$) represents the irreversibilities of the component i. That is, it indicates the degradation of energy between the required resources and the obtained product. Thus, the component with greater irreversibilities should be a focus of improvement; for instance, that is the case for the H component, whose destruction is noticeable because high quality energy is used to warm up a room close to the ambient conditions; moreover, it is highly variable.

On the other hand, the unit exergetic cost of the fuel of each component ($k_{F,i}^*(\bar{x})$), contains the irreversibilities accumulated until that component i. Consequently, the unit cost of the resources is related to the system overall configuration and collects the energy degradations previously generated up to that component. So this variable indicates where and how the components are interrelated in terms of costs and allows for improvements and control optimization. That is, for example, the reason why DHW tank accumulates high destructions in the fuel unit exergetic cost value since it collects all the irreversibilities encountered until arriving there.

C.3.2.1.1. Results Discussion

As a building system is very dependent to changeable conditions, ST should be dynamically applied. Therefore, not only the thermal model is continuously varying but also the flow costs allocation. The aim of this example was to resolve in a global way the issues connected with changeable productive structure.

For that, V3V was studied under simplified and incremental standpoint: the simplified configuration was chosen for the representation of all-or-nothing V3V while the second one was selected for the modulating valve. The possible configurations of the rest of the components were also considered along a super-structure.

As a result, the heater reveals to be a very irreversible component with notable variable costs due to its sensitivity towards the environment conditions. That justifies the dynamic cost allocation study: the variable unit exergetic cost of each component fuel and product were calculated every 10 minutes along the testing period.

C.3.2.2. (iii) School's AHU Case Study

This example is the continuation of the (iii) case study of **Chapter B**, where the thermal system of a school in Palermo is created to cover the heating, cooling, ventilation and DHW demands. The physical scheme and the corresponding flow numbering of the system are represented in Figure C. 21.

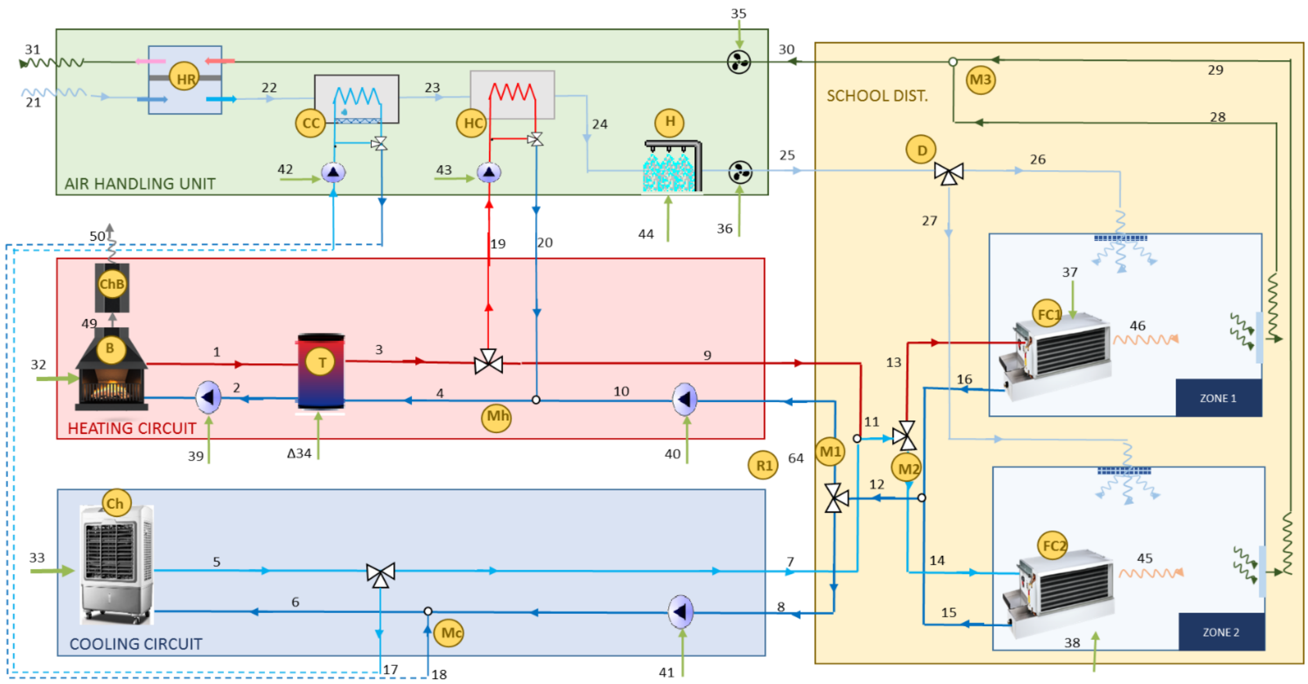


Figure C. 21 Physical scheme of the system facility

For thermoeconomic application, each system exergy flow (50 flows, see Figure C. 21) must be calculated among the 8760 hours of the year. Since air is cooled and dehumidified (or warmed and humidified) across the AHU during the summer (winter) time, *chemical exergy* of air was included in the analysis [44].

According to *physical exergy*, only the thermal part was consider inasmuch as working with mechanical part means a duplication in flow quantity [45]. In any case, the thermal component weight is sensitively higher, so, mechanical part can be neglected. Although avoiding that means not considering the fans and pumps individually, their electrical consumptions were introduced together with the circuit main components.

Besides, R flows recognition is a key step for the components categorization since dissipative elements are directly connected with them. Dissipative components can appear in two different configurations: *system-environment* or *system-system*. Therefore, dissipative components can be located before the R release to the environment, usually related to legal requirements. Such is the boiler chimney for pollutants filtration (Bc) where the fumes ($R_{Bc} = E_{47}$) exergetic cost of cleaning-up should be attributed to the boiler.

Otherwise, dissipative elements can be intermediate components positioned inside the system and they are essential for closing the energy cycle. They are typically connected with thermodynamic requests. That is, precisely, the perspective of the case 3 chosen for the 3- way valves representation (Mh, Mc, M1, M2, M3): an exergy destruction appears ($R_{M_i} = E_{D_{Mi}}$) because different temperature flows are mixing; nevertheless, a control system aimed at minimizing exergy destructions can completely avoid those irreversibilities.

Productive components are afterwards detailed in Table C. 23.

C.3.2.2.1. Thermoeconomic dynamic model

The main idea is to create a generic procedure to work with a single versatile dynamic productive super-structure all over the year.

It must be indicated that the study was developed using the ST in the *PF* formulation (demand-driven model). This *PF* formulation is the most appropriate, since it allows determining the necessary resources to obtain an objective of production of the system, as well as calculating the flows unit costs from the external resources unit costs.

However, for simplicity reasons, the $\langle \mathbf{PF} \rangle$ matrix has been obtained from the relationship of the *FP* (supply-driven model) and *PF* representation. After all, the construction of the $\langle \mathbf{FP} \rangle$ matrix is the one that has a simpler and more direct physical meaning. Therefore, although the study has been done under the *PF* model, the independent input variables were ① the system total resources E_e; ② bifurcation and distribution parameters α_{ij}, ψ_{ij} (to make the nomenclature clearer, $\alpha^{\,i}_{\,j}$ and $\psi^{\,i}_{\,j}$ naming was used instead); and, ③ components unit exergy consumption k_i. Once that has been done, the *PF* representation was attained through the relations between both representations.

① The first E_e are the following: gas natural for the boiler (E_{32}) and electricity for chiller (W_{33}); (ΔE_{34}); electricity input in fans (W_{35}, W_{36}) and pumps (W_{39} ... W_{43}); and electricity in humidifier (W_{44}) and fan coils (W_{45}, W_{46}).

② The second α_j^i concerns to productive components with more than one output. Definitions are gathered in Table C. 21 (an example is exposed in Table C. 22).

Table C. 21 α_j^i bifurcation parameters

α_j^i bifurcation parameters	
$\alpha_{Cb}^{B} = \frac{E_{49}}{P_B}$	$\alpha_{T}^{B} = 1 - \alpha_{Cb}^{B}$
$\alpha_{HC}^{T} = \frac{E_{19}-E_{20}}{P_T}$	$\alpha_{FC}^{T} = \frac{E_9-E_{10}}{P_T}$
$\alpha_{CC}^{Ch} = \frac{E_{17}-E_{18}}{P_{Ch}}$	$\alpha_{FC}^{Ch} = \frac{E_7-E_8}{P_{Ch}}$
$\alpha_{FC1}^{TOT} = \frac{E_{13}-E_{16}}{P_{FC_{TOT}}}$	$\alpha_{FC2}^{TOT} = \frac{E_{14}-E_{15}}{P_{FC_{TOT}}}$
$\alpha_{HR}^{Dem1} = \frac{E_{28}}{P_{Dem1}}$	$\alpha_{Z1}^{Dem1} = 1 - \alpha_{HR}^{Dem1}$
$\alpha_{HR}^{Dem2} = \frac{E_{29}}{P_{Dem2}}$	$\alpha_{Z2}^{Dem2} = 1 - \alpha_{HR}^{Dem2}$
$\alpha_{H}^{H-C} = \frac{P_T}{P_T+P_{Ch}}$	$\alpha_{H}^{H-C} = 1 - \alpha_{c}^{H-C}$

where:

- $P_{FC_{TOT}} = E_{11} - E_{12}$
- $P_{Dem1} = E_{26} + E_{46}$
- $P_{Dem2} = E_{27} + E_{45}$
- *rest* P_i *is in Table C. 23*

Note that:

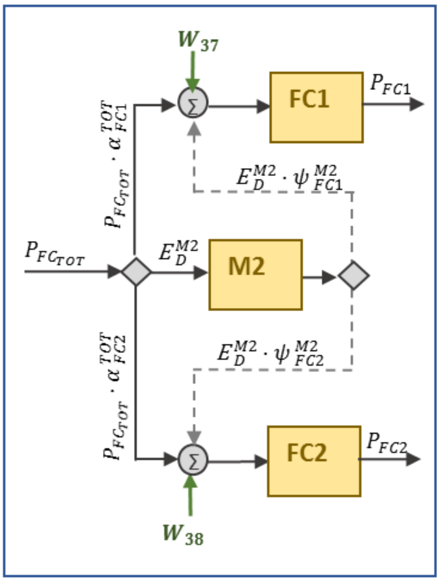
- $\alpha_{HC}^{T} + \alpha_{FC}^{T} \leq 1$
- $\alpha_{CC}^{Ch} + \alpha_{FC}^{Ch} \leq 1$
- $\alpha_{FC1}^{TOT} + \alpha_{FC2}^{TOT} \leq 1$

The ψ_j^i parameters are related to dissipative components with more than one R output, which are, indeed, connected to the 3-way valves (Mh, Mc, M1 and M2).

Table C. 22 E_D^{Mi} and ψ_j^i & example of M2/FC1/FC2

$E_D^{Mh} = (E_9 - E_{10}) + (E_{19} - E_{20}) - (E_3 - E_4)$
$E_D^{Mc} = (E_9 - E_{10}) + (E_{19} - E_{20}) - (E_3 - E_4)$
$E_D^{M1} = (E_9 - E_{10}) + (E_7 - E_8) - (E_{11} - E_{12})$
$E_D^{M2} = (E_{11} - E_{12}) - (E_{13} - E_{16}) - (E_{14} - E_{15})$
$E_D^{M3} = E_{28} + E_{29} - E_{30}$

$\psi_{HC}^{Mh} = \frac{E_{19}-E_{20}}{(E_{19}-E_{20})+(E_9-E_{10})}$	$\psi_{FC}^{Mh} = 1 - \psi_{HC}^{Mh}$
$\psi_{CC}^{Mc} = \frac{E_{17}-E_{18}}{(E_{17}-E_{18})+(E_7-E_8)}$	$\psi_{FC}^{Mc} = 1 - \psi_{HC}^{Mh}$
$\psi_{FC1}^{M2} = \frac{E_{13}-E_{16}}{(E_{13}-E_{16})+(E_{14}-E_{15})}$	$\psi_{FC2}^{M2} = 1 - \psi_{FC1}^{M2}$



Consequently, the j productive components associated with the corresponding valve E_D^{Mi} are penalized by the $E_{D_j}^{Mi} = E_D^{Mi} \cdot \psi_j^{Mi}$ term, where ψ_j^{Mi} refers to the distribution coefficient. Such definitions are shown in Table C. 22 and the example of M2/ FC1/ FC2 components is depicted on the right part.

Regarding to that example (and the application of case 3 representation for 3-way valves), M2 is the dissipative component that diverges and mixes the heat/cool going to FC1 and FC2 productive components. During the mixing, E_D^{M2} residue is emerged and attributed to FC1 and FC2 according to the ψ_{FCi}^{M2} weight. Besides, the useful heat/cool $P_{FC_{TOT}}$ is spread to FCs by means of α_{FCi}^{TOT} parameter.

③ The k_i is calculated as the ratio between fuel and product. Table C. 23 contains the system productive components with their symbolic definition of fuel, product and associated residue.

Table C. 23 Structure of productive components

Comp.	FUEL	PRODUCT	RESIDUE
B	E_{32}	$(E_1 - E_2)$	E_{47}
Ch	$W_{33} + E_{41}$	$(E_5 - E_6)$	
T	$(E_1 - E_2) + \Delta E_{34} + W_{39} + W_{40}$	$(E_3 - E_4)$	
FC1	$(E_{13} - E_{16}) + W_{37}$	E_{46}	$E_{D_{FC1}}^{Mh} + E_{D_{FC1}}^{Mc} + E_{D_{FC1}}^{M1} + E_{D_{FC1}}^{M2}$
FC2	$(E_{14} - E_{15}) + W_{38}$	E_{45}	$E_{D_{FC2}}^{Mh} + E_{D_{FC2}}^{Mc} + E_{D_{FC2}}^{M1} + E_{D_{FC2}}^{M2}$
CC	f^{CC}	p^{CC}	$E_{D_{CC}}^{Mh} + E_{D_{CC}}^{Mc}$
HC	$(E_{19} - E_{20}) + W_{43}$	p^{HC}	$E_{D_{HC}}^{Mh} + E_{D_{HC}}^{Mc}$
HR	$(E_{30} - E_{31}) + W_{35}$	$(E_{22} - E_{21})$	$E_{D_H}^{M3}$
H	f^H	p^H	
D	E_{25}	$E_{26} + E_{27}$	

f^C	Heating F $((E_{17} - E_{18}) + W_{42} + E_{23})$; Cooling F $((E_{17} - E_{18}) + W_{42} + (E_{24} - E_{23}))$
p^C	Heating P (E_{22}); Cooling P $(E_{24} - E_{22})$
p^{HC}	Heating P $(E_{23} - E_{24})$; Cooling R $(E_{24} - E_{23})$
f^H	Heating F $(E_{44} + W_{36})$; Cooling F $E_{44} + W_{36} + E_{24}$
p^H	Heating P $(E_{25} - E_{24})$; Cooling P (E_{25})
$E_{D_j}^{Mi}$	Residue allocation due to the exergy destruction of mixer Mi in component j

Although the objective is to set a generic approach for dynamically work all over the year (even if the control changes in the future), diverse fuel and product (even residue) definition were given to some components according to cooling or heating periods ($f^{CC}, p^{CC}, p^{HC}, f^H, p^H$); those are hereafter explained.

Hence, to begin with, the productive purpose of the HC during the wintertime is to warm up the incoming air to the specified set point. In such way an increase in the thermal exergy occurs equal to the increment between the incoming and outgoing air ($\Delta E_{air}^{HC} = E_{24} - E_{23}$). On summer time, by contrary, the aim is to destroy exergy to achieve the 14°C set point temperature; after all, the drawing flow is closer to ambient condition than the entering one, ($E_{24} - E_{23} < 0$). Therefore, HC works as a dissipative component with a $\Delta E_{air} < 0$ goal. Because of that, the $|\Delta E_{air}^{HC}|$ should be joined with CC, since it directly depends on the CC working conditions.

Pursuant to those observations, one of the CC resources in cooling time, together with the chiller input, is $|\Delta E_{air}^{HC}|$ in order to produce a change in air condition ($\Delta E_{air}^{CC} = E_{24} - E_{22}$). On the other side, considering the specific control, the CC is not involved during heating period. Therefore, in that period, there is not cooling income ($(E_{17} - E_{18}) + W_{42} = 0$) and the ventilation flow bypasses the component without suffering any change ($E_{23} = E_{22}$).

Something similar happens with the humidifier (H) in summer time: the airflow simply goes across the component. Even so, the electricity consumption of the driving fan W_{36} is there accounted.

Figure C. 22 and Figure C. 23 depict the productive structure of heating and cooling period; the deactivated components are lightened and no participating flows are crossed out. In such way, the generic functional diagram of the super-structure can be seen.

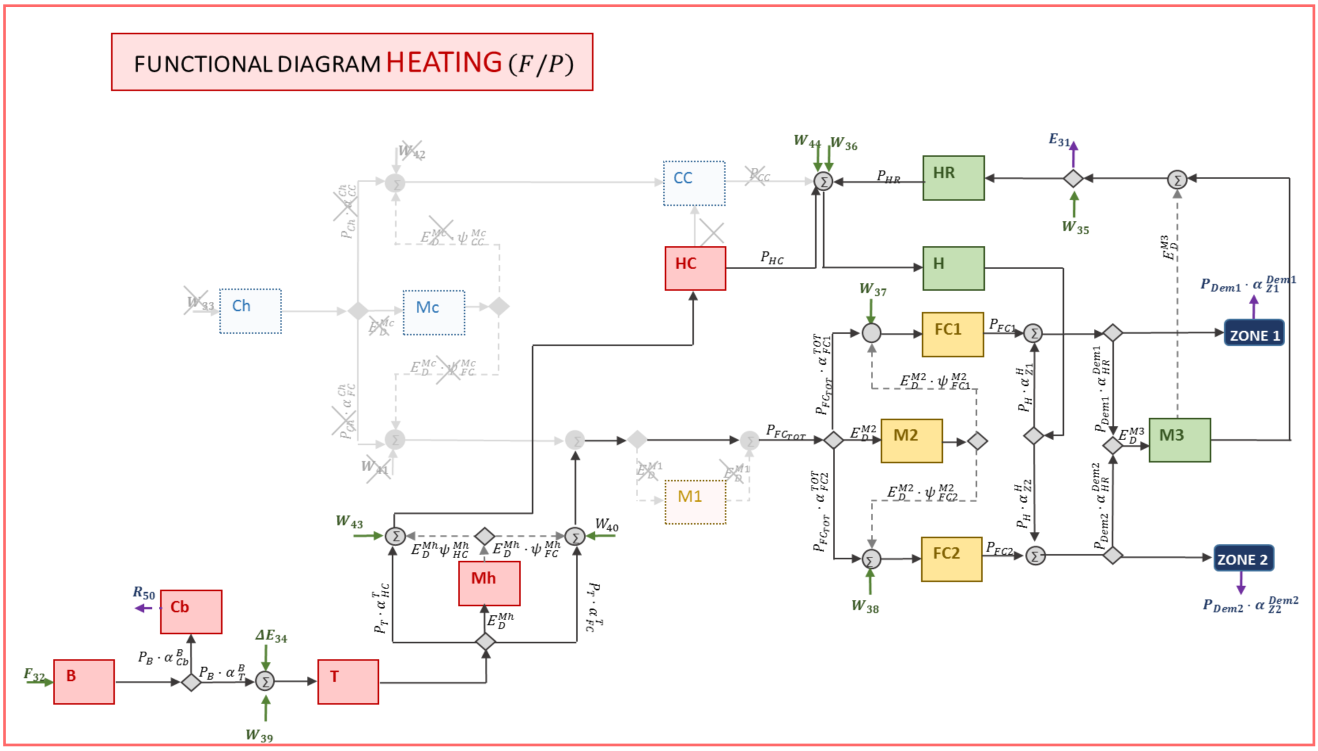


Figure C. 22 Functional diagram of heating period according to the established control

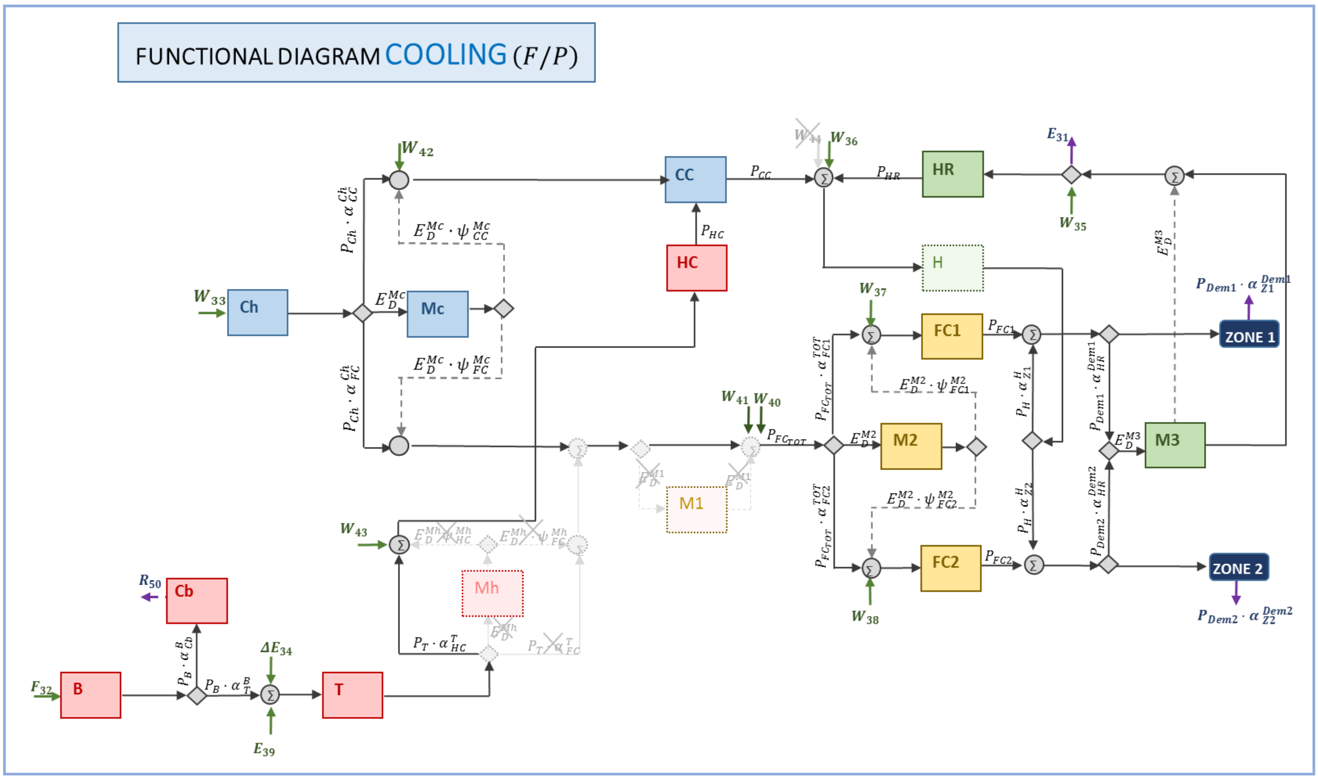


Figure C. 23 Functional diagram of cooling period according to the established control

In the functional diagrams, two new components where added: ZONE 1 and ZONE 2. There are not real components but they were included to highlight the product of the school's whole system: $P_{Dem1} \cdot \alpha_{Z1}^{Dem1}$ and $P_{Dem2} \cdot \alpha_{Z2}^{Dem1}$. They refer to the building exergy demand and they can have positive or negative value.

On the one hand, $P_{Demi} \cdot \alpha_{Zi}^{Dem1} > 0$ means that exergy is used for covering the building requirements. On the other hand, conversely, $P_{Demi} \cdot \alpha_{Zi}^{Dem1} < 0$ is entirely an undesired circumstance since it indicates that more exergy is being extracted than introduced; or what is the same, the zone is performing as an exergy destroyer component (dissipative).

C.3.2.2.1.1. Cost accounting

With such dynamic productive structure, the $\langle \mathbf{KP} \rangle$ and $\langle \mathbf{KR} \rangle$ matrixes of each time step can be calculated. By resolving matrix equations, every component fuel and product exergetic and exergoeconomic unit cost and total cost can be accounted. Moreover, the product cost can be separated in the part related to the productive purpose c_P^e, residue formation c_P^r and fixed costs c_P^z.

Being energy the common known parameter, if the final results want to be given in such unit, that is managed by simply multiplying the finding with the respectively fuel and product quality factor (F_i^{En}/F_i^{Ex} and P_i^{En}/P_i^{Ex}). Even so, while during wintertime energy flow is moving in the same direction as exergy, on summer, however, the flows are counter. That should be taken into account for the F_i^{En} and P_i^{En} definitions.

C.3.2.2.2. Numerical results

Via Trnsys simulation, all the flows thermodynamic data were registered every 3 minutes and integrated in an hourly base during the 8760 hours of the year.

Figure C. 24 depicts the amount of activation hours of productive components (B, Ch, T, FC1, FC2, CC, HC, HR, H) during every month. Moreover, "May" was divided in two (MAYh and MAYc) in order to separately evaluate the first 15 days of heating period and the rest of cooling (see control requisites in **Section B**.2.2.2.1).

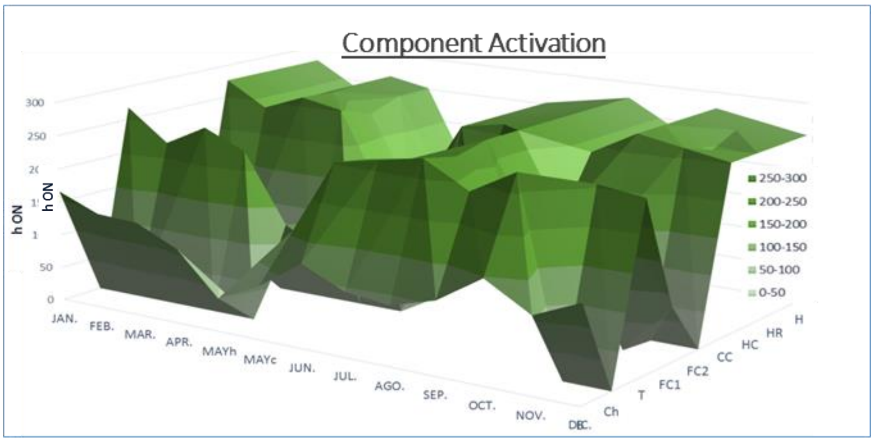


Figure C. 24 System components activation and deactivation during the year

The hourly values of every productive component k_i were assessed and plotted in Figure C. 25. Left chart contains the data of generators and fan coil supporters (B, Ch, FC1, FC2) and it is named *heat-cool circuit*; by comparison, right graph assumes the air handling unit components (CC, HC, HR and H) and is called *AHU circuit*.

Thus, the operating components of each period can be subtracted (for instance, because of its orientation, FC2 seldom participates in wintertime and HC is dissipative during summer).

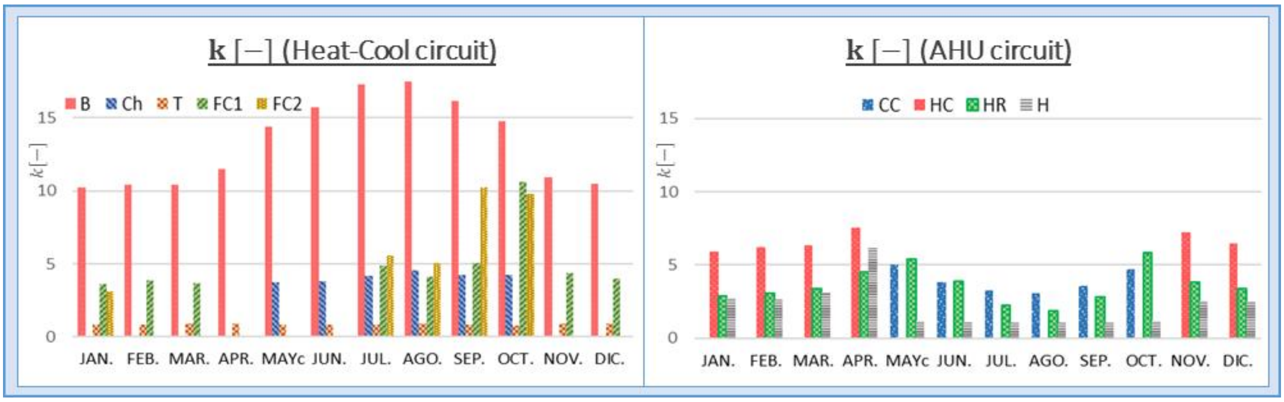


Figure C. 25 Average unit exergetic consumption over the year

The average unit exergetic costs of each month vary depending on the dynamic operation conditions. After all, k_i depends not only on the static component parameters (heat transfer coefficient, tank volume, etc.) but also on changeable thermodynamic parameters (storage temperature, boiler part load ratio, etc.) and external conditions (temperature and humidity). k_B, for example, increases its consumption during cooling time since the returning temperature is closer to the B water supply set T_B^{out}, even if the energetic efficiency remains the same.

Unfortunately, having not constant k_i curves can provoke so-called *induced malfunctions* and cause functioning alterations. Such concern must be taken into account for further thermoeconomic applications such as in diagnosis or in system optimization.

In addition to that, the high irreversibility related to the generation units must be contemplated: even having in B an energetic efficiency close to the 95 %, the exergetic one is lower than 12 % because of the great exergy destructions associated with internal combustion. Similarly, although Ch has an energetic performance higher than the unity (EER > 4), its exergetic efficiency is around 30 % since high quality electricity is used to generate low quality heat flow.

C.3.2.2.2.1. Exergetic costs

Figure C. 26 captures the average unit exergetic costs of productive components during two months of the heating and cooling period. Moreover, product cost is divided among $k_{P_i}^{*,e}$ and

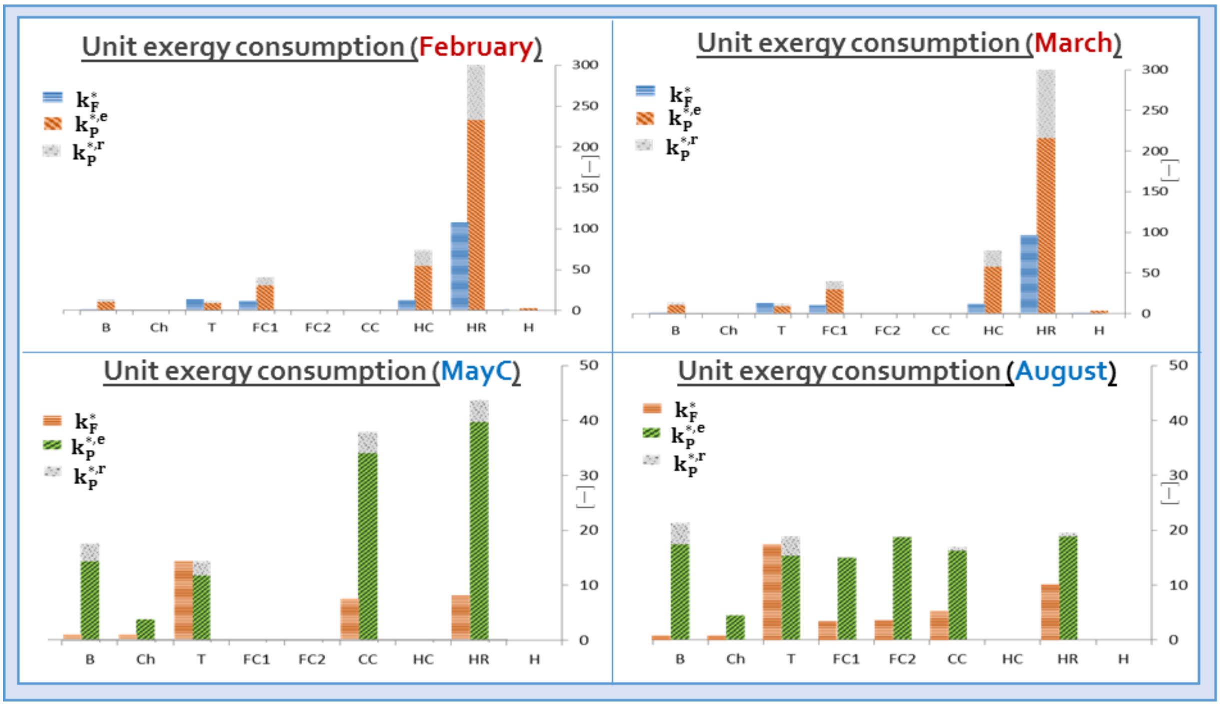


Figure C. 26 Average unit exergy cost in cooling period

$k_{P_i}^{*,r}$.

As known, the difference between the total product unit cost and the fuel unit cost ($k_{P_i}^* - k_{F_i}^*$) represents the costs of irreversibilities due to the inefficiencies and technological limitations (hence, it is related to individual internal k_i). Besides, the unit cost of fuel $k_{F_i}^*$ reflects the relative position of each component according the encountered inefficiencies across the interconnected equipment (so, it is related to the external inefficiencies of the other components). Therefore, the cost increases towards the development of energy transformation chain.

When comparing results for the *heating* period, it can be said that:

- ✓ The cost formation process follows the same tendency during that period.
- ✓ Being HR, from an exergetic point of view, a highly inefficiency component (k_{HR}~3) the cost of product $k^*_{P_{HR}}$ is about 3 times greater than $k^*_{F_{HR}}$.
- ✓ HR can be supposed at the end of the productive chain of AHU since its objective is to get rid of treated exhaust air and to introduce new fresh air. Therefore, it includes the irreversibility appearing in the rest of equipment and has very high $k^*_{F_{HR}}$.
- ✓ From the Second Law perspective, the use of HR in wintertime generates great increase in exergetic cost.

Valuating the results for the *cooling* period, it is worth noting that:

- ✓ The cost formation process is very sensible to cooling specific month.
- ✓ The chilled water $k^*_{P_{Ch}}$ increases from May to August, due to the increase of k_{Ch} (reduction in the exergy performance). That cost participates in the $k^*_{F_{CC}}$ formation. Besides, $k^*_{F_{CC}}$ is also formed by: the electricity of CC driving pump and the exergy destruction associated with HC (which is related to k_B). Moreover, the $k^*_{P_{CC}}$ is connected to k_{CC} which decreases in August.
- ✓ FCs cold production costs ($k^*_{P_{FC1}}$, $k^*_{P_{FC2}}$) are similar to AHU production costs due to their great k_{FC}. Thus, from the Second Law perspective, using FC for extra generation is not the best alternative.

C.3.2.2.2.2. Exergoeconomic costs

For exergoeconomic analysis external economic data are required. Table C. 24 contains the purchasing cost of components as well as some economic data and external resource rates.

Table C. 24 External data: acquisition cost of components & economic data

Comp.	Acquisition Cost
B	7,934 €
Ch	44,062 €
T	7,137 €
FC1	693 €
FC2	693 €
CC	1,040 €
HC	600 €
HR	3,023 €

Comp.	Acquisition Cost
H	4,252 €
Mc	187 €
Mh	114 €
M1	114 €
M2	187 €
M3	114 €
D	100 €
Bc	200 €

Economic Data	
Yearly effective interest i	0.05
Facility useful life (years)	20

Resource	$[c€/kWh_{en}]$
Electricity	21.81
Natural Gas	5.27

Results related to a cooling period month (August) are portrayed in Figure C. 27 where the unit product cost was constructed according to each formation process: $c^{e}_{P_i}$ for useful product formation cost, $c^{r}_{P_i}$ for residues and $c^{z}_{P_i}$ for external costs.

The unit exergoeconomic cost trend (c€/kW$_{ex}$) is the same as the unit exergetic cost (kW$_{ex}$ /kW$_{ex}$) inasmuch as irreversibility is used as a basis of both cost allocation, though the economic data (€) are also used in the c calculations. In Figure C. 27 hourly unit exergoeconomic cost of c_{F_i} was also added in order to show the versatility and detail of the dynamic thermoeconomic approach.

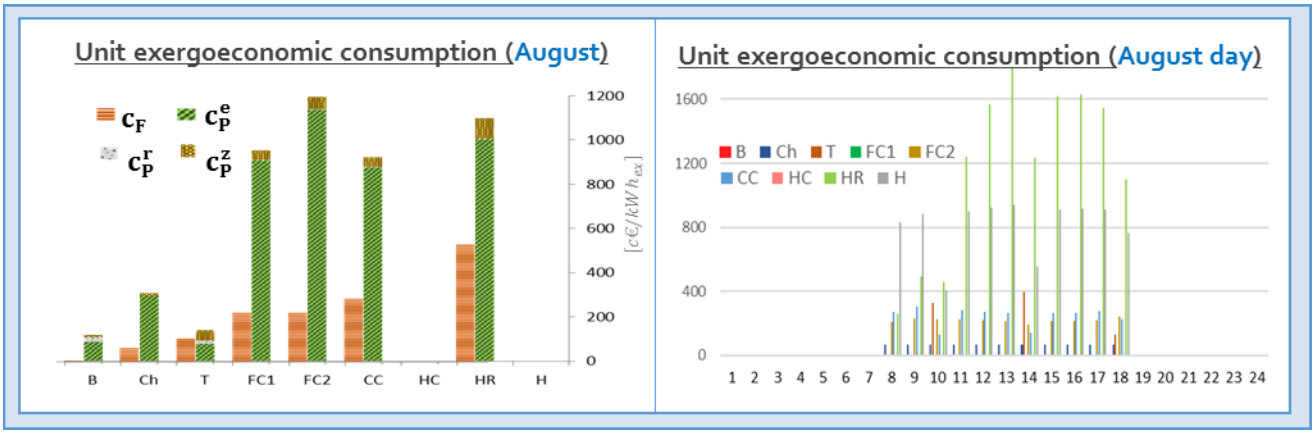


Figure C. 27 Average and hourly unit exergoeconomic cost cooling period

In order to give the results in energetic terms, Figure C. 28 exhibits the average monthly quality factor of products. The low quality of energy associated with AHU transformation chain is there reflected: its heating average is $QF^{Heat}_{P,AHU}$ = 57.84 and the cooling average $QF^{cool}_{P,AHU} = 51.18$.

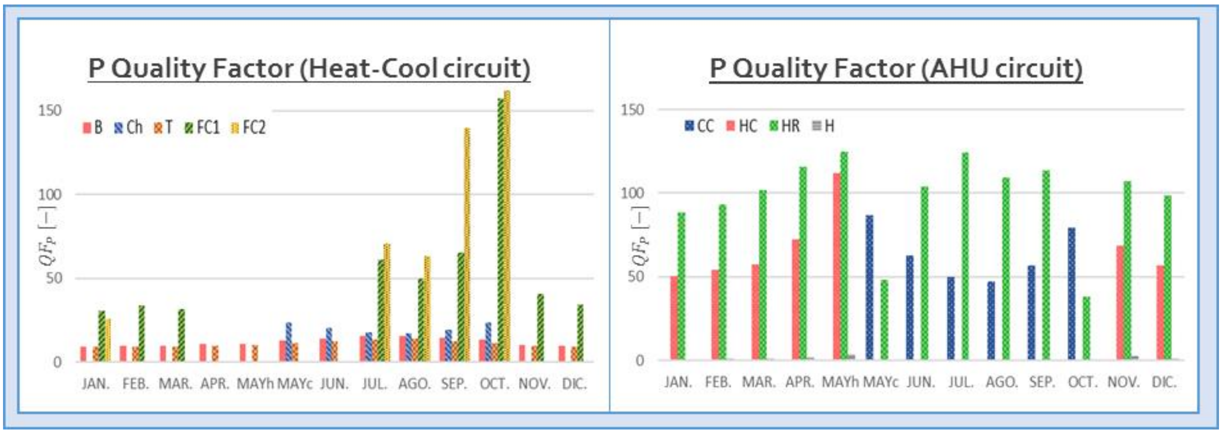


Figure C. 28 Average quality factor of fuels over the year

The monthly total economic cost of final products (Zone 1 and Zone 2 demands) are depicted in Figure C. 29 and the numerical data are gathered in Table C. 25.

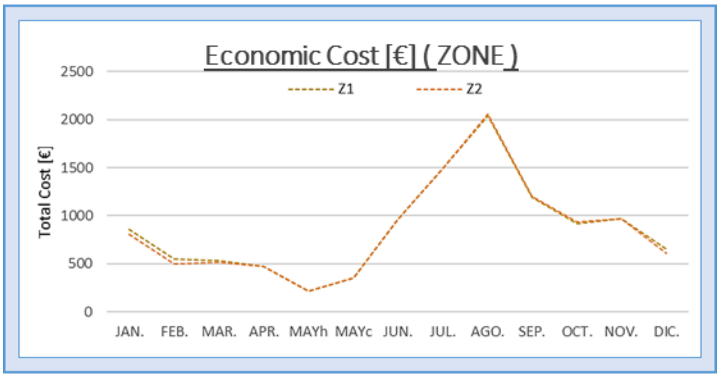


Figure C. 29 Final product average total cost over the year

As it is commonly known, in short, "cold is more expensive than heat".

Table C. 25 Total monthly cost related to production & residue generation and fixed costs

		Total Monthly Economic Cost [€]												
		JAN.	FEB.	MAR.	APR.	MAYh	MAYc	JUN.	JUL.	AGO.	SEP.	OCT.	NOV.	DIC.
Z.1	C_P^{e+r}	638 €	401 €	370 €	356 €	182 €	347 €	955 €	1,482 €	2,032 €	1,180 €	901 €	473 €	463 €
	C_P^{z}	221 €	146 €	159 €	113 €	31 €	6 €	10 €	6 €	7 €	9 €	21 €	497 €	187 €
Z.2	C_P^{e+r}	599 €	367 €	357 €	356 €	182 €	347 €	955 €	1,487 €	2,051 €	1,196 €	916 €	473 €	436 €
	C_P^{z}	207 €	135 €	154 €	113 €	31 €	6 €	10 €	6 €	7 €	9 €	21 €	496 €	177 €

C.3.2.2.3. Results Discussion

Thermoeconomic analysis helps to better understand the cost formation process within an energy system. Exergy is used as the rational parameter to allocate the cost according to the encountered irreversibilities.

To accomplish that study, from the very beginning it should be decided if the study would be done with total exergy values or, conversely, distinguishing between thermal, mechanical and chemical exergy forms. The distinction improves the results but the technical effort is bigger compared to the enhancement. Thus, in such cases similar conclusion are obtained and there is no need for the extra complexity.

In this (iii) case study, a systematic and unambiguous method was developed for the first time to apply the thermoeconomic dynamic approach to a school's AHU facility located in Palermo (Italy) that covers the thermal comfort by considering the indoor air quality as well as the thermal requests.

A generic proposition was given for applying the ST to all the feasible configurations. For that, a super-structure being able to capture all the possibilities concerning the system dynamic operation conditions was created (even if the control changes in the future). Because some components exchange their productive purpose depending on the period of the year (even passing from a productive component to a dissipative one), some adjustments were done. In that way, the exergetic and exergoeconomic unit and total cost of each system component were easily calculated in accordance with the specific functioning mode of every time-step. Some tips of the Second Law versatility and application were given during the results development. The yearly total cost of the whole system turns out to be 19,502 € because of resource consumption and 2,785 € due to inversion, maintenance and operation costs.

C.4. CONCLUSIONS

The basic exergetic method does not allow determining the effect of each component's irreversibilities on the global resources consumption, that is to say, it does not enable to designate the part of the cost of fuel consumption caused by each equipment exergy destruction. To achieve this goal, Thermoeconomics was broadened to combine the Second Law of thermodynamics with economic concepts. Hence, the exergetic cost is the weighted factor of each irreversibility over the global resources consumption and, in order to determine those exergy costs, a productive structure of the facility must be defined. Symbolic Thermodynamics (ST) allows conducting such analysis and is particularly suitable for large scale installations.

In fact, the cost is strictly related to the energy conversion efficiency of the system; therefore, developing a map of cost flows throughout the plant allows identifying the critical points of the system and the ones that should be more urgently addressed by enhancement strategies. The main feature regards to the cost definition; in this research, exergy is the basis.

Thereby, the irreversibility of any process (E_D) is measured as the different among the incoming and outgoing exergy flows of any system, so depends exclusively on thermodynamic system *physical* circumstances.

By comparison, the exergetic cost rest on the *productive* process and not on thermal conditions, so it is different according to the definition of the process perfection degree. Thus, a unique physical structure can have different *productive structures* since the definition of F and P can be sometimes controversial. Therefore, it can change pursuant to the analyst target and criteria. That is one of the mayor barriers of thermoeconomic application.

Apart from that, as commented in **Chapter B**, mass and energy balances are enough to represent any energy system for design, optimization or diagnosis purposes. Although exergy balance is not essential, it gives the additional information about the possible useful work that can be obtained from every flow. By also applying the component utility concept (economic perspective), an exergy cost distribution picture can be achieved to identify the energy degradation processes, associated with cost growth, along the system.

Notwithstanding the findings, the following question arises: why could it be convenient or useful to have an exergoeconomic picture of the system dynamic behavior? The answer is arguable since, after all, the goal is often to improve the design (the best design minimizes *costs* during the system lifetime) and for that the independent design variables ($\bar{\tau}$) need to be modified. As outlined, exergy is a variable constructed by the combination of different thermodynamic intensive and extensive parameters. On the other hand, the design optimization is iterative and it should be done until a global optimum is obtained; so, with regard to exergoeconomics, a true optimum cannot be obtained because of the interdependences of the exergies ($E_1 = f(\bar{\tau}), E_2 = f(\bar{\tau}), E_1 = f(E_2)$).

Nevertheless, the exergetic analysis enables homogenizing the flows in terms of energy quality and making the comparison between components and systems more reliable. Therefore, *exergetic cost* minimization can be considered as a goal but the route should be the modification of the design parameters $\bar{\tau}$.

The management of building energy systems requires a dynamic approach due to the continuous changeable situations. That is the reason why a dynamic procedure of ST application was develop by solving, in a global way, the issues connected with variable productive structure (a software for the dynamic thermoeconomic application is described in the **Annex** section).

Besides, special attention was given to the representation of 3-way valves and inertia components. The V3V was studied under three economic perspectives: simplified, incremental and dissipative standpoints, and, those configurations were applied in different case studies. Likewise, all the possible productive cases of inertia components were incorporated by the i_{st} and o_{st} flows.

Although such variability brings notable complexity, dynamic approach is the only way to deal with building facilities. Accordingly, a very challenging case study was analyzed to serve as a roadmap for the method application, where some components behave as dissipative or productive elements depending on the period of the year.

Based on the same exergetic fundaments, Exergoenvironmics has been evolved which accounts for the irreversibility formation in terms of environmental impacts. Both Exergoeconomics and Exergoenvironmics can also be used in energy audits, since they allow detecting the places where losses occur and quantifies their costs and environmental impacts making easier to propose profitable improvements. Likewise, they can be applied to the synthesis and diagnosis of energy plants as they provide information about the cost formation process, the interactions among thermodynamics, economics, environmental impacts and the interactions among the plant components.

Therefore, the objective of any thermoeconomic methodology is to encourage improvements to increase efficiency, decrease cost and mitigate pollutants emission. Unluckily, they are somehow incomplete since they are based on statistical forecasting, ambivalent decisions, cost estimations, etc. Although the difficulties, Second Law application is worthwhile and precious tool for decision-making. Thanks to it, the objective of energy saving and environmental caring is progressively being achieved.

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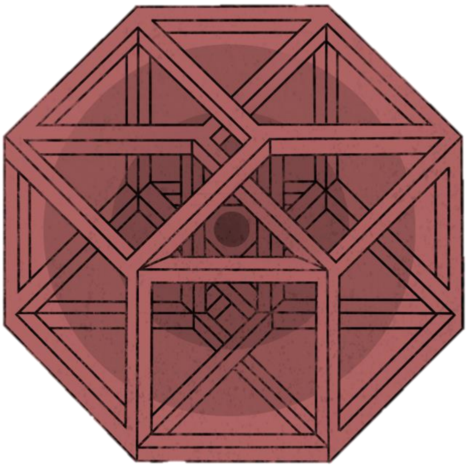

CHAPTER D

Thermoeconomic diagnosis in buildings

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UPV EHU

CHAPTER D

SUBSCRIPT	
T	Total
e	Entries to the system
s	Outputs to the system
n	Number of component
m	Number of fluxes of the system

SUPERSCRIP	
o	Reference condition
ref	Reference condition
$real$	Real condition
$free$	Free condition
$control$	Control system intervention
$anom$	Anomalies

SYMBOLS		
T	[ºC]	Temperature
$\dot{m}$	[kg/s]	Mass flow rate
c_P	[kJ/kgK]	Heat capacity
UA	[W/K]	Overall heat transfer coefficient
$\dot{H}$	[kW]	Enthalpy flow
$\dot{Q}$	[kW]	Heat flow
$\mathbf{F}$	[kJ]	Fuel vector $(n, 1)$
$\mathbf{P}$	[kJ]	Product vector $(n, 1)$
$\mathbf{I}$	[kJ]	Irreversibility vector $(n, 1)$
$\mathbf{R}$	[kJ]	Residues vector $(n, 1)$
ΔF_T	[kJ]	Fuel impact
$\mathbf{k}_F^*$	[kJ/kJ]	Exergetic unit cost vector of fuel $(1, n)$
$\mathbf{k}_P^*$	[kJ/kJ]	Exergetic unit cost vector of product $(1, n)$
$\mathbf{c}_F$	[kJ/kJ]	Exergoeconomic unit cost vector of fuels $(n, 1)$
$\mathbf{MF}$	[kJ]	Malfunction vector $(n, 1)$, endogenous irreversiblities
$\mathbf{DF}$	[kJ]	Dysfunction vector $(n, 1)$, exogenous irreversiblities
$\mathbf{MF}^*$	[kJ]	Malfunction cost vector $(n, 1)$
$[\mathbf{MF}]$	[kJ]	Malfunction matrix (n, n)
$[\mathbf{DF}]$	[kJ]	Dysfunction matrix (n, n)
κ_{ij}	[kJ/kJ]	Marginal exergetic consumption
$\psi_{MF_i^*}$	[kJ/kJ]	Indexes of malfunction impacts
$\langle\mathbf{PF}\rangle$	[kJ]	Distribution matrix of r_{ij} (n, n) PF formulation
$\langle\mathbf{KP}\rangle$	[kJ]	Distribution matrix of unit consumption (n, n), PF formulation
$^t\langle\mathbf{F_T F}\rangle$	[kJ]	External resources portion vector of components $(1, n)$
$\|\mathbf{I}\rangle$	[kJ]	Matricial operators (n, n), PF formulation
$\|\mathbf{P}\rangle$	[kJ]	Matricial operators (n, n), PF formulation
$\|\mathbf{R}\rangle$	[kJ]	Matricial operators (n, n), PF formulation
$unitateako$	[*][4]	Process characterization variable

[4] [*] = units of the corresponding variable

ξ	[*]	Characterization variables
k_j	[kJ/kJ]	Unit exergetic consumption within component j
x	[*]	Independent variables

CHAPTER D: THERMOECONOMIC DIAGNOSIS IN BUILDINGS

D.0. ABSTRACT

The aim of the chapter is to develop a methodology for the direct problem of thermoeconomic diagnosis in HVAC&R systems. The idea is to make the readers aware of its benefits and drawbacks in order to have a critical perspective. After all, the judgmental review and development substantiated along this chapter helps for the essential diagnosis decision making.

In the first section, fuel impact methodology is studied and two new indexes are proposed to assess the effect of the malfunction cost of every component. Besides, new expressions are deducted to calculate the economic cost associated with the anomalies and with control system intervention. However, fuel impact methodology is pointed as not effective in identifying the sources of anomalies.

In the second section, fuel impact formula is combined with characteristic curves to overtake the previous ambiguities. The key finding is that neither of the methodologies is better than the other but they are complementary. By combining both theories, the fuel impact associated with each anomaly is calculated through a reiterative diagnosis study.

In the last section, a flow chart for the real diagnosis application is defined by enhancing the former methodology. A direct and clear procedure is evolved mechanizing the diagnosis application in building systems.

D.1. INTRODUCTION

When a thermal facility is optimized either economically, environmentally or socially, all steps that take part in the process must be carefully considered: the selection of the proper equipment, the implementation of the best control and the enforcement of the optimal maintenance. If an anomaly appears in the real operation of a facility, it can easily ruin the reference operation condition by increasing fuel consumption and consequently the operating cost.

Systems are often poorly maintained and as a consequence experience dramatic degradation of performance due to aging and the presence of malfunctions or faults [1]. Those anomalies do not cause the unit to stop functioning, but they produce degradation in plant performance that could be the beginning of undesirable induced effects which can seriously damage the nominal operational condition of the facility.

By definition, diagnosis is the science that identifies the nature of an illness or a problem by examination of the symptoms. Thereby, thermoeconomic diagnosis is a Second Law based technique oriented to operation analysis. It aims to identify the components affected by any anomaly (*malfunction*) by analyzing the variations in the exergetic efficiencies (or its opposite, unit exergetic consumptions, k). It also attempts to quantify the potential energy recovery of a system by evaluating the additional resource consumption between the actual (operation) and the ideal (reference) conditions. Although (as it will be develop) detection of anomalies does not necessarily involve the use of thermoeconomics, thermoeconomic diagnosis is based on the idea that the same amount of additional irreversibility occurring in different components has a different impact on additional resources consumption to maintain the same product [2]. Furthermore and conversely to other methodologies, as exergy and thermoeconomic analyses are systematic techniques can be applied to whatever system [3]; hence, thermoeconomic diagnosis allows the procedural repetition for all the anomalies, so it is a general methodology.

In spite of such positive aspects, thermoeconomic diagnosis includes some weaknesses. As commented in **Section A**.1.2., exergy represents a synthesis of thermodynamic information so it is not the right tool when the relationship among components are to be analysed. Physical interactions between components can be highly complex and the duty of allocating and quantifying anomalies is a major task [4], which requires more than the comparison of unit exergetic consumption (or what is the same, additional thermodynamic knowledge is required). Therefore, thermoeconomic diagnosis applications can, sometimes, lead to inconsistencies from a mathematical point of view [2]. In addition, the causes of inefficiencies do not always coincide with the location of irreversibilities [5] so a further step is needed. Besides, the theory of thermoeconomic diagnosis is based on average costs and those are not objective values for diagnosis purposes: on the one hand, average costs give no information about future unexpected impacts and, on the other hand, they do not distinguish between the first and the last unit produced. Indeed, if optimization is going to be implemented too, marginal costs should be used.

In consequence, as the application of thermoeconomic indicators always has a level of subjectivity [6], classic thermoeconomic diagnosis needs to be adjusted and contemplated from a thermodynamic point of view for a proper diagnosis application, which is precisely, the aim of this chapter.

D.1.1. Diagnosis in non-industrial applications

As mentioned in **Section C**.1., thermoeconomic diagnosis was mainly developed in industrial applications. In fact, while fault detection and diagnosis is well established in power plants, it is still in its infancy in heating, ventilation, air conditioning and refrigeration (HVAC&R) systems. Actually, the research did not begin until the late 1980's and early 1990's [7] because of, among others, the following reasons:

- In general, most building HVAC&R systems have a limited set of sensors (sensors that are required for control purposes only) and prognostics should be accomplished by continuously monitoring the operations of a system.
- Many building performance problems are balanced with controllers' automatic compensation so occupants experience no discomfort, even if energy consumption and operating costs increase [8].
- Before selecting methods for detection and diagnosis, a good understanding of the anticipated faults is essential. Not many methods can diagnose the fault that exhibits different symptoms at different times and depends on the operational dynamics of the system.
- Multiple simultaneous faults make determining the causes of faults even more difficult.

Notwithstanding the limitations, some diagnosis methods and types were developed for HVAC&R in the last decades which are summarized in Figure D. 1 (full detailed revision is found in [9]). However, although those methodologies identify the specific faults, they do not allow

(1) neither assessing whether the identified faults are serious or minor, nor (2) evaluating quantitatively the degradation of system performance induced by any identified fault.

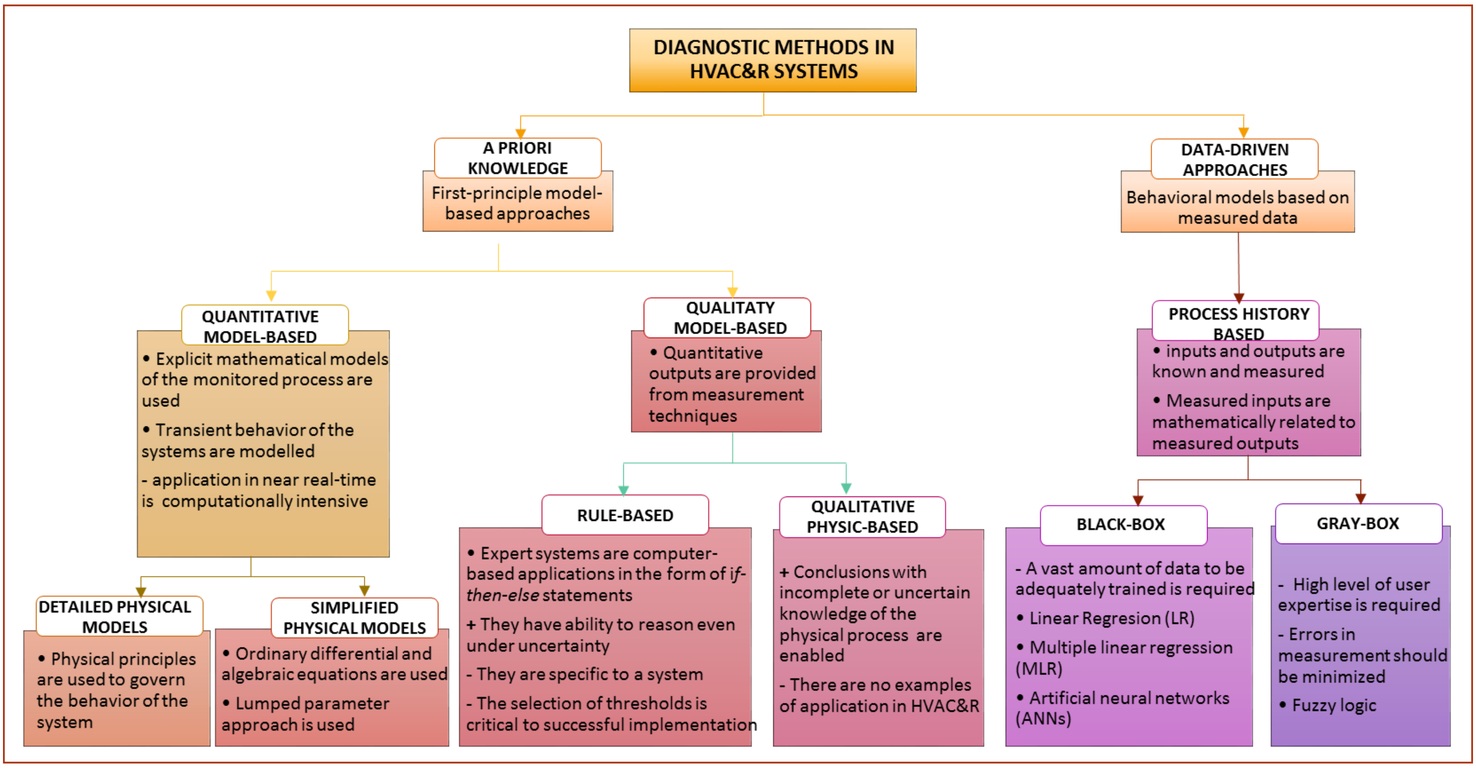

Figure D. 1 Diagnosis methods brief revision for HVAC&R systems

Conversely, the previously mentioned *thermoeconomic methodology* enable (1) analyzing any off-design operating condition, (2) identifying eventual faults (single or multiple) and (3) evaluating for each fault its individual "fuel impact" according to the conventional diagnosis method by comparing only two operation conditions [10]. Nevertheless, they do not allow identifying possible strategies to reduce the inefficiencies caused by anomalies [11].

In spite of that, and focusing on the Second Law applications, some thermoeconomic diagnosis were enforced in HVAC&R systems during the 2010's and, regarding the aim of this chapter, special attention would be given to them.

A conventional thermoeconomic approach was applied on an air-conditioning unit [12] where, by comparison to power plants, a variation in the final product exist. Additionally, difficulties were encountered with the plant productive structure development. Those conceptual ambiguities were specially related to the *condenser* (a dissipative component) and the *throttling valve* (which consumes mechanical exergy to produce an increase of refrigerant thermal exergy) [13]. Nevertheless, solutions were given, on the one hand, by allocating the dissipative units exergy destruction variation due to the anomaly and, on the other hand, by splitting physical exergy into its mechanical and thermal components [1].

Furthermore, some methodological improvements were included in the thermoeconomic diagnosis implementation: (1) fictitious components distortions were avoided by excluding them from the productive structure, (2) null variation of the final product was assumed by multiplying all exergy flows by a *cooling capacity factor* [12] and (3) the effects of refrigerant undercharge were filtered. Besides, sensitivity of performance of the diagnostic technique was discussed [13] and applied in [1] which represents an alternative for the malfunctions differentiation. The same case study was used in [14], but then, a modified productive structure analysis method was performed.

In [8], conversely, fuel impact (F_T) and characteristic curves (CC) thermoeconomic diagnosis methods (which will be during the chapter deeply explained) were evaluated in a commercial refrigeration system with a common relative indicator.

Unfortunately, in all the mentioned applications, a unique operating condition in *steady state* was examined so performances at different load levels were not considered.

Besides, the most challenging enforcement of thermoeconomic diagnosis is to resolve the *direct problem*, which consists of detecting a possible anomaly and its location. It is a difficult task and the reliability of its results has not yet been proven [15]. For the moment, only the *inverse problem* of diagnosis has been solved, i.e., under the *knowledge* of specific anomalies in different components, the procedure involves quantifying the effects of those anomalies in terms of thermoeconomic quantities, such as fuel impact and malfunctions.

D.1.2. Generalities

The first steps of thermoeconomic diagnosis methodology and its development can be found in [16]. As mentioned, the diagnosis procedures rely the comparison among two system working conditions: the *reference* operating condition, without any anomaly (which will be represented by a 0 superscript and is commonly a design condition) and the *real* operating condition (that refers to the actual operating condition of the plant, characterized by an overall efficiency lower than that of the reference condition because of the presence of at least one failure). In other words, an anomaly or *intrinsic malfunction* produces changes in the operation condition compared to a reference situation, when some parameters remain constant; for instance, if the same product is maintained, the resource consumption would diverge from the reference since the component with the intrinsic malfunction would have a different $\Delta k = k - k^0$ value.

Both working conditions correspond to the same facility, so that they have the same symbolic structure [17]. The diagnosis should be able to detect the efficiency deviations, locate the root causes and quantify their effects in terms of additional consumption or economic impacts. Nevertheless, when executing diagnosis, the analyst does not know neither the number of anomalies nor their localization; moreover, it should be remembered that location of irreversibilites is not the same as its causation.

Thermoeconomic diagnosis application needs some previous requirements:

- Correct definition of reference condition is required.
- Operation and reference conditions should be close enough to accept linear model (hypothesis of small perturbations) [4].
- To approach the diagnosis objective, proper definition of control volumes and of productive structure of flows are required. This cannot be obtained relying on pure exergy balances, but it is based on two thermoeconomic concepts of **Chapter C** which are productive structure and exergy cost.

D.2. FUEL IMPACT DIAGNOSIS METHODOLOGY

The contribution given by the malfunctioning component to the variation of the total plant fuel consumption is given by the *fuel impact formula*, first suggested in [6] .The *fuel impact* is the difference between the resource consumption of the plant in real operating condition (F_T) and the resource consumption in the reference condition (F_T^0):

$$\Delta F_T = F_T - F_T^0 \tag{D. 1}$$

Such expression can be stated in two different ways that are thoroughly described.

D.2.1. Fuel impact

The fuel impact is represented by summing the increase of irreversibilities arisen from unexpected anomalies and the increase of final product generated by the increase of resource consumption of the plant as follows:

$$① \ \Delta F_T = {}^{\mathbf{t}}\mathbf{u} \cdot [\mathbf{\Delta I} + \mathbf{\Delta P_S}] \tag{D. 2}$$

Production variation is the difference between operating and reference condition:

$$\mathbf{\Delta P} = \mathbf{P} - \mathbf{P^0} \tag{D. 3}$$

The growth of irreversibilities ($\mathbf{\Delta I}$) is expressed as:

$$\mathbf{\Delta I} = \left((\mathbf{K_D} - \mathbf{U_D}) \cdot \mathbf{P}\right) - \left(\left(\mathbf{K_D^0} - \mathbf{U_D}\right) \cdot \mathbf{P^0}\right) = \mathbf{\Delta K_D} \cdot \mathbf{P^0} + (\mathbf{K_D} - \mathbf{U_D}) \cdot \mathbf{\Delta P} \tag{D. 4}$$

Henceforth, the increase of irreversibilities is decomposed into two components; the first one is due to the increase of the unit exergy consumption in the components themselves and the second one depicts the adjustment in the product each component must undergo in order to suit the new operating conditions. The first component is called *malfunction* $\mathbf{MF}$:

$$\mathbf{MF} = \mathbf{\Delta K_D} \cdot \mathbf{P^0} \tag{D. 5}$$

The second component is called *dysfunction* $\mathbf{DF}$ and is induced in every component because of the malfunctions in the other components. It consists in the increment of component irreversibility due to the variation of its local production caused by the malfunction of other components [18]:

$$\mathbf{DF} = (\mathbf{K_D} - \mathbf{U_D}) \cdot \mathbf{\Delta P} \tag{D. 6}$$

Consequently, the fuel impact can be expressed as follows:

$$① \ \Delta F_T = {}^{\mathbf{t}}\mathbf{u} \cdot [\mathbf{MF} + \mathbf{DF} + \mathbf{\Delta P_S}] \tag{D. 7}$$

D.2.1.1. MF and DF analysis

For further analysis and a better diagnosis comprehension, another alternative form to express the Eq.(D. 4) can be given by defining the malfunction and dysfunction matrixes. This arrangement displays the real provenance of the fuel impact, this is to say, it makes it easy to detect and quantify the reason why a component varies its consumption due to both its own anomaly (information acquired through $\mathbf{MF}$ vector) and the extra consumption induced by anomalies located in other equipment (data obtained through the $[\mathbf{DF}]$ matrix).

Indeed, $\mathbf{MF}$ vector can be decomposed into the sum of an external malfunction vector ($\mathbf{MF_e}$) and internal malfunction vector (${}^{\mathbf{t}}\mathbf{u} \cdot [\mathbf{MF}]$). The first term is due to the variation in the marginal exergy consumption of the external resources (i.e. flows associated with the environment) while the latter is obtained by multiplying the transposed unitary vector and the matrix $[\mathbf{MF}]$ that shows the variation in the marginal exergy consumption of the components because a degradation in the component efficiencies themselves:

$$ {}^{\mathbf{t}}\mathbf{MF} = {}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k_e} \cdot \mathbf{P_D^0} + {}^{\mathbf{t}}\mathbf{u} \cdot \left(\boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0}\right) \tag{D. 8} $$

$$ \mathbf{MF_e} = {}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k_e} \cdot \mathbf{P_D^0} \tag{D. 9} $$

$$ [\mathbf{MF}] = \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0} \tag{D. 10} $$

Likewise, $\mathbf{DF}$ vector can also be decomposed into the sum of a dysfunction induced by extra external resource consumption ($\mathbf{DF}_{\boldsymbol{e}}$) and the dysfunctions generated by other components downgraded behavior, which are the product of $[\mathbf{DF}]$ matrix and the unitary vector ($[\mathbf{DF}] \cdot \mathbf{u}$).

Indeed, dysfunction is split as follows:

$$ \mathbf{DF} = |\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\mathbf{P_s} + \left(|\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0}\right) \cdot \mathbf{u} \tag{D. 11} $$

$$ \mathbf{DF_e} = |\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\mathbf{P_s} \tag{D. 12} $$

$$ [\mathbf{DF}] = |\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0} \tag{D. 13} $$

The component DF_{ie} of Eq.(D. 12) represents the dysfunction quota associated with the variation of the final product $DF_{ie} = \sum_{h=1}^{n} \theta_{ih} \Delta P_s$. Conversely, the component DF_{ij} of the dysfunction matrix $[\mathbf{DF}]$ shows the irreversibility increase on the component induced by a malfunction in the component j: $DF_{ij} = \sum_{h=1}^{n} \theta_{ih} \Delta\kappa_{hj} P_j^0$, where θ_{ij} stands for the weight of the malfunction effect (i.e. it represents the irreversibility generated in the component j to obtain a unit of the product i).

It is easy to observe the relation between the dysfunction matrix and the malfunction matrix:

$$ [\mathbf{DF}] = |\mathbf{I}\rangle \cdot [\mathbf{MF}] \tag{D. 14} $$

Meaning that dysfunction is generated when output variation exists because a malfunction takes place. In other words, the degradation of a component does not only create the increase of irreversibilities in the component itself, but also in the previous components [18]. Reminding that the final product should be constant, more resources would be needed for the same product in the failing component, hence, the components beyond would be forced to produce more local resources. So the dysfunction cannot be corrected by itself but decreasing the malfunction which has generated it.

D.2.1.2. Malfunction cost

A malfunction cost in the component i (MF_i^*) is defined as the additional external fuel required for the malfunction affecting the component i. It is easy to check that the fuel impact can be set forth in terms of the variation of the external marginal exergy consumption and the variation of products of the components as:

$$② \ \Delta F_T = \left({}^{\mathbf{t}}\mathbf{k}_{\mathrm{e}} \cdot \mathbf{P} \right) - \left({}^{\mathbf{t}}\mathbf{k}_{\mathbf{e}}{}^{\mathbf{0}} \cdot \mathbf{P}^{\mathbf{0}} \right) = {}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k}_{e} \cdot \mathbf{P}^{\mathbf{0}} + {}^{\mathbf{t}}\mathbf{k}_{\mathbf{e}} \cdot \boldsymbol{\Delta}\mathbf{P} \qquad \text{(D. 15)}$$

Inserting the definition of $\mathbf{k}_{\mathbf{P}}^*$ and :

$$\Delta F_T = \left({}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k}_{e} + {}^{\mathbf{t}}\mathbf{k}_{\mathbf{P}}^* \cdot \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \right) \cdot \mathbf{P}^{\mathbf{0}} + {}^{\mathbf{t}}\mathbf{k}_{\mathbf{P}}^* \cdot \boldsymbol{\Delta}\mathbf{P}_{\mathbf{s}} \qquad \text{(D. 16)}$$

Thus, the fuel impact is split into two components: the first one is the malfunction cost brought about by the unit marginal exergy consumption variation, which considers the amount of additional resources consumed in the real operating condition in relation to the reference condition. Therefore, the associated vector $\mathbf{MF}^*$ is:

$${}^{\mathbf{t}}\mathbf{MF}^* = \left({}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k}_{e} + {}^{\mathbf{t}}\mathbf{k}_{\mathbf{P}}^* \cdot \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \right) \cdot \mathbf{P}_{\mathbf{D}}^{\mathbf{0}} \qquad \text{(D. 17)}$$

and the second one, is the malfunction cost originated by the final product increment, being $\mathbf{MF}_e^*$ the corresponding vector:

$$\mathbf{MF}_{\mathbf{e}}^* = \mathbf{k}_{\mathbf{P_D}}^* \cdot \boldsymbol{\Delta}\mathbf{P}_{\mathbf{s}} \qquad \text{(D. 18)}$$

and then:

$$② \ \Delta F_T = {}^{\mathbf{t}}\mathbf{u} \cdot \left(\mathbf{MF}^* + \mathbf{MF}_{\mathbf{e}}^* \right) \qquad \text{(D. 19)}$$

When the fuel impact relation is used as a diagnostic tool, some statements need to be borne in mind [5]:

- If a component has no malfunction and there are no dysfunctions in other components induced by it, its malfunction cost is null.
- The cost of malfunctions in each component is equal to the actual additional total fuel consumption the component is responsible for.
- If a variation of final product exists, the portion of fuel impact due to that increment must be taken into account.

So as a conclusion, it can be said that malfunction cost MF_i^* in the component i gives the potential exergy saving that can be obtained if the reference condition is restored in that component; and the production cost $MF_{e,i}^*$ provides the information of the unavoidable cost generated by extra unintentional production, that would be saved while malfunction cost is corrected.

To assess the significance of the malfunction cost and the production cost of each component in relation to the whole fuel impact, two ψ indexes are proposed:

$$\psi_{MF_i^*} = \frac{MF_i^*}{\Delta F_T} \tag{D. 20}$$

$$\psi_{MF_{e,i}^*} = \frac{MF_{e,i}^*}{\Delta F_T} \tag{D. 21}$$

The component with highest $\psi_{MF_i^*}$ index would be identified as the component that provokes highest extra resource consumption, so that it is pinpointed as the largest faulty component.

As a final summary of fuel impact analysis, there are two perspectives to evaluate the fuel impact. On the one hand, in ① the variation of irreversibility in each component is the sum of the malfunction and the dysfunctions generated in the component due to the anomalies in the other components and, then, the total plant fuel impact equals the sum of component irreversibility variations plus the variation of total plant product. From the other perspective ②, the impact on total fuel due to each component is given by the irreversibility quota associated with the variation of the unitary exergy consumption in the component itself and the effects induced by this variation on the final products.

If the reader wants to delve more deeply into diagnosis roots and its mathematical development, the paper [19] together with [15] illustrate the direct way to achieve that aim.

D.2.2. Filters for undesirable effects

To make the comparisons between reference and real conditions reliable, some effects should be considered in advance [20]: the *control system intervention effect* as well as the *total production effect.*

D.2.2.1. Control System Effect

As a generic statement, the facility's control system is based on set-points referred to variables of specific components, such as temperature. The values of these temperatures depend on the system thermodynamic whole state. An anomaly can cause fluctuations in those values that give rise to the intervention of the control system, which alters the reference conditions imposing some barriers to the malfunction propagation. This control effect should be filtered to properly compare reference and real operating conditions so that both cases have an equivalent behavior. An artificial condition is obtained by starting from the real condition and restoring the same regulation as in the reference condition, known as *free condition*, which should be virtually determined. This means that diagnosis would now be made by the comparison between the free and reference conditions, so that the malfunctions induced by the regulation system are avoided. The free condition contains the same faults (anomalies) of the real condition, but the control commands are adjusted as in the reference.

In prior works, free condition obtainment is approached from a *mathematical* point of view [20]. Since anomalies are considered small enough, reference condition is close to real condition, so that each regulation parameter effect can be linearly treated. After defining regulation equations for each parameter and calculating the Lagrange multipliers associated with the control system, the plant is modelled and the free condition values are obtained.

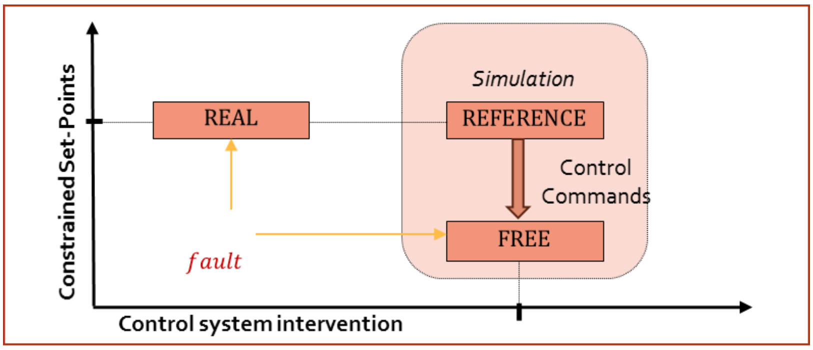

Figure D. 2 Free condition obtainment

However, in this chapter an innovative method to filter the effect of regulation is proposed. Instead of using a mathematical development, the free condition is obtained directly by simulation; this artificial condition is acquired starting from the reference condition and restoring the same regulation as in the operation condition. To do that, reference and faulty (real) conditions are simulated together and the same control intervention is forced in both of them. Figure D. 2 summarizes the characteristics of the three working conditions: reference, real and free conditions.

D.2.2.2. Total production effect

In previous works diagnosis is applied in systems with no output variation [21]. What is more, in [6] diagnosis is defined as the methodology that enables the localization of anomalies and the calculation of the consumed resources that can be saved by keeping constant the quantity and specifications of the final product.

Meanwhile, some recent works have been published with a variation in a single output product, for example, in [13] were the unique variation is easily filtered. Nevertheless, in the case of housing energy supply facilities, there is commonly more than one principal output, such as heating, cooling or DHW demands. Because of those multiple outputs, the production effect ($\mathbf{\Delta P_S}$) should be considered.

D.2.3. Economic Impact

If we want to express the fuel impact formula not only in exergetic cost terms but also in *exergoeconomic cost* terms, the progression can be done as follows: economic impact is defined as the difference between the total fuel cost in real operating condition and in reference condition:

$$\Delta C_{F_T} = C_{F\,T} - C_{F\,T}^{\,0} \tag{D. 22}$$

In order to calculate the economic cost associated to the control system intervention ($\Delta C_{F_T}^{control}$) and to that related to anomalies (calculated through diagnosis, $\Delta C_{F_T}^{anom}$) Eq.(D. 22) is split into two components:

$$\Delta C_T = \left(C_{F_T} - C_{F_T}^{free}\right) + \left(C_{F_T}^{free} - C_{F_T}^{0}\right) = \Delta C_{F_T}^{control} + \Delta C_{F_T}^{anom} \tag{D. 23}$$

Therefore, the economic impact can be outlined as in Figure D. 3.

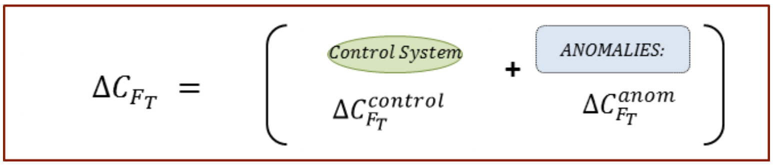

Figure D. 3 Economic impact obtainment

The economic cost related to the control system operation is obtained as:

$$\Delta C_{F_T}^{control} = C_{F\,T} - C_{F\,T}^{\,free} = \ {}^{t}\mathbf{c_F} \cdot \mathbf{F_T} - \ {}^{t}\mathbf{c_F}^{\mathbf{free}} \cdot \mathbf{F_T^{free}} \tag{D. 24}$$

being $\mathbf{c_F}$ the unit economic cost of fuels in each condition.

The economic cost related to the anomalies is calculated similarly to the previous procedure as:

$$\Delta C_{F_T}^{anom} = \ {}^{t}\mathbf{c_F}^{\mathbf{free}} \cdot \mathbf{F_T^{free}} - \ {}^{t}\mathbf{c_F}^{\mathbf{0}} \cdot \mathbf{F_T^{0}} = \mathbf{\Delta c_{F_e}} \cdot \mathbf{P^0} + \mathbf{c_{F_e}} \cdot \mathbf{\Delta P} \tag{D. 25}$$

Introducing $\mathbf{\Delta P}$ between free and reference and the definition:

$$\Delta C_{F_T}^{anom} = \left(\mathbf{\Delta c_{F_e}} + \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \mathbf{\Delta \langle KP \rangle}\right) \cdot \mathbf{P^0} + \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \mathbf{\Delta P_s} \tag{D. 26}$$

Economic impact related to anomalies is also partitioned into the additional exergoeconomic cost regarding malfunction ($\mathbf{C_{MF^*}}$) and the exergoeconomic cost owing to final product variation between free and reference conditions ($\mathbf{C_{MF_e^*}}$).

$${}^{t}\mathbf{C_{MF^*}} = \left(\mathbf{\Delta c_{F_e}} + \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \mathbf{\Delta \langle KP \rangle}\right) \cdot \mathbf{P^0} \tag{D. 27}$$

$${}^{t}\mathbf{C_{MF_e^*}} = \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \mathbf{\Delta P_{s_D}} \tag{D. 28}$$

D.2.4. Case Study

As said before, although the real aim of diagnosis is to solve the direct problem, the selected case study performs the opposite way with the purpose of incorporating and interpreting the displayed theory.

For that, the procedure to be followed will be as follows: the case study facility will be faithfully recreated with dynamic calculations using Trnsys v17 [22] through a double simulation. One simulation refers to the reference condition and the other shows the anomalous operating condition. The latter would contain a known failure imposed into a specific component. Consequently, the degradation generated will be studied in terms of fuel and economic impact, malfunctions, dysfunctions and malfunction costs, in order to judgmentally check the general results.

Besides, the diagnosis procedure will take into account the effects of the control system by filtering its induced effects. As an innovative contribution to this diagnosis methodology, a new way for filtering the induced malfunctions caused by the regulation system is introduced. Instead of obtaining the free condition by using a mathematical development, the free condition is calculated by simulation.

Furthermore, the final product variation is taken into account so the fuel impact is related to the anomalies caused by irreversibility increment and final product change.

D.2.4.1. (vi) Heating & DHW System Case Study

The case study refers to the heating and DHW system of a 16 householder multi-family flat, located in Bilbao (Spain). This system is a typical heating installation of the Basque Country [23]. The energy supply system consists of a natural gas condensing boiler. Working at a high temperature mode, 28kW power can be obtained with a manufacturer energy efficiency of 97 % (17 % exergy efficiency). The other components of the installation are a hydraulic compensator, three-way valves, a heat exchanger and a 1000 litter DHW storage tank. In addition, there are three circulation pumps, one in the generation circuit, another in the distribution circuit and the last one in the DHW production circuit, see Figure D. 4. The heating demand is represented through the heat dissipation of a radiator system and a three-way valve. The DHW is given by a DHW tank and a three-way valve that ensures hot water at a constant temperature.

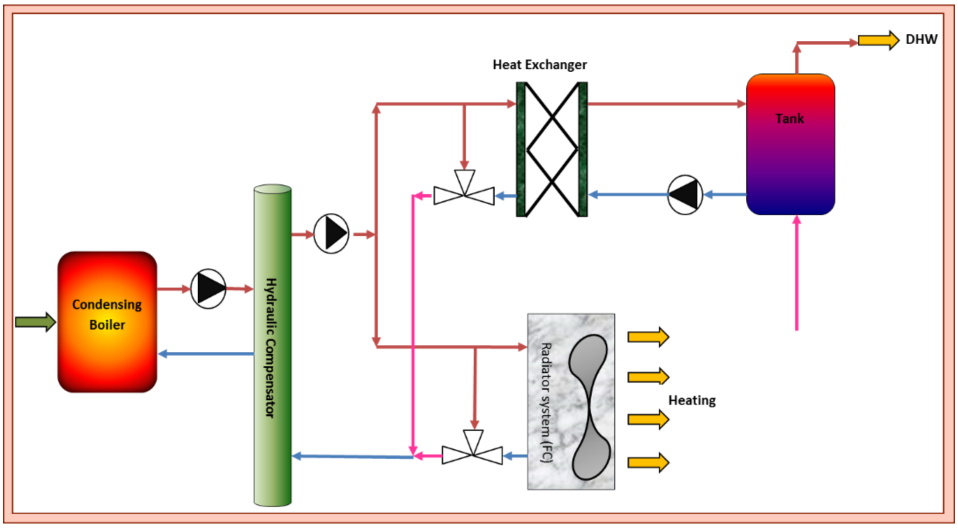

Figure D. 4 Scheme of the study case facility

As already mentioned, the analysis is done with Trnsys v17. The heating demand follows a typical profile of Northern Spain dwelling [24], which is estimated using Trnsys type 56 with 1h time-step; DHW demand is obtained by Task 26 Domestic Hot Water calculator program [25]. Both demands are hourly stored in external files and afterwards implemented in the diagnosis simulation. The various components appearing in the case study are simulated using simplified models available from the Trnsys library.

13 components and 24 flows were considered for the analysis, see Figure D. 5. Two inputs coming from external sources are considered: natural gas ($\dot{E}_{20}$) and the contribution given by the tank ($\Delta\dot{E}_{21}$), which is the difference between the initial and final exergy the tank has in the considered period and they are represented by green arrows. Yellow arrows indicate the final products leaving the system, such as DHW ($\dot{E}_{23}$) and heating demand ($\dot{E}_{19}$).

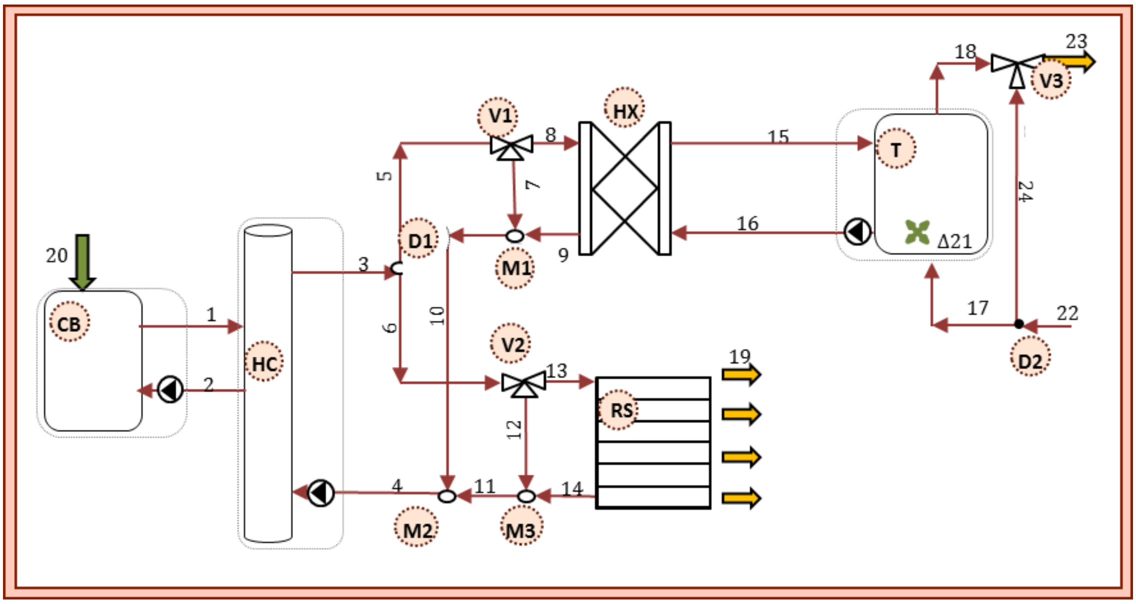

Figure D. 5 Numbering of flows and naming of components of the system

As can be seen in the graph, the three circulation pumps have not been taken into consideration due to the small power of these elements. Performing the analysis considering those pumps and separating the exergy into its thermal and mechanical components is more accurate and realistic. Indeed, any anomaly that changes a flow rate can decrease the overall efficiency of the system [26] and therefore the pumps can be a source of dysfunction or induced effects but, in order to avoid confusions with excessive nomenclature, they have not been taken into account. Thus, the calculations do not contain the effect of pressure on the values of physical exergy of the water flow.

The list of components used for the analysis is in Table D. 1 where their numbering and their abbreviation are represented.

Table D. 1 Brief description of Components

	COMPONENT	LEGEND
①	Condensing Boiler	CB
②	Hydraulic Compensator	HC
③	heating and DHW Diverter	D1
④	DHW three-way valve	V1
⑤	DHW Mixer	M1
⑥	Heat Exchanger	HX
⑦	Heating three-way valve	V2
⑧	Heating and DHW Mixer	M2
⑨	Heating Mixer	M3
⑩	Radiators System	RS
⑪	DHW Tank	T
⑫	DHW three-way valve	V3
⑬	DHW Diverter	D2

The *control* of the plant is such that DHW takes priority over heating. The units are activated and deactivated depending mainly on the tank temperature (T_{19}) and on the heating demand profile. If the tank temperature is below 62 ºC, the boiler is activated until it reaches 70 ºC. When the temperature difference between the heat exchanger primary inlet and the tank temperature is higher than 7 ºC, DHW production is activated; if the temperature difference is lower than 4 ºC, the three-way valve (located upstream of the heat exchanger) acts bypassing the heat flow through the compensator.

Heating demand is turned on according to the outside temperature together with a specific time schedule. Consequently, owing to the heating demand profile ($\dot{Q}_{heat}$), the boiler return temperature (T_2) decreases and when it drops below 60 ºC the boiler is activated.

The three-way valve associated with DHW output is adjusted to provide hot water ($\dot{m}_{DHW}$) at T_{DHW} =55 ºC temperature.

D.2.4.1.1. Fault

Any component can be chosen for containing the fault and the produced effects would depend on the location of such component in the productive structure. The chosen fault is deliberately incorporated on the *radiator system* (RS) by means of a 10 % reduction in its energy performance (the ratio between the useful heat given by the radiator system and the enthalpy difference between the inlet and the exit of the heating water).

D.2.4.1.2. Filtering Control System Effect

Because of the reasons given above, the control system intervention needs to be annulated by means of the free condition. Following the guidelines established in **Section D**.2.2.1, Figure D. 6 displays the assembly process used in Trnsys v17 interface where reference and free conditions are lumped together in the same simulation. *REF* index is used for naming the reference condition and *FREE* refers to the free condition (see *FAULT* incorporated in the bottom edge of Figure D. 6). Control and components connections are also portrayed in the same figure. The corresponding control is applied in the upper reference condition (see differential controllers icon in the top part) so it executes the start-up and shutdowns and regulation commands for the components according to the set-points (see intermittent grey arrows in *REF* facility and green arrows going from *Control REF* to *REF* facility). At the same time, those commands are sent to the operation condition installation (see green arrows going from *Control REF* to *FREE* facility) in order to follow the same start-stop sequence (for reasons of clarity, only commands to pumps are depicted and 3-way valves commands are not shown).

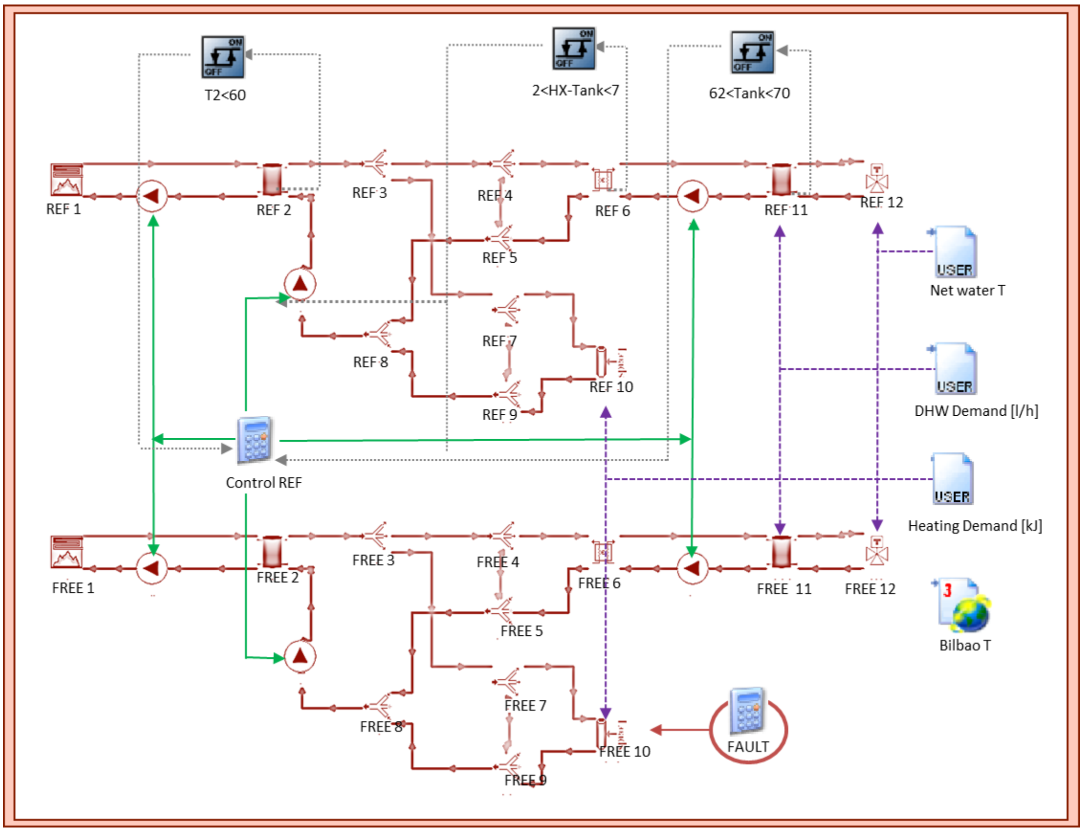

Figure D. 6 Free condition acquirement by imposing the same control interventions in Trnsys interface

In the present case, as explained ahead, the heating demand is previously defined through discrete thermal power values (see *Heating Demand [kJ]* User icon at the right part of the figure). DHW demand is defined by a modulating three-way valve which includes both cold water (see *Net water T* User icon) and DHW flow that leaves the tank (see *DHW Demand [l/h]* demand icon). As it can be seen, both conditions share and cover the same demand files and environmental conditions (see purple arrows and *Bilbao T* type).

D.2.4.1.3. Total production effect

There are two principal outputs considered in the installation: heating and DHW demand. Heating is defined by the power requested by the users, so that free condition and reference condition give the same heating output ($\dot{Q}_{heat} = \dot{Q}^0_{heat}$); as the environmental conditions are maintained, then $\Delta P_{s_{heat}} = 0$. Conversely, DHW is defined by the demanded water flow ($\dot{m}_{DHW}$) at a specific output temperature ($T_{DHW} = 55$ °C). This can be obtained thanks to the modulation of the thermostatic 3-way valve (V3) which mixes mains cold water ($\dot{m}_{cold}$ at T_{net} temperature) with the warm water flow coming from the storage tank ($\dot{m}_{hot}$ at T_{18}). So the DHW power is calculated as follows:

$$\dot{Q}_{DHW} = \dot{m}_{DHW} \cdot c_P \cdot (T_{DHW} - T_{net}) = \dot{m}_{hot} \cdot c_P \cdot (T_{18} - T_0) + \dot{m}_{cold} \cdot c_P \cdot (T_{net} - T_0) = \dot{H}_{18} + \dot{H}_{24} \quad \text{(D. 29)}$$

where $\dot{H}_{18}$ corresponds to the enthalpy flow coming out from the storage tank and $\dot{H}_{24}$ to the enthalpy flow coming from the mains water.

Because of the control enforcement for the free condition obtainment, V3 acts in the same way in both operating conditions: $\dot{m}_{hot} = \dot{m}^0_{hot}$ and $\dot{m}_{cold} = \dot{m}^0_{cold}$. However, as tank output temperature is a function of the tank storage temperature ($T_{18} = T_{18}(T_{21})$) and owing to the inserted failure, the instantaneous storage temperature is different: $T_{18} \neq T^0_{18}$. So, as $\dot{H}_{18} \neq \dot{H}^0_{18}$ a production output variation would inevitably exists, i.e. $\Delta P_{s_{DHW}} \neq 0$.

As mentioned, diagnosis theory is easily understandable if the total output remains the same in both conditions, as the fuel impact would be related exclusively to the additional fuel consumption due to anomalies. However, still, only one of the output variations can be avoided, since DHW is directly activated when a failure takes place.

D.2.4.1.4. Numerical Example

The reference and free conditions portrayed were simulated for the completely heating season comprising from the 1st of November until the 30th of April, with a 30 s time-step. As plotting heating and DHW demands for the whole heating period could be cumbersome to visualize, only a January 5-days profile is depicted in Figure D. 7.

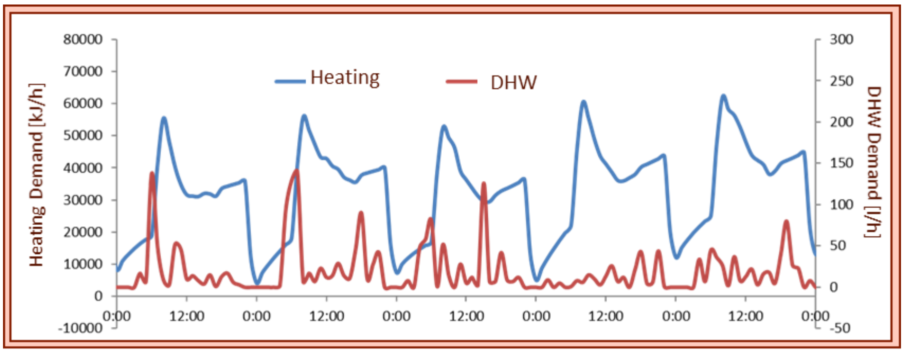

Figure D. 7 Heating and DHW demand during 5 days

Once the three simulations are done and the required data are obtained, the exergy of the flows in every time-step are calculated. With the purpose of plotting clear graphics, Figure D. 8 depicts the natural gas exergy consumption of the CB only during the January 5-days. As it can be seen, the blue and red lines, which refer to the reference and free condition, show that the

CB in both conditions is switched on at the same point in the abscissa axis. The green line, which corresponds to the operating condition, conversely, is switched on in a different time, whenever

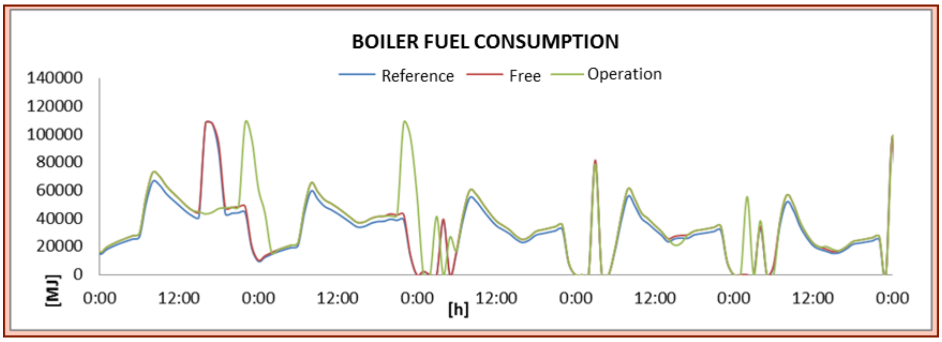

Figure D. 8 Boiler exergy consumption during the January 5 -days in the three conditions

its operating control system intervenes.

The accumulated exergy in each flow is computed at the end of the entire heating period for the three conditions: reference, free and real, see the values obtained in Table D. 2. Once the exergy values are calculated, thermoeconomic diagnosis is applied.

Table D. 2 Accumulated exergy values for reference, free and real condition $[\boldsymbol{GJ_{ex}}]$

$[MJ]$	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}
REFERENCE	29.1	23.4	102.4	97.4	13.4	89.0	11.1	2.3	1.8	12.9	84.5
FREE	29.1	22.9	85.8	80.3	13.1	72.7	10.9	2.2	1.8	12.7	67.7
OPERATION	29.1	23.0	101.7	96.3	17.0	84.7	15.3	1.7	1.3	16.6	79.7

E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}	E_{19}	E_{20}	ΔE_{21}	E_{22}	E_{23}	E_{24}
54.6	34.5	30.0	2.2	1.7	0.0	0.4	1.0	34.2	0.0	0.0	0.3	0.0
38.7	34.0	29.1	2.2	1.7	0.0	0.4	1.0	37.2	0.0	0.0	0.2	0.0
52.3	32.3	27.5	1.6	1.3	0.0	0.4	1.0	36.0	0.0	0.0	0.3	0.0

D.2.4.1.4.1. MF and DF analysis

Table D. 3 exhibits the diagnosis results according to Eq.(D. 7) perspective. The columns show the final product variation ($\mathbf{\Delta P_s}$), malfunction $\left(MF_{e,i} + MF_i\right)$ values and dysfunction $\left(DF_{e,i} + DF_i\right)$ values for each component. The sum of the last four columns equals to the growth of the irreversibility ($\mathbf{\Delta I}$), this is to say, the quota of fuel impact related to the existence of the anomaly.

The F_T^0 and F_T^{free} values correspond to the total fuel consumption of the facility in the reference and the free condition, respectively. The difference between these two values, as well as the sum of all cells of Table D. 3, coincides with the value of the fuel impact $[\Delta F_T^{anom} = 3010\ MJ]$ due to the existence of anomalies.

Table D. 3 Diagnosis expressed by the sum of $\Delta\mathbf{I} + \Delta\mathbf{P_S}$ $[\boldsymbol{MJ_{ex}}]$

		$\Delta\mathbf{P_s}$	$\Delta\mathbf{I}$			
			MF		**DF**	
			$\mathbf{MF}_e$	$\mathbf{MF}_i$	$\mathbf{DF}_e$	$\mathbf{DF}_i$
①	CB	-	147	-	-1250	3640
②	HC	-	-	-12	-26	78
③	D1	-	-	-	-	-
④	V1	-	-	-	-	-
⑤	M1	-	-	2	-	-
⑥	HX	-	-	-	-	-
⑦	V2	-	-	-	-	-
⑧	M2	-	-	39	-2	-9
⑨	M3	-	-	59	-5	-29
⑩	RS	-	-	382	-	-
⑪	T	-	-	-	-29	29
⑫	V3	-105	-	180	-77	-
⑬	D2	-	-2	-	-	-
			F_T^0 $[MJ]$=		34174	
			F_T^{free} $[MJ]$=		37184	

When analyzing the results, much attention should be given to the following points:

- $\Delta\mathbf{P_s}$ in the RS component $[\Delta P_{s_{10}} = 0\ MJ]$ is null and a negative value exists in M4 final product variation $[\Delta P_{s_{12}} = -105\ MJ]$. This result reinforces the statement of the constant final heating production and reduction of DHW due to the presence of a fault in the free condition.
- If the malfunction vector $\mathbf{MF}$ is considered, as it was expected, malfunction mostly affects RS [MF_{10}=382 MJ], although CB malfunction does not go unnoticed [MF_1=147 MJ]. In order to understand this fact, **MF** should be divided into malfunctions due to component exergy consumption variation MF_i and due to the external resources variation $MF_{e,i}$. CB is fully affected by the external resource variation [$MF_{e,1}$=147 MJ].
- The components located upstream from the anomaly (HC [MF_2=-12MJ], M2 [MF_8=39 MJ] and M3 [MF_9=59 MJ]) also have malfunctions. These types of malfunctions are identified as *induced malfunctions*, since those modules do not incorporate the anomaly itself.
- The component most affected by other component malfunctions is definitely the first device of the energy transformation chain, i.e. the CB with a [DF_1 = 2390 MJ].
- There are some components with negative dysfunction values, such as M3 [DF_9 = -5 MJ] or V3 [DF_{12} = -77 MJ] which are related to the negative final production variation; this is because not all dysfunctions are caused by malfunctions but also because of the existence of $\Delta\mathbf{P_s}$ that induces $\mathbf{DF_e}$. So these dysfunctions do not have a negative impact by themselves, as they are associated to a variation of the overall production.

For further analysis and a better diagnosis comprehension, an alternative to express the component dysfunctions is by its matrix Eq.(D. 13) displayed in Table D. 4 .

- The sum of each line $\sum_j DF_{ij}$ corresponds to the total dysfunction generated in the component i which coincides with the corresponding DF column of Table D. 3. For example, the sum of the first line ($\left[\sum_j DF_{1j} = 3640\ MJ\right]$ dysfunctions which appear in CB) is equal to the first row of Table D. 4 $[DF_1 = 3640\ MJ\ ]$.

- Through this table, the induced effect on the component i provoked by a malfunction in the component j can be visualized. For example, the $\left[DF_{1,8} = 204\ MJ\right]$ matches the dysfunction of the CB sparked by the M2.

Table D. 4 DF matrix $[\boldsymbol{MJ_{ex}}]$

	DF_e	[DF]												
①	-1250	-	-61	-330	-	12	2	-	204	345	2240	-6	1234	-
②	-26	-	-	-7	-	-	-	-	4	7	48	-	26	-
③	-	-	-	-	-	-	-	-	-	-	-	-	-	-
④	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑤	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑥	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑦	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑧	-2	-	-	-16	-	-	-	-	-	1	4	-	2	-
⑨	-5	-	-	-42	-	-	-	-	-4	2	10	-	5	-
⑩	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑪	-29	-	-	-	-	-	-	-	-	-	-	-	29	-
⑫	-77	-	-	-	-	-	-	-	-	-	-	-	-	-
⑬	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	⓪	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬

D.2.4.1.4.2. Malfunction cost

Table D. 5 shows the diagnostic results obtained from the other perspective, Eq.(D. 19). The last two columns display the *key indexes* whose objective is the identification of the default component. Some aspects sustain the comments previously made in **Section D**.2.1.2:

Table D. 5 Diagnosis expressed by the sum of Malfunction Costs $[\boldsymbol{MJ_{ex}}]$

		MF^*	MF_e^*	ψ_{MF^*}	$\psi_{MF_e^*}$
①	CB	147	-	5%	-
②	HC	-73	-	-2%	-
③	D1	-396	-	-13%	-
④	V1	-	-	-	-
⑤	M1	-	-	-	-
⑥	HX	-	-	-	-
⑦	V2	-	-	-	-
⑧	M2	244	-	8%	-
⑨	M3	413	-	14%	-
⑩	RS	2683	-	89%	-
⑪	T	-	-	-	-
⑫	V3	1481	-1487	49%	-50%
⑬	D2	-2	-	-	-
		$\Delta F_T^{Anom}\ [MJ] =$		3010	

- The most significant malfunction cost is in RS [$MF_{10}^{*} = 2683\ MJ$]. This is because all the irreversibility increments generated by this component is held in this term. In other words, MF_{10}^{*} encloses the malfunctions and dysfunctions associated with RS and that value is equal to the actual additional fuel consumption the RS is responsible for (MF_{10} of Table D. 3 plus column $\sum_i DF_{i,10}$ of Table D. 4).

- The malfunction cost of the components which have no malfunction and which do not induce dysfunctions in other components is null.

- Some malfunction costs are negative [$MF_2^{*} = -73\ MJ$] and [$MF_3^{*} = -396\ MJ$]. This is because the dysfunctions induced by those components to the remainder components are negative. This means that they bring about less local production in the other components (compared to the reference condition), so that they generate a negative dysfunction which is accounted for in their own malfunction cost (see column $\sum_i DF_{i,2}$ and column $\sum_i DF_{i,3}$ in Table D. 4).

- V3 has a malfunction cost originated by the final product variation [$MF_{e,12}^{*} = -1487\ MJ$] which is almost neutralized by the induced malfunction cost [$MF_{12}^{*} = 1481\ MJ$]. This means that the component 12 is hardly affected by the anomaly.

ψ_{MF^*} (Eq.(D. 20)) and $\psi_{MF_e^*}$ (Eq.(D. 21)) indexes have been calculated for every component to assess the effect of the malfunction cost of each component regarding the fuel impact calculated in the diagnosis. As it can be checked, all of them sum 100 %.

- The component with the highest $\psi_{MF_i^*}$ index is RS [$\psi_{MF_{10}^*} = 89$ %]. This result implies that 89% extra fuel consumption is due to an anomaly allocated in the radiator system, which in turn causes an overconsumption in other components [5 % CB, 8 % M2, 14 % M3 and 49 % V3] and an under consumption in some others [-2 % HC, -13 % D1] due to induced effects. The under consumption refers to the saving caused by the negative cost of malfunctions, which is in turn due to the induced negative dysfunctions in the other components.

- Likewise, V3 has a 50 % fuel consumption saving, [$\psi_{MF_{e,12}^*} = -50\%$] merely because a fraction of the additional fuel consumption is used for the generation of less final products in free condition.

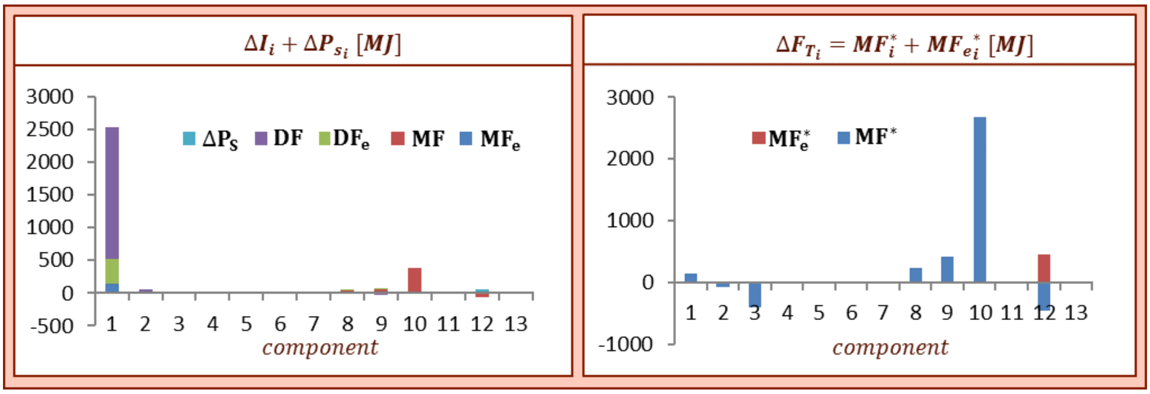

Figure D. 9 (a) Component MF and DF analysis (b) Component cost analysis

In Figure D. 9 (a) and (b) both Table D. 4 and Table D. 5 are graphically depicted. In this way, the behavior of each component is easily visualized. Figure D. 9 (a) represents every component malfunction, dysfunction and final product variation between free and reference condition. As noticed, CB detach from the other components because of its high induced dysfunction, therefore, CB is identified as the component that suffers more because of RS anomaly. Similarly, Figure D. 9 (b) pictures the fuel impact in terms of malfunction costs; obviously, RS has the greater responsibility in the total extra fuel consumption.

D.2.4.1.4.3. Economic Impact

To complement the fuel impact study, Table D. 6 reflects the economic cost related to the anomalies ($\Delta C_{F_T}^{anom}$) showing the exergoeconomic cost regarding malfunction ($\mathbf{C_{MF^*}}$) and the exergoeconomic cost owing to final product variation between free and reference conditions ($\mathbf{C_{MF_e^*}}$).The following comments are put forward:

Table D. 6 Diagnosis Economic Impact

		C_{MF^*}[€]	$C_{MF_e^*}$[€]
①	CB	8	-
②	HC	-4	-
③	D1	-22	-
④	V1	-	-
⑤	M1	-	-
⑥	HX	-	-
⑦	V2	-	-
⑧	M2	13	-
⑨	M3	23	-
⑩	RS	147	-
⑪	T	-	-
⑫	V3	81	-82
⑬	D2	-	-
		$\Delta C_{F_T}^{Anom}$ =164 €	

- As it could be expected, as RS is the component containing the anomaly, it is also the one with the largest exergoeconomic malfunction cost [$C_{MF_{11}} = 147$ €].
- Throughout the heating period of simulation, the estimated total overrun due to the presence of the anomaly is quantified in an amount of [$\Delta C_F = 164$ €]. That cost is the sum of every component economic contribution according to their ψ_{MF^*} index weight (i.e. 8 € due to induced malfunction cost in CB, -22 € in D1 or 23 € in M3).

D.2.4.1.5. Cost due to control system operation

By applying Eq.(D. 23) the cost of the real operating condition and its variation in relation to the free condition is calculated. The results are depicted in Table D. 7.

Table D. 7 Overall Economic Impact [€]

$\Delta C_{F_T}^{control}$	$\Delta C_{F_T}^{anom}$	ΔC_{F_T}
-64 €	164 €	**102 €**

Some comments about these results are in the following:

- An increase in cost exists when the control operation of the reference condition is applied in the real condition to obtain the free condition. Therefore the performance of the control system has a negative impact in the cost [-64€]. This is because in the real operating condition, the set points fixed by the control system restrict the range of values of some variables (i.e. the minimum return temperature of the boiler, the tank storage temperature, and so on) whereas in free condition those values are not limited. Consequently, the input required by the boiler is much lower (see E_2 and E_{20} values in Table D. 2).
- As a result, the total extra cost due to a 10 % energy performance degradation of the *radiator system* is equal to 102€.

D.2.4.2. Results Discussion

The thermoeconomic methodology set forth herein is very effective in the quantification of malfunction effects. Nevertheless, as pointed out by Lazzaretto [6], the contribution given by the terms MF_i are not the effects due to *intrinsic malfunctions* exclusively, since the variations of unit exergy consumption can be caused by induced perturbations as well. As the results show, not only the anomalous component (RS) has malfunction cost but also the most of the rest equipment (CB, HC, D1, M2, M3, V3, D2).

The component efficiencies are strongly dependent on the working condition; this means that an *intrinsic malfunction* is often accompanied by induced malfunctions and, as the components are closely interconnected through their productive structure, this results in a propagation of induced effects throughout the system. Therefore, the information given by the terms DF_{ij} represents only a part of the overall *induced effects*.

Then, the methodology used in this work is not effective in identifying the sources of anomalies, but only in identifying the component which provokes larger extra consumption through the higher $\psi_{MF_i^*}$ index (without knowing if that component contains the anomaly or not).

In fact, as some other induced effects can appear, the ψ_{MF^*} index of components with no intrinsic anomalies can have a value different to zero. However, two cases can happen: either a single element of the column ψ_{MF^*} can be the only one different from zero or several elements of the column ψ_{MF^*} can have comparable values. In the first case, the diagnosis problem is completely solved. A single (significant) anomaly is present in the plant, so all the fuel impact, calculated as the difference between the fuel consumption in free and reference conditions, is due to that anomaly. Its complete removal allows a technical energy saving equal to the fuel impact. In the second case, the problem cannot be solved, a priori, without using a mathematical model of the facility [21]. The reason is that the ψ_{MF^*} method uses an indicator referred to unit exergy consumption, masking the true dependence from the thermodynamic variables, temperature, pressure, mass flow and composition. A mathematical approach based on the true independent variables of the system is therefore required.

D.2.5. Fuel impact diagnosis limitations

Regarding and summarizing the above discussion, malfunctions can be obtained directly from MF and DF analysis only if: (1) the product of i component is a local independent variable and is the only degree of freedom of the component in reference conditions and (2) k_{ij} does not depend on that product [5]. As foreseeable, those conditions are unrealistic as the interdependencies among unit exergy consumption are often noticeable. Because of that, even the principle of superposition fails, inasmuch as the fuel impact in the operating condition is different from the summation of the single anomalies fuel impacts [27].

Therefore, ΔF_T fuel impact formula is not enough to prevent the effect of independent variables affecting incidentally in one or more components behaviour. Those effects are known as *induced malfunctions* and their knowledge becomes a crucial step for the diagnosis implementation [28]. Among them, different induced malfunctions are distinguished (each type is labelled and shortly explained in Figure D. 10): they can be due to (i) changes in ambient conditions, (ii) fuel quality variations, (iii) different plant production, (iv) control system intervention and (v) the internal thermodynamic interactions.

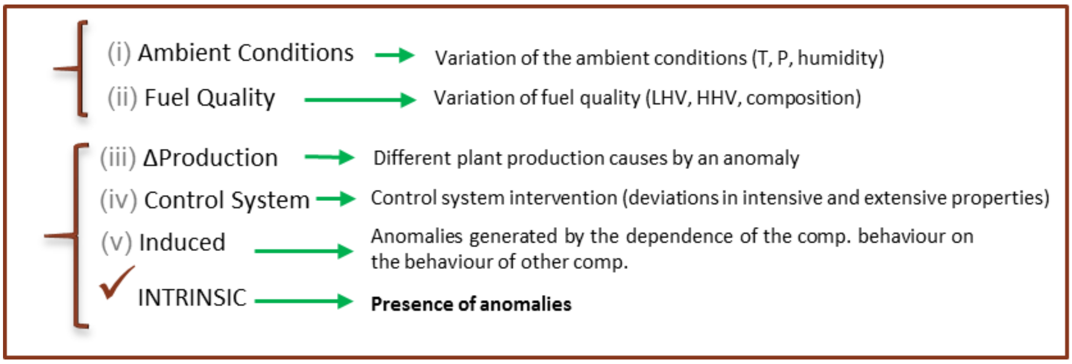

Figure D. 10 Malfunction Classification

Consequently, as the malfunction and dysfunction analysis does not discriminate between intrinsic and induced malfunctions, it cannot be considered a fully reliable approach. After all, if only exergetic variables define the system, the real thermodynamic parameters interactions (the relationships between temperatures, composition, mass flow rates, etc.) are hidden.

With the idea of overcoming such problem some methodologies were develop. For example, [27] develops a way to outweigh the internal effects that corresponds to their progressive filtration: as already mentioned, control actions were avoided with *free condition* and *efficiency curves* were used for filtrating the non-linarites. Even so, free condition is not required for the location of the cause of malfunction but only for the estimation of the total fuel impact caused by the intervention of the control system [2].

For the non-linarites arrangement, by comparison, anamnesis was performed: the analysis is repeated during the plant life and the results are compared. The discrimination between real anomalies and "disturbs" associated with the non-linear behaviour of components [29] can be done by the plant history analysis. In the [27] work, such model is based on neuronal network and requires of a sufficiently large number of reliable operating conditions. After such filtrations, the residual effects are directly associated with the intrinsic anomalies.

Another possibility for the induced effect differentiation is to consider the functional relationships among the thermodynamic variables by means of components *characteristic curves CC* [2]. As exergetic values do not allow having the required number of independent variables, those are calculated in a second step where the comparison utilizes the homogeneity of useful work [10]. The CC mathematical and graphical application is explained in [30]. One of the CC weaknesses arises when the reference component CC does not exist, so such behaviour needs to be simulated somehow. In addition, this approach is able to highlight malfunctioning components but does not provide the fuel impact originated by each one because the approach is individually done and the global perspective is lost (nevertheless, considering its potentiality, next section enforces this methodology).

Apart from the explained options, *reconciliation of malfunction variable approach RMV* [31] was also developed which is extended in [32] to reduce the complexity of the analysis. Beyond the thermoeconomic perspective, and owing to its limitations, other ways of thermodynamic diagnosis were evolved. Among others they are: fuzzy logic [33], quantitative causality analysis, linear regression, genetic algorithm methods [34], malfunction fingerprinting [35], etc. Comparison of some methods are in [36].

D.3. CHARACTERISTIC CURVE DIAGNOSIS METHODOLOGY

According to its capacity, this section is based on the characteristic curves [2] of the components.

The characteristic curves of a component i consist of a set of relationships expressing a thermodynamic quantity π_i that characterizes the component behavior as a function of some variables (ξ_i) involved in the component operation. The generic characteristic curve associated with the reference operating condition takes the form of Eq.(D. 30) and a specific working point (R) inside that curve is represented by Eq.(D. 31):

$$\pi_i^0 = f^0(\xi_i^0) \tag{D. 30}$$

$$\pi_i^{0,R} = f^0(\xi_i^{0,R}) \tag{D. 31}$$

The selected thermodynamic parameter representing the component (π_i) can be different depending on the chosen criteria. Toffolo and Lazzaretto [37] recommend component *irreversibility* because then the indicator takes a strictly positive value in case there is presence of anomalies. Nevertheless, in order to make a direct comparison with the previous fuel impact diagnosis method, the dependent thermodynamic quantity to express will be the component unit exergy consumption (k_i). The variables ξ_i chosen for these curves are the mass flow rates, temperatures and pressures, designated as operation independent variables x_i. Hence, the appearance of the generic characteristic curve used for reference condition and its specific working point (R) are:

$$k_i^0 = f^0\left(x_i^0\right) \tag{D. 32}$$

$$k_i^{0,R} = f^0\left(x_i^{0,R}\right) \tag{D. 33}$$

Let us now assume that because the induced effects are transferred downstream, the $x_i^{0,R}$ values change according to the physical constraints imposed by the component characteristic to $x_i^{0,A}$. Therefore, the component will be working in a new operating condition point (A) but, still, the point will belong to the reference condition characteristic curve (f^0):

$$k_i^{0,A} = f^0\left(x_i^{0,A}\right) \tag{D. 34}$$

Moreover, let us consider a new situation where the component contains an anomaly, which means the presence of an intrinsic malfunction. In this case again, the component will be in a different working point (B) with different independent variable values (x_i^B). But nonetheless, since the component i contains a fault, the characteristic curve connected to faulty condition (f) would be different from the reference one (f^0):

$$k_i^B = f\left(x_i^B\right) \tag{D. 35}$$

D.3.1. Characteristic Curves

This study needs to be individually implemented in each component. As said above, the generic component i would have two values for its unit exergy consumption, one associated with the reference condition (k_i^0), and the other one with the faulty operating condition (k_i).

According to what was previously explained, even if the component does not contain any anomaly, the independent thermal variables in reference condition ($x_i^{0,R}$) would be different from those on faulty operating condition (x_i^B) due to induced effects. If the component i contains a fault, the characteristic curve connected to faulty condition (f) would be different from reference curve (f^0). In that case, a new unit exergy consumption value can be calculated; this is mathematically obtained by inserting the values of the independent variables of faulty operating conditions in the reference characteristic curve.

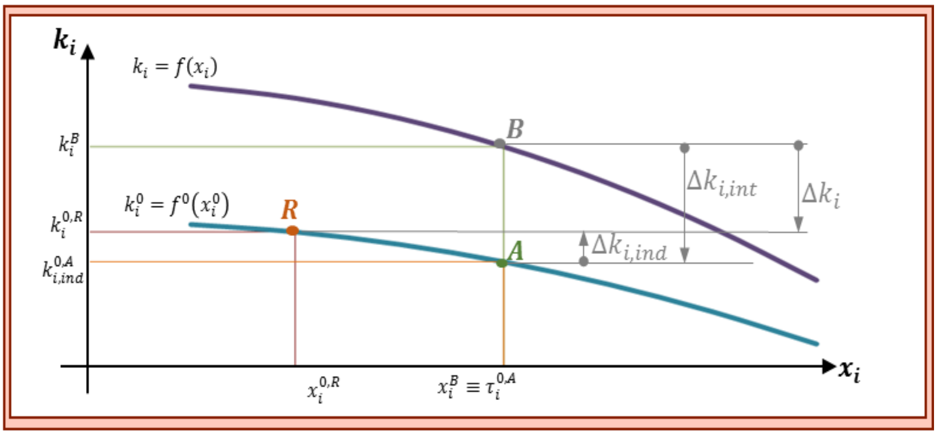

Figure D. 11 Unit exergy consumption in reference and operating

$$k_{i,ind}^{0} = f^{0}\left(x_i^{o,A}\right) \quad \text{(D. 36)}$$

Figure D. 11 depicts the three cases.

As a result, the increase of the unit exergy consumption (Δk_i) can be divided into induced and intrinsic unit exergy consumption variation ($\Delta k_{i,ind}$, $\Delta k_{i,int}$) as follows:

$$\Delta k_{i,ind} = k_{i,}^{0}\left(x_i^{A}\right) - k_i^{0}\left(x_i^{R}\right) \quad \text{(D. 37)}$$

$$\Delta k_{i,int} = k_i\left(x_i^{B}\right) - k_i^{0}\left(x_i^{A}\right) \quad \text{(D. 38)}$$

Consequently, the malfunction of each component can be expressed as the sum of intrinsic and induced malfunctions:

$$MF_i = MF_{i,int} + MF_{i,ind} = \Delta k_{i,int} \cdot P_i^{0} + \Delta k_{i,ind} \cdot P_i^{0} \quad \text{(D. 39)}$$

This formulation allows calculating individually the effects that anomalies produce in every component depending on the thermodynamic independent variables.

A generic procedure is therefore established to locate the origin of system intrinsic and induced malfunctions from the analysis of the faulty operating conditions, where the only possible source of uncertainty is the inaccuracy in the reconstruction of component characteristic curves, due to the required amount of data.

D.4. REVISION OF BOTH METHODOLOGIES

Both techniques of thermoeconomic diagnosis give different essential information:

- Malfunction and dysfunction diagnosis procedure uses the Fuel-Product productive structure in order to relate each component inputs and outputs to the rest of the subsystems. It does not differentiate between intrinsic and induced malfunction but, the dysfunctions provoked by j belonging to a malfunction in i can be estimated as well as those generated due to the final production variations. Likewise, the way that the whole plant efficiency changes when the efficiency of any component varies is easily calculated. Moreover, as the productive structure is also used for cost accounting, either the *exergetic cost* or the *economic cost* of every flow and of the overall system can be assessed too [19], in addition to the *cost impact* generated by the anomalies [15].
- Characteristic curves change the perspective and refer to the components individually. This method enables distinguishing between the induced and intrinsic malfunctions in every component by considering the actual links among the thermodynamic independent variables (pressure, temperature mass flows and composition) and the exergy unitary consumptions.

D.4.1. Combination of both methodologies

Supposing that *more than one* intrinsic malfunction has taken place in the system, the MF and DF diagnosis is not able to furnish any information about the incidence of each one on the total fuel impact, since the irreversibility variation causes a different fuel impact depending on the position of the component where the fault has occurred.

When various anomalies appear in the system, each anomaly would induce effects in the component j with the anomaly itself, varying its $\Delta k_{j,int}$ (intrinsic malfunction) and in the rest of components i varying both the unit exergy consumption $\Delta k_{i,ind}$ (induced malfunctions) and the local production ΔP_i (dysfunctions). The objective is to distinguish between the $\Delta k_{i,ind}$ and ΔP_i produced by each anomaly so the extra consumption can be attributed to the malfunctioning component j which has generated them. Thanks to the MF and DF diagnosis, this last extra consumption provoked by j related to the ΔP_i variation is accounted for through DF_{ij}, but further information is needed for accounting the remaining induced malfunction effects.

Consequently, if the information acquired by this diagnosis is complemented with the characteristic curves analysis, the subsystem with higher intrinsic malfunction can be recognized and identified as the faultiest component. However, even now, the extra consumption caused by $\Delta k_{i,ind}$ cannot be attributed to any component, nor can the one belonging to the final production variation ΔP_s, because this analysis is individually performed and the induced effects could have been caused by more than one component.

Notwithstanding those barriers, thanks to characteristic curves analysis, the component identified as the faultiest one (let us say j component) can be virtually erased and a second diagnosis study can be executed. In this way, the decrease of the fuel impact accounted from the first study ($\Delta \mathrm{F}_T^{1^{st}}$) to the next one ($\Delta \mathrm{F}_T^{2^{nd}}$) would express the savings gained when the anomaly in j is repaired:

$$\Delta F_{save} = \Delta \mathrm{F}_T^{1^{st}} - \Delta \mathrm{F}_T^{2^{nd}} \tag{D. 40}$$

In the same way, that ΔF_{save} would correspond to the sum of the intrinsic malfunctions in j $\left(MF_{j,int}^{1^{st}}\right)$ and its induced effects calculated in the first study $\left(\sum_i DF_{ij}^{1^{st}} + \sum_i MF_{ij,ind}^{1^{st}}\right)$ plus the final production variation $\left(\Delta\Delta P_s^{1^{st},2^{\mathrm{nd}}}\right)$ and the dysfunction it generates between both situations $\left(\Delta DF_e^{1^{st},2^{\mathrm{nd}}}\right)$:

$$\Delta F_{save} = \left[MF_{j,int}^{1^{st}} + \sum_i DF_{ij}^{1^{st}} + \sum_i MF_{ij,ind}^{1^{st}}\right] + \left[\left(DF_e^{1^{st}} - DF_e^{2^{nd}}\right) + \left(\Delta P_s^{1^{st}} - \Delta P_s^{2^{nd}}\right)\right] \tag{D. 41}$$

As $MF_{j,int}^{1^{st}}$, $\sum_i DF_{ij}^{1^{st}}$ and $DF_e^{1^{st},2^{nd}}$, $\Delta P_s^{1^{st},2^{nd}}$ are calculated through one of the above methodologies, $\sum_i MF_{ij,ind}^{1^{st}}$ can be easily obtained with a simple subtraction.

If this is repeated as many times, or steps, as intrinsic malfunctions exist, the diagnosis is solved. Figure D. 12 outlines the methodology routine.

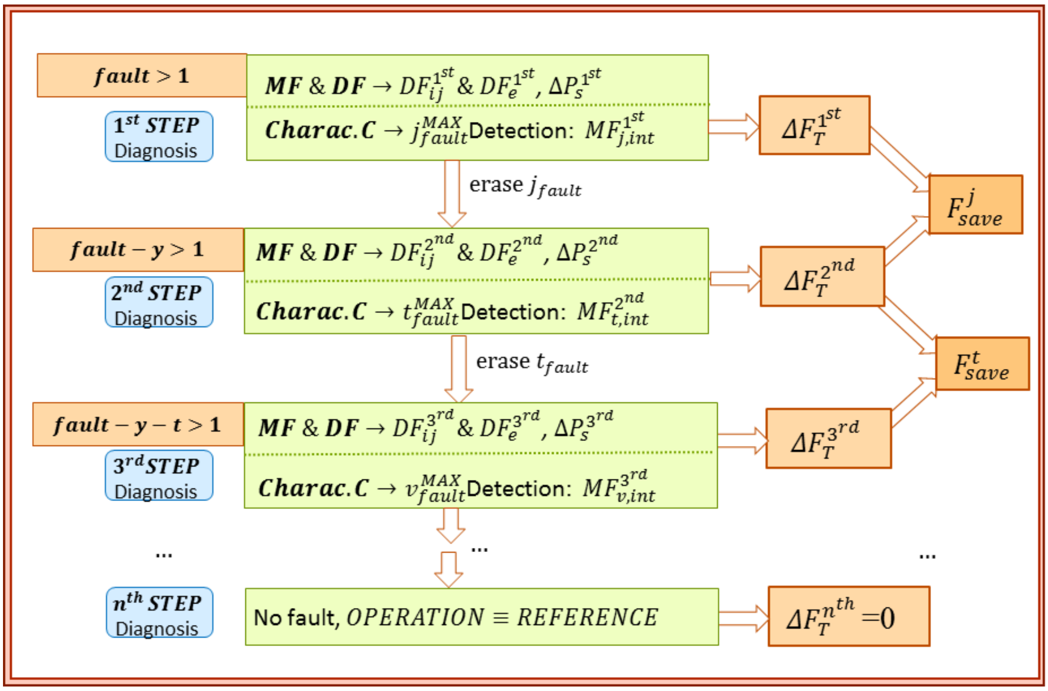

Figure D. 12 Diagnosis methodology through the combination of MF&DF study and characteristic curves

D.4.2. Case Study

The combined methodology presented above (fuel impact formula and characteristic curves implementation) will be applied in the previous (iv) *Heating & DHW System Case Study* in order to enhance the uncompleted diagnosis research. In this case, however, instead of a unique failure two anomalies are integrated.

Nevertheless, before presenting the case study, it should be remembered that research on building thermal facilities implies *dynamic approaches* according to the changing behavior of the variables such as climate, user demand and so on, which directly interferes in the start-up and shutdowns of the elements integrated in the installation. Therefore, as diagnosis involves the *comparison* between two variable conditions, it should be dynamically implemented.

D.4.2.1. (vi) Heating & DHW System Case Study

The reference generic facility coincides with the previous (vi) case study (Figure D. 4) where a full explanation of all components is found.

As known, the first and sensitive step for the analysis is defining the productive structure for each time-step following the pattern given in **Section C**.3.1. As previously remarked, the system dynamic behavior interferes in the modulation of components, so that the productive structure varies depending on the components which are turned on in that precise moment. Figure D. 13 (analogous to Figure C.16) illustrates two of the possible cases: case t_1 depicts the situation where only DHW demand is requested while case t_2 shows the situation where only heating demand is claimed. Noticeably, both cases are associated with two different productive structures.

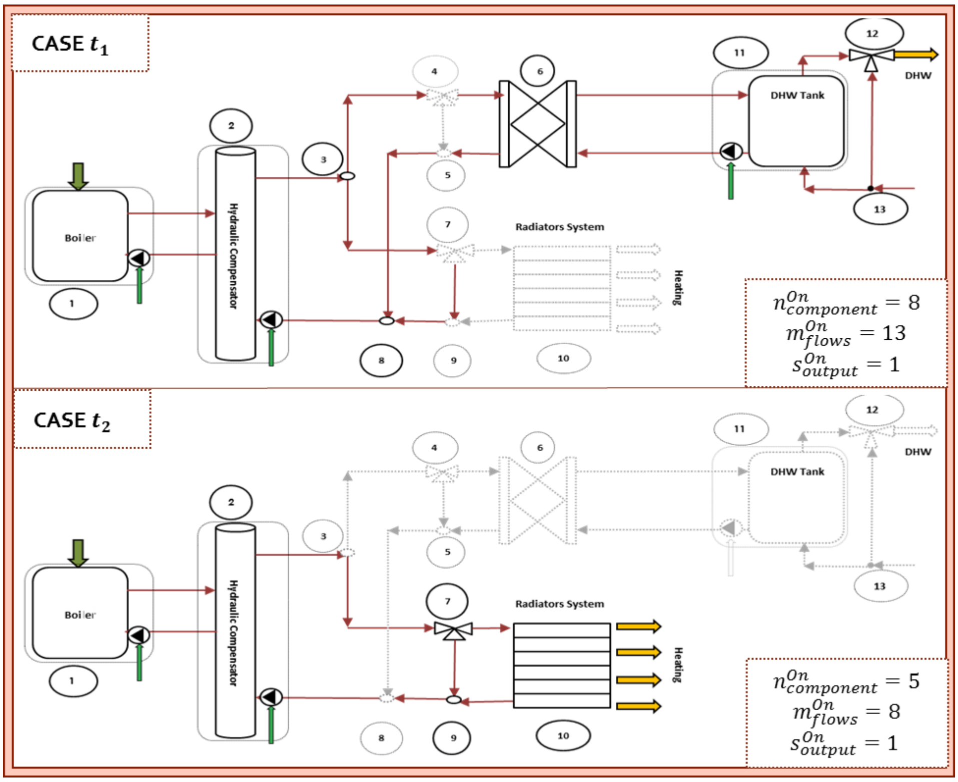

Figure D. 13 Different operation situations related to different productive structures

As done in the **Section C**.3.2.1.2., an overall "static" thermoeconomic model is built to contemplate all the possible dynamic conditions. Table D. 8 specifies F, P and k for every component according to the naming of Figure D. 5.

Table D. 8 Generic productive structure for "static" overall thermoeconomic model

COMPONENT		F	P	k
①	CB	$\dot{E}_{20}$	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_{20}/(\dot{E}_1 - \dot{E}_2)$
②	HC	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_3 - \dot{E}_4$	$(\dot{E}_1 - \dot{E}_2)/(\dot{E}_3 - \dot{E}_4)$
③	D1	$\dot{E}_3$	$\dot{E}_5 + \dot{E}_6$	$\dot{E}_3/(\dot{E}_5 + \dot{E}_6)$
④	V1	$\dot{E}_5$	$\dot{E}_7 + \dot{E}_8$	$\dot{E}_5/(\dot{E}_7 + \dot{E}_8)$
⑤	M1	$\dot{E}_7 + \dot{E}_9$	$\dot{E}_{10}$	$(\dot{E}_7 + \dot{E}_9)/\dot{E}_{10}$
⑥	HX	$\dot{E}_8 - \dot{E}_9$	$\dot{E}_{15} - \dot{E}_{16}$	$(\dot{E}_8 - \dot{E}_9)/(\dot{E}_{15} - \dot{E}_{16})$
⑦	V2	$\dot{E}_6$	$\dot{E}_{12} + \dot{E}_{13}$	$\dot{E}_6/(\dot{E}_{12} + \dot{E}_{13})$
⑧	M2	$\dot{E}_{10} + \dot{E}_{11}$	$\dot{E}_8$	$(\dot{E}_{10} + \dot{E}_{11})/\dot{E}_8$
⑨	M3	$\dot{E}_{12} + \dot{E}_{14}$	$\dot{E}_{11}$	$(\dot{E}_{12} + \dot{E}_{14})/\dot{E}_8$
⑩	RS	$\dot{E}_{13} - \dot{E}_{14}$	$\dot{E}_{19}$	$(\dot{E}_{13} - \dot{E}_{14})/\dot{E}_{19}$
⑪	T	$(\dot{E}_{15} - \dot{E}_{16}) + \Delta\dot{E}_{21}$	$\dot{E}_{18} - \dot{E}_{17}$	$[(\dot{E}_{15} - \dot{E}_{16}) + \Delta\dot{E}_{21}]/(\dot{E}_{18} - \dot{E}_{17})$
⑫	V3	$\dot{E}_{18} + \dot{E}_{24}$	$\dot{E}_{23}$	$(\dot{E}_{18} + \dot{E}_{24})/\dot{E}_{23}$
⑬	D2	$\dot{E}_{22}$	$\dot{E}_{17} + \dot{E}_{24}$	$\dot{E}_{22}/(\dot{E}_{17} + \dot{E}_{24})$

D.4.2.1.1. Characteristic Curves Diagnosis

As previously pointed out, building facilities are strictly linked to dynamic fluctuations. At every time-step the thermodynamic operation variables ($\bar{x}$) change so the unit exergy consumption $k_i(\bar{x},t)$[5] of every component also varies. This means that, in the same way as for the diagnosis method, the CC study should be repeated for each component individually for every time-step during the whole heating season.

As there are 13 components, at least 13 characteristic curves must be defined. The main goal is to define a curve which recreates the same component behavior based on the Trnsys v17 algorithm; the methodology is similar to the thermal model developed in **Section B**.3.1., but in this case, a step forward is done and k_i dependent variable is the objective variable. For that purpose, the Trnsys component mathematical reference guidebook together with its Fortran programming have been analyzed. In such way, the independent variables $\bar{x}$ and physical specific characteristics of every component were considered. As an example, the heat exchanger characteristic curve is here calculated:

One needs to bear in mind the definition of its unit exergy consumption written in Table D. 8:

$$k_6 = \frac{\dot{E}_8 - \dot{E}_9}{\dot{E}_{15} - \dot{E}_{16}} \quad \text{(D. 42)}$$

The formula for the generic physical i water exergy flow is expressed as follows:

$$\dot{E}_i = c_P \cdot \dot{m} \cdot T_i - T_0 - T_0 \cdot ln\left(\frac{T_i}{T_0}\right) \quad \text{(D. 43)}$$

were c_p is the fluid specific heat, $\dot{m}$ is the mass flow rate and T_0 refers to the ambient temperature.

The independent variables $\bar{x}_6$ and physical characteristics chosen for the heat exchanger are: the primary and secondary inlet temperatures (T_8, T_{16}) (which are likewise outputs of V1 and T),

[5] All the k_i, along this work, should be regarded as dependent aggregated variables $k_i(\bar{x},t)$ Because of space reasons k_i is used instead of $k_i(\bar{x},t)$.

the mass flow rates ($\dot{m}_{prim}, \dot{m}_{sec}$), the ambient temperature (T_0) and the overall heat transfer coefficient UA. So that (T_9, T_{15}) output temperatures depend on those variables.

In order to calculate them, the Trnsys heat exchanger algorithm relies on the effectiveness approach: the model starts determining whether the primary or the secondary side is the minimum capacitance side:

$$C_{prim} = c_P \cdot \dot{m}_{prim} \tag{D. 44}$$

$$C_{sec} = c_P \cdot \dot{m}_{sec} \tag{D. 45}$$

$$C_{max} = \max(C_{prim}, C_{sec}) \tag{D. 46}$$

$$C_{min} = \min(C_{prim}, C_{sec}) \tag{D. 47}$$

After that, it calculates the effectiveness based upon the specified flow configuration and on UA:

$$\varepsilon = \frac{1 - e^{\left(-\frac{UA}{C_{min}}\cdot\left(1-\frac{C_{min}}{C_{max}}\right)\right)}}{1 - \frac{C_{min}}{C_{max}} \cdot e^{\left(-\frac{UA}{C_{min}}\cdot\left(1-\frac{C_{min}}{C_{max}}\right)\right)}} \tag{D. 48}$$

Following this trajectory, the heat exchanger outlet temperatures are computed, which would be at the same time the input parameters of M1 and T.

$$T_9 = T_8 - \varepsilon \cdot \left(\frac{C_{min}}{C_{prim}}\right) \cdot (T_8 - T_{16}) \tag{D. 49}$$

$$T_{15} = T_{16} + \varepsilon \cdot \left(\frac{C_{min}}{C_{sec}}\right) \cdot (T_8 - T_{16}) \tag{D. 50}$$

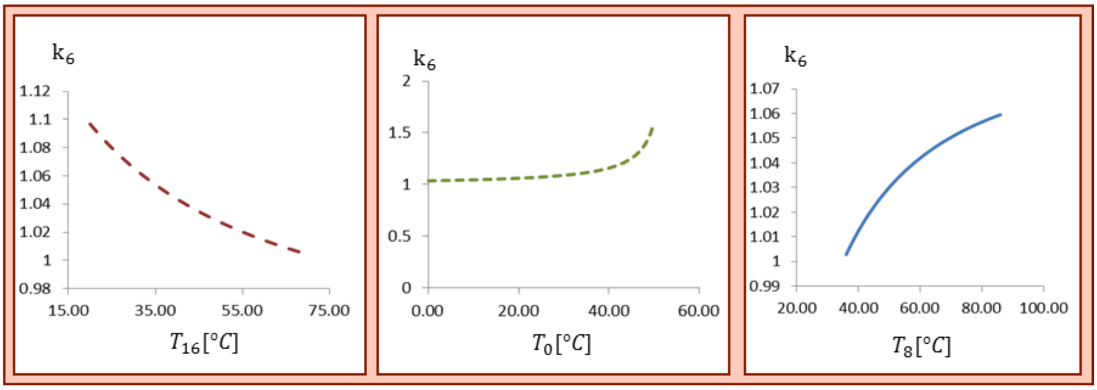

Figure D. 14 Behavior of heat exchanger exergetic consumption according to a changeable independent variable

In this way k_6 can be calculated and plotted. Figure D. 14 depicts the behavior of k_6 when one of the independent variables changes its value while the others remain constant (the chosen values for the graphic representation are $UA = 133888\frac{kJ}{h \cdot K}$, $\dot{m}_{prim} = 1920\frac{kg}{h}$, $\dot{m}_{sec} = 1860\frac{kg}{h}$, $T_{16} = 35°C$, $T_0 = 15°C$, $T_8 = 75°C$).

D.4.2.2. Numerical Example

The DHW and space heating energy demand are the same as the previous example.

D.4.2.2.1. Multi-Faults

As said, two faults are deliberately incorporated on the *radiator system* (RS) and *heat exchanger* (HX) by degrading some of their physical characteristics. An anomaly is set through a 10 % reduction in the RS *energy performance*; and in HX the *overall heat transfer coefficient* is diminished 35 %.

Figure D. 15 depicts the reference and faulty operation characteristic curves of those components when one of their independent variables changes its value while the rest remain constant.

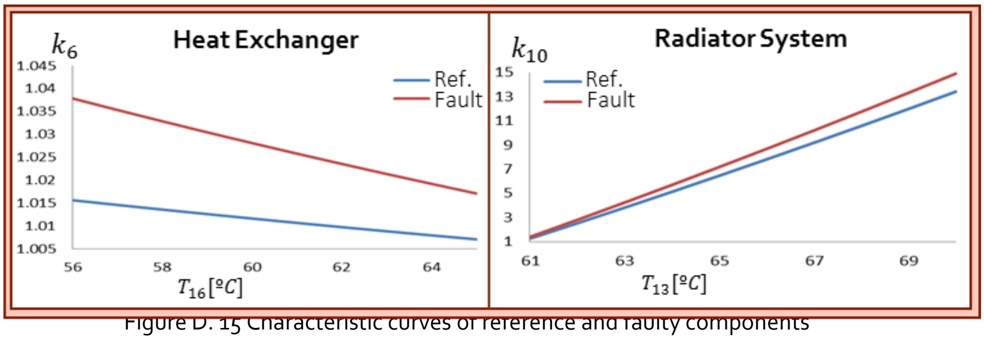

Figure D. 15 Characteristic curves of reference and faulty components

According to **Section D**.2.4.1.2., free condition was obtained together with the reference one; so, diagnosis was performed comparing those dynamic situations. Even if the study was hourly done, Table D. 9 contains the accumulated exergy of every flow at the end of the simulation period for reference and free operating conditions.

Table D. 9 Accumulated exergy values for reference and free condition $[GJ_{ex}]$

[GJ]	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}
REF.	122.9	100.1	372.3	351.8	192.0	180.3	153.3	38.9	29.8	182.9	169.2
FREE	122.9	99.2	369.8	348.4	190.7	179.1	151.9	38.8	29.8	181.7	166.7

E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}	E_{19}	E_{20}	ΔE_{21}	E_{22}	E_{23}	E_{24}
57.6	122.7	111.6	37.2	28.3	0.2	6.5	2.3	149.1	0.04	0.2	5.8	0.03
57.7	121.4	109.2	36.2	27.5	0.2	6.4	2.3	155.3	0.05	0.2	5.6	0.03

D.4.2.2.2. Thermoeconomic Diagnosis

At first, an hourly MF and DF diagnosis with two faults was carried out and the values obtained were accumulated later on, see Table D. 10. The first column identifies each component with its corresponding number. The second column contains the malfunction (MF_i) of every component. The expanded dysfunction matrix comes next where the dysfunction according to the exergy consumption variation associated with the external resources ($DF_{e,i}$) and the other components (DF_{ij}) are reflected; the last column corresponds to the final product variation.

Table D. 10 MF and DF tables extracted from diagnosis accumulation [$\boldsymbol{MJ}$]

MF & DF 1st DIAGNOSIS																
	$MF^{1^{st}}$	$DF_e^{1^{st}}$	$[DF^{1^{st}}]$													$\Delta P_s^{1^{st}}$
①	-1214	-1396	-	557	-24	-	-	1255	-	-486	-	6617	-34	-21	-	-
②	-450	-9	-	-	-80	-	-	-48	-	52	-	480	104	-	-	-
③	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
④	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑤	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑥	206	-12	-	-	-	-	-	-	-	-	-	-	-10	-	-	-
⑦	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑧	-136	-14	-	-	87	-	-	32	-	-23	-	-15	-25	-	-	-
⑨	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑩	1093	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑪	-40	-6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑫	-1	-15	-	-	-	-	-	-	-	-	-	-	-	-	-	-129
⑬	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		⓪	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	

- As was predicted, the components with higher malfunctions are those containing the anomalies (components HX, and RS; $MF_6^{1^{st}} = 206\ MJ$ and $MF_{10}^{1^{st}} = 1093\ MJ$ repectively). However, these values are related to both intrinsic and induced malfunctions so *no immediate conclusions* can be extracted.

- This is also the reason why the other components exhibit non null values for the malfunctions ($MF_1^{1^{st}} = -1214\ MJ$; $MF_2^{1^{st}} = -450\ MJ$; $MF_8^{1^{st}} = -136\ MJ$; $MF_{11}^{1^{st}} = -40\ MJ$ and $MF_{12}^{1^{st}} = -1\ MJ$) due to the propagation of induced effects throughout the system which generates a $\Delta k_i < 0$.

- As justified in **Section D**.2.4.1.3, since the free condition is imposed, the faults produce less final product variation, $\Delta P_s^{1^{st}} < 0$. This fact influences each component's performance inducing a negative dysfunction $\sum_i DF_{i,e}^{1^{st}} = -1452\ MJ$.

- Mostly all malfunctions generate a local output variation; therefore, a dysfunction is created. The $DF_{i,j}^{1^{st}}$ matrix element exhibits the dysfunction part of i caused by a malfunction in j. The effects are commonly suffered by the components located upstream of the anomalies. Consequently, CB is the one undergoing the highest dysfunctions (sum of the first line): $DF_1^{1^{st}} = DF_{1,2}^{1^{st}} + DF_{1,3}^{1^{st}} + DF_{1,6}^{1^{st}} + DF_{1,10}^{1^{st}} + DF_{1,11}^{1^{st}} + DF_{1,12}^{1^{st}} = 7864\ MJ$.

- Conversely, RS is the component inducing the greatest dysfunction (sum of the 10th column): $DF_{1,10}^{1^{st}} + DF_{2,10}^{1^{st}} + DF_{6,10}^{1^{st}} + DF_{8,10}^{1^{st}} = 7082\ MJ$.

- The dysfunctions generated by HX $\left(\sum_i DF_{i,6}^{1^{st}} = 1239\ MJ\right)$ are also noticeable, but do not cause as much impact because they are located ahead in the supply chain.

- The existence of $\Delta P_{S_{DHW}}^{1^{st}} < 0$ is reflected in the last column.
- The sum of all components reflects the fuel impact related to the first diagnosis with three anomalies: $\Delta F_T^{1^{st}} = 6296\ MJ$.

D.4.2.2.3. Characteristic curves Diagnosis

Alternative analysis was done considering the characteristic curves diagnosis methodology and applying it hourly in every component. Subsequently, the values achieved in the first analysis step are accumulated and depicted in Table D. 11. The column $\mathrm{MF}_{\mathrm{int}}^{1^{st}}$ contains the intrinsic malfunctions derived from anomalies; the column $\mathrm{MF}_{\mathrm{ind}}^{1^{st}}$, alternatively, displays the induced malfunction due to the non-flat efficiency curves. The sum of both columns indicates the total malfunction for each component. The last column remarks the dysfunction values.

Table D. 11 MF and DF first analysis step through characteristic curves

		CHARACTERISTIC CURVES		
		$\mathrm{MF}_{\mathrm{int}}^{1^{st}}$	$\mathrm{MF}_{\mathrm{ind}}^{1^{st}}$	$\mathrm{DF}^{1^{st}}$
①	CB	-	-1214	6467
②	HC	-	-450	500
③	D1	-	-	-
④	V1	-	-	-
⑤	M1	-	-	-
⑥	HX	323	-117	-22
⑦	V2	-	-	-
⑧	M2	-	-136	42
⑨	M3	-	-	-
⑩	RS	1212	-119	-
⑪	T	-	-40	-6
⑫	V3	-	-1	-15
⑬	D2	-	-	-

- This procedure allows dividing and quantifying the induced malfunctions from the intrinsic ones. Henceforth, the results show clearly that the components with intrinsic malfunctions are $\left(MF_{6,int}^{1^{st}} = 323\ MJ\right)$ and $\left(MF_{10,int}^{1^{st}} = 1212\ MJ\right)$; therefore the components are HX and RS respectively.
- Nevertheless, this methodology does not permit one to identify the source of every component dysfunction, but only to calculate the total dysfunction $DF_i^{1^{st}}$ value.

D.4.2.3. Combination of both methods

As more than one intrinsic malfunction has taken place in the system, the subsystem with higher intrinsic malfunction can be recognized and identified as the faultiest component, in this case the RS. After erasing that anomaly, that is, restoring its reference characteristic curve, another simulation has been conducted in order to quantify the decrease of fuel impact accounted from the first study to the second one. In order to save space, the MF results of characteristic curves of the second analysis step are shown in Table D. 12, together with the $\mathbf{DF}$, $\mathbf{DF_e}$ and the final product vector taken from the other diagnosis analysis.

Table D. 12 MF, DF and ΔPs analysis in the second analysis step

		CHARACTERISTIC CURVES		MF & DF DIAGNOSIS		
		$MF_{int}^{2^{nd}}$	$MF_{ind}^{2^{nd}}$	$DF_e^{2^{nd}}$	$DF^{2^{nd}}$	$\Delta P_s^{2^{nd}}$
①	CB	-	-2048	-754	2197	-
②	HC	-	-143	1	82	-
③	D1	-	-	-	-	-
④	V1	-	-	-	-	-
⑤	M1	-	-	-	-	-
⑥	HX	317	-118	-6	-9	-
⑦	V2	-	-	-	-	-
⑧	M2	-	-45	-11	59	-
⑨	M3	-	-	-	-	-
⑩	RS	-	18	-	-	-
⑪	T	-	-33	-12	-	-
⑫	V3	-	-1	-10	-	-76
⑬	D2	-	-	-	-	-

- In this 2nd case, as the anomaly in RS is corrected, only HX has intrinsic malfunctions, where $\left(MF_{6,int}^{2^{nd}} = 317\ MJ\right)$ outstands among all. Its value is slightly different to the one in the first study, owing to the reparation of the faultiest component that varies the faulty thermodynamic operation conditions.
- $DF_{i,e}^{2^{nd}}$ is again very remarkable. Indeed, as the fault is on the HX, the DHW final production is still lower than in the reference condition and that has an influence on the consumption reduction $\left(\sum_i DF_{i,e}^{2^{nd}} = -792\ MJ\right)$.
- In this case, as fewer anomalies are taken into account, $\Delta P_{s_{DHW}}^{2^{nd}}$ is closer to zero.
- The fuel impact related to the second diagnosis with one anomaly is: $\Delta F_T^{2^{nd}} = -590\ MJ$.

Therefore, it is in accordance with Eq.(D. 40): $\Delta F_{save} = 6886\ MJ$. So that the induced malfunction generated by the anomaly in RS is equal to: $\sum_{10} MF_{10j,ind}^{1^{st}} = -695\ MJ$.

General results are summarized in Table D. 13 where each column corresponds to one of the anomalies deliberately inserted in the study and the rows $\mathrm{MF_{int}}$, $\sum \mathrm{MF_{ind}}$ and $\sum \mathrm{DF}$ correspond to the intrinsic, induced malfunctions and dysfunctions the faulty components have in every study; the row $\mathrm{DF}_e+\Delta \mathrm{P_s}$ indicates the effect the anomaly produces in the final production variation and its consequences. Finally, the $\Delta \mathrm{F_{anomaly}}$ outlines the fuel impact of each anomaly.

In this way the weight of fuel impact on each anomalous component can be attributed:

- The fault in RS generates an extra consumption of 6886 MJ where 7599 MJ are due to the fault itself and the remaining $-714\ MJ$ are owed to the final production decrease.

Table D. 13 Diagnosis general results [MJ]

	$RS'anomaly$	$HX'anomaly$
MF_{int}	1212	317
$\sum MF_{ind}$	-695	-1270
$\sum DF$	7082	1230
$DF_e + \Delta P_s$	-714	-867
$\Delta F_{anomaly}$	6886	-590

- The fault in HX generates an extra consumption of $-590\ MJ$ where $277\ MJ$ are due to the fault itself and the remaining $-867\ MJ$ are owed to the final production decrease.

D.4.2.4. Results Discussion

New diagnosis methodology was proposed for the anomalies location by the combination of two techniques. In fact, it is not possible to signal the component where the intrinsic anomaly is present without a mathematical approach that separates it between intrinsic and induced effects. On the one hand, *characteristic curves* diagnosis allows one to account for each component's *intrinsic* and *induced* malfunction on an individual basis. While, on the other hand, conventional *fuel impact* diagnosis is achieved through the whole system productive structure.

The key finding is that neither of the methodologies is better than the other but they are complementary for a proper diagnosis. By means of the malfunction and dysfunction method, the fuel impact due to each malfunction can be accounted for and the one owing to the final production variation can be identified. Nonetheless, the method does not allow distinguishing between intrinsic and induced effects. On the contrary, the individual characteristic curves methodology allows us to differentiate them. By combining both theories, the fuel impact associated with each anomaly can be calculated through a reiterative diagnosis study.

Hence, the methodology allows studying components in a local way and learning how they affect globally. Thus, not only the efficiency degradation of the abnormal components are detected but also the extra fuel charge generated by each fault is accounted.

This theory is applied in a DHW and heating facility with two faults where RS is identified as the faultiest component. It provokes an overall extra consumption of $6886\ MJ$ during the heating period because of the incited effects on the others ($6387\ MJ$), the effects prompted in the component itself ($1212\ MJ$) and that are generated by changing the final production ($-714\ MJ$).

D.5. DIRECT PROBLEM RESOLUTION

Up to this moment, the *inverse problem* of diagnosis has been entirely solved, i.e., under the *knowledge* of specific anomalies in different components, the procedure quantifies the effects of those anomalies in terms of fuel impact and malfunctions. A new methodology was set up to separate the induced and intrinsic effects. After all, when a fault (an intrinsic malfunction) occurs in a system, the characteristic curves representing the anomalous components are altered and the non-faulty components suffer changes in their operation mode because of the system strong thermodynamic interdependences. The aim, therefore, is to distinguish among intrinsic and induced effects, so that the key point is based on the proper thermodynamic model of the system.

Despite this engaging diagnosis methodology, the application was virtually done within the current knowledge of the fault location and by means of simulation. Besides, the way of developing characteristic curves may be, in some cases, cumbersome and tedious being a source of uncertainty.

Considering those facts, an innovative way of filtering all induced effects by is developed in order to create an unambiguous and systematic *direct* diagnosis methodology. Such methodology was applied in a real facility; so, problems related to the real application (for example, free condition obtainment) were overcome.

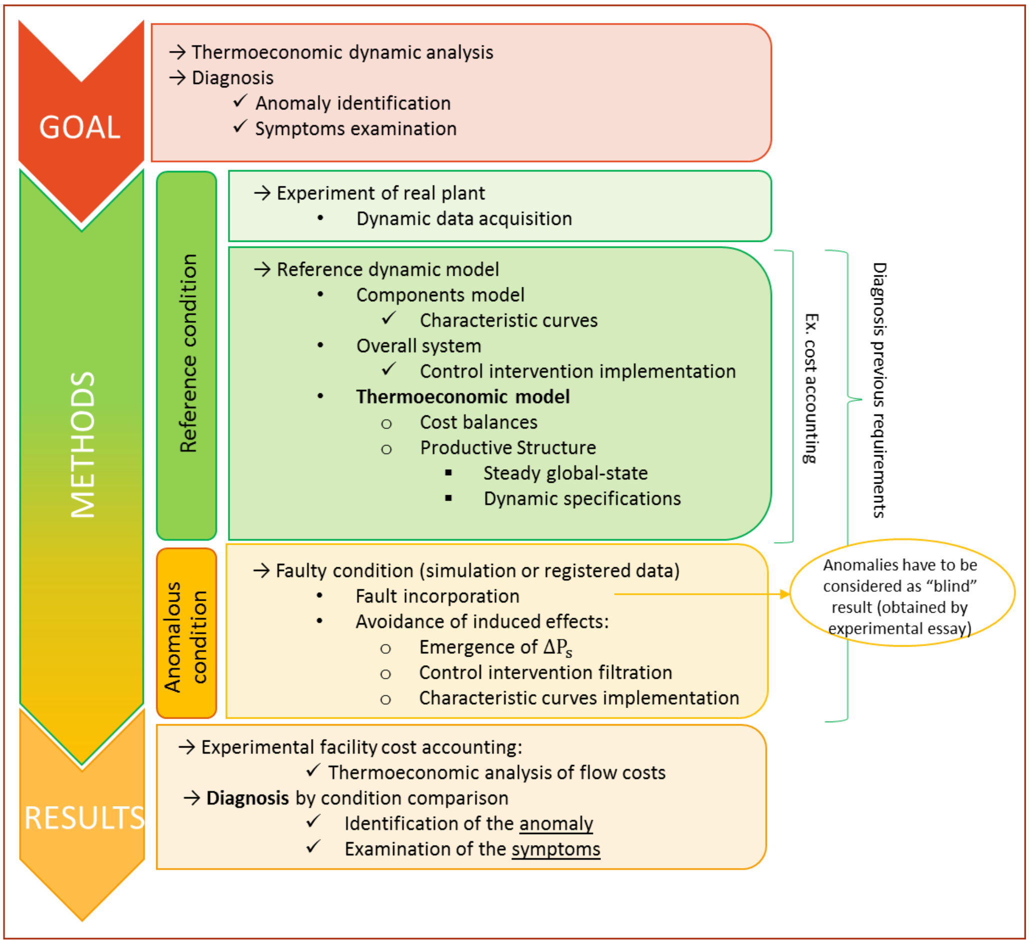

Figure D. 16 Work flow chart

Figure D. 16 shows the work flow chart to be followed for the diagnosis application: to begin with, as a real plant is studied, the first step is to acquire the data for creating the reference dynamic thermal model (**Chapter B**). Thermoeconomic model needs to be afterwards defined for accomplishing the dynamic cost accounting (**Chapter C**). The subsequent step is related to the faults detection through a new simulation technique used to detect malfunctions in a straightforward manner.

Such method will be developed going through a practical case study.

D.5.1. Case Study

The selected example is the one of **Chapter C** (v) *Solar Energy Building System Case Study*. Hitherto, the first two steps (reference thermal model and thermoeconomic model) are already completed in **Section C**.3.2.1.

As said, the main idea is to serve as a guide for diagnosis direct problem implementation in real buildings HVAC&R systems.

D.5.1.1. (v) Solar Energy Building System Case Study

The facility coincides with the example (v) whose components are listed in Table D. 14. As indicated, the reference condition is already modelled by means of Trnsys simulation software and Matlab according to the real registered data.

Table D. 14 List of components of the system

		Components
①	B	Boiler
②	D1	B Diverter
③	V1	B Mixer
④	HC	Hydraulic Compensator
⑤	V2	Distribution V3V
⑥	V3	HX Mixer
⑦	D3	HX Diverter
⑧	V4	H Mixer
⑨	D4	H Diverter
⑩	HX	Heat Exchanger
⑪	H	Heating System
⑫	T1	DHW Tank
⑬	T2	Solar Tank
⑭	V5	SC Mixer
⑮	D5	SC Diverter
⑯	SC	Solar Collector

Using such thermal model, two faults were incorporated in different components by changing their physical parameters: one was accomplished in the *hydraulic compensator* by increasing 4 times its loss coefficient (kJ/hm^{2}K) and the other one in the *solar storage tank* by augmenting it in 1.5.

The earlier mentioned (i) and (ii) induced malfunctions in **Section D**.2.5 were avoided by considering identical dynamic ambient conditions and the same fuel quality of the reference essay in the faulty condition. Total plant production (iii), however, was not possible to null since, although heating demand [kWh] remains the same $\Delta P_S^{heat} = 0$, DHW demand [l/h] exergetic value depends on the storage tank temperature which is directly affected by the anomaly $\Delta P_S^{DHW} \neq 0$, as previously described. The remaining induced malfunctions, conversely, were at once filtered in the same Trnsys simulation (that is, indeed, the novelty of the application).

On the one hand, (v) characteristic curves was applied in every individual subsystem; each component thermal characteristic model was individually incorporated and the same independent variables of operating conditions ($\bar{x}$) were considered. Instead of doing it separately (as in **Section D**.4.2.1.1), CC implementation was concurrently done taking advantage of faulty operation variables. In such way, the dependent outputs of non-anomalous components coincide with the operating dependent values (as, even having induced effects, the operation point has only been moved along the characteristic curve); conversely, those values are different in the faulty components (since the thermal CC model has been modified).

On the other hand, the (iv) effect of the control system intervention was prevented by the so-called *reference-forced condition*. After all, the operation condition is dependent to the control system because, indeed, it introduces an additional characteristic curve (which is a relation among variables of the system). Such reference-forced condition is similar to the previously mentioned *free condition* but, instead of virtually applying the reference control to the operating condition, it is inversed so the operating control is virtually included in the reference one. Fundamentally, the control is associated with the modulation (or activation-deactivation) of pumps and V3V. The reason for the reversion regards to the real experimental diagnosis application, inasmuch as the faulty operating condition is the monitored one, so the control would be acting directly there and not in the reference. This new configuration condition is simultaneously obtained during the Trnsys simulation, as described in **Section D**.2.2.1, but imposing the operating control to the reference condition.

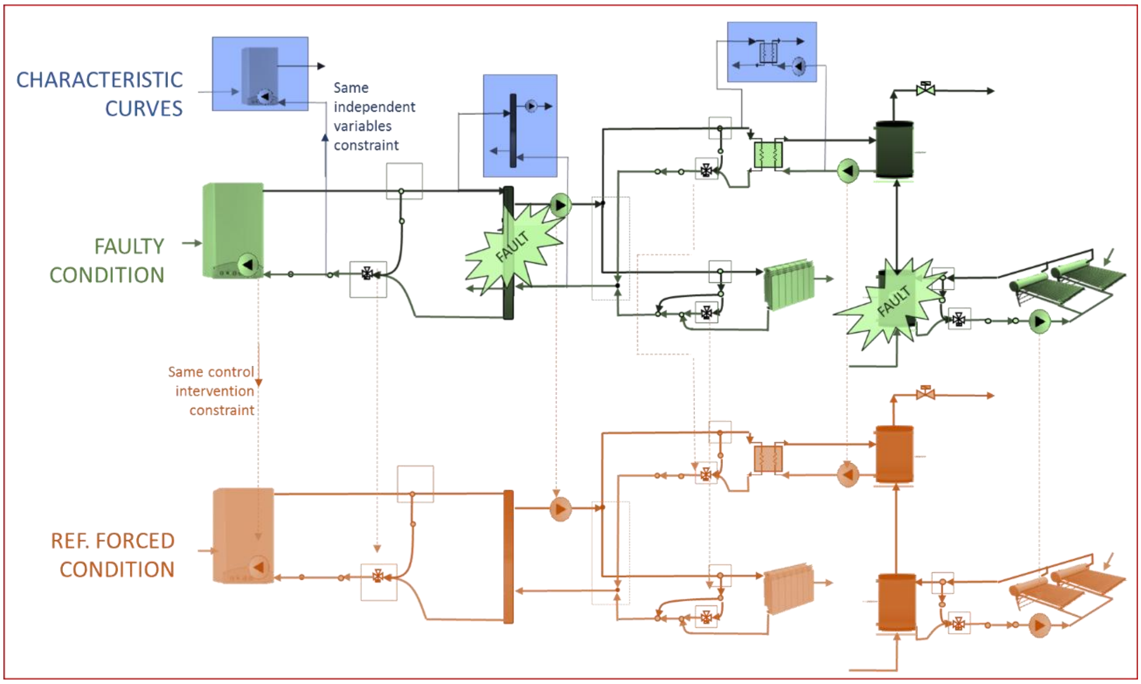

Figure D. 17 Simultaneous obtainment of faulty data, characteristic curves and reference forced condition

Figure D. 17 depicts schematically how to implement simultaneously in Trnsys the faulty condition, characteristic curve and reference forced condition (because of space reasons only three components characteristic curves are shown).

When that is configured, diagnosis formulae is easily implemented every time step; so that the comparison between faulty, characteristic curve outputs and reference forced condition can be done to obtain the intrinsic MF_{intr}^{i} and induced malfunctions MF_{induc}^{i} and dysfunctions DF^{i} of every component.

D.5.1.1.1. Numerical results

As mentioned, the faulty system has two faults (one in the hydraulic compensator and the other in the solar tank). The reference-forced condition and characteristic curve output values were obtained at once with the faulty operation condition simulation. Thermodynamic data were extracted every ten seconds and diagnosis equations were implemented by considering the cumulated values every ten minutes; the global results are shown in Table D. 15.

Table D. 15 Global results of diagnosis in a two-faulty system

			DIAGNOSIS (2 faults: HC . T2)		
			ΔI		
		ΔP_s	MF		DF
			MF_{induc}	MF_{intr}	
①	B		106		605
②	D1				
③	V1				
④	HC		-2	119	4
⑤	V2		-2		-2
⑥	V3				
⑦	D3				
⑧	V4		1		-1
⑨	D4				
⑩	HX		-26		7
⑪	H				
⑫	T1	-1	-160		141
⑬	T2	-10	4	12	-25
⑭	V5				
⑮	D5				
⑯	SC		316		-309
			$F_T^0[kJ] =$		76528
			$F_T\,[kJ] =$		77305

Accordingly, the fuel impact due to those two faults is equal to $\Delta F_T^{2HC,T2} = 777\ kJ$ and the anomaly in HC provokes the highest intrinsic effects ($MF_{intr}^{HC} = 119\ kJ$), so it should be first repaired. As mentioned, it is not possible to maintain the same DHW production since is directly connected to the temperature of the T1 storage tank (which is closely related to the effects of the anomalies), hence $\Delta P_S^{DHW} = 1\ kJ$. If the distinction between intrinsic and induced malfunctions reached by characteristic curves is not done, boiler B can be misunderstood as an anomalous component (see the high dysfunctions and induced malfunctions $MF_{induc}^{B} = 106\ kJ, DF^{B} = 605\ kJ$).

In consequence, next step includes the repair of the faulty components. Table D. 16 shows, firstly, the results when the fault in HC is fixed and, secondly, when T2 is readjusted. Pursuant to the outcomes, the fault in T2 creates a *well-function* since the consumption in referenced-

Table D. 16 Global results of diagnosis in one-faulty system

			DIAGNOSIS (1 fault: HC)		
			ΔI		
		ΔP_s	MF		DF
			MF_{induc}	MF_{intr}	
①	B		114		665
②	D1				
③	V1				
④	HC		-2	119	6
⑤	V2		-1		-1
⑥	V3				
⑦	D3				
⑧	V4		1		-1
⑨	D4				
⑩	HX		-7		-2
⑪	H				
⑫	T1	-10	-60		40
⑬	T2				
⑭	V5				
⑮	D5				
⑯	SC		-1		
			$F_T^0[kJ] =$		76522
			$F_T\ [kJ] =$		77382

			DIAGNOSIS (1 fault: T2)		
			ΔI		
		ΔP_s	MF		DF
			MF_{induc}	MF_{intr}	
①	B		-8		-56
②	D1				
③	V1				
④	HC				-1
⑤	V2				
⑥	V3				
⑦	D3				
⑧	V4				
⑨	D4				
⑩	HX		-18		8
⑪	H				
⑫	T1	9	-105		105
⑬	T2	-10	4	12	-25
⑭	V5				
⑮	D5				
⑯	SC		316		-309
			$F_T^0[kJ] =$		76463
			$F_T\ [kJ] =$		76385

forced condition is higher than in operation ($\Delta F_T^{1_{T2}} = -78\ kJ$). The reason has to do with the control intervention filtration that decreases the boiler negative impacts and reduces the DHW output product. Conversely, the anomaly in HC creates a remarkable impact ($\Delta F_T^{1_{HC}} = 860\ kJ$), especially in the boiler performance; moreover, the solar branch is not affected.

As shown, the principle of superposition of impact formula fails: the summation of the fuel impacts of single anomalies is different from the fuel impact of the two-faulty operating condition, indeed, $\Delta F_T^{1_{T2}} + \Delta F_T^{1_{HC}} > \Delta F_T^{2_{HC,T2}}$. Furthermore, it should be noticed that referenced-forced condition fuel consumption F_T^0 is different in each case because is directly connected to operation circumstances and, therefore, to the existing fault.

In any case, the component with the anomaly is easily identified (the one associated with an intrinsic malfunction) and the produced symptoms in component i are shown (those related to the induced effects of thermodynamic dependences MF_{induc}^i and those connected to the production variation ΔP_i). Therefore, diagnosis is correctly performed.

D.5.1.1.2. Results Discussion

Compliant with the case study, the anomalous condition has two faults: one in the hydraulic compensator (HC) and the other in the solar tank (T2). Although the anomalies were deliberately incorporated they have to be considered as a "blind" result, as if they were directly obtained from real monitoring. Being such consideration true, the diagnosis direct problem is easily solved once every component reference dynamic model is known. For that, a single simulation methodology was develop to filter all the induced effects.

The reference-forced condition and characteristic curves output values were obtained at once with the faulty operation condition simulation: same operation control intervention was imposed to the reference and same independent input values were introduced to the dynamic models of individual component.

Regarding the numerical results, the first diagnosis analysis clearly pointed out the faulty components by delimiting their weight in terms of intrinsic malfunctions. Predictably, since the HC is permanently turned on, the impact of its anomaly is almost 10 times higher than the one of T2; the induced effects are also highlighted and, according to the results, the boiler is proved to be highly affected. Moreover, mono-failure diagnosis studies demonstrated the inaccuracy of the fuel impact formula due to the thermodynamic strong interdependences.

D.6. CONCLUSIONS

The target of this chapter was to create an unambiguous procedure for diagnosis direct problems in building thermal facilities. For that, the diagnosis methods in HVAC&R systems were summarized and the utility of thermoeconomic diagnosis was discussed by means of theoretical and practical procedures; the pros and cons of thermoeconomic diagnosis were described and its weaknesses were one by one overcome.

Thermoeconomic diagnosis application has been for the first time, for author's best knowledge, *dynamically* implemented in a building thermal facility. In this case, contrary to what was done before, the dynamism of the energy supply facility was considered, inasmuch as their state constantly changed because of the heating, DWH or air conditioning demands varied continuously in time. Among the encountered issues, the more remarkable are the following:

- Multi production objective causes the continuous intervention of the control command.
- The definition of productive structure is controversial due to the dynamism. The system can have more than one productive structure depending on the switching-on and switching-off of the components.
- The performance of any component is heavily influenced by all other components because of the system balancing.
- Final product variation cannot be nulled and must be taken into account in the diagnosis.

Among the inserted enhancements: (1) diagnosis was stated either in exergy and monetary terms, (2) an innovative combination of ΔF_T and CC analysis was done and (3) a new way for filtering the induced malfunctions due to control intervention and components interconnections was introduced at once by simulation.

Besides, the most challenging enforcement of thermoeconomic diagnosis was resolved: the *direct problem*. Its objective is to (1) identify the faults and (2) analyze their symptoms by comparing the performance of the new system with the reference one.

As justified, the main goal is to distinguish among intrinsic and induced malfunctions, so that the key point is based on the proper thermodynamic model of the system. Accordingly, fault detection can be achieved by only contemplating the thermodynamic variables and avoiding the aggregated exergetic parameters; or what is the same, by simply detecting the component with a modified characteristic curve. Although such statement, thermoeconomic diagnosis interrelates the components and enables the calculation of the cost increments effects along the system. Furthermore, if the productive structure is already defined (for example, for previous exergetic cost accounting purposes of **Chapter C**), thermoeconomic diagnosis analysis does not require greater computational effort.

As a consequence, the detection of the malfunction itself does not solve the diagnosis problem; only when the effects of an anomaly are known it is possible to decide the treatment. Therefore, as the information about the impact of the anomalies is given, thermoeconomic diagnosis can be considered a good technique for decision-making processes, such as for maintenance or enhancement purposes.

If thermoeconomic information is added, although not strictly necessary to detect faults, the information for identifying the importance of a malfunction is obtained. After all, thermoeconomic diagnosis allows weighting the faults and their effects according to the growth of exergetic cost.

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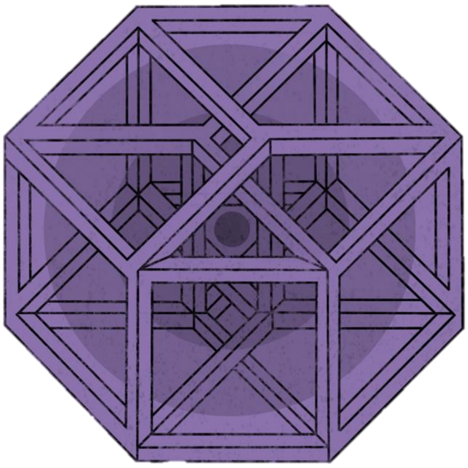

CHAPTER E

Dynamic advanced exergy analysis in buildings

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CHAPTER E

SYMBOLS

F	[kJ]	Fuel
P	[kJ]	Product
E_D	[kJ]	Total exergy destruction
E'_D	[kJ]	Total exergy destruction in new thermodynamic conditions
ε	[-]	Exergetic efficiency
ε'	[-]	Exergetic efficiency in new thermodynamic conditions
E_D^{AV}	[kJ]	Avoidable exergy destruction
E_D^{UN}	[kJ]	Unavoidable exergy destruction
E_D^{EN}	[kJ]	Endogenous exergy destruction, based on the decomposition method
$E_D^{EN^*}$	[kJ]	Endogenous exergy destruction, based on the real characteristic curves
E_D^{EX}	[kJ]	Exogenous exergy destruction
$E_{D,i\rightarrow k}^{EX}$	[kJ]	Exogenous exergy destruction that i provokes in k
E_D^{MEX}	[kJ]	Mexogenous exergy destruction
$E_D^{AV\cdot EN}$	[kJ]	Avoidable endogenous exergy destruction
$E_D^{AV\cdot EX}$	[kJ]	Avoidable exogenous exergy destruction
$E_D^{UN\cdot EN}$	[kJ]	Unavoidable endogenous exergy destruction
$E_D^{UN\cdot EX}$	[kJ]	Unavoidable exogenous exergy destruction

CHAPTER E: DYNAMIC ADVANCED EXERGY ANALYSIS IN BUILDINGS

E.0. ABSTRACT

This chapter refers to the alternative application of Second Law analysis called Dynamic Advanced Exergy Analysis (DAEA) in a heating and DHW experimental facility. For the first time an advanced exergy analysis using dynamic conditions is applied to a building energy supply system.

DAEA provides insights on the components exergy destruction (E_D) by distinguishing the inefficiencies that can be prevented by improving the quality of the equipment (avoidable E_D) and the ones constrained because of technical limitations (unavoidable E_D). Besides, exergy destruction can also be related to the inherent irreversibilities of the element (endogenous E_D) and those coming from the interconnection with the others (exogenous E_D). That information is worthwhile and cannot be obtained by any other approach.

The key aspect of this chapter is associated with the dynamic behavior of the facility so that novel solutions and terms of exergy destructions are assessed for the rational implementation of the DAEA in building energy installations.

E.1. INTRODUCTION

As explained in **Chapter A**, in a *conventional exergy analysis*, the exergetic efficiency (ε) is used as an indicator to characterize a component in terms of its performance and to compare it to similar components in other systems [1]. It is defined as the ratio between the productive purpose (the goal) of the component *Product* (P), and the resources required for that objective, *Fuel* (F) [2] (both of them in exergy terms); in addition, if no exergy losses are assumed, the difference between the F and P is equal to the exergy destruction (E_D) of the component [3]. However, as already justified, this analysis cannot satisfactorily evaluate the mutual interdependencies among the system components, so that, it does not consider the real potential for improving every component [4].

To overcome those barriers, among other theories, the *advanced exergetic analysis* (AEA) was developed. By this methodology, the part of the inefficiencies caused by the component on its own and that caused by the interactions with others can be evaluated, as well as the fraction which can be avoided through technological improvements [4],[5],[6]. Consequently, the main purpose of a plant analysis in the AEA is the identification of the causes of irreversibilities and their effects in terms of E_D and thus, in terms of performance [7].

As stated above, there are some irreversibilities that every component may have which cannot be reduced even using the best and current technical alternatives, due to physical, technological and economic constraints or limitations. They are known as unavoidable exergy destruction (E_D^{UN}) [4],[8], whereas the remaining part is named as avoidable exergy destruction (E_D^{AV}). Hence, the splitting up of these two inefficiencies gives a realistic picture of the potential each component has for improving its thermodynamic effectiveness.

In addition to this, there is another way to distinguish the irreversibilities: some exergy destructions encountered in a component are due to the inefficiencies of the other components. This means that E_D occurring in one component of a system does not only depend on its performance, but it is also influenced by the inefficiencies of the remaining components [9]. That part of the E_D associated with the exergy destruction in other components is called exogenous exergy destruction (E_D^{EX}), while the part caused only by internal irreversibities within the component itself is named as endogenous exergy destruction (E_D^{EN}). Thus, the separation of those two exergy destructions enables us to better understand the interactions of the system components and to consider those interactions in optimization procedures. Nonetheless, the calculation of E_D^{EN} and E_D^{EX} for a component is more difficult than that of E_D^{UN} and E_D^{AV}, and this is a major challenge of AEA.

Subsequently, the avoidable and unavoidable E_D can be related to the endogenous and exogenous ones. That information can be used to investigate: (1) which part of the exergy destruction within a component can be decreased by improving the component itself ($E_D^{EN.AV}$), (2) which part can be reduced by a structural enhancement of the overall system or by improvements in other components ($E_D^{EX.AV}$), and (3) & (4) the exergy destructions which cannot be prevented (reflected by $E_D^{EX.UN}$ and $E_D^{EN.UN}$). In consequence, the information acquired by the AEA can be applied for system design, control improvement and maintenance purposes.

The novel aspects and originality of the present chapter are associated with the AEA application to a building thermal facility and especially with proceeding from a steady-state analysis to a dynamic one. For this reason, the proposed methodology is called Dynamic Advanced Exergy Analysis (DAEA), which adds some new aspects to the steady-state AEA. Thus, the aims of the chapter is to present a guideline on how to apply a detailed DAEA.

In the literature, we find some applications of AEA in buildings. For example, [10] applies an AEA to an air conditioning system using average values to evaluate the cooling process during the day and the accumulation process at night. Ref. [11] applies AEA to low-exergy analysis for existing building heating systems. In a similar way, [12] makes a comparison between two geothermal district heating systems based on an AEA. Although these papers are related to buildings framework, none of them (or any other similar paper) considers the dynamic state of the system in the AEA. This makes the present study problably the first one in the application of DAEA.

On the other hand, AEA has been applied in several research studies to different industrial fields: Refs. [6] and [13] apply this method to combined cycle power plants; [3] performs a detailed AEA to an absorption refrigeration machine, and [14] examines a gas engine heat pump drying system. An AEA application to cogeneration systems is presented in [15]. Despite the abundance of studies about AEA, as we said above all of them have been carried out in a steady-state context.

To be clear in the DAEA application a (vii) *Stirling and Condensing Boiler Case Study* is used; therefore, the theoretical part and application are together explained.

E.2. CASE STUDY

The experimental facility of the Laboratory for the Quality Control in Buildings (LQCB) has been used to obtain the needed data. The facility customized for the DAEA application is based on a micro-cogeneration Stirling engine and a condensing boiler (a Stirling was chosen in order to introduce a groundbreaking component in building system). That engine supplies 1 kW electricity and 3.7-5 kW thermal energy from the combustion gases, depending on the operating temperatures and modulation. Additional 20 kW thermal energy can be produced in an auxiliary boiler inside this unit. Another equipment used in the energy conversion layer of the facility is a natural gas condensing boiler which provides 28 kW thermal energy with a manufacturer energetic efficiency (based on the lower heating value) of 97% .

These components provide the required thermal energy and DHW equivalent to the demand of three single-family dwellings located in Vitoria (northern Spain). Additionally, there is a 35 l hydraulic compensator, a plate heat exchanger, a 1000 l storage tank, distribution pipes, hydraulic pumps, three-way valves, and a fan coil, as shown in Figure E. 1.

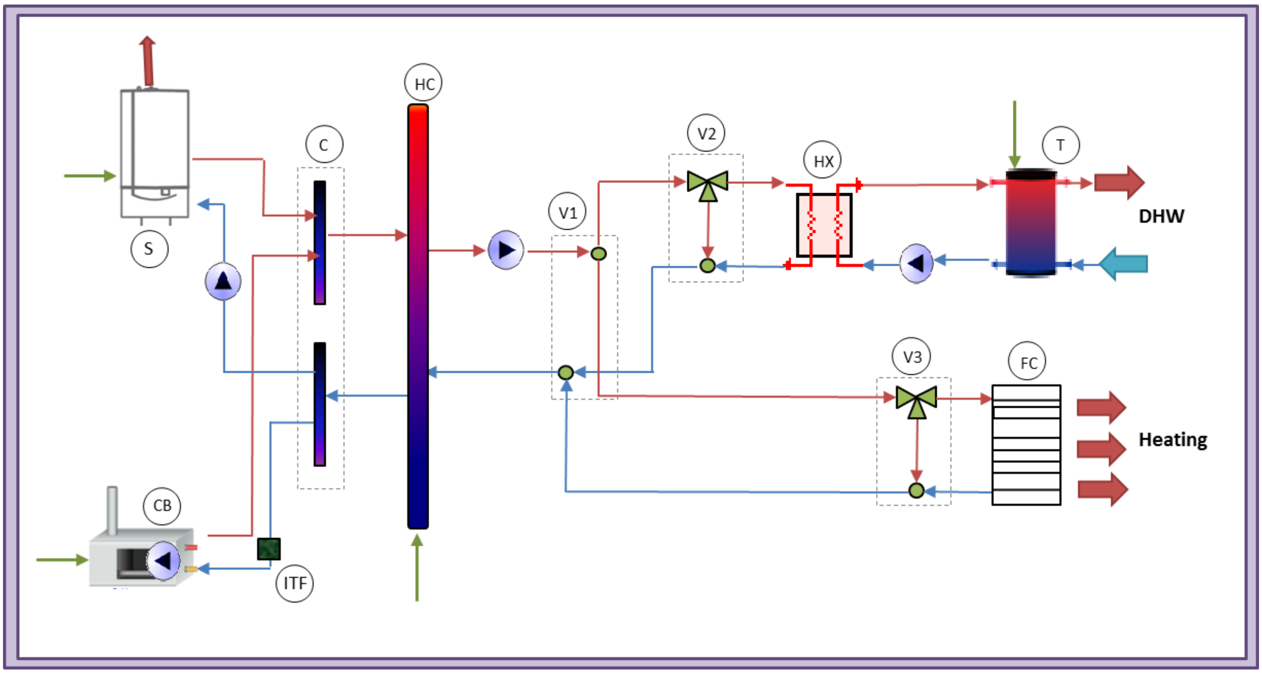

Figure E. 1 Scheme of the building thermal facility under study

The DHW demand profile has been previously discretized and programmed and is controlled by a high accuracy flow meter. This profile uses 5-minute discrete values, which are continuously compared with the energy data obtained from the temperature and flow meters associated with the facility. The emulation of the heating demand is done through a 5RYardi HP 250 fan coil battery together with a three-way valve, so that the heating demand profile defined in advance and calculated through Trnsys is matched by its modulation and operation of that component.

The control strategy is such that the Stirling engine has priority over the condensing boiler so that it is switched on either when there is demand for thermal energy or when the average temperature of the DHW tank falls below 60°C. It is managed by a CPU together with an expansion module and is connected via Ethernet to a PC.

E.2.1. Selection of the Components

In order to properly conduct a DAEA, the next step requires the suitable selection of every subsystem, with respect to their productive final purpose. For instance, if the supply and return collectors located above the hydraulic compensator are individually considered (driving mixer and returning diverter separately), no productive final purpose can be defined for them. Conversely, if they are jointly handled instead, the productive purpose of this component would be the coverage of both the DHW and the heating demand. In a similar way, the splitter and the mixer of the three-way valve right before the fan coil should be considered inside the same component; in such way, the goal would be to supply the heating demand. Following those

Table E. 1 List of components used for DAEA

NAME	DESCRIPTION
S	Micro-cogeneration Stirling Engine
CB	Condensing Boiler
ITF	CB Inlet Temperature Fixing
C	Supply and Return Collectors
HC	Hydraulic Compensator
V1	DHW and Heating Mixer & Splitter
V2	HX Mixer & Splitter
HX	Heat Exchanger
V3	Heating Mixer & Splitter
T	Storage Tank
FC	Fan Coil

considerations, the components used for the analysis are listed in Table E. 1, where their names and abbreviations are shown.

E.2.2. Conventional Exergy Analysis

Following the guidelines of **Chapter B**, the models of the individual components and of the overall system are completed (and mass and energy balances are fulfilled, and also the entropy is validated) so the DAEA can be initiated. The first step is to conduct a conventional exergy analysis in order to calculate the exergy destruction and exergetic efficiency of each component. The definition of the dynamic exergetic efficiency is a delicate step and probably one of the most important ones in the research fulfilment. As cited before, the variable that unambiguously characterizes the performance of a component from the thermodynamic viewpoint is an appropriately defined exergetic efficiency, i.e., the ratio between the product P and the fuel F in the studied component [5]. Even this systematization, the definition of F and P must be carefully considered since special exceptions can occur in dynamic situations (see **Chapter C**.3).

Taking into account the considerations of **Section C**.3.1, a conventional dynamic exergetic analysis can be performed. It is assumed that for all the components the system boundaries are at the reference environment dynamic temperature, consequentially, there are no exergy losses associated with the components [16]. Hence, exergy losses would only appear at the level of the overall facility and for every component the difference between F and P would correspond to the exergy destruction E_D within this component.

E.2.3. Unavoidable & Avoidable Exergy Destructions

As stated before, the unavoidable exergy destruction is constrained by technological limitations and is calculated considering each component in isolation (i.e., separated from the system) assuming the most favourable operating conditions. These conditions refer to the minimum exergy destruction and are associated with very low temperature differences and very small thermal and mechanical losses within the component being analysed [6],[17], based on the assumption that the generated amount of product remains unchanged. Nevertheless, the assumptions for simulating unavoidable conditions depend on the engineers' personal expertise and scope, so, they are arbitrary to some extent.

The avoidable exergy destruction in the component k of the system ($E_{D,k}^{AV}$) is the difference between the total and the unavoidable exergy destructions within the same component:

$$E_{D,k}^{AV} = E_{D,k} - E_{D,k}^{UN} \tag{E. 1}$$

Having reached this point, it is important to note that even if the unavoidable and avoidable exergy destructions are individually acquired, the behavior of the remaining components affects the calculation of both exergy destructions. This happens because the independent variable values remain the same as in reality or, in other words, when calculating avoidable exergy destruction, real input data are enforced to the component with the best attainable technology, and the effect of the remaining components is included in those imposed input data. Consequently, $E_{D,k}^{UN}$ and $E_{D,k}^{AV}$ encompasses both, the inefficiencies encountered because better quality equipment could be developed and the irreversibilities which can be prevented by avoiding the interactions among the components. For this reason the combinations of $E_{D,k}^{UN \cdot EN}/E_{D,k}^{UN \cdot EX}$ and $E_{D,k}^{AV \cdot EN}/E_{D,k}^{AV \cdot EX}$ exist.

E.2.3.1. Application to the experimental building thermal facility

For calculating $E_{D,k}^{UN}$, the major sources of inefficiency in each component need to be first identified and, afterwards, the minimum exergy destruction criterion should be applied. Different groups of components are hereafter exposed and listed according to their level of difficulty.

- **C/V1/V2/V3)** The irreversibilities in the mixers and splitters are mainly caused by mixing streams at different temperatures and pressures. Thus, if the control system acts in a way that equal temperatures and pressures are assumed, the unavoidable exergy destruction can be set to zero.
- **ITF)** The aim of this component is to guarantee the best thermal conditions of the inlet flow to the condensing boiler. Hence, all the irreversibilities should be avoidable if that flow is already at its nominal state.
- **FC)** The exergy destruction within the fan coil can be minimized by selecting the fan coil with the highest energetic efficiency in the market.

- **HX)** Entropy generation will appear in all cases in a heat exchanger. Indeed, the exergy destruction will always be positive due to the existence of a pinch point ΔT_P [18]. Despite that premise, the $E_{D,HX}$ value can be reduced through the following ways: (1) matching streams of similar heat capacity rates, thus, achieving parallel temperature profiles; (2) selecting very small minimum temperature differences of the average temperatures of the hot and cold streams; (3) considering an adiabatic heat exchanger; (4) neglecting pressure losses; and, 5) choosing a constant and maximum available heat transfer coefficient.

- **HC/T)** The main cause of irreversibility in those components is the mixing of the high and low-temperature portions of the storage medium. To enhance the storage performance, it is therefore necessary to decrease the mixing losses by inserting the heat transfer fluid in the temperature layer, which is closer to its temperature, this is to say, managing the injection of heat into the corresponding temperature level by a correct stratification [19]. Moreover, it is shown that the exergy storage capacity increases as the degree of stratification arises. In addition, the exergy capacity is greater for storages at mean temperatures near to the ambient temperature and decreases as it diverges from the ambient temperature. Besides, the selection of the inlet stream temperature may be a compromise between the required charging rate and exergy performance since the temperature should be as low as possible for charging and as high as possible for discharging [20]. The exergy destruction is decreased by augmenting the thermal conductivity of the heat exchanger inside the tank [20]. Additionally, the heat losses are reduced by applying adiabatic boundary conditions, i.e., by improving insulation levels.

  Bearing all that in mind, the criteria taken for calculating the E_D^{UN} in HC and T are set out below: (1) as the inlet and outlet positions of the heat transfer fluids are fixed, the incoming flows cannot be inserted in different specific layers. Nevertheless, the maximum stratification profile should be considered; (2) due to the *RITE* legal requirements (*regulations for thermal installations in buildings*) [21], the storage temperature should be greater than 60 °C in order to avoid legionella formation and the same rule also influences the inlet fluid temperature; (3) the DHW charging and discharging depend on the user demand profile, so no optimal heat process periods can be enforced; (4) there is no heat exchanger inside the tank of LQCB experimental facility; (5) finally, thermal insulation should be added to the tank surface, so that it becomes adiabatic.

- **S/CB)** Systems with the combustion processes are usually by far the components with highest exergy destruction, hence, a detailed separated exergy analysis should be carried out. The main causes of inefficiencies in a combustion process are friction, mixing, chemical reaction and heat transfer [22], and each of them have the following characteristics: (a) the E_D caused by friction is significantly lower than the ones caused by chemical reactions and heat transfer; (b) E_D due to isobaric mixing depends, once again, on the differences in temperature and chemical composition of the streams that are mixed. That exergy destruction can be sometimes diminished, but it is often entirely unavoidable; (c) E_D resulted from chemical reactions can be reduced by letting the reactions take place closer to their thermodynamic equilibrium; however, the exergy destruction associated with chemical reactions will always be very high; (d) the E_D associated with heat transfer depends on (1) the difference between the average thermodynamic temperatures of the combustion gases and the heated fluid, and (2) the temperature level, at which the heat transfer takes place. It should be noted that although four causes of E_D are considered here by following the procedure in [22], all these processes occur in real processes simultaneously and not successively.

According to the mentioned considerations, E_D^{UN} was calculated under the assumptions that (1) no pressure drop during combustion occurs, (2) the combustion is stoichiometric (λ=1), in order to minimize the exergy destruction due to chemical reactions, (although this would increase the adiabatic combustion temperature, and thereby, the heat transfer inefficiencies), and (3) the minimum temperature difference for the heat transfer is just unattainable. Incidentally, the composition of the combustion gases in the unavoidable conditions would be different from that in the real case.

After substantiating each component characteristic, Table E. 2 was filled out in such a way that the causes of inefficiencies are firstly exhibited, and next, the ways to assess the unavoidable E_D are summarized.

Table E. 2 Justification and achievement of the unavoidable exergy destruction in every component

n	CAUSES for E_D	UNAVOIDABLE E_D Achievement
C,V1,V2,V3	Mixing with different states	Mixing at equal temperatures and pressures are assumed
ITF	Mixing for achieving the required conditions	Flow enters with the same thermodynamic conditions as required CB's inlet
FC	Thermal and pressure losses	Highest energetic efficiency + no pressure losses
HX	Existence of pinch point ΔT, pressure and thermal losses	Minimum ΔT of the average temperatures + adiabatic HX + no pressure losses + constant and maximum available heat transfer coefficient
HC,T	Mixing, tank average T, charging rate, heat losses to the environment	Insulation addition to the tank boundaries + no pressure losses
S,CB	Friction, mixing, chemical reaction, heat transfer	Stoichiometric combustion (λ=1) + minimum ΔTª for the heat transfer + no pressure losses

Along with the above criteria, it is worth highlighting that the $E_{D,k}^{UN}$ for each component must be dynamically calculated in every time step, and then, different $E_{D,k}^{UN}$ values would emerge while the productive conditions vary.

E.2.4. Endogenous & Exogenous Exergy Destructions

The endogenous exergy destruction of the component k ($E_{D,k}^{EN}$) reflects that part of the overall E_D which exclusively is related to the intrinsic irreversibilities within the component itself.

As developed in [23], there are various approaches for splitting the exergy destruction into its endogenous and exogenous parts. Some of those methods are based on the analysis of theoretical thermodynamic cycles; so, they cannot be applied to systems in which it is not possible to create a theoretical cycle [24]. Others are focused on results obtained from the exergetic sensitivity analysis and on further graphical representations [25]; hence, they need laborious mathematical work. Those are approaches based on exergy balance methods or on equivalent component methods. Accordingly, the main drawback associated with those approaches is the large number of non-standard simulations that cannot always be easily conducted by using commercial software [26]. Nonetheless, a new straightforward and time-saving methodology has recently been developed [27] based on a systematic approach derived from general process design and synthesis principles. Consequently, this methodology will be summarized and implemented below.

This methodological *decomposition method* is based on the idea that the exergy concept is independent from the whole structure, so that $E_{D,k}^{EN}$ in every component can be individually evaluated according to its characteristics. In this way, the facility can be divided into reversible and irreversible subgroups. The term $E_{D,k}^{EN}$ results from keeping the component k operating at its current exergetic efficiency (ε_k) while all the remaining components are assumed to be totally reversible, i.e. exhibiting a 100 % exergetic efficiency [27]. Notwithstanding these simplifications, it must be noted that the "idealization" of the remaining components should not change the organization and the structure of the flowsheet as they are used to determine

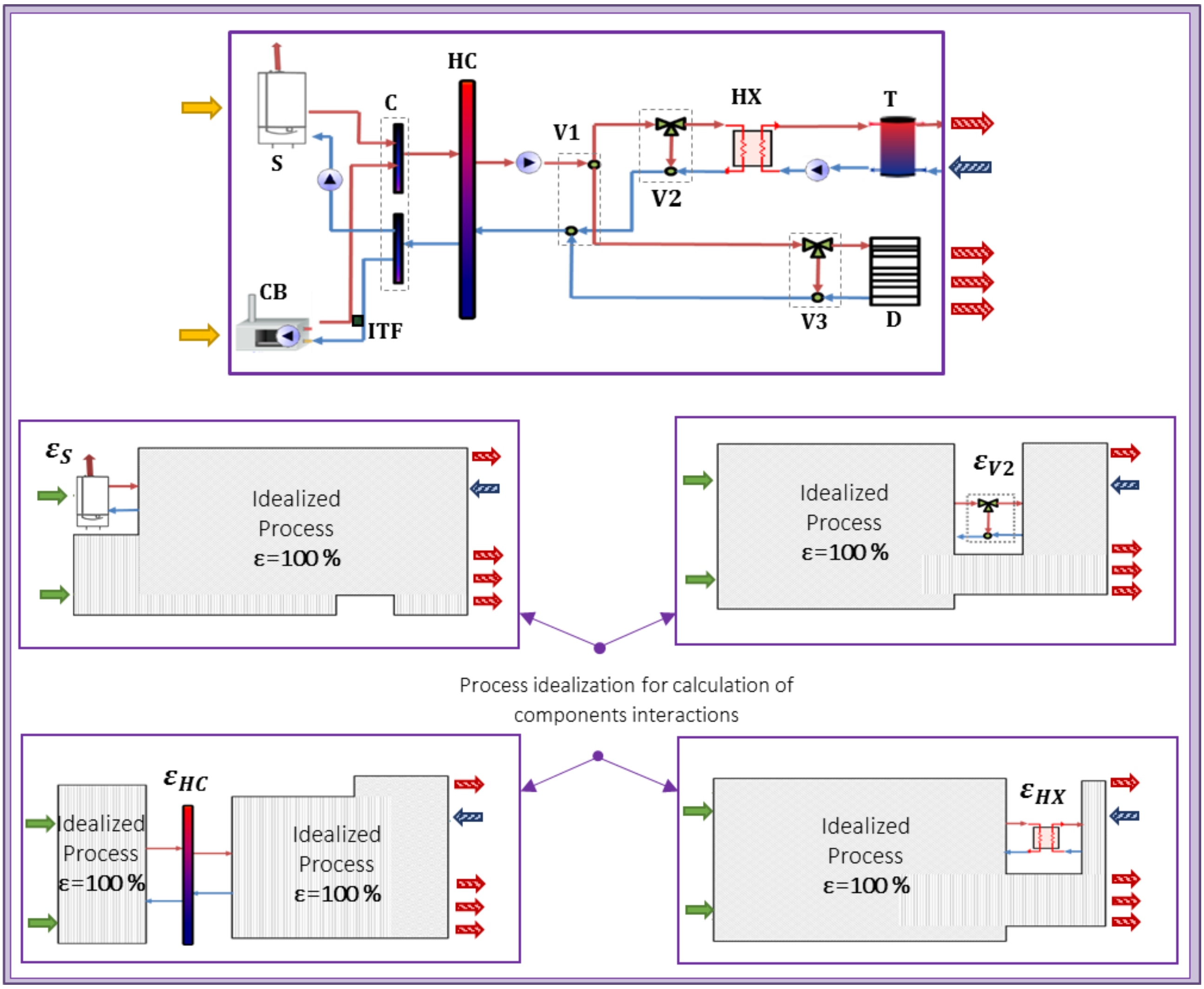

Figure E. 2 Decomposition method for calculation of the $\boldsymbol{E_D^{EN}}$, adapted from Ref. [27]

the endogenous exergy destruction within the considered component. Likewise, the overall product(s) must remain the same as in the real facility. As a result, it is possible to determine the productive contribution and the inefficiencies associated with different components.

The graphical representation of this approach is depicted in Figure E. 2. The upper part of the figure shows the facility under study where the *real* incoming resources and outgoing final products are displayed. The other four pictures illustrate how the endogenous exergy destruction in components S,V2, HC and HX are calculated, while their ε_k as well as the outgoing final product(s) (grated flags) are maintained the same as in the experimental facility.

Once the endogenous exergy destruction of the *k*th component is determined, the exogenous part can be calculated by subtracting this value from the real $E_{D,k}$ as shown in the following equation.

$$E_{D,k}^{EX} = E_{D,k} - E_{D,k}^{EN} \quad \text{(E. 2)}$$

Accordingly, $E_{D,k}^{EX}$ represents that part of the exergy destruction in component k that exists because of the inefficient operation of the remaining components in the given structure of the system.

E.2.4.1. Application to the experimental building thermal facility

To begin with the calculation of $E_{D,k}^{EN}$ in our case study, the product of each component P_k needs to be defined first. That product expresses the reason for owning and operating the component being considered under real conditions (i.e. with irreversibilities), while considering the rest of the system under a (hypothetical) ideal operation (i.e. without irreversibilities). In this regard, attention to the following issues is essential in the analysis of the building thermal facilities:

Table E. 3 Description of the components and their final objective product used for calculation of the $\boldsymbol{E_{D,k}^{EN}}$

k	P_k for $\mathbf{E_{D,k}^{EN}}$ calculation
S	$(F_T + P_{Heat}) \cdot \%P_S$
CB	$(F_T + P_{Heat}) \cdot \%P_{CB}$
ITF	Not applicable
C	$F_T + P_{Heat}$
HC	$F_T + P_{Heat}$
V1	$F_T + P_{Heat}$
V2	F_T
HX	F_T
V3	P_{Heat}
T	P_{DHW}
FC	P_{Heat}

$\boldsymbol{P_{Heat}}$	Heating exergy demand
$\boldsymbol{P_{DHW}}$	DHW exergy demand
F_T	Exergy of the heat flow supplied to the tank

$\%\boldsymbol{P_S}$	The share of S to fulfill the demand
$\%\boldsymbol{P_{CB}}$	The share of CB to fulfill the demand

- DHW is one of the outgoing products of the facility supplied by the storage tank T located at the end of the production chain. That means that the conditions of DHW exclusively depend on the storage thermal conditions, not on the activation or deactivation of the other components. Two different situations are brought as examples to make that clear (this is similar to **Section C**.3.1.1.). In one case the requested DHW is entirely covered by the tank discharge, while in another situation there might be no demand for DHW; however, because of the temperature control strategy of the tank, the heat generation units are turned on to achieve the set-point temperature within the tank. Hence, the DHW demand should only be considered as the product of the tank ($P_T = P_{DHW}$); whereas for the remaining components of the system the product (or part of the product) is the flow of thermal energy supplied to the tank(F_T) as shown in Table E. 3.

- The product associated with the heating demand needs to be carefully considered. One might think that the exergy of the heating demand corresponds to the exergy supplied by the fan coil (i.e. the exergy of the flow of thermal energy at the surface temperature of the fan coil). Nonetheless, the exergy of the delivered heat has to be calculated at the room air temperature (≈20 ℃), since the aim of a heating device in a real facility would be tempering the room air, in order to satisfy the comfort conditions. Therefore, the heating exergy demand is much lower than the supplied exergy by the fan coil, and, hence, the endogenous exergy destruction in this component ($E_{D,FC}^{EN}$) is very high. That causes relatively high exogenous exergy destructions in other components of the system, and makes the quality mismatch between the required and the supplied heating exergies: one of the main sources of inefficiencies in all components of the system.

Some components of the system, such as the condensing boiler inlet temperature fixing (ITF) and the pumps do not have productive purposes. The aim of those components are to satisfy some specific conditions for the boiler and to provide the mass flow by balancing the pressure losses, respectively. Indeed, they are merely used to make the operation of the facility possible. Hence, all their E_D would correspond to the exogenous part, as they are entirely caused by the operation of other components in the system.

E.2.4.2. Binary Exogenous Exergy Destructions

Once the exogenous exergy destruction ($E_{D,k}^{EX}$) within every component is calculated, it can be split into several parts, each one generated from a specific component in the system. That is done by combining scenarios of *two* components working with their real exergetic efficiency ε while all other components operate reversibly with a virtual unitary exergetic efficiency. In this situation, the exergy destruction in the component k ($E'_{D,k}$) consists of two parts: the endogenous exergy destruction that has been already calculated and the exogenous one caused only by the irreversibilities in the component i ($E_{D,i\to k}^{EX}$). The value of the latter is obtained by subtracting $E_{D,k}^{EN}$ from the new exergy destruction of the *k*th component estimated in this new stage as:

$$E_{D,i\to k}^{EX} = E'_{D,k} - E_{D,k}^{EN} \qquad \text{(E. 3)}$$

Figure E. 3 visualizes the methodology to obtain the binary exogenous exergy destruction caused within component k by the irreversibilities within component i.

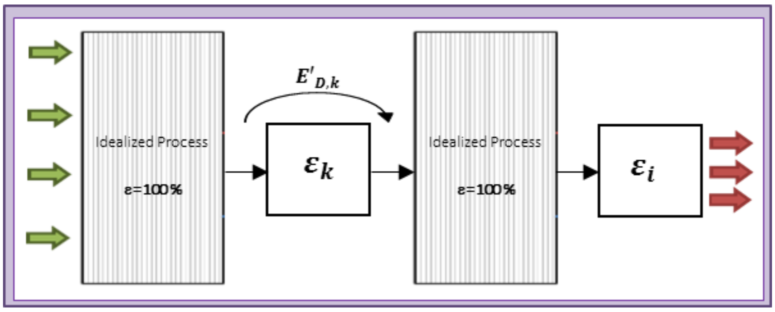

Figure E. 3 Graphical explanation of the methodology to obtain $E^{EX}_{D,i\rightarrow k}$

The analysis of binary interactions between upstream and downstream components of the energy chain reveals that the second components are the ones which mainly cause E_D in the upstream ones. In fact, if there is no energy recirculation within the system being considered, the exogenous exergy destruction within component i caused by the irreversibilities occurring in the upstream component k ($E^{EX}_{D,k\rightarrow i}$) is zero, because $E'_{D,i}$ would be exactly the same as the $E^{EN}_{D,i}$ (see Figure E. 4).

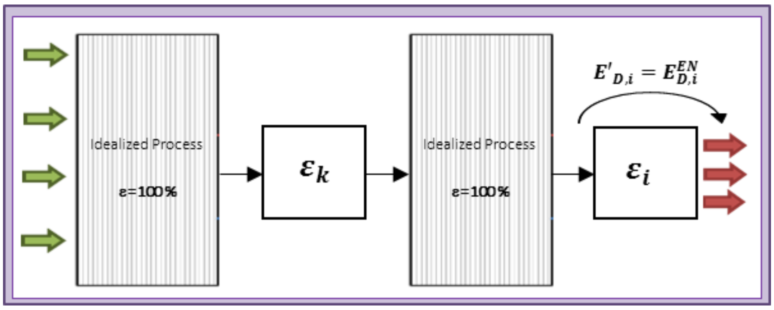

Figure E. 4 Graphical justification for $\mathbf{E'_{D,i}} = E^{EN}_{D,i}$ in the downstream component *i*

E.2.5. Mexogenous Exergy Destructions

Apart from the endogenous and exogenous exergy destructions, there is an additional exergy destruction in each component caused by the simultaneous interactions between the component being considered and the rest of the system operating under its real efficiency. This is called mexogenous (i.e. mixed exogenous) exergy destruction [28] and is calculated by subtracting the sum of the binary exogenous exergy destructions from the total exogenous exergy destruction within the *k*th component, as shown in the following equation.

$$E^{MEX}_{D,k} = E^{EX}_{D,k} - \sum_{\substack{i \\ i\neq k}}^{n} E^{EX}_{D,i\rightarrow k} \qquad \text{(E. 4)}$$

E.2.6. Considering Real Characteristic Curves

The decomposition method offers an appealing approach to obtain the endogenous exergy destruction within different components of a system, since the required mathematical effort and calculation time are significantly lower than those by other methods. However, this approach deals only with exergetic variables (such as F_k, P_k and ε_k), which should remain constant, without considering the real physical characteristics of the components under different operating conditions; therefore, the approach can lead to some controversial results. For instance, when only one component of the system is operating under its real conditions (with its real ε_k) and the rest of the system is assumed to be ideal ($\varepsilon = 1$), it can happen that the virtual product that this component is supposed to cover (P_k) is inconsistent (e.g., outside of the component operating range, for example, too low demand for CB is not feasible). Moreover, the ε of the component in different operating conditions does not remain the same.

Consequently, a similar standpoint can be carried out if, instead of working with constant exergetic efficiencies, the real one under the new thermodynamic conditions (ε'_k) is considered, based on the characteristic curves of each component (see **Section D**.3.1). The endogenous exergy destruction obtained from this approach ($E_{D,k}^{EN^*}$) represents the *authentic* E_D that a component would have, when supplying the corresponding P_k.

The difference between the endogenous exergy destruction based on the real characteristic curves of the components ($E_{D,k}^{EN^*}$) and the one obtained according to the decomposition method ($E_{D,k}^{EN}$) refers to the irreversibilities due to the fact that the component needs to adapt itself to the new thermodynamic conditions (ε_k).

$$\Delta E_{D,k}^{EN} = E_{D,k}^{EN^*} - E_{D,k}^{EN} \qquad \text{(E. 5)}$$

E.2.7. Combination of the UN/AV, EN/EX Parts of Exergy Destruction

Overviewing the general DAEA developed so far, E_D in the component k of the system has been divided into its avoidable and unavoidable parts and into its endogenous and exogenous sections in the present paper. Those parts of exergy destruction can be combined to calculate the following variables: (1) $E_{D,k}^{AV.EN}$ is the exergy destruction that can be reduced by the improvement of the kth element itself; (2) $E_{D,k}^{AV.EX}$ is the exergy destruction which can be decreased by enhancing the performance of the other components; (3) $E_{D,k}^{UN.EN}$ is the exergy destruction which states the inherent limitations of the component being considered; and (4) $E_{D,k}^{UN.EX}$ is the exergy destruction that embodies the structural constraints and components interactions. They are calculated as follows:

$$E_{D,k}^{AV\cdot EN} = \frac{E_{D,k}^{AV} \cdot E_{D,k}^{EN}}{E_{D,k}} \qquad \text{(E. 6)}$$

$$E_{D,k}^{AV\cdot EX} = \frac{E_{D,k}^{AV} \cdot E_{D,k}^{EX}}{E_{D,k}} \qquad \text{(E. 7)}$$

$$E_{D,k}^{UN\cdot EN} = \frac{E_{D,k}^{UN} \cdot E_{D,k}^{EN}}{E_{D,k}} \qquad \text{(E. 8)}$$

$$E_{D,k}^{UN\cdot EX} = \frac{E_{D,k}^{UN} \cdot E_{D,k}^{EX}}{E_{D,k}} \qquad \text{(E. 9)}$$

E.3. NUMERICAL VALUES AND RESULTS

As previously mentioned, the LQCB experimental facility was used for a 4-day test. In the present analysis 18 thermocouples Pt 100, 1/10 DIN (with an uncertainty of $\pm 0.15°C$), 7 flowmeters (with an accuracy of $\pm 0.1\%$), 1 gas meter of Class 1.5 for the fuel consumption and 1 electric meter of Class 1 for measuring the generated electricity by the Stirling were used.

The DHW and heating demands were calculated with Trnsys v17 and then the control system was accordingly programmed. Those demands are illustrated in Figure E. 5. Although the data were acquired every 10 seconds, the mathematical dynamic model was built based on a 5-minute time step, since that time step was considered enough to accurately represent the transient start-up and shut-down of the components.

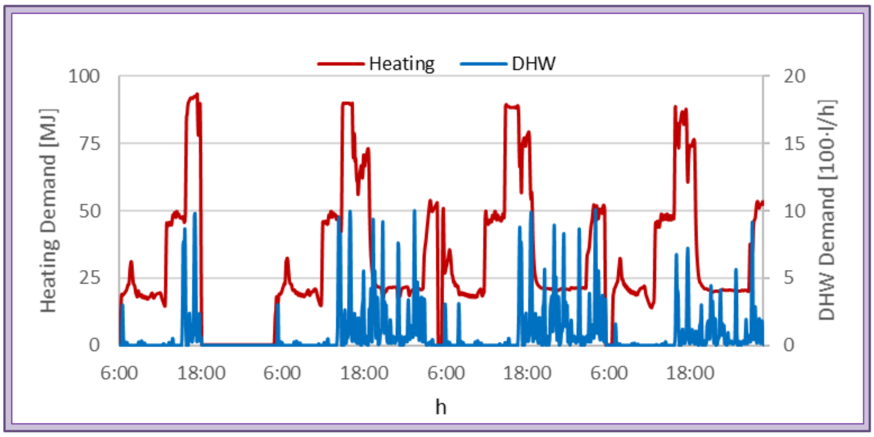

Figure E. 5 Heating and DHW demand to be covered by the facility

As discussed in **Section B**.3.1., the mathematical characterization equation of every component has been obtained by means of Trnsys and Matlab combination. The relative error between the experimental data and the simulation results is less that ± 3 % for each individual component of the facility. However, when all the subsystems are linked, the maximum error for the total facility is lower than ± 9 %. This is larger than the error for the individual components, because the uncertainty raises when all the components are simultaneously modelled.

E.3.1. Conventional Exergy Analysis

A conventional exergetic analysis serves to calculate the exergy destruction of each component ($E_{D,k}$) in every time-step. Nevertheless, the same can be assessed by applying an exergy balance for each component and the entire system.

Figure E. 6 illustrates the total exergy destruction in the 4-day period ($E_D^{TOT} = 1259\ kWh$) as well as the percentages of the contribution of exergy destruction within different components to the total exergy destruction. The causes of $E_{D,k}$ in all components are individually justified in **Section E**.2.3.1 and summarized in Table E. 2.

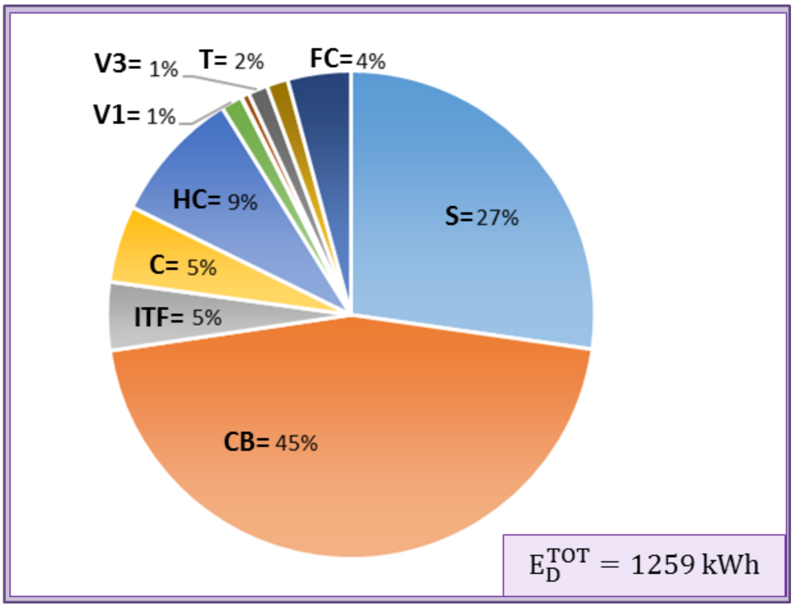

Figure E. 6 Average contribution of $\boldsymbol{E_{D,k}}$ in each component to the overall exergy destruction

As expected, components including a combustion process have by far the highest exergy destructions. Due to the previously explained control strategy, CB works as a back-up device and its operating hours are thus less than S. However, 46 % of the overall exergy destruction occurs in CB and only 27 % in S. One reason that $E_{D,S}$ is much lower than $E_{D,CB}$ is because S generates heat and electricity simultaneously, so that its exergetic efficiency is much higher than ε_{CB}. Another reason is that CB has a higher nominal capacity than S.

Following the instructions written in **Section E**.2.3.1, in item (S/CB), those destructions are separated into the following groups according to their causes: (a) friction, (b) mixing, (c) chemical reactions and (d) heat transfer. The results show that almost all the irreversibilities belong to the last two categories, being nearly 59.7 % and 64.3 % due to chemical reactions in S and CB, respectively, and 40.2 % and 35.6 % because of the heat transfer inefficiencies in S and CB, respectively (see Figure E. 7).

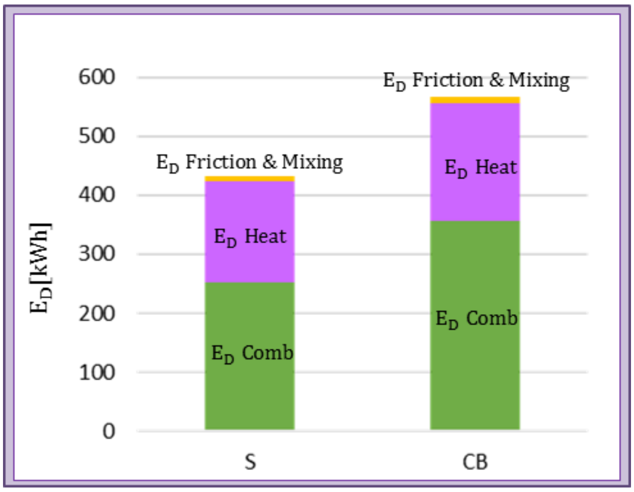

Figure E. 7 Exergy destruction distribution for the combustion engines based on the Ref. [22]

E.3.2. Unavoidable / Avoidable E_D

The unavoidable and avoidable E_D of each component were dynamically calculated following the guidelines outlined above and the average percentage results are presented in Figure E. 8.

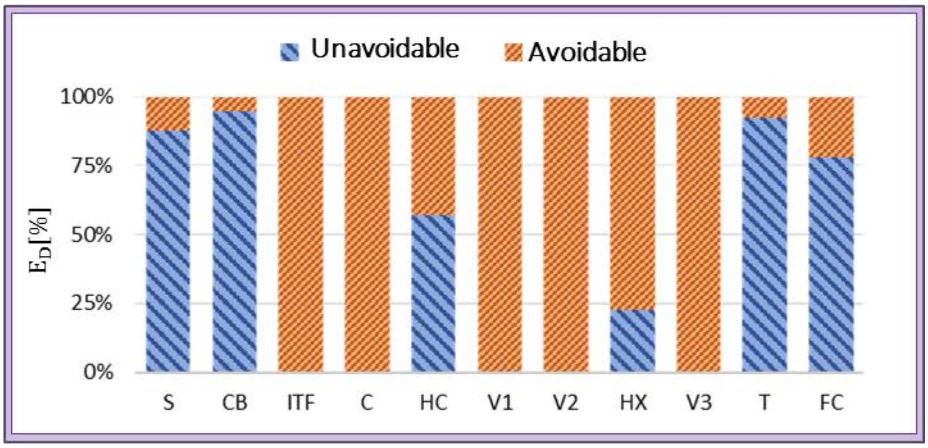

Figure E. 8 Percentage of unavoidable and avoidable exergy destructions in each component of the experimental facility

As it can be seen, the E_D^{UN} within the components are quite larger than the avoidable one (E_D^{AV}). For example, in S and CB, approximately 88 % of the exergy destruction is unavoidable, because when destructions on chemical reactions are reduced, the internal heat transfer irreversibilities are however increased, due to the rise of the combustion temperature.

The average results of the conventional exergy analysis together with the DAEA are listed in Table E. 4.

Table E. 4 Average results of the DAEA and the conventional exergy analysis

Component k	F_k [kWh]	P_k [kWh]	ε_k [%]	$E_{D,k}$ [kWh]	$E_{D,k}^{UN}$ [kWh]	$E_{D,k}^{AV}$ [kWh]
S	456.01	111.77	25%	344.24	302.67	41.56
CB	665.36	91.44	14%	573.92	542.62	31.30
ITF	116.75	59.31	51%	57.44	0.00	57.44
C	180.30	115.29	64%	65.01	0.00	65.01
HC	146.93	35.01	24%	111.92	63.99	47.93
V1	94.39	76.61	81%	17.78	0.00	17.78
V2	234.41	233.74	100%	0.68	0.00	0.68
HX	29.24	22.78	78%	6.46	1.47	4.99
V3	84.80	68.50	81%	16.30	0.00	16.30
T	32.77	14.97	46%	17.80	16.49	1.31
FC	65.33	12.34	19%	53.00	41.32	11.68

As a consequence of the facility's physical model, the values of E_D diminish significantly after the HC component, that is to say, the irreversibilities decrease a lot once the energy passes through the HC component. This can be easily explained because after that unit, the downstream components are split into the DHW branch and the heating branch, so they are dealing with a lower flow of energy (and exergy), and therefore, less exergy destruction takes place.

E.3.3. Endogenous/ Exogenous E_D

The contribution of endogenous and exogenous exergy destructions within different components for the 4-day test are illustrated in Figure E. 9.

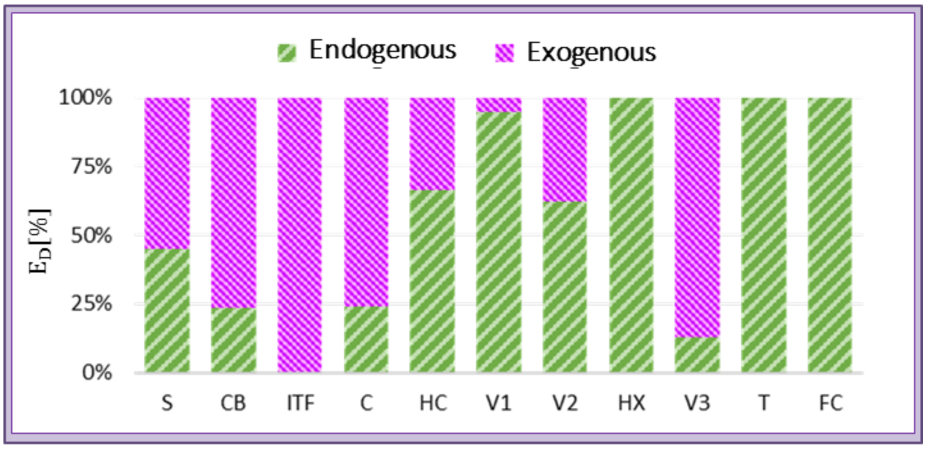

Figure E. 9 Share of endogenous and exogenous exergy destructions in each component

As noted above, the closer the components to the final products, the lower the amount of their exogenous exergy destruction. In other words, due to the fact that the main product of the system remains constant $\left(E_{P,TOT} = P_{DHW} + P_{Heat}\right)$, if the downstream components cause additional exergy destruction, the upstream components need to produce more output to offset those additional irreversibilities; that situation results in a larger E_D in those upstream components. This is the main reason that explains the high value of E_D^{EX} in both heat generator engines.

Having no productive purpose, the exergy destruction in ITF is completely exogenous. On the contrary, the exergy destruction in the heat exchanger (HX), storage tank (T) and fan coil (FC) are entirely endogenous, because those components are located at the end of the energy supply chain and are connected to the final product of the system directly.

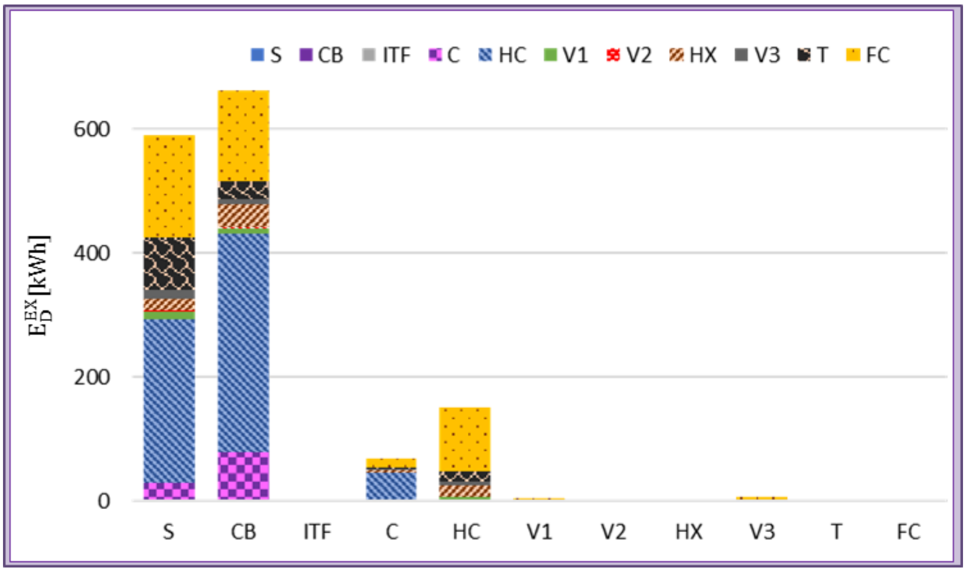

Figure E. 10 Average Binary exogenous exergy destruction of every component

The exogenous exergy destruction in every component can be split to consider the contributions from each other component by using the binary interrelation approach. Figure E. 10 displays those binary interactions in terms of exergy destruction, colored according to the component associated with its origin.

As expected, FC is the component with a noticeable contribution to the exogenous E_D in the upstream components, not only because it is located at the end of the heating branch, but also because of its very large endogenous exergy destruction.

E.3.4. Considering Real Characteristic Curves

A step forward in the application of DAEA is the calculation of endogenous exergy destruction within every component based on the real exergetic efficiency of this component (ε'_k), instead of using a constant one, when the thermodynamic state of the system changes at every time step. The difference between the endogenous exergy destruction obtained from the above-mentioned method and the one calculated based on the decomposition approach ($\Delta E_{D,k}^{EN}$) indicated that, in some cases, dealing with constant ε for calculation of $E_{D,k}^{EN}$ is rather a simplifying assumption that might lead to controversial results.

Figure E. 11 compares the values of $E_{D,k}^{EN}$ and $E_{D,k}^{EN^*}$ for different components of the system.

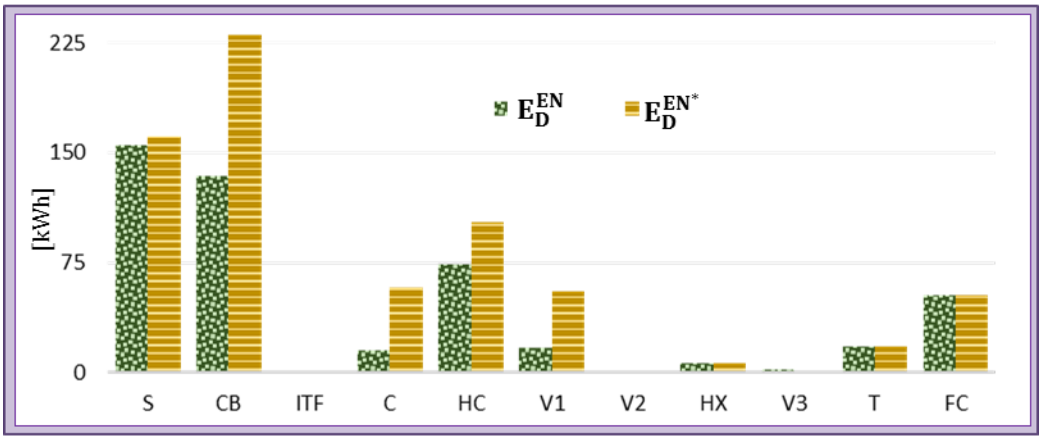

Figure E. 11 Endogenous exergy destruction of every component obtained from the decomposition method ($E_{D,k}^{EN}$) and from the real characteristic curves ($E_{D,k}^{EN^*}$)

The major difference is found in the condensing boiler, because its real exergetic efficiency curve, ε'_{CB}, is not flat and decreases significantly when the demand decreases. Other components with relatively large $\Delta E_{D,k}^{EN}$ are the supply and return collectors (C) and the hydraulic compensator (HC), because their endogenous exergy destructions, caused mainly by mixing of fluids with different temperatures, changes significantly at different operating conditions. For the remaining components the endogenous exergy destruction is similar in both methods.

E.3.5. Combination of the UN/AV, EN/EX Parts of Exergy Destruction

Table E. 5 Detailed aggregated results obtained from the DAEA

Comp. k	E_D [kWh]	Unavoidable		Avoidable	
		$E_D^{UN,EN}$ [kWh]	$E_D^{UN,EX}$ [kWh]	$E_D^{AV,EN}$ [kWh]	$E_D^{AV,EX}$ [kWh]
S	302.67	149.25	153.43	5.67	35.96
CB	542.62	125.39	417.23	8.41	22.28
ITF	0.00	0.00	0.00	0.00	57.16
C	0.00	0.00	0.00	15.36	49.13
HC	63.99	48.41	15.58	25.58	22.29
V1	0.00	0.00	0.00	16.87	0.91
V2	0.00	0.00	0.00	0.40	0.25
HX	1.47	1.49	0.00	4.97	0.00
V3	0.00	0.00	0.00	2.11	14.21
T	16.49	16.13	0.00	1.67	0.00
FC	41.32	39.55	0.00	13.44	0.00

Finally, new findings can be identified when unavoidable and avoidable exergy destructions are combined with the endogenous and exogenous exergy destructions. Detailed results from the

DAEA application to the experimental building thermal facility for a period of 4 days are given in Table E. 5; the upgrading prospective of each component can be there detected.

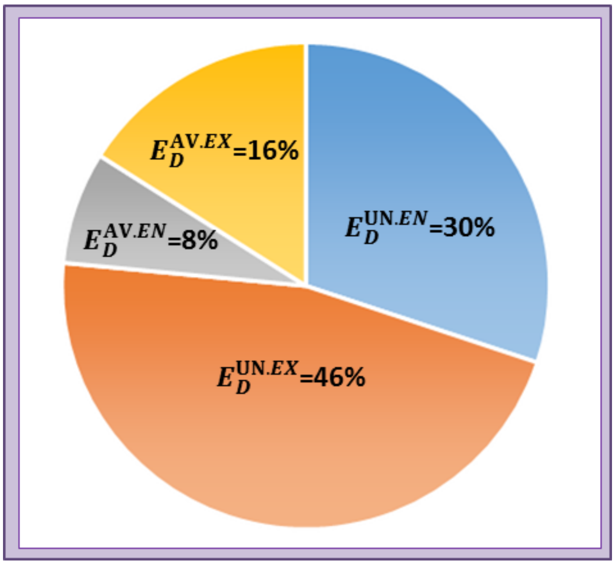

Figure E. 12 Contributions of $E_D^{UN.EN}$, $E_D^{UN.EX}$, $E_D^{AV.EN}$, $E_D^{AV.EX}$ to the total exergy destruction in the whole system

Similarly, Figure E. 12 depicts in a comprehensive manner the portions of the four possible combinations in the entire system.

It can be seen that more than three quarters of the overall exergy destruction is unavoidable, 39 % of it being due to the components' internal limitations, while the remaining 61 % are due to the interactions among components and to system structural restrictions.

Concerning the avoidable exergy destruction, only 8% of the total E_D can be reduced by using the best technological alternatives currently feasible in the market, whereas 15 % of the global exergy destruction can be avoided by improving the interrelations among components of the system, through, for example, customizing / improving the control system.

In summary, the results obtained from the DAEA indicate that the improvement potential of the system is rather low and limited. Likewise, the fact that $E_D^{AV.EX}$ is higher than $E_D^{AV.EN}$ proves that the interdependencies among system components are relatively strong, and, therefore, priority for the improvement should be given to a better control strategy in order to enhance the overall efficiency. Nevertheless, it must be noted that $E_D^{AV.EX}$ considers both, the interconnections between components as well as the imperfections coming from the others, because they are not using the best equipment available in the current market.

All this obtained information should be used for control strategy optimization, or fault detection approach, or even design optimization.

E.4. CONCLUSIONS

For the first time, a Dynamic Advanced Exergy Analysis (DAEA) was applied to a building thermal energy system. Buildings are major contributors to the primary energy demand, so that the awareness of their improvement potential is an essential requirement for reducing energy demand and CO_2 emissions. That assessment can be made through a DAEA application, as presented in this chapter.

A DAEA allows engineers to determine which irreversibilities could be avoided in the current technical limitations, by splitting the exergy destruction into avoidable and unavoidable parts. Moreover, a DAEA identifies the inefficiencies caused by the component itself as well as those coming from the imperfections of the remaining components using the concepts of endogenous and exogenous exergy destructions. Consequently, it provides very useful information that cannot be achieved through a conventional exergetic analysis.

Nevertheless, even with the attractiveness of that analysis, some shortcomings need to be mentioned. First, the calculation of unavoidable exergy destruction is associated with some subjectivity during its estimation. Even so, this standpoint depends also on the engineers' judgement; so, accordingly, the chosen criteria are explained in detail and justified throughout this chapter.

Besides, when endogenous and exogenous E_D are calculated, some information might be lost if some real thermodynamic quantities, such as a varying exergetic efficiency are not considered. However, that can be overcome by the incorporation of the real characteristic curves of the components.

Finally, apart from the insight that a detailed distribution of the exergy destruction E_D can provide, one of the advantages in the application of DAEA is that there is no need to predefine any reference conditions to evaluate the performance of a system. Hence, it is a generic method that can be used for control, diagnosis or even design purposes. In addition to that, as exergy destruction is employed as the base parameter, the real involvement of every component within the overall system is regarded. This implication should not be noticed if exergetic efficiency (ε) would have been taken instead; as it can happen that, even if the upstream components have higher efficiencies than the downstream ones, the exergy destruction is much higher in the former than in the latter group, due to the bigger amount of exergy those components deal with. That is the case, for example, of the supply and return collector (C) and the fan coil (FC). As a result, some information can be misinterpreted if the E_D is not used.

Moreover, one of the innovative features of this chapter is associated with the dynamism used in the DAEA, since a steady state can never be related to building energy supply facilities.

To conclude, a DAEA elaborately resolves the way to allocate the inefficiencies of a system within its components, by considering both, the internal irreversibilities as well as those due to the interconnections between components. Owing to the dynamic character, its application in building facilities seems to be more complicated than in systems where a steady state operation can be assumed; despite that, a DAEA can be equally applied by merely adjusting some assumptions. Therefore, a step forward on the reduction of the energy use can be achieved by using the information provided by this analysis.

The future steps should be the economic quantification of those results as well as the environmental impact calculation, or what is the same, the translation from exergetic units to the monetary and CO_2 emission ones. That can be performed with the aid of exergoeconomic and exergoenvironmental analyses of **Chapter C**. Likewise, DAEA can be also implemented in a diagnosis application.

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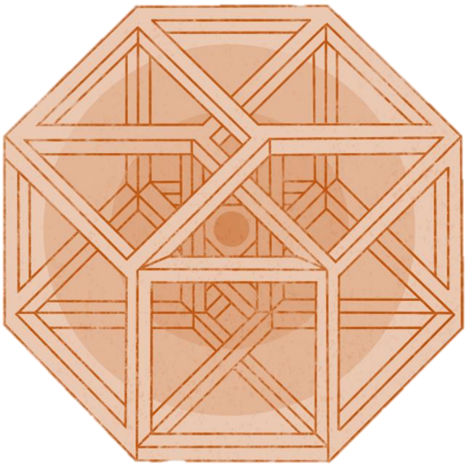

CONCLUSIONS

Contributions • Future Lines

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CONCLUSIONS • CONTRIBUTIONS • FUTURE LINES

The core challenge of the thesis is to introduce thermoeconomic dynamic analyses in buildings energy systems. For that, the guiding principle is based on the idea that the application of any theory must be judgmentally examined, from base statements until arriving to adjustable alternatives.

Actually, the building sector provides the perfect backdrop for the pioneering dynamic applications of Second Law analyses. After all, energy saving in buildings is an imperative worldwide need and exergy-based theories go along with that purpose.

Following such assignments, the introductory **Chapter A** justifies the use of *exergy* by concluding that exergy based efficiencies describe better the resource utilization as well as the connection between energy qualities, which is a key indicator for systems synthesis and optimization. Besides, it indicates that energy based analyses can derive to controversial or even misleading results whether the exergetic analyses enable homogenizing the flows in terms of energy quality and making the comparison between components and systems more reliable. Unfortunately, as mentioned along such chapter, studies that connects buildings with exergy barely exists because the difficulties of the implementation, which are, indeed, resolved during this thesis.

Thus, according to the buildings field, dynamism is the mainstay so steady state studies are senseless and variable approaches are, by contrast, the backbone of any analysis (even if the large bibliography seldom contemplates such statement). Because of that, thermoeconomic analyses must be adapted to every specific circumstances and all the steps of the implementation must be carefully analyzed to enforce properly the theory and to interpret right the results. Figure F. 1 collects the main objectives achieved during the development of the thesis.

Accordingly, **Chapter B** justifies the use of *dynamic thermal models* and proposes two new methodologies: one for configuring non-existing systems and the other one for simulating monitored facilities. As substantiated, the First Law modelling is a crucial previous step for the Second Law further implementations.

Although the basic use of exergy does not enable to allocate the evolution of consumptions and costs, its combination with economic perspective gives the picture of cost formation process. Moreover, *Symbolic Thermoeconomics* (ST) allows conducting such analysis in a generic way using exergy as the weighted factor of each irreversibility over the global resources consumption. As a groundbreaking income, **Chapter C** explains the manner to applicate dynamically ST in buildings referring, as deeply as possible, the ins and outs and the attainable readings according to the analyst target and criteria. To achieve such aim, a super-structure layout is proposed which is each time step adjusted to the current configuration of the facility.

Nevertheless, the definition of a dynamic productive structure can be ambiguous and, therefore, one of the mayor barriers of thermoeconomic application. In addition, it is concluded that *exergetic cost* minimization should be considered as a goal but the route should be based on the modification of the design elemental parameters.

As a practical attained goal, the **Annex** develops a dynamic software based on Thermoeconomics for the supervision of buildings thermal real facilities. However, the big obstacle is that the accuracy of the results are directly proportional to the number of sensors.

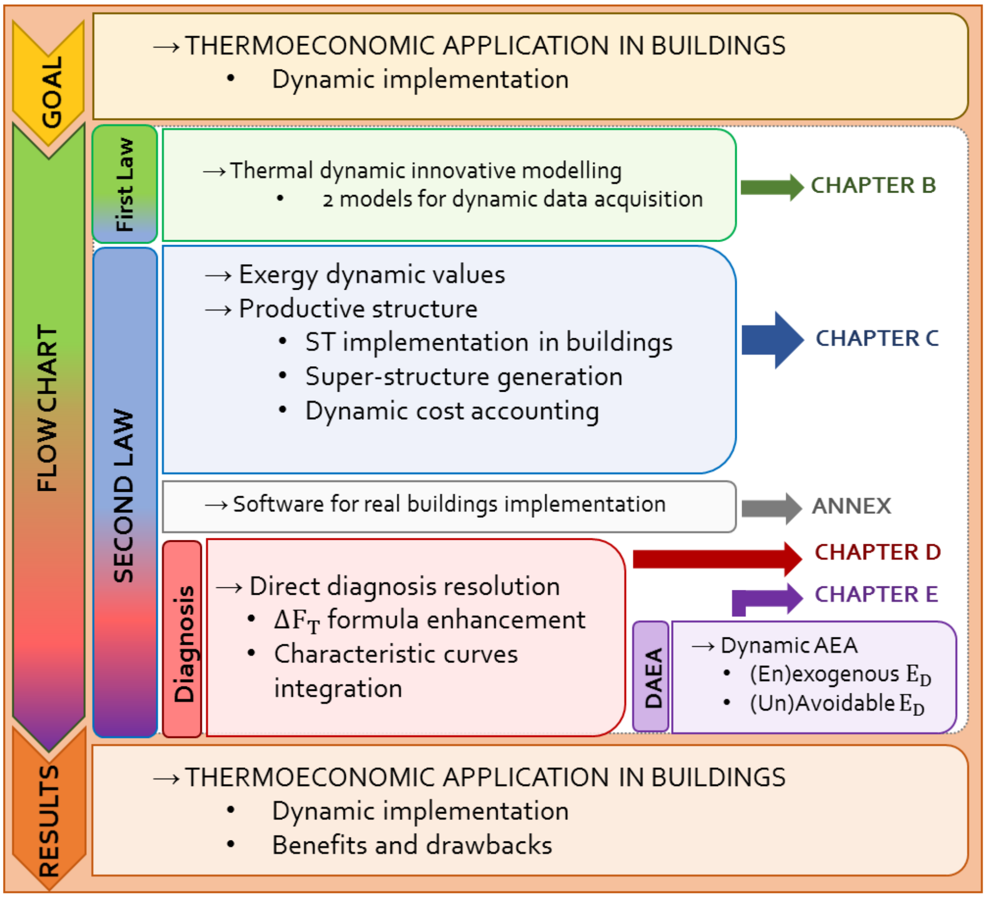


Figure F. 1 Work flow according to the thesis objectives

Another target fulfilment is the Second Law implementation for diagnosis in buildings systems, since, if thermoeconomic information is added, even not strictly necessary to detect faults, the information for identifying the importance of anomalies is obtained. To begin with, the common used fuel impact formula is discerningly analyzed and enhanced through the combination of characteristic curves.

Thereby, in **Chapter D** for the first time dynamic direct *thermoeconomic diagnosis* problem is solved in real systems (i.e. determining an anomaly according to the produced symptoms); inasmuch as, until this thesis, previous thermoeconomic diagnosis studies were mainly done by previously determining the fault and after quantifying their effects. Once more, the advantages and drawbacks of the theory are exposed and specific case studies validate the new theory. Consequently, the suggested diagnosis methodology not only detects the malfunctions but also the provoked effects to make possible the decision for the treatment.

Another Second Law based analysis choice is the *Dynamic Advanced Exergy Analysis* (DAEA) that identifies the inefficiencies caused by the component itself as well as those coming from the imperfections of the remaining components using the concepts of avoidable/unavoidable and endogenous/exogenous exergy destructions. Moreover, one of the leading features of the **Chapter E** is associated with the dynamism used in the DAEA. Yet again, benefits and difficulties are intensely summarized.

Apart from the theoretical contributions, seven building energy systems case studies are used to accomplish the indicated objective of the thesis.

- (i) nZEB Building Case Study
- (ii) Building Retrofit Case Study
- (iii) School's AHU Case Study
- (iv) Simple DHW facility
- (v) Solar Energy Building System Case Study
- (vi) Heating & DHW System Case Study
- (vii) Stirling and Condensing Boiler Case Study

Likewise, as justified, the thermodynamic data needed for any Second Law application are the same as for the common energetic studies (temperatures, mass flows, concentrations, etc.) but exergy aggregated variables are used instead. Thus, it is a second step analysis but it offers an additional information for a more comprehensive understanding of the energy systems.

Accordingly, this research implies a position of healthy skepticism, which means an attitude of prudence against the already assigned ideas and theories of the Second Law analyses. As a general result, although the difficulties, thermoeconomic application is worthwhile and precious tool for decision-making. Thanks to it, the objective of energy saving and environmental caring can be progressively achieved.

CURRENT RESEARCH CONTRIBUTIONS

The following Table F. 1 and Table F. 2 collect the contributions (by means of publications and congresses) provided during the PhD period that gives robustness to the content of the thesis. Each one is linked to the corresponding chapter topic.

Table F. 1 Contributions of the thesis by means of international journals and books

PUBLICATIONS & SCIENTIFIC TECHNICAL DOCUMENTS		
RELATED TO	INFO.	CONTENT
Chapter A Chapter C	**Title:** **Authors:** **Journal:**	A Symbolic Exergoeconomic study of a retrofitted heating and DHW facility Picallo-Perez A., Sala-Lizarraga J. M., Iriba-Solabarrieta E., Hidalgo-Betanzos Juan M. *Sustainable Energy Technologies and Assessments, 27, 119-133. (2018)*
Chapter A Chapter C	**Title:** **Authors:** **Book:**	New Exergetic Methodology to Promote Improvements in nZEB Picallo-Perez A., Hidalgo-Betanzos Juan M., Sala-Lizarraga J. M. *Application of Exergy*, 978-1-78923-267-7
Chapter D	**Title:** **Authors:** **Journal:**	A comparative analysis of two thermoeconomic diagnosis methodologies in a building heating and DHW facility Picallo-Perez A., Sala-Lizarraga, J. M., Escudero-Revilla C. *Energy and Buildings 146 160–171 (2017)*
Chapter D	**Title:** **Authors:** **Journal:**	Application of the malfunction thermoeconomic diagnosis to a dynamic heating and DHW facility for fault detection Picallo-Perez, A., Sala-Lizarraga, J. M., Iribar-Solabarrieta, E., Odriozola-Maritorena, M., & Portillo-Valdés, L. *Energy and Buildings*, Vol *135*, Pages 385-397 (2017)
Chapter D	**Title:** **Authors:** **Journal:**	Thermoeconomic Approach to the Diagnosis of A DHW Microcogeneration Plant Picallo-Perez, A., Iribar-Solabarrieta, E., Apaolaza A. & Sala-Lizarraga, J. M. *Modern Environmental Science and Engineering, Vol 2 Number 8, Pages 507-514 (2016)*
Chapter C	**Title:** **Authors:** **Journal:**	Symbolic Thermoeconomics in building energy supply systems Picallo, A., Escudero, C., Flores, I., & Sala, J. M. *Energy and Buildings. Vol 127, Pages 561-570 (2016)*

Table F. 2 Contributions of the thesis by means of congresses

CONTRIBUTIONS TO SCIENTIFIC CONFERENCES		
RELATED TO	INFO.	CONTENT
Annex	**Title:**	Software for the supervision of heating and DHW facilities through Exergoeconomics application
	Authors:	Picallo-Perez A., Renilla R., Heredia M., Sala Lizarraga J.M
	Congress:	*VIIII European Conference on Energy Efficiency and Sustainability in Architecture a Planning + II Advanced Construction Congress (2018, Bilbao, Spain)*
	AWARD:	**BEST PAPER AWARD**
Chapter B Chapter C	**Title:**	Thermoeconomic analysis under dynamic operating conditions for space heating and cooling systems in an educational building
	Authors:	Picallo-Perez A., Catrini P., Piacentino A., Sala Lizarraga J.M
	Congress:	*The 13th Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES (Palermo, Italy)*
Chapter C	**Title:**	Application of Thermoeconomy for an intelligent management of air conditioning systems
	Authors:	Picallo-Perez A., Sala Lizarraga J.M, Pérez-González D., Gomez-Elvira I
	Congress:	*VIII European Conference on Energy Efficiency and Sustainability in Architecture a Planning + I Advanced Construction Congress (2017, San Sebastian, Spain)*
Chapter A	**Title:**	Nueva metodología para fomentar mejoras en EECN *New methodology to promote improvements in nZEB*
	Authors:	Picallo-Perez A., Hidalgo-Betanzos J.M, Sala Lizarraga J.M
	Congress:	IV Congreso Edificios Energía Casi Nula 2017 *(2017, Madrid, Spain)*
Chapter C	**Title:**	Symbolic thermoeconomic analysis in a nZEB cogeneration facility for heating and DHW supply
	Authors:	Picallo-Perez A, Perez D, Ruiz de Laramendi X, Sala Lizarraga J.M.
	Congress:	*10CNIT. 10º Congreso Nacional de Ingeniería Termodinámica (2017, Lleida, Spain)*
Chapter C	**Title:**	Análisis exergético y cálculo de costes en una instalación geotérmica para calefacción y ACS del Pais Vasco *Exergetic analysis and costs assessment in a geothermal facility for heating and DHW in the Basque Country*
	Authors:	Perez D, Picallo-Perez A, Ruiz de Laramendi X, Sala Lizarraga J.M.
	Congress:	*V Congreso de Energía Geotérmica en la Edificación y la Industria (2017, Madrid, Spain)*
Chapter C	**Title:**	Thermoeconomics, a tool for improving sustainability in buildings
	Authors:	Picallo A., Iribar E., Martin A., Hernandez A., Sala J.M.
	Congress:	*VII European Conference on Energy Efficiency and Sustainability in Architecture a Planning (2016, San Sebastian, Spain)*
Chapter D	**Title:**	Thermoeconomic approach to the diagnosis of a DHW Microcogeneration plant
	Authors:	Picallo A., Perez-Iribarren E., Sala J.M., Apaolaza A.
	Congress:	*12th REHVA World Congress CLIMA 2016 (2016, Aalborg, Denmark)*
Chapter B	**Title:**	Testing and analysis of the results of a condensing boiler and solar collectors hybrid installation for heating and DHW
	Authors:	Picallo A., Perez-Iribarren E., González-Pino I, Heras J., Sala J.M.
	Congress:	*VI European Conference on Energy Efficiency and Sustainability in Architecture a Planning (2015 San Sebastian, Spain)*
Chapter B	**Title:**	Planta experimental para ensayos de instalaciones térmicas híbridas *Experimental Plant for testing thermal hybrid facilities*
	Authors:	Picallo A., Perez-Iribarren E., González-Pino I, Heras J., Sala J.M.
	Congress:	*Climatización 2015 (2015, Madrid, Spain)*

Besides, a book entitled "*EXERGY ANALYSIS AND THERMOECONOMIC OF BUILDINGS – design and analysis for sustainable energy systems*" written with Pr. José María Sala-Lizarraga is accepted and in editing process with the international ELSEVIER INC. renowned company.

Other two papers related to **Chapter D** and **Chapter E** are in the way of being published by international journals, named:

"DYNAMIC ADVANCED EXERGY ANALYSIS IN BUILDING HEATING SYSTEMS –Dynamic Modelling, Avoidable/Unavoidable, Endogenous/Exogenous and Mexogenous Exergy Destruction Assessment" Picallo-Perez Ana, Sala Jose Mª, Tsatsaronis George, Sayadi Saeed.

"OVERVIEW AND IMPLEMENTATION OF DYNAMIC THERMOECONOMIC & DIAGNOSIS ANALYSIS IN HVAC&R SYSTEMS" Picallo-Perez Ana, Lazzaretto Andrea, Sala Jose Mª.

FUTURE LINES OF RESEARCH

Although the work of this thesis ends here, it opens the way for future lines of research with the common goal of achieving an even greater energy savings in buildings:

According to the practical application of the investigation, the proposed thermoeconomic software can be considerably refined: a non-charge application should be built rather than a combination of the license needed Matlab and Excel. In addition, the speed of calculation, programming, processing, etc., can be potentially enhanced to create an easy-use and versatile tool for cost accounting.

Besides, thermoeconomic diagnosis can be included in the same software. Ultimately, once the reference system is defined, thermoeconomic diagnosis does not require extra data compared to the previous cost accounting. Such program can become a firm management tool for buildings maintenance and optimization, inasmuch as it locates the system anomalous behaviors and avoids unwanted interruptions or penalties in costs.

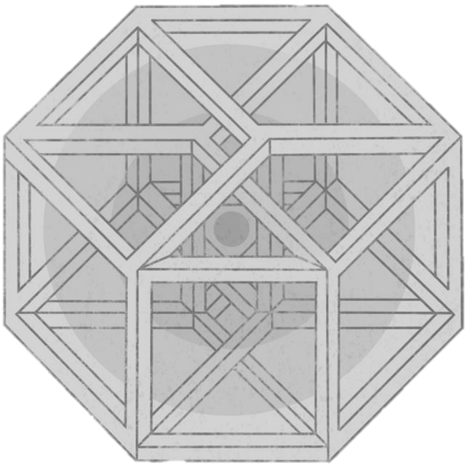
Notwithstanding the suitability of the software for optimization and maintenance purposes in buildings energy systems, the main constrain is the limitation of sensors that obstruct the real-time monitoring and reaction. Therefore, more measuring devices should be integrated in building energy system to make feasible their proper and optimal management.

Another prospect deals with the improvement of the direct diagnosis problem since, being a recent finding, residues are not taken into account during the research. Hence, the next step can be the incorporation of dissipative components to consider all the possibilities in building systems.

Ventilation systems, for example, are essentially dissipative facilities that are extending more and more in the residential and tertiary sector because of the indoor air quality requirements. Unfortunately, they are very complex systems and their thermoeconomic behavior is diffusely treated. Indeed, the central idea is to consume external resources to extract the indoor processed air (and therefore, an airflow with a cost) and replace it with another flow of the outside (which should be previously treated to meet the comfort conditions). Thus, the objective of the ventilation is to pay/consume for destroying exergy; so that, an anomaly in ventilation system would be associated with less exergy destruction, an issue that seems contradictory and should be deeply investigated.

Apart from that, a brief comment of exergoenvironment application was given along the work. Correspondingly, environment impact quantification can also be a further complementary research in order to obtain the global energetic, economic and environmental picture of the system. As said, its implementation is analogous to the explained one but Life Cycle Analysis information is required too. In such case, the analysis would be performed *from cradle to grave.*

Lastly, because of the giving reasons, EU Directives as well as provincial governments should consider the incorporation of exergy analyses to obtain the additional useful information and to get faster the pointed objectives. After all, the conclusions of this thesis support the Second Law analyses and suggest them as an appropriate tool for helping to clarify the worldwide concerns.



ANNEX

Software for thermoeconomic dynamic calculation

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ANNEX: SOFTWARE FOR THERMOECONOMIC DYNAMIC CALCULATION

Annex.0. OBJETIVES

The aim of this Annex is to describe a generic software for the supervision and cost accounting of thermal facilities in buildings following the theory and guidelines of **Chapter C**. By means of Thermoeconomics the costs of products (heating, cooling, DHW, etc.) are accounted as well as the costs of internal flows at each time interval according to the established control strategy. Therefore, the true losses and the performances of every component are evaluated.

Hitherto, the program is composed by the combination of Matlab, where the calculations are done, and Excel, where the data are registered and results are exhibited. The workflow consists of three phases, as outlined in Figure Annex. 1:

1. Symbolic definition of the general parameters of the system (only once, at the beginning).
2. Numerical values (each time-step).
3. Calculations and results obtainment (each time-step).

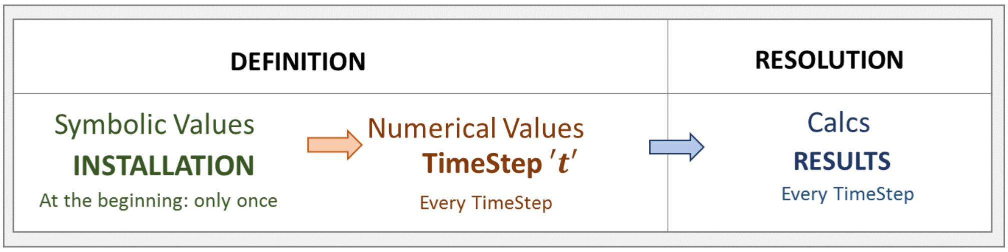


Figure Annex. 1 The three main phases of the program

As indicated in Figure Annex. 1, the first two phases (symbolic and numerical determination) refer to the definition of the installation; the third phase consists of solving matrices.

The preceding step deals with the definition of the required system symbolic definition in Excel, or what is the same, the specification of the *generic static structure* of the system. Afterwards, numerical data are inserted and calculations are done every time-step by means of Matlab. From that, *dynamic productive structure* is derived; the respective results are then copied to Excel.

Annex.1. SYMBOLIC VALUES

This section is done only once at the beginning in the interface of Excel and refers to the symbolic determination of the *static structure* of the facility. As developed in **Section C**.3, such structure includes all the possible configurations of the system and it is enough with annulling the not participating flows to meet the active dynamic structure at every time-step.

Annex.1.1. Determination of the installation

The first stage is the system configuration data filling, see Table Annex. 1. Accordingly, the system flows are numbered from 1 to i.

Table Annex. 1 Whole system main configuration

Productive Components	n	Total Flows	i	External Inputs	e
Dissipative Components	d	Residue Outputs	r	Useful output products	s

Likewise, the inputs (e) and outputs (s and r) are defined according to their i numbering. Besides, inputs are related to their 'TYPE' and the 'Ext. Val' (external valuation) characteristics.

- The section 'TYPE' refers to the resource nature (see Table Annex. 2 (b)).
- The section 'Ext. Val' is associated with the external valuation, that is, if no external valuation is connected with that input '1' is written whereas the respective value is written in the opposite case.

Table Annex. 2 (a) External input and output characterization (b) Resource type naming (c) External valuation

	EXTERNAL RESOURCES				
	F_e	TYPE	Ext.Val.	P_s	
1	e_1			s_1	1
...	...			...	...
e	e_e			s_e	s

TYPE	
0	-
1	ELEC
2	DHW
3	NG
4	GASOIL
5	BIOMASS
6	OTHER

Ext.Val.	
1	NO
Value	YES

The next step is based on every n subsystem identification through its physical and productive structure, see Table Annex. 4.

- For determining the *physical structure*, the incoming flows are determined by the corresponding i flow number in the first column while the outgoing flows are written in the second one.
- Later on, each component is represented as a black box in the table of the *productive structure* with an entry corresponding to F and an output P (or R) composed by the combinations of incoming and outgoing physical flows; firstly, productive components are defined and, after, dissipative elements. Accordingly, the different F, P and R are delimited trough brackets '[ ]' regarding the flow number. That is, within the brackets the flow or set of flows that determines each of the resources or products appear.

Table Annex. 4 Determination of static physical and productive structure

	PHYSICAL STRUCTURE		PRODUCTIVE STRUCTURE		
	INPUTS	OUTPUTS	FUEL	PRODUCT	
1	$\sum i_{in_1}$	$\sum i_{out_1}$	$[i^1_{F_1}] + [i^2_{F_1}] + \cdots$	$[i^1_{P_1}] + [i^2_{P_1}] + \cdots$	1
...	...	...	...	...	...
n	$\sum i_{in_n}$	$\sum i_{out_n}$	$[i^1_{F_n}] + [i^2_{F_n}] + \cdots$	$[i^1_{P_n}] + [i^2_{P_n}] + \cdots$	n

Moreover, if exergetic and energetic F, F^{En} and P, P^{En} symbolic definition are different (as in the case of (iii) *School's AHU Case Study* of **Chapter C**), the analogous Table Annex. 3 needs to be filled but for energy terms.

Table Annex. 3 Determination of static physical and productive structure in Energy units

Do they have a different EXERGETIC and ENERGETIC structure? (YES = 1 / NO = 0)	1

	EN. PHYSICAL STRUCTURE		EN. PRODUCTIVE STRUCTURE		
	INPUTS	OUTPUTS	FUEL	PRODUCT	
1	$\sum i_{in_1}$	$\sum i_{out_1}$	$[i^1_{F_1^{en}}] + [i^2_{F_1^{en}}] + \cdots$	$[i^1_{P_1^{en}}] + [i^2_{P_1^{en}}] + \cdots$	1
...	...	...	...	...	...
n	$\sum i_{in_n}$	$\sum i_{out_n}$	$[i^1_{F_n^{en}}] + [i^2_{F_n^{en}}] + \cdots$	$[i^1_{P_n^{en}}] + [i^2_{P_n^{en}}] + \cdots$	n

Annex.1.2. Determination of the external information

Table Annex. 5 Costs and economic data of input resources and components

RESOURCES	[c€/kWh eNergy]	Quality Factor
Electricity	21,81	1
Mains water [€/m3]	0,52	-
Natural Gas	5,27	1,04
Gasoleo	9,43	1,04
Biomass	4,10	1,03
Other	0	1

ECONOMIC DATA	
i = annual effective interest	0.05
n= useful life of the system (years)	20
Capital recovery factor	0.08

	ACQUISITION COST [€]
1	
...	...
n	

The calculation of exergoeconomic costs needs external information. Therefore, the unit economic costs [€/kWh] of the e resource inflows (fuel, electricity, cold water, etc.) is needed, as well as the vector of the acquisition, operation and maintenance costs [€] of the n components.

Other economic data are also needed, such as the effective interest and the useful lif e of each component; all this information is included in Table Annex. 5. It should be noted that if the costs of the resources vary each time-step, these tables should be updated.

Annex.2. NUMERICAL VALUES AND CALCULATIONS

Once defining the static productive structure, numerical data and the respective results are extracted every time-step. These phases are divided into four main steps, as indicated in Figure Annex. 2:

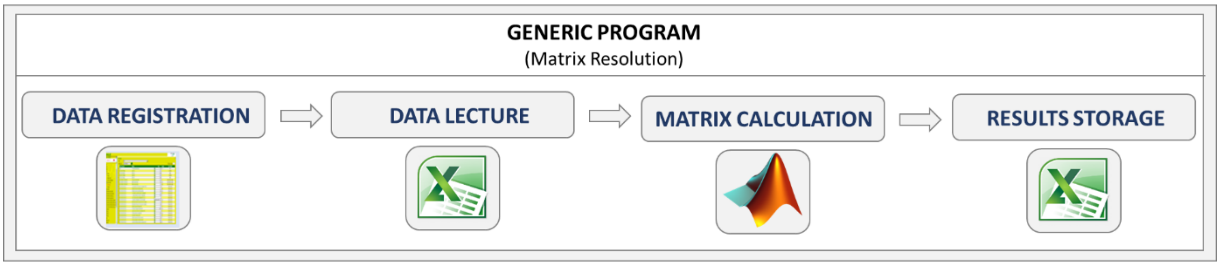


Figure Annex. 2 Disaggregation of the generic program

1. Transfer and validation of monitored or simulated data.
2. Exergy calculations and data reading (from Excel).
3. Selection of the active dynamic structure, matrix calculations and results obtainment (through MATLAB).
4. Record and results analysis.

The initial step refers to the recording of the data from the sensors or from simulation. In addition, its noise filtering and validation is done. When the data of all the sensors are written in the Excel, the corresponding exergy flows are calculated according to their symbolic formula (there can be flows with zero value).

Afterwards, the identification of the active mode of operation in the precise time-step is made, that is, the components participating at that moment are detected. In this way, the *physical* and *productive dynamic structure* of the installation corresponding to that time-step are defined. As known, the activation/deactivation of the equipment is made depending on the position of the pumps and three-way valves (i.e. according to the annulated flows).

The internal program of Matlab identifies among the subgroups the active n_i^{ON}, d_i^{ON}, i_i^{ON}, r_i^{ON}, e_i^{ON}, s_i^{ON} ones (since the inactive will have null fuels and/or null products $F_{OFF} = 0$ and/or $P_{OFF} = 0$) and then the matrices and vectors are extracted corresponding to the thermoeconomic study.

The last step refers to the results obtainment and analysis.

Annex.2.1. Exergy determination according to the sensor

Usually, the data read by the sensors are the following:

- Temperatures (T_i)
- Enthalpies ($m_i \cdot \Delta T_i$)
- Valve opening percentages (v_i)
- Fuel consumption (gasoil, natural gas, electricity, etc.) (F_i)
- Activation, modulation and deactivation of pumps (on-off $Bi_{0/1}$, percentages $Bi_{\%}$)

From these variables, and depending on the type of flow, the formula for the symbolic calculation of exergy B_i is programmed, such as:

- Heat flow: $E_{heat} = Q_{heat} \cdot \left(1 - \frac{T_0}{T_i}\right)$
- Electric flow: $E_{elec} = W_{elec}$
- Mass flow: $E_{mass} = m_{mass} \cdot c_{P_{mass}} \cdot \left[(T_i - T_0) - T_0 \cdot ln\left(\frac{T_i}{T_0}\right)\right]$
- Fuel flow: $E_{fuel} = m_{fuel} \cdot f_i \cdot LHV$

where $\left(1 - \frac{T_0}{T}\right)$ is the Carnot factor; T_0 and T_i are the ambient and i flow temperatures in K; c_P is the specif ic heat of the mass flow; LHV is the low heating value and f_i are the fuel function tabulated coefficients (i.e. in this case gas oil, 1.04).

Table Annex. 6 Exergetic value of flows

Exergetic value of flows [kW]		
E_1	...	E_i
	⋮	⋮

The i flows of the system, which are precisely the links between the components and the environment, are defined according to the available sensors or data and copied to Excel, see Table Annex. 6. These allow, in turn, the determination of the components (which are considered as 'black boxes'). Therefore, the study detail is directly proportional to the number of existing sensors or extracted data.

Annex.2.2. Results obtainment and analysis

In the 'RESULTS' sheet of Excel, the following tables are overwritten, in which the active equipment is highlighted and the inactive equipment of that moment is hidden:

- Table of unit exergy consumptions (k_i [-]) and energy and exergy efficiencies (ε_i, η_i [%]) of components respective F_i and P_i.
- Table of unit exergetic costs of fuels ($k^*_{F_i}$[-]), products ($k^{e,*}_{P_i}$[-]) and residues ($k^{r,*}_{P_i}$[-]).
- Table of unit and total exergoeconomic costs referred only to the consumption of external resources in exergy units (c_{F_i}, C_{F_i} and $c^e_{P_i}$, $c^r_{P_i}$, $C^e_{P_i}$, $C^r_{P_i}$ [c€/kW$_{ex}$]) and in energy units (c_{F_i}, C_{F_i} and $c^e_{P_i}$, $c^r_{P_i}$, $C^e_{P_i}$, $C^r_{P_i}$ [c€/kW$_{en}$]).

- Table of unit and total exergoeconomic costs referring to fuel consumption and investment costs, acquisition and operation of equipment; in exergy and in energy units ($c_{P_i}^e$, $c_{P_i}^r$, $c_{P_i}^z$ $C_{P_i}^e$, $C_{P_i}^r$, $C_{P_i}^z$ [c€/kW$_{ex}$] and [c€/kW$_{en}$]).

Even such list, the results to be displayed can be chosen according to the objective of the study. Thus, several tables can be modified and/or deleted, and new tables and more visual graphics can be included.

Annex.2.3. The internal program of Matlab

Down below the algorithm programed in Matlab (connected to Excel) is shown.

Annex.3. ALGORITHM

AAAProgramaTOT

```
for mes=1:1
% me situo en el MES
Localiz='C:\Users\apicallo001\LCCE\1.Beca_Doctorado\15.Estancia\2018\2.PADOVAlazzaretto\4.Research\2.EstudioSolar\3.Diagnosis\';
MesNum=int2str(mes);
d='V3V_3.xlsx';

filename=strcat(Localiz,d);
AAAProductStruc

strcat('Los calculos EXERGETICOS UNITARIOS están copiados en el excel MES:_',int2str(mes))

clear all
end
```

1. AAAProductStruc

```
aLeerDatos
%define estructura generica con todo ON
aEstructura
%Define estructura activa instantanea
aEstructuraDin

% Para los n componentes y m flujos
F=Af*B;
P=Ap*B;
Ps=Ap*Bs;

Aux_e=Af/[Ap;alfa_e;alfa_x];
FP=[Aux_e(:,1:(n))];

PF =diag(P)*FP'*inv(diag(F));

%compruebo que salga bien

kd =F./P;
kd =diag(kd);
KP =PF *kd;
Ft_F =ones(1,(n))*(eye((n))-PF);
Pt_P =ones(1,(n))*(eye((n))-FP);

ValoracionExt

ke =Ft_F *kd;
KP_ampliada =[ke;KP];
Bcomprob=[Af-kd*Ap;alfa_e;alfa_x]\Je;
Bcomprob=Bcomprob';
Bcoste=[Af-Ap;alfa_e;alfa_x]\Je;

%calculo costes

kp_e=(inv(eye((n))-KP))'*(ke)';

aMatrizKR

kp=(inv(eye((n))-KP-KR)'*(ke)';
kp_r=kp-kp_e;

kf =Ft_F'+PF'*kp;

B_kp =kp.*P;
B_kp_e=kp_e.*P;
B_kp_r=kp_r.*P;
B_kf =kf.*F;

FtEco=(ones(1,(n))*(eye((n))-PF)).*Ce';
FtEcoCO2=(ones(1,(n))*(eye((n))-PF)).*CO2e';
```

```
keEco=(ke).*FtEco;
keEcoCO2=(ke).*FtEcoCO2;

%calculos costes Termoeconomicos
cp_eEco=(inv(eye((n))-KP))'*keEco';
cp_rEco=(inv(eye(n)-KR*inv(eye(n)-KP))-
eye(n))'*cp_eEco;
cp_Eco=cp_eEco+cp_rEco;

cp_eEcoCO2=(inv(eye((n))-KP))'*keEcoCO2';
cp_rEcoCO2=(inv(eye(n)-KR*inv(eye(n)-KP))-
eye(n))'*cp_eEcoCO2;
cp_EcoCO2=cp_eEcoCO2+cp_rEcoCO2;

cp_zEco=(inv(eye(n)-KP))'*(Z(1:(n),:)./P);


%Considerando solo Coste Fueles
cfEco2=PF'*cp_Eco+FtEco';
CfCost2=(cfEco2).*F;

cfEco2_CO2=PF'*cp_EcoCO2+FtEcoCO2';
CfCost2_CO2=(cfEco2_CO2).*F;

Cp_eCost_CO2=cp_eEcoCO2.*P;
Cp_rCost_CO2=cp_rEcoCO2.*P;
Cp_Cost_CO2=cp_EcoCO2.*P;

%Considerando Costes Totales
cpEco_f=cp_Eco+cp_zEco;
cfEco=PF'*cpEco_f+FtEco';

Cp_Cost=cp_Eco.*P;
Cp_eCost=cp_eEco.*P;
Cp_rCost=cp_rEco.*P;
Cp_zCost=cp_zEco.*P;
CfCost=(cfEco).*F;

BCostesEnergeticos
BoRehacerEstructura
B2CopiarExcel
```

2. aLeerDatos

aaaCrearVectorExcel

```
nmse=xlsread(filename,'LecturaDatos','C1:G2');
nP=nmse(1,1);
nD=nmse(2,1);
n=nD+nP;
m=nmse(1,3);
sR=nmse(2,3);
mP=m-sR;
e=nmse(1,5);
sP=nmse(2,5);
s=sP+sR;
```

aPosicion

```
B=xlsread(filename,'LecturaDatos',posB);
E=xlsread(filename,'LecturaDatos',posE);
Z=xlsread(filename,'LecturaDatos',posZ);
Cost_entr=xlsread(filename,'LecturaDatos',pos_ent)
;
C_entr=Cost_entr(:,1);
CO2_entr=Cost_entr(:,2);

[Prueba,txt,todoF]=xlsread(filename,'Estructura',po
sEstructuraF);
[Prueba,txt,todoP]=xlsread(filename,'Estructura',po
sEstructuraP);

OnOff_E_B=xlsread(filename,'Estructura',posEstruc
F_E_B);

if OnOff_E_B==1

[Prueba,txt,todoF_E]=xlsread(filename,'Estructura',
posEstructuraF_E);

[Prueba,txt,todoP_E]=xlsread(filename,'Estructura',
posEstructuraP_E);
end

EntrSal=xlsread(filename,'Estructura',posEntrSal);

%Defino flujos Entrada y Salida
entry=EntrSal(1:e,1);
entrType=EntrSal(1:e,2);
entryValor=EntrSal(1:e,3);
SalidaExt=EntrSal(1:s,4);

B=B';
E=E';
```

3. aEstructura

```
%Creo Matrices vacias
Ap(n,m)=0;
Af(n,m)=0;
Entra(n,m)=0;
Sale(n,m)=0;

%Generar matriz de incidencia ESTRUCTURA
FISICA (entra / sale)
aIncidenciaExergia
aIncidenciaEnergia

%Creo matrix alfa_e + VECTOR ENTRADA + SALIDA
aMatricesEntradasSalidas
```

```
Je=[zeros(n,1);Bentr;zeros(m-n-e,1)];


%llamo a subprogramas para el cálculo de las
Bifurcaciones:
% aplico TEORÍA DE COSTES
cFiguales
cPiguales

%Creo matriz de Bifurcaciones

if size(alfa_xF,1)==0
if size(alfa_xP,2)<m
alfa_xP(size(alfa_xP,1),m)=0;
end
alfa_x=[alfa_xP];

elseif size(alfa_xP,1)==0
if size(alfa_xF,2)<m
alfa_xF(size(alfa_xF,1),m)=0;
end
alfa_x=[alfa_xF];
else
if size(alfa_xP,2)<m
alfa_xP(size(alfa_xP,1),m)=0;
end
if size(alfa_xF,2)<m
alfa_xF(size(alfa_xF,1),m)=0;
end
alfa_x=[alfa_xP;alfa_xF];
end
```

4. aEstructuraDin

```
F=Af*B;
P=Ap*B;

contNOm=0;
contNOn=0;
contNOnP=0;
contNOnD=0;
contNOe=0;
contNOs=0;
contNObP=0;
contNObF=0;
for i=1:m
if B(i,1)==0
contNOm=contNOm+1;
numNOm(contNOm,1)=i;
end
end
for i=1:n
if F(i,1)==0 && P(i,1)==0
contNOn=contNOn+1;
numNOn(contNOn,1)=i;
end
end
for i=1:nP
if F(i,1)==0 && P(i,1)==0
contNOnP=contNOnP+1;
numNOnP(contNOnP,1)=i;
end
end
for i=1:nD
if F(i+nP,1)==0 && P(i+nP,1)==0
contNOnD=contNOnD+2;
numNOnD(contNOnD,1)=nP+i;
end
end
for i=1:e
if Bentr(i,1)==0
contNOe=contNOe+1;
numNOe(contNOe,1)=entry(i,1);
numNOentr(contNOe,1)=i;
end
end
for i=1:s
if B(SalidaExt(i,1))==0
contNOs=contNOs+1;
numNOs(contNOs,1)=SalidaExt(i,1);
end
end
for i=1:length(x_bifurP)
if x_bifurP(i,1)==0
contNObP=contNObP+1;
numNObP(contNObP,2)=i;
end
end
for i=1:length(x_bifurF)
if x_bifurF(i,1)==0
contNObF=contNObF-1;
numNObF(contNObF,1)=i;
end
end

%Elimino Columnas y filas de 0 de las Ap y Af / Entra
y Sale; y columnas de alfa_e y
%alfa_xP y alfa_xF
Ap2=Ap;
Af2=Af;
Entra2=Entra;
Sale2=Sale;
alfa_e2=alfa_e;
alfa_xP2=alfa_xP;
alfa_xF2=alfa_xF;

if OnOff_E_B==1
Ap2_E=Ap_E;
Af2_E=Af_E;
else
Ap2_E=Ap;
Af2_E=Af;
end


for i=1:contNOm
Ap(:,numNOm(contNOm+1-i)=[];
```

```
Af(:,numNOm(contNOm+1-i))=[];
Entra(:,numNOm(contNOm+1-i))=[];
Sale(:,numNOm(contNOm+1-i))=[];
alfa_e(:,numNOm(contNOm+1-i))=[];
end
for i=1:contNOn
Ap(numNOn(contNOn+1-i),:)=[];
Af(numNOn(contNOn+1-i),:)=[];
Entra(numNOn(contNOn+1-i),:)=[];
Sale(numNOn(contNOn+1-i),:)=[];
end

if OnOff_E_B==1
for i=1:contNOm
Ap_E(:,numNOm(contNOm+1-i))=[];
Af_E(:,numNOm(contNOm+1-i))=[];
Entra_E(:,numNOm(contNOm+1-i))=[];
Sale_E(:,numNOm(contNOm+1-i))=[];
end
for i=1:contNOn
Ap_E(numNOn(contNOn+1-i),:)=[];
Af_E(numNOn(contNOn+1-i),:)=[];
Entra_E(numNOn(contNOn+1-i),:)=[];
Sale_E(numNOn(contNOn+1-i),:)=[];
end
else
Ap_E=Ap;
Af_E=Af;
end


if size(alfa_xF,1)==0
else
for i=1:contNOm
alfa_xF(:,numNOm(contNOm+1-i))=[];
end
end

if size(alfa_xP,1)==0
else
for i=1:contNOm
alfa_xP(:,numNOm(contNOm+1-i))=[];
end
end


%Elimino filas de 0 de alfa_xP y alfa_xF
if contNObP==0
else
for i=1:contNObP
alfa_xP(numNObP(contNObP+1-i),,:)=[];
end
end
if contNObF==0
else
for i=1:contNObF
alfa_xF(numNObF(contNObF-1-i),:)=[];
end
end
%Redimensiono la matriz
if size(alfa_xF,1)==0
alfa_x=[alfa_xP];
elseif size(alfa_xP,1)==0
alfa_x=[alfa_xF];
else
alfa_x=[alfa_xP;alfa_xF];
end


%Elimino filas de 0 de alfa_e y Bentr
Bentr2=Bentr;
entry2=entry;
entryValor2=entryValor;
for i=1:contNOe
Bentr(numNOentr(contNOe+1-i),:)=[];
alfa_e(numNOentr(contNOe+1-i),:)=[];
entry(numNOentr(contNOe+1-i),:)=[];
entryValor(numNOentr(contNOe+1-i),:)=[];
end

%Elimino los flujos 0 de las B, Be, Bs y E
Be2=Be;
Bs2=Bs;
B2=B;
E2=E;
for i=1:contNOm
Be(numNOm(contNOm+1-i),:)=[];
Bs(numNOm(contNOm+1-i),:)=[];
B(numNOm(contNOm+1-i),:)=[];
E(numNOm(contNOm+1-i),:)=[];
end

%Elimino los equipos 0 de las CO2e Ce

Ce2=Ce;
CO2e2=CO2e;
Z2=Z;
for i=1:contNOn
Ce(numNOn(contNOn+1-i),:)=[];
CO2e(numNOn(contNOn+1-i),:)=[];
Z(numNOn(contNOn+1-i,:)=[];
end

nP2=nP;
nD2=nD;
n2=n;
m2=m;
sR=sR;
mP2=mP;
e2=e;
sP2=sP;
s2=s;

n=n-contNOn;
nP=nP-contNOnP;
nD=nD-contNOnD;
m=m-contNOm;
e=e-contNOe;
s=s-contNOs;
```

```
%los datos genericos estás guardados con la
nomenclatura 2
Je=[zeros(n,1);Bentr;zeros(m-n-e,1)];
```

5. ValoracionExt

```
contENTRY2=0;
for i=1:m
if Be(i,1)==0
else
contENTRY2=contENTRY2+1;
entryNuev(contENTRY2,1)=i;
end
end

Ft_F2=ones(1,(n))*(eye((n))-PF);
for comp=1:n
kePond=0;
keDiv=0;
for entr=1:e
if Entra(comp,entryNuev(entr))~=0

kePond=kePond+Be(entryNuev(entr))*entryValor(e
ntr);
keDiv=keDiv+Be(entryNuev(entr));

Ft_F2(1,comp)=Ft_F2(1,comp)*(kePond/keDiv);
end
end
end
 Ft_F=Ft_F2;

compEntraNuev(1,n)=0;
for comp=1:n
for entr=1:e
if Entra(comp,entryNuev(entr)~=0
compEntraNuev(1,comp)=comp;
end
end
end
for comp=1:n
if compEntraNuev(1,comp)==0
Ft_F(1,comp)=0;
end
end
```

6. aMatrizKR

```
%matrices KR
if n==0
KR=[];
else
KR(n,n)=0;
end

for res=1:nD
for prod=1:nP

KR(res+nP,prod)=kp_e(prod)*KP(prod,res+nP)/(kp_
e(res+nP)-ke(res+nP))*P(res+nP)/P(prod);
end
end

Rs=KR*inv(eye(n-KP)*Ps;
Ps_p=Ps-Rs;
```

7. BCostesEnergeticos

```
F_E=Af_E*E;
P_E=Ap_E*E;
rmto_E=P_E./F_E;

%calculos costes Termoeconomicos en BASE
ENERGETICA
facF=F./F_E;
facP=P./P_E;

cp_eEco_E=cp_eEco.*facP;
cp_rEco_E=cp_rEco.*facP;
cp_Eco_E=cp_Eco.*facP;

cp_eEcoCO2_E=cp_eEcoCO2.*facP;
cp_rEcoCO2_E=cp_rEcoCO2.*facP;
cp_EcoCO2_E=cp_EcoCO2.*facP;

cp_zEco_E=cp_zEco.*facP;

%Considerando solo Coste Fueles
cfEco2_E=cfEco2.*facF;
cfEco2_CO2_E=cfEco2_CO2.*facF;

%Considerando Costes Totales
cpEco_f_E=cpEco_f.*facF;
cfEco_E=cfEco.*facF;
```

8. BoRehacerEstructura

```
%Rehacer cosas para Copiar
%Bcomprob AMPLIADA

contZeros=0;
Bcomprob2=ones(1,m2);
```

```
for i=1:m2
for j=1:contNOm
if numNOm(j,1)==i
Bcomprob2(1,i)=0;
end
end

end
for i=1:m2
if Bcomprob2(1,i)==0
else
contZeros=contZeros+1;
Bcomprob2(1,i)= Bcomprob(1,contZeros);
end
end

%[F P diag(kd)]AMPLIADA
F2=Af2*B2;
P2=Ap2*B2;
for i=1:n2
if P2(i,1)==0
kd2(i,1)=0;

else
kd2(i,1)=F2(i,1)/P2(i,1);

end
end

 %[F_E P_E rmto_E]AMPLIADA
F_E2=Af2_E*E2;
P_E2=Ap2_E*E2;
for i=1:n2
if F_E2(i,1)==0
rmto_E2(i,1)=0;
else
rmto_E2(i,1)=P_E2(i,1)/FE2(i,1);
end
end

%[kf kp_e kp_r] AMPLIADA


contZeros=0;
kf2=ones(n2,1);
kp_e2=ones(n2,1);
kp_r2=ones(n2,1);

%[cfEco2  CfCost2]
cfEco22=cfEco2;
CfCost22=CfCost2;

%[cfEco (cp_eEco+cp_rEco) cp_zEco CfCost
(Cp_eCost+Cp_rCost+Cp_zCost) Z]
cfEco_2=cfEco;
cp_eEco2=cp_eEco;
cp_rEco2=cp_rEco;
cp_zEco2=cp_zEco;
CfCost_2=CfCost;
Cp_eCost2=Cp_eCost;
Cp_rCost2=Cp_rCost;
Cp_zCost2=Cp_zCost;
Z2=Z;

%[cfEco2_CO2 cp_eEcoCO2 cp_rEcoCO2
CfCost2_CO2 Cp_eCost_CO2 Cp_rCost_CO2]
cfEco2_CO2_2=cfEco2_CO2;
cp_eEcoCO22=cp_eEcoCO2;
cp_rEcoCO22=cp_rEcoCO2;
CfCost2_CO2_2=CfCost2_CO2;
Cp_eCost_CO22=Cp_eCost_CO2;
Cp_rCost_CO22=Cp_rCost_CO2;

%[cfEco2_E cp_eEco_E cp_rEco_E]
cfEco2_E2=cfEco2_E;
cp_eEco_E2=cp_eEco_E;
cp_rEco_E2=cp_rEco_E;

%[cfEco_E cp_zEco_E ]
cfEco_E2=cfEco_E;
cp_zEco_E2=cp_zEco_E;

%[cfEco2_CO2_E cp_eEcoCO2_E cp_rEcoCO2_E]
cfEco2_CO2_E2=cfEco2_CO2_E;
cp_eEcoCO2_E2=cp_eEcoCO2_E;
cp_rEcoCO2_E2=cp_rEcoCO2_E;

for i=1:n2
for j=1:contNOn
if numNOn(j,1)==i
kf2(i,1)=0;
kp_e2(i,1)=0;
kp_r2(i,1)=0;

cfEco22(i,1)=0;
CfCost22(i,1)=0;

cfEco_2(i,1)=0;
cp_eEco2(i,1)=0;
cp_rEco2(i,1)=0;
cp_zEco2(i,1)=0;
CfCost_2(i,1)=0;
Cp_eCost2(i,1)=0;
Cp_rCost2(i,1)=0;
Cp_zCost2(i,1)=0;
Z2(i,1)=0;

cfEco2_CO2_2(i,1)=0;
cp_eEcoCO22(i,1)=0;
cp_rEcoCO22(i,1)=0;
CfCost2_CO2_2(i,1)=0;
Cp_eCost_CO22(i,1)=0;
Cp_rCost_CO22(i,1)=0;

cfEco2_E2(i,1)=0;
cp_eEco_E2(i,1)=0;
cp_rEco_E2(i,1)=0;
cp_zEco_E2(i,1)=0;
cfEco_E2(i,1)=0;
cp_zEco_E2(i,1)=0;
```

```
cfEco2_CO2_E2(i,1)=0;
cp_eEcoCO2_E2(i,1)=0;
cp_rEcoCO2_E2(i,1)=0;

end
end

end
for i=1:n2
if kf2(i,1)==0
else
contZeros=contZeros+1;
kf2(i,1)=kf(contZeros,1);
kp_e2(i,1)=kp_e(contZeros,1);
kp_r2(i,1)=kp_r(contZeros,1);

cfEco22(i,1)=cfEco2(contZeros,1);
CfCost22(i,1)=CfCost2(contZeros,1);

cfEco_2(i,1)=cfEco(contZeros,1);
cp_eEco2(i,1)=cp_eEco(contZeros,1);
cp_rEco2(i,1)=cp_rEco(contZeros,1);
cp_zEco2(i,1)=cp_zEco(contZeros,1);
CfCost_2(i,1)=CfCost(contZeros,1);
Cp_eCost2(i,1)=Cp_eCost(contZeros,1);
Cp_rCost2(i,1)=Cp_rCost(contZeros,1);
Cp_zCost2(i,1)=Cp_zCost(contZeros,1);
Z2(i,1)=Z(contZeros,1);


cfEco2_CO2_2(i,1)=cfEco2_CO2(contZeros,1);
cp_eEcoCO22(i,1)=cp_eEcoCO2(contZeros,1);
cp_rEcoCO22(i,1)=cp_rEcoCO2(contZeros,1);
CfCost2_CO2_2(i,1)=CfCost2_CO2(contZeros,1);
Cp_eCost_CO22(i,1)=Cp_eCost_CO2(contZeros,1);
Cp_rCost_CO22(i,1)=Cp_rCost_CO2(contZeros,1);


cfEco2_E2(i,1)=cfEco2_E(contZeros,1);
cp_eEco_E2(i,1)=cp_eEco_E(contZeros,1);
cp_rEco_E2(i,1)=cp_rEco_E(contZeros,1);
cp_zEco_E2(i,1)=cp_zEco_E(contZeros,1);
cfEco_E2(i,1)=cfEco_E(contZeros,1);
cfEco2_CO2_E2(i,1)=cfEco2_CO2_E(contZeros,1);
cp_eEcoCO2_E2(i,1)=cp_eEcoCO2_E(contZeros,1);
cp_rEcoCO2_E2(i,1)=cp_rEcoCO2_E(contZeros,1);

end
end


PF2=zeros(n2,n);
FP2=zeros(n2,n);
Ft_F2=zeros(1,n);
Pt_P2=zeros(1,n);

%[FPdiag(kd)]AMPLIADA
%[FPding(kd)]AMPLIADA
j=0;
for i=1:n2
if P2(i,1)==0
FP2(i,:)=zeros(1,n);
PF2(i,:)=zeros(1,n);
Ft_F2(1,i)=0;
Pt_P2(1,i)=0;
else
j=j+1;
FP2(i,:)=FP(j,:);
PF2(i,:)=PF(j,:);
Ft_F2(1,i)=Ft_F(1,j);
Pt_P2(1,i)=Pt_P(1,j);
end
end

FP3=zeros(n2,n2);
PF3=zeros(n2,n2);

j=0;
%[FPdiag(kd)]
for i=1:n2
if P2(i,1)=0
FP3(:,i)=zeros(n2,1);
PF3(:,i)=zeros(n2,1);
else
j=j+1;
FP3(:,i)=FP2(:,j);
PF3(:,i)=PF2(:,j);
end
end

%KR&KP
KP2=zeros(n2,n);
KR2=zeros(n2,n);
ke2=zeros(1,n);


j=0;
for i=1:n2
if P2(i,1)==0
KR2(i,:)=zeros(1,n);
KP2(i,:)=zeros(1,n);
ke2(1,i)=0;
else
j=j+1;
KR2(i,:)=KR(j,:);
KP2(i,:)=KP(j,:);
ke2(1,i)=ke(1,j);
end
end

KR3=zeros(n2,n2);
KP3=zeros(n2,n2);

j=0;

for i=1:n2
if P2(i,1)==0
KR3(:,i)=zeros(n2,1);
KP3(:,i)=zeros(n2,1);
```

```
else
j=j+1;
KR3(:,i)=KR2(:,j);
KP3(:,i)=KP2(:,j);
end
end
```

9. B2CopiarExcel

```
xlswrite(filename,Bcomprob2,'LecturaDatos',posBc
omprob);

% Resultados
xlswrite(filename,[F2P2kd2],'Resultados',posF_P);
xlswrite(filename,[F_E2P_E2rmto_E2],'Resultados',
pos_FP_E);


xlswrite(filename,[kf2kp_e2kp_r2],'Resultados',posk
f_kp);

xlswrite(filename,[cfEco22*100cp_eEco2*100cp_rE
co2*100CfCost22Cp_eCost2Cp_rCost2],'Resultados'
,pos_cSoloFuel);
xlswrite(filename,[cfEco_2*100(cp_eEco2*100+cp_r
Eco2*100)cp_zEco2*100CfCost_2(Cp_eCost2+Cp_r
Cost2+Cp_zCost2)Z2],'Resultados',pos_cTodoCost);
xlswritefilename,[cfEco2_CO2_2cp_eEcoCO22cp_r
EcoCO22CfCost2_CO2_2/1000Cp_eCost_CO22/100
0Cp_rCost_CO22/1000],'Resultados',pos_cSoloFuel
_CO2);

xlswrite(filename,[cfEco2_E2*100cp_eEco_E2*100c
p_rEco_E2*100],'Resultados',pos_cSoloFuel_E);
xlswrite(filename,[cfEco_E2*100(cp_eEco_E2*100+
cp_rEco_E2*100)cp_zEco_E2*100],'Resultados',pos
_cTodoCost_E);
xlswrite(filename,[cfEco2_CO2_E2cp_eEcoCO2_E2
cp_rEcoCO2_E2],'Resultados',pos_cSoloFuel_CO2_
E);

% tengoqueampliarmatricesydefinirposiciones
xlswrite(filename,Ft_F2,'PF','B3');
xlswrite(filename,PF3,'PF','B4');
xlswrite(filename,Pt_P2,'PF',posPtPcop);
xlswrite(filename,FP3,'PF',posFPcop);

xlswrite(filename,ke2,'PF',poske_cop);
xlswrite(filename,KP3,'PF',posKPcop);
% xlswrite(filename,ke_r2,'PF',poske_rcop);
xlswrite(filename,KR3,'PF',posKRcop);
```

○ aaaCrearVectorExcel

```
% crearvectorconlassiglasdelExcel:
for n=1:26
primera=double('A');
siguiente=primera+1*(n-1);
alf1(n,:)=strcat(siguiente);
end
for n=1:26
primera=double('A');
siguiente=primera+1*(n-1);
alf2(n,:)=strcat('A',siguiente);
end
for n=1:26
primera=double('B');
siguiente=primera+1*(n-2);
alf3(n,:)=strct('B',siguiente);
end
for n=1:26
primera=double('C');
siguiente=primera+1*(n-3);
alf4(n,:)=strcat('C',siguiente);
end
for n=1:26
primera=double('D');
siguiente=primera+1*(n-4);
alf5(n,:)=strcat('D',siguiente);
end
v_excel=char(alf1,alf2,alf3,alf4,alf5);
```

○ aPosicion

```
% leerexcel
if 2+m<27
posB=[v_excel(2),'5:',v_excel((2+(m-1))),'5'];
else
posB=[v_excel(2),'5:',v_excel((2+(m-1)),:),'5'];
end

if 2+(m-1)<27
posE=[v_excel(2),'10:',v_excel((2+(m-1))),'10'];
else
posE=[v_excel(2),'10:',v_excel((2+(m-1)),:),'10'];
end

posZ=['J15:J',int2str(15+(n-1))];
pos_ent=['C36:D41'];

posEstructuraF=['C4:D',int2str(4+(n-1))];
posEstructuraP=['F4:G',int2str(4+(n-1))];

posEstrucF_E_B=['G',int2str(6+(n-1))];
posEstructuraF_E=['C',int2str(11+(n-
1)),':D',int2str(9+2*n)];
posEstructuraP_E=['F',int2str(11+(n-
1)),':G',int2str(9+2*n)];

if e<s
```

```
posEntrSal=['L4:O',int2str(4+(e-1))];
else
posEntrSal=['L4:O',int2str(4+(s-1))];
end


% escribirexcel

if 2+(m-1)<27
posBcomprob=[v_excel(2),'6:',v_excel((2+(m-
1))),'6'];
else
posBcomprob=[v_excel(2),'6:',v_excel((2+(m-
1)),:),'6'];
end


posF_P=['B3:D',int2str(3+(n-1))];
poskf_kp=['G3:I',int2str(3+(n-1))];
pos_cSoloFuel=['L3:Q',int2str(3+(n-1))];
pos_cTodoCost=['U3:Z',int2str(3+(n-1))];
pos_cSoloFuel_CO2=['AD3:AI',int2str(3+(n-1))];


pos_FP_E=['B',int2str(7+n),':D',int2str(6+2*n)];
pos_cSoloFuel_E=['L',int2str(7+n),':N',int2str(6
+2*n)];
pos_cTodoCost_E=['U',int2str(7+n),':W',int2str(
6+2*n)];
pos_cSoloFuel_CO2_E=['AD',int2str(7+n),':AF',i
nt2str(6+2*n)];

posPtPcop=['B',int2str(6+n)];
posFPcop=['B',int2str(7+n)];

if 4+n<27
poske_cop=[v_excel(4+n),'3'];
posKPcop=[v_excel(4+n),'4'];
poske_rcop=[v_excel(4+n),int2str(6+n)];
posKRcop=[v_excel(4+n),int2str(7+n)];
else
poske_cop=[v_excel(4+n,:),'3'];
posKPcop=[v_excel(4+n,:),'4'];
poske_rcop=[v_excel(4+n,:),int2str(6+n)];
posKRcop=[v_excel(4+n,:),int2str(7+n)];
end
```

○ aIncidenciaExergia

```
% DefinirEntradas+
for j=1:n
c<todoF(j,1);
if iscellstr(c)==0
c=[c{:}];
Entra(j,c)=1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})<0
[C,remain]=strtok(remain,'+');
end
Entra(j,str2double(C))=1;
end
end
end
% DefinirSalidas-
for j=1:n
c=todoF(j,2);
if iscellstr(c)==0
c=[c{:}];
Sale(j,c)=-1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Sale(j,str2double(C))=-1;
end
end
end



%
GenerarmatrizdeESTRUCTURAPRODUCTIVA(
AfyAp)

% FUELES(Ponerlesigno+/-alosFueles)

for j=1:n
c=todoP(j,1);
if iscellstr(c)==0
c=[c{:}];
Af(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})<0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
```

```
if SE==1
Af(j,str2double(C))=-1;
else
Af(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end


% PRODUCTOS(Ponerlesigno+/-
alosProductos)

for j=1:n
c=todoP(j,2);
if iscellstr(c)==0
c=[c{:}];
Ap(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE<1
Ap(j,str2double(C))=-1;
else
Ap(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end
end
end
```

- ## aIncidenciaEnergia

```
Ap_E(n,m)=0;
Af_E(n,m)=0;
Entra_E(n,m)=0;
Sale_E(n,m)=0;

if OnOff_E_B=1
%
GenerarmatrizdeincidenciaESTRUCTURAFISIC
A(Entra_E/Sale_E)
% DefinirEntradas+
for j=1:n
c=todoF_E(j,1);
if iscellstr(c)==0
c=[c{:}];
Entra_E(j,c)=1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Entra_E(j,str2double(C))=1;
end
end
end
% DefinirSalidas-
for j=1:n
c=todoF_E(j,2);
if iscellstr(c)==0
c=[c{:}];
Sale_E(j,c)=-1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Sale_E(j,str2double(C))=-1;
end
end
end
```

```
%
GenerarmatrizdeESTRUCTURAPRODUCTIVA(
Af_EyAp_E)

% FUELES(Ponerlesigno+/-alosFueles)

for j=1:n
c=todoP_E(j,1);
if iscellstr(c)==0
c=[c{:}];
Af_E(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE==1
Af_E(j,str2double(C))=-1;
else
Af_E(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end


% PRODUCTOS(Ponerlesigno+/-
alosProductos)

for j=1:n
c=todoP_E(j,2);
if iscellstr(c)<0
c=[c{:}];
Ap_E(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE==1
Ap_E(j,str2double(C))=-1;
else
Ap_E(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end


end
```

○ aMatricesEntradasSalidas

```
% ordenolasentradas
[EntO,orden]=sort(entry(:,1));
EntO=[entry(orden)entrType(orden)];


% Creovectoresnulos
alfa_e(e,m)=0;
Bentr(e,1)=0;
% creomatrizalfa_e+vectorBentr
for i=1:e
alfa_e(i,entry(i))=1;
% Aquíledoyvaloresnumericos
Bentr(i,1)=B(entry(i));
end

% creomatrizdecostesCeyCO2e
Ce(m,1)=0;
CO2e(m,1)=0;
Be(m,1)=0;
for i=1:m
```

```
for e2=1:e
if i==EntO(e2,1)
% Aquíledoyvaloresnumericos
Be(i,1)=B(EntO(e2,1));
Ce(i,1)=EntO(e2,2);
CO2e(i,1)=EntO(e2,2);
end
end
end

% ¡OJO!SEMULTIPLICAPORENTRA
Fe=Entra*Be;
calcCentra

[SalidaExt,orden]=sort(SalidaExt(:,1));
Bs(m,1)=0;
for i=1:m
for s2=1:s
if i==SalidaExt(s2,1)
% Aquíledoyvaloresnumericos
Bs(i,1)=B(SalidaExt(s2,1));
end
end
end
```

- ## cFiguales

```
% detectosilasalidafor mapartedelFuel
x_bifurF=[];
alfa_xF=[];
for equip=1:n
for flujos=1:m
if -Sale(equip,flujos)==1
if -
Sale(equip,flujos)==Af(equip,flujos)|Sale(equip,
flujos)==Af(equip,flujos)
% strcat('E',num2str(flujos))

% aquíheidentif
icadolasalidaquecorrespondeaFuelFnumSal
FnumSal=flujos;
c=todoP(equip,1);
numP=strfind(c,'[');
parentes=c;
i=1;

FuelNum=[];

% Aquíidentif icolossubgruposdefueles[F1],[F2]
whilei<(length(numP{1})+1)

[C,parentes]=strtok(parentes,['[',']']);
cruz=strfind(C,'+');
if length(C{1})==1&cruz{1}>0
i=i-1;
else
Fuel(i,1)=C;
prod=C;
% Aquisacolosfuelos(Bi-Bj)
SE=0;
resto=prod;
numBP=strfind(C,'+');
numBN=strfind(C,'-');

if length(numBP{1})>0|length(numBN{1})>0
%
AquícreomimatrizFuelNum=[P1P2]porcadaco
mponente
for
pos=1:(length(numBP{1})+length(numBN{1})+1
)
if length(resto{1})>0
[prod,resto]=strtok(resto,['+','-']);
if SE==1
fuelnum=str2double(strcat('-',prod));
else
fuelnum=str2double(prod);
end
signal=length(C{1})-length(resto{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end


end
FuelNum(pos,i)=fuelnum;
end
else
fuelnum=str2double(prod);
FuelNum(1,i)=fuelnum;
end
% Aquiterminodesacarlosfuelos(Bi-Bj)
end
i=i+1;
end
% FnumSal
x2_bifur=[];
alfa2_x=[];
for i2=1:size(FuelNum,2)
for j2=1:size(FuelNum,1)
```

```
if FuelNum(j2,i2)==FnumSal|FuelNum(j2,i2)==-FnumSal
% identificodóndeestáelFueldesalidaehagoP(x)/Q(x).
% Seránsolo2flujos:entrada(+)ysalida(-)
for j3=1:size(FuelNum,1)
if FuelNum(j3,i2)>0
% Aquíledoyvaloresnumericos
P_x=B(FuelNum(j3,i2));
else
Q_x=B(-FuelNum(j3,i2));
end
end


if P_x==0||Q_x==0
x2_bifur=0;
else
x2_bifur=P_x/Q_x;
end

for j3=1:size(FuelNum,1)
if FuelNum(j3,i2)>0
alfa2_x(1,FuelNum(j3,i2))=1;
else
alfa2_x(1,-FuelNum(j3,i2))=-x2_bifur;
end
end
end
end
end

if size(alfa2_x,2)<size(alfa_xF,2)
alfa2_x(size(alfa2_x,1),size(alfa_xF,2))=0;
elseif size(alfa_xF,2)<size(alfa2_x,2)&&size(alfa_xF,2)~=0
alfa_xF(1,size(alfa2_x,2))=0;
end

x_bifurF=[x_bifurF;x2_bifur];
alfa_xF=[alfa_xF;alfa2_x];

end
end
end
end
```

○ <u>cPiguales</u>

```
% detectocuantosproductoshayparahacer->Cp1=Cp2
alfa_xP=[];
x_bifurP=[];

for equip=1:n
c=todoP(equip,2);
numP=strfind(c,'[');
parentes=c;
i=1;

ProductNum=[];

% Aquíidentificolossubgruposdeproductos[P1],[P2]
whilei<(length(numP{1})+1)

[C,parentes]=strtok(parentes,['[',']']);
cruz=strfind(C,'+');

if length(C{1})==1&cruz{1}>0
i=i-1;
else
Product(i,1)=C;
prod=C;
% Aquisacolosproductos(Bi-Bj)
SE=0;
resto=prod;
numBP=strfind(C,'+');
numBN=strfind(C,'-');

if length(numBP{1})>0|length(numBN{1})>0
% AquícreomimatrizProductNum=[P1P2]porcada componente
for pos=1:(length(numBP{1})+length(numBN{1})+1)
if length(resto{1})>0
[prod,resto]=strtok(resto,['+','-']);
if SE==1
% strcat('-E',prod)
productnum=str2double(strcat('-',prod));
else
% strcat('E',prod)
productnum=str2double(prod);
end
signal=length(C{1})-length(resto{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=ç0;
end
end
```

```
end
ProductNum(pos,i)=productnum;
end
else
% strcat('E',prod)
productnum=str2double(prod);
ProductNum(1,i)=productnum;
end
% Aquiterminodesacarlosproductos(Bi-Bj)
end
i=i+1;
end
%
SehacreadolamatrizProductNumparaelcompo
nenteequip

%
conseguirelvalordelabifurcacioncp1=cp2b=P(x)
/Q(x)
if i-1>1
% elvalordeP(x)
x2_bifur=0;
alfa2_x=0;

for j2=1:i-1
Pmultip=0;
Pmult=0;

for i2=1:size(ProductNum,1)
% Aquíledoyvaloresnuméricos
if ProductNum(i2,j2)~=0
if ProductNum(i2,j2)>0
Pmult=B(ProductNum(i2,j2));
alfa2_x(j2,ProductNum(i2,j2))=1;
else
Pmult=-B(-ProductNum(i2,1));
alfa2_x(j2,-ProductNum(i2,j2))=-1;
end
Pmultip=Pmultip+Pmult;
end
end
% aquíobtengolaxdelabifurcacion

% ¿EXISTENESOSFLUJOS?

x2_bifur(j2,1)=Pmultip;

end

Pdivide=0;
cPmas=1;
whilePdivide==0
if x2_bifur(cPmas,1)==0
cPmas=cPmas+1;
else
Pdivide=x2_bifur(cPmas,1);
end
if cPmas==(length(x2_bifur)+1)
Pdivide=1;
cPmas=cPmas-1;
end
end
for div=1:length(x2_bifur)
x2_bifur(div,1)=x2_bifur(div,1)/Pdivide;
end

% copiarlasxenlamatrizalfa_xP
for j2=2:i-1
for i2=1:size(ProductNum,1)
if ProductNum(i2,cPmas)~=0
if ProductNum(i2,cPmas)>0
alfa2_x(j2,ProductNum(i2,cPmas))=-
x2_bifur(j2,1);
else
alfa2_x(j2,-
ProductNum(i2,cPmas))=x2_bifur(j2,1);
end
end
end
end
alfa2_x(cPmas,:)=[];
x2_bifur(cPmas,:)=[];

if size(alfa2_x,2)<size(alfa_xP,2)
alfa2_x(size(alfa2_x,1),size(alfa_xP,2))=0;
elseif
size(alfa_xP,2)<size(alfa2_x,2)&&size(alfa_xP,2
)~=0
alfa_xP(1,size(alfa2_x,2))=0;
end

else

x2_bifur=[];
alfa2_x=[];

end

%
Sehacreadolamatrizalfa2_xparaelcomponente
equip

x_bifurP=[x_bifurP;x2_bifur];
alfa_xP=[alfa_xP;alfa2_x];
end
% x_bifurP
% alfa_xP
```

Annex.4. CONCLUSIONS

This Annex corresponds to the practical application of **Chapter C**: a software based on Thermoeconomics for the supervision of buildings thermal facilities.

The use of the program requires the same thermodynamic data of the common energetic studies (temperatures, mass flows, concentrations, etc.). Therefore, it is a versatile tool that does not request additional data, but it offers essential information for an adequate understanding of the cost formation process.

From the data recorded, the dynamic calculation of costs of each component and system flow are systematically calculated. Hence, the key points of improvement and control optimization are easily identified.

For the moment, the program consist of a combination of Excel and Matlab but the idea is to create a license-free tool for Thermoeconomic application. Next step deals with the implementation of the thermoeconomic diagnosis (**Chapter D**) that allows, through a comparison between the operational and reference condition, to locate the system anomalous behaviors avoiding unwanted interruptions and preventing penalties in costs.

2018

ANA PICALLO PEREZ

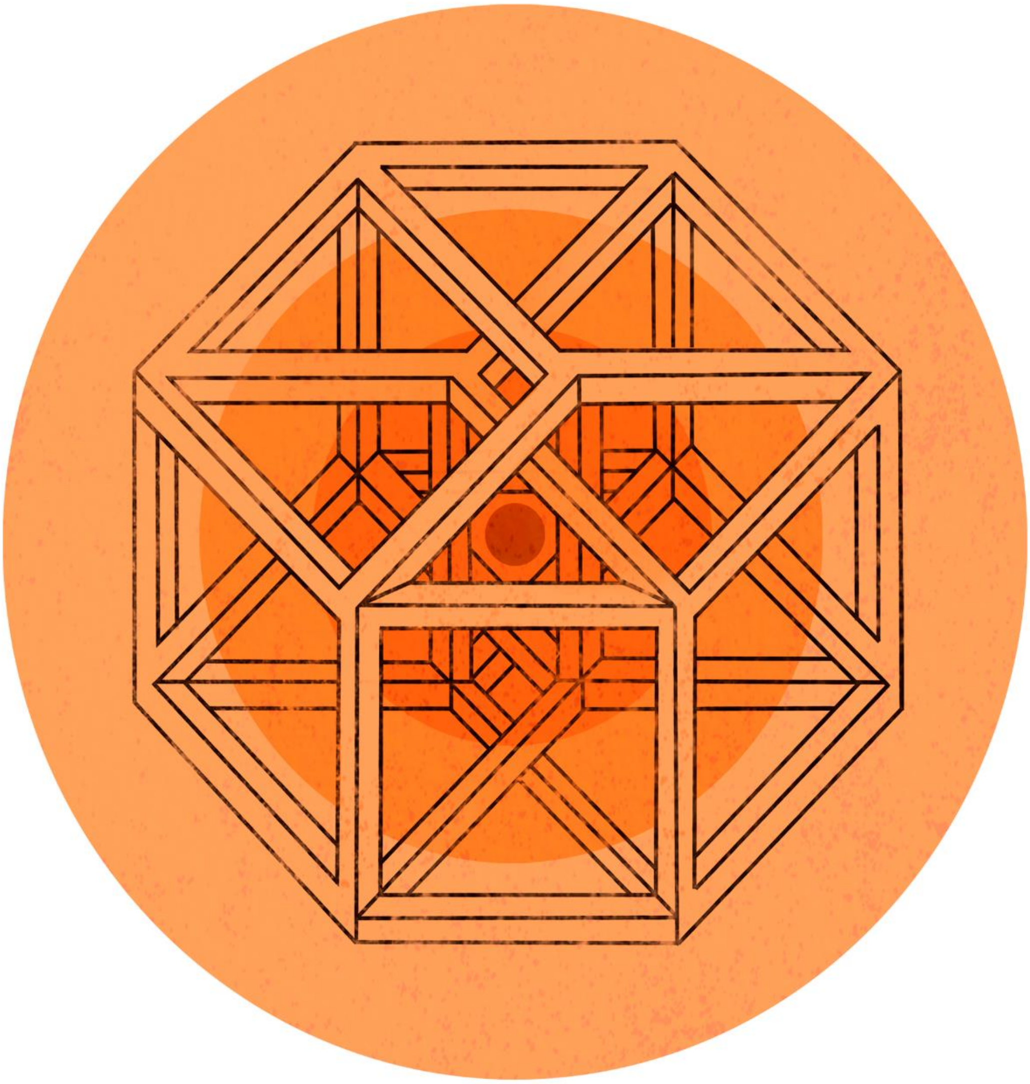
DIRECTOR: JOSE MARIA SALA LIZARRAGA

eman ta zabal zazu

UPV EHU

TERMOEKONOMIA

eraikinen sistema termikoetan energia eta
ekonomia ebaluatzeko tresna



2018

ANA PICALLO PEREZ
ZUZENDARIA: JOSE MARIA SALA LIZARRAGA

eman ta zabal zazu
UPV EHU

Mikel eta Irenerentzat
Irene eta Mikelentzat

Nahiz ez sinetsi hiruki baten
barruan dagon begian,
gezur guztitan dago egi bat
eta gezur bat egian.
Naufragatuta baldin bazaude
itsasoraren erdian
errezazazu tarteka baina
segi zazu igerian

Jon Martin Bertso berriak itxaropenari jarriak

ESKERRAK

Eskerrak eman nahi dizkiot, egun hauetan edo aurreko edozein unetan, Tesia errealitate bihurtzea ahalbidetu duten pertsona guztiei.

Hasteko, Pr. José María Sala Lizarraga eskertu nahi dut, tesia burutzeko aukera emateagatik, konfiantzagatik eta haren etengabeko ikuskapenagatik. Ezbairik gabe, lan hau ezinezkoa baita bere ezagutza, motibazio eta interes handirik gabe.

Hiru hilabeteko egonaldietan jasotako laguntza ere ezagutzera eman nahi dut. Lehenengoa, Berlineko TU Energia Ingeniaritza Institutuan, Pr. George Tsatsaronis-en gainbegiradan. Nire jakituria garatu eta hedatu egin baitzuen Exergia Garatuaren Analisian haren esperientziarekin eta ardurarekin.

Bigarrena, Palermo Unibertsitateko DEIMen, non Pr. Antonio Piacentino-ren dedikazioa eta gidaritza ezinbestekoak izan ziren hotz eta girotze sistemen analisietarako. Haren ikerketa taldearekin lan egiteko eman zidan aukera ere eskertu nahi diot.

Hirugarrena, Padova Unibertsitateko Ingeniaritza Industrialeko Departamentuan, Pr. Andrea Lazzaretto-ren zuzendaritza jarraituarekin. Hark nire ideak antolatu zituen, tesiaren egitura inspiratuz eta gogoeta egitera bultzatuz.

Zaragoza Unibertsitateko Pr. Miguel Ángel Lozano eta Pr. Luís Serra ere aitortu nahi ditut, ikerketaren hobekuntza sakatu zutelako.

Eusko Jaurlaritzaren Eraikinen Kontrol Kalitaterako Laboratorioa (EKKL) aipatu behar da, bereziki Etxebizitzako Zuzendaria D. Agustin de Lorenzo zeinek azterketetarako entseguak baimendu zituen. Ezin dira ahaztu, jakina, Termika Saileko lankideak: Iván Flores, César Escudero, Imanol Ruiz de Vergara, Eider Iribar, Carlos García, Daniel Pérez, zeintzuek modu eskuzabalean tesiaren hobekuntza erraztu zuten.

Saincal Taldea, batik bat José Luis Cortijo, teoriari praktikotasuna eta errealismoa emateagatik.

Dudarik gabe unibertsitateetako lankide eta lagunak: Irati, Cata, Niko eta Erik, Bilbon horien solasaldiengatik eta geldialdi bizigarriengatik, Saeed eta Mathyas, euren denboragatik eta laguntzagatik; eta baita Andreas eta Elisa ere, horien energia positiboak eta humore onak Berlineko egun grisak kolorez pintatzen zituztelako. Pietro, hainbestetan entzun, pentsatzera derrigortzen eta barre eginarazten ninduelako. Niko, gogoberotasunagatik eta Gianluca, Padovaren ingurutik deskonektatzeko txangoan eramateagatik.

“Kuadrillako” neskak, behar ditudanean hortxe egoteagatik eta “los truchas” egunak argitzeagatik; eta gainontzeko lagun guztiak ikerketa hau merezi duen abentura bilakatzeagatik.

Ama, Aita, Laura eta Maria, munduko pertsonarik ikaragarrienak direlako.

Mikel eta Irene, dauden lekuan daudela, haien bizitza zati bat dudalako barnean.

KAPITULU GUZTIAK

AKRONIMOAK	
AHU	Aire tratamenduko unitatea
B.A.	Gela airea
Banak.	Berokuntza banaketa eta EUB zirkuitu primaria
Bilt.	Biltzailea
COP	Eraginkortasun koefizientea
DAEA	Exergia analisi aurreratu dinamikoa
ECT	Exergia kostuen teoria
EEA	Exergia ekonomia metodologia
EED	Energia efizientzia direktiba
EFA	Ingenearitza analisi funtzionala
Env.	Inguratzailea
EPBD	Eraikin direktiben energia eraginkortasuna
EUB	Etxeko ur beroa
FEA	Exergoekonomia lehen metodologia
HVAC&R	Berokuntza, aireztapena, aire girotua eta hozketa
IAQ	Barne aire kalitatea
iEKG	Ia kontsumorik gabeko eraikina
Igorp.	Berokuntza igorpena eta EUB horniketa
L.M.	Lehen mailako energia
LIFOA	Azkenekoa-sartu-lehengoa-irten metodologia
LQCB	Eraikinen kalitate kontrolerako laboratorioa
MS	Estatu kideak
Pil.	Bero banaketa eta EUB pilaketa sistema
Sork.	Bero sorkuntza
SPECO	Exergia kostu espezifikoa
ST	Termoekonomia sinbolikoa
TADEUS	Energia sisteman termoekonomia diagnostiko metodologia
TFA	Termoekonomia analisi funtzionala
Trnsys	Transient System Simulation Tool

OINARRIZKO MATEMATIKA	
ΔY	Y aldagaiaren aldakuntza
$\dot{Y}$	Y aldagaia denbora unitateko
$\mathbf{Y}$	Y aldagaiaren bektorea edo matrizea
$\mathbf{Y_D}$	Y aldagaiaren matrize diagonala
$^{\mathbf{T}}\mathbf{Y}$	$\mathbf{Y}$ matrizearen iraulia
Y_{ij}	$\mathbf{Y}$ matrizearen i lerroko eta j zutabeko osagaia
$\mathbf{u}$	Bektore unitarioa
$\mathbf{U_D}$	Identitate matrizea

IKERKETAREN LABURPENA

Europar Batasuneko helburu garrantzitsuenen artean lehen mailako energiaren kontserbazioa dago, mundua jasaten ari den klima aldaketa etengabea medio. Eraikinak amaierako energiaren ia % 40aren arduradun dira EBean eta Espainian, aldiz, eraikin arloak kontsumo totalaren % 28 behar du. Beraz, guztizko energia kontsumoan sektore horren rola nabarmena da eta espezialista ugari eraikinen eraginkortasun energetikoa sustatzeko lanean dago.

Eraikinetan *exergia* kontzeptuaren onurak ezagunak dira jadanik, energiaren erabilera egokiaren oinarrirako eta energia kalitateen arteko moldaketarako funtsezkoak baitira. Azkeneko gertakaria eraikinetan oso erabilgarria da energia kalitate baxuko eskariak daudelako, kasurako, berokuntza, hozkuntza eta etxeko ur beroa.

A Kapituluaren asmoa energia etekinaren hobekuntza aukera handiak erakustea da, zein ezin den ohiko energia analisiarekin lortu; bietan, bai eraikin berrietan bai etxebizitza birgaituetan.

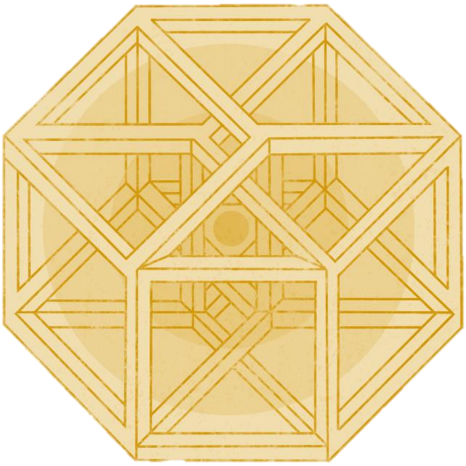
Eraikinak denboran zehar uneoro aldatzen direnez, *modelo dinamikoak* inperatiboak dira. **B Kapitulua**n bi metodo berritzaile garatzen dira horien adierazpen trantsitorioentzako.

Gainera, exergia analisiak edozein energia bihurketa faseko kostu ekonomiko formakuntzaren identifikazioan laguntzen du, zein, zehazki, **C Kapitulu**aren xedea den. Ikasketa hori *termoekonomia*ren oinarria da eta, beste aplikazioen artean, osagai bakoitzaren exergia aldagaiak lotzen ditu. Atal berritzailea dinamismoaren barneraketan datza eta, gainera, **Eranskin**eko software dinamikoarekin sostengatzen da.

Are gehiago, diagnostiko termoekonomikoaren helburua osagaien anomaliak identifikatzea da horien sintomak etekin exergetikoen aldakuntzen arabera aztertuz eta horien berreskurapen faktorea zenbatuz; zoritxarrez, teoria zenbait alderdietan erren dago. **D Kapitulu**ak aplikazioaren hainbeste puntu gainditzen ditu eta diagnostiko dinamikoaren problema zuzena egoki ebazten du.

E Kapituluan, aldiz, *exergia analisi aurreratu dinamikoa* aplikatzen da eraikinetan lehen aldiz. Beraz, erronka dinamikoen arazoak ebazten dira.

Ikerketaren osotasuneko asmoa eraikinen sistema termikoetan bigarren legearen aplikazioen alde onak eta txarrak erakustea da. Azken batean, zentzu kritikoa baita edozein aplikazioaren oinarri nagusia eta eraikinen energia eta ekonomia aurrezpenaren oinarrirako bide zuzen bakarra.



A KAPITULUA

Eraikinetan beharrezko energia aurrezpena

A KAPITULUA

AZPIINDIZEAK	
EUB	Etxeko ur beroa
$Heat$	Berokuntza
TOT	Total
0	Giroa
op	Operatiboa
$trans$	Transmisioa
$vent$	Aireztapena
inf	Infiltrazioa
g_{solar}	Eguzki irabaziak
g_{int}	Barne irabaziak

SINBOLOAK		
T	[ºC]	Tenperatura
c_P	[kJ/kg·K]	Bero ahalmena
$\dot{m}$	[kg/s]	Masa emaria
$\dot{Q}$	[kJ/s]	Bero emaria
$\dot{E}$	[kJ/s]	Exergia emaria
η	[%]	Energia etekina
ε	[%]	Exergia etekina

A KAPITULUA: BEHARREZKO ENERGIA AURREZPENA

A.0. LABURPENA

Sarrera kapitulu honek energia sistemetan Termoekonomia aplikatzeko motibazioa justifikatzen du. Horretarako, lehenik eta behin tesiaren helburuen eta metodologia jarraituaren azalpen laburra egingo da. Ostean, eraikinen energiaren egungo egoera labur aipatuko da jarraian exergiaren kontzeptua barneratuz.

Azken finean, nahiz eta eraikinak energia kontsumitzaile handiak izan horien energia aurrezpen potentziala izugarri handia da. Horregatik Europar direktibek *ia energia kontsumorik gabeko* (iEKG) eraikinak sortzeko bidea eta eraikinen birgaitzeak bultzatzen dituzte.

Zoritxarrez, hobekuntzak ezin dira guztiz sustatu energia parametroa soilik erabiliz; exergia erabili behar da energia kantitateaz gain kalitatea aintzat hartzen duelako. Eraikinen exergia analisia energia transformazio kate osoan zehar aplikatu behar da (hots, energia sorkuntzatik energia kontsumora iritsi arte). Beraz, exergia eskariaren kalkulurako giltzarriak garatzen dira.

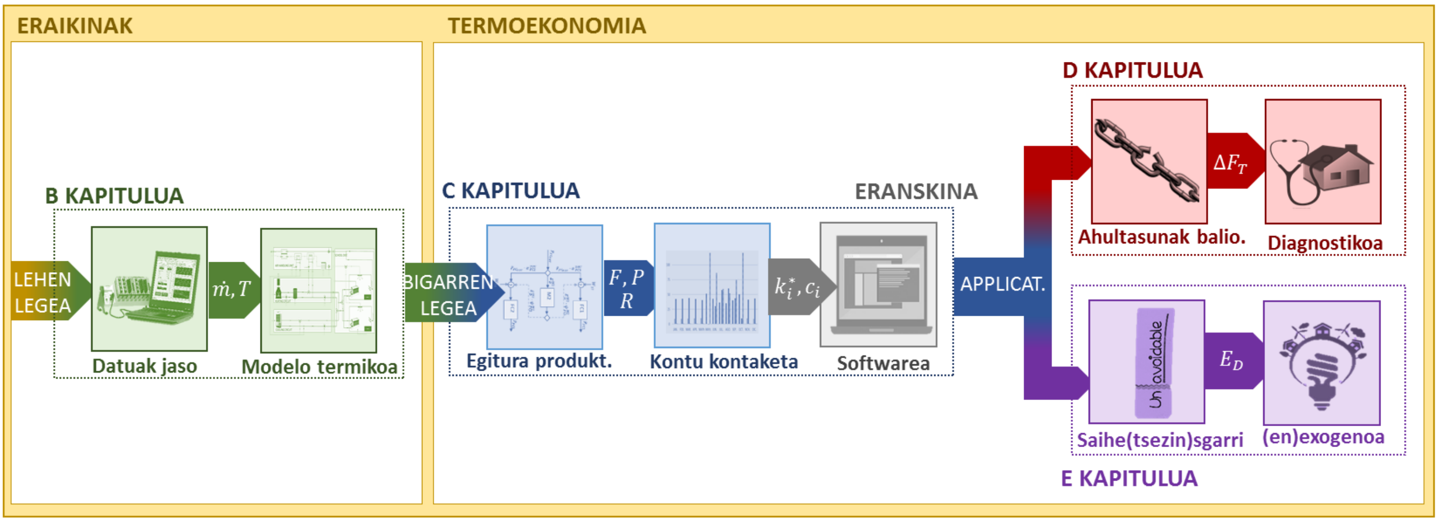
Exergiak barneratuz eraikinen energia aurrezpen potentzialak eta hobekuntzak bi adibideen bidez adierazten dira: lehenengoak energia azterketa soilaren mugak azpimarratzen ditu iEKG eraikin batean. Bestalde, bigarrenak exergia eskariaren kalkulu metodoa justifikatzen du eta sistemen berrikuntzak alderatzeko exergiaren erabilera bidezkotzen du.

A.1. HELBURUAK ETA METODOLOGIA

Sarrera eraikinen energia sistemetan *exergia* parametroaren erabilpenaren justifikazioarekin bat dator. Nahiz eta sistemen ahultasunak analizatzeko tresna ezin hobea izan, exergia analisia gutxitan aplikatu da eraikinen arloan, eta are gutxiago *bigarren legea*ren (*edo Termoekonomia*ren) aplikazioak, alegia, termoekonomia kostu kontaketa eta diagnostikoa.

Asmoetan nagusia termoekonomia analisiak eraikinen era orokorrean barneratzea da (datozen problemak ebatziz eta horien emaitzak hobetuz) edozein inplementazio konplexuagoari ere irtenbidea emanez. Giltzarriak metodologiaren dinamismoarekin zerikusia dauka.

Esan antzera, sarrerako **A Kapitulu** honek exergia eraikinetan aplikatzearen abantailak eta oztopoak barneratzen ditu baina, halere, datozen bigarren legearen aplikazioaren aurretiazko urratsa da soilik, hain zuzen, tesiaren xedea. Berez, hauxek dira bigarren legea aplikatzeko proposatzen diren pausuak, ikus Irudia A. 1:



Irudia A. 1 Eraikinetan termoekonomia aplikatzeko urratsak

✓ **B KAPITULUA**. Lehen legearen metodologia:

1. *Datuak jaso.* Lehenengo urratsa termodinamikaren aldagaien lorpenean datza; esaterako, giro baldintzak edota eraikinaren/instalazioaren beharrizanak.
2. *Modelo termikoa*. Masa eta energia balantzeen arabera, bi metodologia sinpleren bidez osagai bakoitza eta sistema osoa adierazten dira hortik fluxuen exergia kalkulatzeko beharrezko datuak jasotzeko.

✓ **C KAPITULUA** / **ERANSKINA**. Bigarren legearen metodologia:

3. *Egitura produktiboa*. Energia sistemaren analisi kritikoa egin behar da kostu kontaketa metodo baten bitartez (edo bigarren legearen aplikazioarekin). Horretarako, osagaiak zein exergia fluxuak sailkatu behar dira.
4. *Kostu kontaketa*. Exergian oinarritutako kostu kontaketa inplementazioarekin exergia kostu unitarioak eta bestelako emaitza erabilgarriak lortzen dira. Gainera, super-egitura berritzaile batek, STan oinarritua, barne loturen adierazpenak ahalbidetzen ditu.
5. *Softwarea*. Programa dinamiko berri batek sistema errealen aplikaziorako hobekuntza eta kostu kontaketarako inplementazio oro jasotzen ditu. Horrela, emaitzen analisi kritikoarekin prozesuko puntu berezienak identifikatu eta ondorengo aplikazioak gehi daitezke.

✓ **D KAPITULUA**. **E KAPITULUA**. Aplikazioak:

6. *Ahultasunen balioztatzea*. Exergia analisiaren ekarpen bat energia katean zeharreko exergia suntsiketen kokapena eta kuantifikazioa da zein ahalik eta gehien minimizatu behar den.
7. *Diagnostikoa*. Lehen aldiz, anomalien detekziorako eta horien eraginen kontaketarako diagnostiko termoekonomikoaren problema zuzena ebatzi egiten da. Gainera, anomaliak konponduz eta exergia suntsiketak murriztuz, eraikinen energia sistemak optimizatu edota berritu daitezke.

8. *Saihe(sgarri)tsezin*. Exergia analisi aurreratuaren aplikazioak exergia narriaduraren zein zati ekidin daitekeen eta zein teknikoki mugatua dagoen adierazten du.
9. *(en)Exogenoa*. Are gehiago, osagaien jarrerarekin harremana duten zein kanpoko elementuekin lotuta dauden eraginak zenbatetsi daitezke. Berriro ere, AEA metodologia era dinamikoan lehen aldiz aplikatzen da.

Teoria hori guztia zazpi ikerketa kasurekin finkatu egiten da kasuak zehazki definituz eta garatuz:

- (i) iEKG eraikinaren ikerketa kasua
- (ii) Eraikin birgaitzearen ikerketa kasua
- (iii) Eskola baten ATU ikerketa kasua
- (iv) DHW instalazio sinplea
- (v) Eraikinean eguzki sistemaren ikerketa kasua
- (vi) Berokuntza eta EUB sistemaren ikerketa kasua
- (vii) Stirling eta galdara ikerketa kasua

Ondorioz, lehen aldiz dinamismoa hartu da kontuan termoekonomia aplikazioetan. Are gehiago, teoria bakoitzaren onurak eta desabantailak ematen dira puntu ahulak ebatziz.

Emaitza gisa, termoekonomia mundu mailako eraikinetan energia aurrezteko, ekonomia murrizteko eta iraunkortasuna sustatzeko tresna egokitzat jotzen da.

A.2. SARRERA

A.2.1. Beharrezko energia aurrezpena

Baliabide naturalek giza ekintzak ahalbidetzen dituzte. Tamalez, iturri ez berriztagarrien akidura saihestea ia ezinezkoa da eta izakien etorkizunerako arrisku nabaria da. Hortaz, kontsumoaren murrizketa nahitaezko beharra da prozesuen diseinurako eta operaziorako. Halere, gizakia maila altuko konfortera horrenbeste ohitu da, ustiapen abiadurak eta baliabideen birsorkuntzak ezin baitute bat egin; gutxiago oraindik populazio handitzeak dakartzan egoera iraungaitzak kontuan hartuz gero.

Ondorioz, energia eskaria murrizteko gizartearen grina jadanik jakina da. Are gehiago, Europar Batasunaren egungo helburu nagusietako bat lehen mailako energiaren kontserbazioan eta CO_2 isurien beherapenean datza, munduaren etengabeko klima aldaketa medio.

Erref. [1]-en adierazi lez, energiaren erabilera joerak berdin jarraituz gero, 2007.urtetik 2035.urtera fuel olioaren igoera % 30 izango da eta ikatzaren eta gas naturalaren joera % 50.

Gainera, eraikinen energia kontsumoa azkar batean igo da azken urteotan, beste gauza batzuen artetik, populazio handitzeagatik, osasun beharrizan zorrotzengatik, barne giro erosotasun handiagoagatik, etab. Europako egoeraren arabera, hirugarren sektorea (eraikinak eta zerbitzuak) amaierako energia kontsumo totalaren % 40aren arduraduna da eta CO_2 guztizko igorpenen % 50arena [2]. Espainian, ordea, nazioko energiaren % 28 erabiltzen da eraikinetan, % 18 etxebizitzetan eta gainontzeko % 10 zerbitzuetan, [3]. Zorigaitzez, egungo joerak ehunekoen igoera asaldagarria dakar. Orduan, energia kontsumoa jaisteko behar larria dago, batez ere berokuntza, aireztapen eta aire girotu sistemetan (HVAC&R) [4].

Edonola ere, eraikinen bizitzan zehar (eraikuntzan, erabileran eta deuseztapenean) energia kantitate handiak erabiltzen dira beharrezko zerbitzuak eskaintzako eta eraikuntza materialen sorkuntzarako. Ondorioz, datozen urteotan energia hobekuntzarako potentzial nabarmenak daude. Testuinguru horrek energia aurrezpenerako Europar politika berriak ekarri zituen, esaterako, *energia etekinerako direktiba* (EED) eta *eraikinen erabilera energetikoaren direktiba* (EPBD). EPBDaren 2010eko azken eguneratzearen arabera, 2020.urtetik aurrera eraikin berri guztiak ia energia kontsumorik gabeko (iEKG) eraikinak izan behar dira, eta hori da, hain justu, energia positiboen aitzineko urratsa. Horregatik, sistemen eraginkortasun energetikoa oso garrantzitsua da ikerketa ekintza askoren helburu nagusia bilakatuz [5].

Alde batetik, urte hauetan zehar aurrerapen handiak egin dira material, fatxada eta estalki berrien aplikazioetan energia sistemen garapenerako; batik bat instalazio hibridoetan energia berriztagarrien barneraketarekin.

Aurrekari horien arabera, Passivhaus estandarteak energia eskari baxuko eraikina adierazten du eta iEKG eraikinen erreferentziatzat erabiltzen da. Proiektuaren diseinuan era eraikuntzan zehar prozedura oso zehatzean oinarritzen da eta energia eskari baxua ahalbidetzen du.

Beste alde batetik, berritzapenen inbertsioak erakargarri egiteko potentzial handia dago (egoitzetan zein hirugarren sektorean), azalera guztizko % 1 soilik urtero birgaitu arren. Errealitate hori aldatzeko, EBak zeinbat direktiba proposatu ditu energia efizientzia hobetzeko.

Hala eta guztiz ere, eraikinak diseinatzeko energia oinarrizko parametrotzat erabiltzen da eta, beranduago frogatu antzera, zenbait inkongruentzia sor daitezke analisi horrekin. Eraikin arloko azterketa gehienek termodinamikaren lehen legean dute funtsa, alegia, bai energia etekinen bai lehen mailako energiaren bai CO_2 jarioen arabera gauzatu dira, adibidez [6]. Energiaren kalitateak ez dira aintzat hartzen eta galerak bakarrik dira erabili gabeko energiak, oro har bero fluxuak, taldeen perfekzio ezak eta galera gehigarriek dakartzaten itzulezintasunak kontuan hartu gabe.

Sistematik informazio erabilgarria lortzeko, *energia analisia*z gain *exergia analisia* egin behar da; lor daitekeen lan erabilgarri maximoa zenbakitzen baitu [7] energia kalitatea eta kantitatea batuz [8]. Exergiak, energiak ez bezala, ez du kontserbazio legerik jarraitzen eta suntsitzen da prozesuen atzeraezintasunen energia narriadurarekin [9]. Beste era batean esanda, eraikinen sistema energetikoen diseinurako, analisirako eta optimizaziorako oso erabilgarria da prozesuan zehar zeozer suntsi daitekeen ideia. Energia balantzeak ez ditu efizientzia gabezia errealak identifikatzen eta, horregatik, energian soilik kontzeptuak oinarritzea ez du zentzurik eta emaitza okerrak ekar ditzake.

A.2.2. Exergia analisia

Baliabide naturalen kontsumo murrizketa energiaren *lan erabilgarria* eta eraldaketarako gaitasuna kontuan hartuz lor daiteke.

Energia motek beste eretan bihurtzeko ahalmen ezberdina dute. Energiaren kalitateak eraldaketarako gaitasuna adierazten duenez, energia kantitate berdinak kalitate ezberdina izan ditzakete beste motetan bihurtzeko trebetasunaren arabera. Orokorrean, energia mota guztien artean erreferentziatzat *lana* hartzen da, hau da, energiaren kalitatea lan erabilgarrian bilakatzeko abileziarekin neurtzen da eta *exergia* deritzo [7].

Energia mota batzuk lanean guztiz eralda daitezke (energia elektrikoa, kasurako) eta, hortaz, energia oro exergia da. Baina, beste energia mota batzuen zati bat baino ezin da lanean bilakatu (beroa, adibidez); ondorioz, zati bat baino ez da exergia.

Exergiak termodinamikaren lehenengo eta bigarren legeak batzen ditu itzulezintasunek efizientzia ezak barneratuz [10]. Hori dela eta, energiaren degradazioa adierazten du [11] eta informazio termodinamikoaren sintesia da; horregatik osagaien jarrera teknikoa deskribatzeko erabilgarria da [12] eta sistema ezberdinen arteko alderaketa baimentzen du. Gainera, lana eta kapitala exergia termikoetan adieraz daitezke eta horien baliokideak exergia metodo hedatuetan sar daitezke [13].

Alabaina, exergia zentzugabea da lan erabilgarriaren muga edo ahalmena adierazteko erreferentzia girorik edo "giro hilik" gabe; hortaz, exergia analisiaren arazo larriena erlatibitatea da [11]. Are gehiago, termoekonomia parametroak aldagai fisikoen zenbait nahasketekin egiten direnez, exergia parametroa magnitude fisikoetatik lortzean informazioa galtzen da. Ondorioz, bigarren legeak ez du eraginkortasunaren "esanahia" adierazten (parametro fisikoak edo geometrikoak behar dira). Edozein kasutan, exergia aldagai termodinamikoaren multzo dependentea izanagatik ere [14], energia sistemen diseinurako, optimizaziorako eta mantenurako informazio garrantzitsua eskaintzen du.

Abantaila horiengatik guztiengatik, exergia analisia tresna egokia da itzulezintasunak murriztuz energia efizientziaren hobekuntza bultzatzeko. Industria mailan anitz erabili denez industria prozesuekin eta energia plantekin lotuta erreferentzia ugari daude, esaterako, PEM fuel zelulak [15], azukre plantak [16] edo lehor plantak [17]. Bestalde, exergia analisia eraikuntza arloan askoz gutxiago erabili da eta oso argitarapen gutxi daude nahiz eta gero eta ospe handiago izan (adibidez low-ex eraikinen aplikazioen bitartez).

Esaterako, azterketa exergetikoak egin dira aire-lurreko bero ponpekin [18]-[19] edota eguzki bero biltzaileekin [20]. Antzeko eran, simulazio metodologietan zenbait exergia analisi gaineratu dira, hala nola ospitale baten trigenerazio sisteman [21].

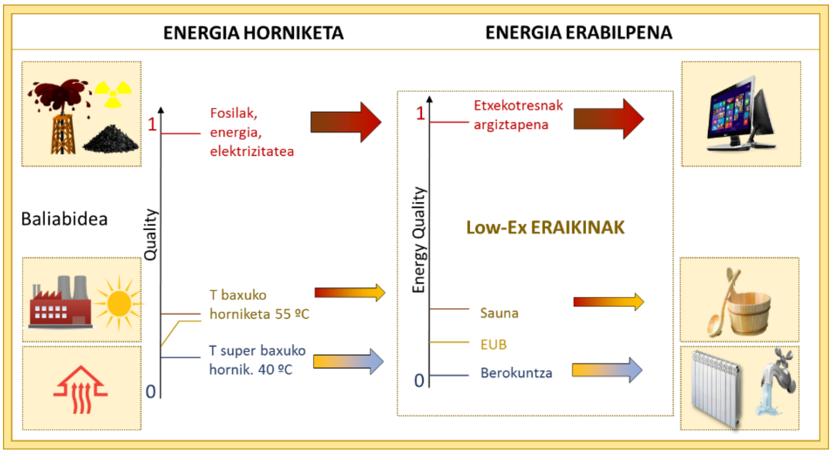
Exergiaren eraikinetan barneratzeko zailtasunen zenbait arrazoi ondorengoak izan daitezke:

- Giro baldintzatik urruneko sistemetan, industria aplikazio gehienetan adibidez, giro baldintza estandarte finkatuak erabil daitezke emaitzen zehaztasunean galera nabarmenik gabe. Eraikin zerbitzuek, aldiz, giro baldintzetatik gertu egiten dute lan eta, beraz, ezinbestekoa da horien aldakuntzak barneratzea. Ondorioz, exergiak giro tenperaturaren aldaketen arabera fluktuatzen du eta hori aztertzeko zenbait ikerketa egin dira, besteak beste, eraikin zerbitzuetan [22], [23], [24] edo lur bero ponpetan [25].
- Gainera, eraikinen exergia analisiek etekin exergetiko oso baxuak erakusten dituzte. Hala nola EUB sorkuntzarako efizientzia exergetikoa % 3,2-10,8 [26]; berokuntzarako % 2,5 to 7,4 [27] edo aire girotzerako sisteman % 3,4 [28] dira zeintzuek publizitate txartzat jo daitezkeen.

(Eraikin sistemen ikerketa exergetikoaren informazio eta zehaztasun gehiago [29]-n dago).

A.3. ENERGIA KALITATEA ERAIKINETAN

Eraikinen energia eskariak kalitate ezberdinak dauzka eta asko dira horiek asetzeko iturburuak. Argindarra etxetresna elektrikoetan eta argiztapenean erabiltzen da eta energia kalitateko altuko bestelako baliabide batzuk, ordea, berokuntzarako, aireztapenerako edota EUBrako erabiltzen dira (alegia, gas naturala edo erregai fosilak). Elektrizitate eskaria, berokuntza, hozkuntza edo EUB eskariak ez bezala, energia kalitate altua da. Azkenekoen helburua baita barne tenperatura kanpo girotik pare bat gradu gorago edo beherago mantentzea. Beraz, energia sorkuntza kalitatearen eta eskari kalitatearen artean ez dago elkarrekikotasunik, [30]. Emaitza gisa exergia suntsiketa nabarmenak daude (kalitate narriadurak) eta energia galerak baino askoz garaiagoak dira. Irudia A. 2ak energia baliabidearen arabera erabilpen egokia erakusten du.



Irudia A. 2Energiaren erabilera egokia energia horniketaren arabera

Low-ex eraikinak, iEKG eraikinak ez bezala, eskariak asetzeko energia kalitate ezberdinetatik probetxua lortzen du. Horiek energia galerak eta exergia suntsiketak murrizten dituzte. Beraz, sistemaren eraginkortasunaren igoerak itzulezintasunen jaitsiera adierazten du eta, ondorioz, energiaren erabilpen egokiagoa. Eraikinen exergia etekinetan funtsa du [31] lanak.

Eraikuntza arloan azterketa energetikoa aunitz arruntagoa izanagatik ere, exergia aplikatu behar da. Analisi hori bietan egin behar da, etxebizitzen azalean eta sistemetan. Helburua prozesu guztiko urratsen optimizazioa da: eraikinaren diseinutik hasita, eraikuntza eta azterketa faseekin jarraituz, kontrola eta mantenua hobetu arte.

A.3.1. Berokuntza eta EUB eskariak

Azken urteotan zehar energia eraginkortasunen esfortzuak bi norabideetan egin dira: alde batetik, azaleko elementuak hobetu dira (fatxadak, leihoak, estalkiak, etab.) eta, bestetik, sistemak (berokuntza, hozkuntza, aireztapena eta argiztapena). Halere, osagaien hobekuntza indibiduala ez da nahikoa: eraikinak oso sistema konplexuak dira eta azalak, giroak zein sistemak osotasunean egiten dute lan modu integratu batean.

Eraikin baten energia hornitzeko sistemaren kudeaketak (aireztapenerako, hozkuntzarako, berokuntzarako edota EUBrako) energia kargen aurretiazko zenbaketa behar du. Eraikin motaren arabera zehaztapen ezberdinak bete beharko dira [32], besteak beste, konfort termikoa [2] eta barne aire kalitatea (IAQ) [33].

Hortaz, *energia eskaria* eraikinaren ezaugarriekin, erabiltzaileen patroiekin eta lekuko klimarekin bat dator. Energia galeren eta irabazien balantzeetatik karga profil oso irregularrak lortzen dira [34]. HVAC&R sistemek beharrizan horiek asetzea dute xedea energia transformazio prozesuen bitartez. Plantaren sarreran energia kanpo baliabideak kontsumitzen dira zeintzuen kantitatea eta igorpenak mugatu edo minimizatu behar diren.

Orduan, energia eskaria ($\dot{Q}_{heat}$) erabiltzaileentzako barne giroa konfort baldintzetan mantentzeko beharrezko energia kantitatea da eta ISO 13790 (2008) araua jarraituz kalkulatzen da. Berokuntza periodoari dagokionez, eskari totala guztizko galerak (hormetan zeharreko transmisioa, aireztapena eta infiltrazioak) ken irabaziak (eguzki zein barne) da:

$$\dot{Q}_{heat} = \left(\dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{inf}\right) - \left(\dot{Q}_{g_{solar}} + \dot{Q}_{g_{int}}\right) \quad \text{(A. 1)}$$

Aitzineko balantzea eraikinaren zona orotan burutzen da eta ondoren eraikinaren eskari orokorrean batzen da. Eremu termikoen balantzeak bero eta materia fluxuak barneratzen ditu, adibidez aireztapena eta infiltrazioa, baina ez ditu hezedura edo hezetasun galtzea kontuan hartzen.

Berokuntzarako exergia eskaria ($\dot{E}_{heat}$) energia eskariaren baitan kalkulatzen da eta energia horren exergia edukia adierazten du, alegia, barnealdea konfort egoeran mantentzeko beharrezko lan minimoa. Hortaz, gehiegizko exergia horniketa erabilpen galeretan edo exergia suntsiketetan bihurtzen da berokuntza (edo hozkuntza) sistema eta eskari puntuaren artean.

Bi metodo daude $\dot{E}_{heat}$ kalkulurako: sinplifikatua eta zehaztua. Nahiz eta lehenengoa gehiago erabili, esaterako [35] lanean, bigarrena erabiliko da. Biak Annex 49 [36] dokumentuan sakonki garatzen dira. Zehaztuaren ezberdintasuna da exergia eskaria aireztapenarekin eta gainontzekoarekin bereizten dituela. Bietako batek ere ez ditu exergia kimikoak ezta konbekziozko exergien eta erradiazio exergien hormen trukeak kontuan hartzen.

Ideia nagusia da T_{op} tenperaturarako *barne energia* baten kalitate faktorea (exergiaren eta energiaren arteko harremana, E/Q) txikiagoa dela T_{op} tenperatura berdineko *bero energia*ren kalitate faktorearekin konparatuz. Era horretan, exergia eskaria zehaztu beharrean, lehenik eta behin aireztapenerako eskariaren zein zati berotu (edo hoztu) behar den aztertu behar da eta, ondoren, gainontzekoa giroa tenperatura operatibora eramateko beharrazko exergia kalkulatu behar da.

Laburtzeko, exergia eskarirako bi osagai bereizten dira: lehenik kanpoko aireztapeneko airea egokitzeko exergia beharra zehazten da eta, bigarrenik, exergia eskari gehiago badago, bero moduan entregatu behar da T_{op} tenperatura operatiboan. Hortaz, bero eskaria bi sarreretan banatzen da: kanpo airearen aurretiazko prestakuntzan eta barneko girotzean.

Energia balantzea egitean, energia eskaria totala $\dot{Q}_{heat}$ aireztapen galerekin konparatzen da. Guztizko eskaria baino txikiagoa bada, aireztapen airea T_{op} tenperatura operatibora igo behar da. Horrela exergiaren ekarpen minimoa ziurtatzen da datorren adierazpenarekin kalkulatuz:

$$\dot{E}_{vent} = \dot{Q}_{vent} \cdot \left[1 - \frac{T_0}{\left(T_{op} - T_0\right)} \cdot ln\left(\frac{T_{op}}{T_0}\right)\right] \quad \text{(A. 2)}$$

T_0 giro tenperatura eta $\dot{Q}_{vent}$ barne airea girotzeko beharrezko beroa dira, alegia:

$$\dot{Q}_{vent} = \dot{m}_{vent} \cdot c_P \cdot (T_{op} - T_0) \qquad \text{(A. 3)}$$

Guztizko eskariaren eta $\dot{Q}_{vent}$ beroaren arteko diferentzia bero lez eman behar da T_{op} tenperaturan; beraz, exergia osagarria da:

$$\dot{E}_{heat} = \left(1 - \frac{T_0}{T_{op}}\right) \cdot (\dot{Q}_{heat} - \dot{Q}_{vent}) \qquad \text{(A. 4)}$$

Guztizko eskaria aireztapen galera baino gutxiagoa bada ($\dot{Q}_{heat} < \dot{Q}_{vent}$), airea ez da T_{op} tenperaturara igo behar. Horrela, ez da bero gehigarririk beharko, barne eta eguzki irabaziekin orekatzen baita. Egoera hartan, airearen tenperatura honela girotu beharko da:

$$\Delta T_{vent} = \frac{\dot{Q}_{heat}}{\dot{Q}_{vent}} \cdot (T_{op} - T_0) \qquad \text{(A. 5)}$$

Eta beraz, beharrezko exergia da:

$$\dot{E}_{vent} = \dot{Q}_{vent} \cdot \left[1 - \frac{T_0}{\Delta T_{vent}} \cdot ln\left(\frac{\Delta T_{vent} + T_0}{T_0}\right)\right] \qquad \text{(A. 6)}$$

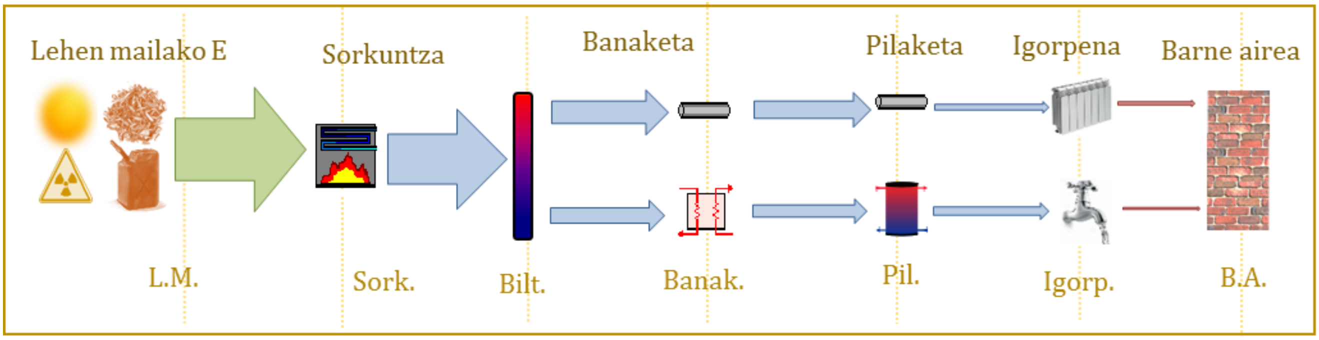
Hozkuntzan, bestalde, bi egoera nagusi daude: $T_0 > T_{op}$ kasuan, energia fluxu natural orok nahi ez diren irabaziak direnez, beti beteko da $\dot{Q}_{heat} > \dot{Q}_{vent}$. Beraz, aireztapeneko airea beti jeitsi beharko da T_{op} tenperaturara. $T_0 < T_{op}$ egoeran, alderantziz, hozkuntza beharrak (energia irteera) ez du exergia eskaririk adierazten, nahi ez den exergia lagapena baizik. Exergia hori barne irabaziekin lortzen da eta T_{op} tenperaturako bero fluxuaren bidez probetxua lor daiteke.

Edozein kasutan ere, exergia eskaria energia eskariaren % 10 izan oi da eta, jakina, T_0 eta T_{op} tenperaturen menpekoa da.

EUBa hornitzeko energia eskaria ($\dot{Q}_{DHW}$) beharrezko set-point tenperaturaren eta emariaren araberakoa da. Antzeko moduan, exergia eskaria set-point tenperaturaren eta emariaren funtzio da.

A.3.2. Eraikinaren sistema termikoa eta eskariaren asetzea

Eraikinaren energia horniketarako zenbait osagaiek hartzen dute parte zeintzuek estalduratik hasita sorkuntzara iritsi arteko katean ondorengoak diren: eraikinaren azala, elementu



Irudia A. 3 Eskaria asetzeko ohiko energia katea terminalak, energia banaketa eta biltegiratze sistemak, sorkuntza elementuak eta energia bektoreak (fuela, argindarra, energia termikoa, etab.). Jomuga konfort eskariak asetzea da lehen mailako energia berriztagarriak eta fosilak eraldatuz, energia katea zeharkatuz eskariak bete arte, ikus Irudia A. 3.

A.4. IKERKETA KASUA

Teoria hobeto ulertzeko bi adibideetan aplikatuko da.

Lehenengoaren helburua eraikinaren energia kate osoan zehar energia eta exergia eraginkortasunen arteko ezberdintasunak adieraztea da. Horretarako, lehen mailako energiatik hasiko da beharrezko eskari estaldurara iritsi arte. Helburu horrekin Arabako, Espainiako iparraldea, iEKG eraikin bat aztertuko da (Passivhaus ziurtagiriarekin) eta termodinamikaren lehenengo eta bigarren legeak urteko analisi dinamikoak aplikatuko dira. iEKG eraikinen hainbat oztopo azpimarratuko dira.

Bigarren adibidearen xedea energia kate osoko eraginkortasunaren hobekuntza adieraztea da berokuntza eta EUB eskariko sistema berriztatu batean exergia analisiaren bitartez. Birgaitzea sistema termikoan baino ez denez egin, eraikinaren aurretiazko eta egungo eskariak berberak dira. Exergia metodo zehaztuaren eta sinplifikatuaren arteko bereizketa ere egiten da eta egokiagotzat zehaztua hautatzen da.

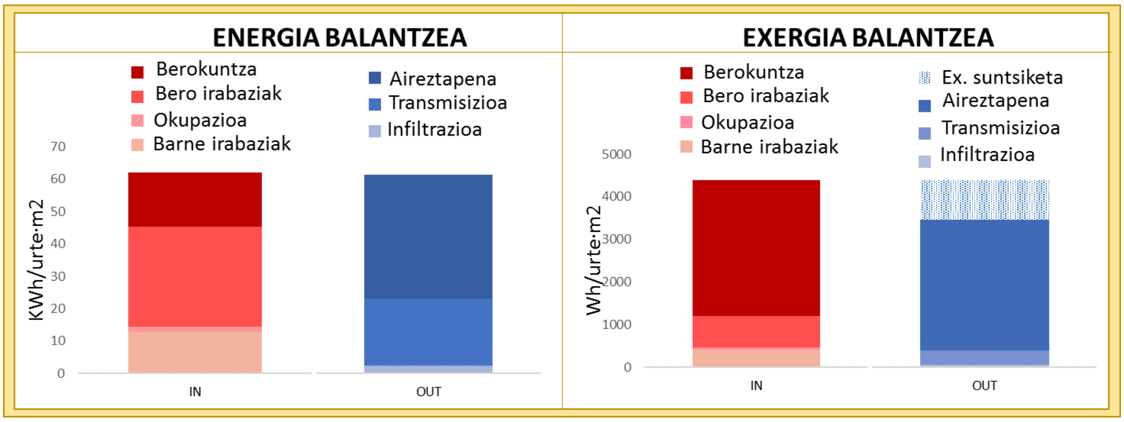
A.4.1. (i) iEKG eraikinaren ikerketa kasua

Irudia A. 4 Arabako familia bakarreko etxebizitza

Teoria iEKG etxebizitza batean aplikatu zen eraikinen exergia erabilpena egokiago ulertzeko. Familia bakarreko etxea da guztizko 176 m² azalera erabilgarriarekin eta Araban (Espainiako iparraldean) dago D1 klima eremuan. Urteko berokuntza eskaria mugaren azpian egoteagatik Passivhaus ziurtagiria dauka [37], ikus Irudia A. 4.

A.4.1.1. Energia eta exergia eskariak

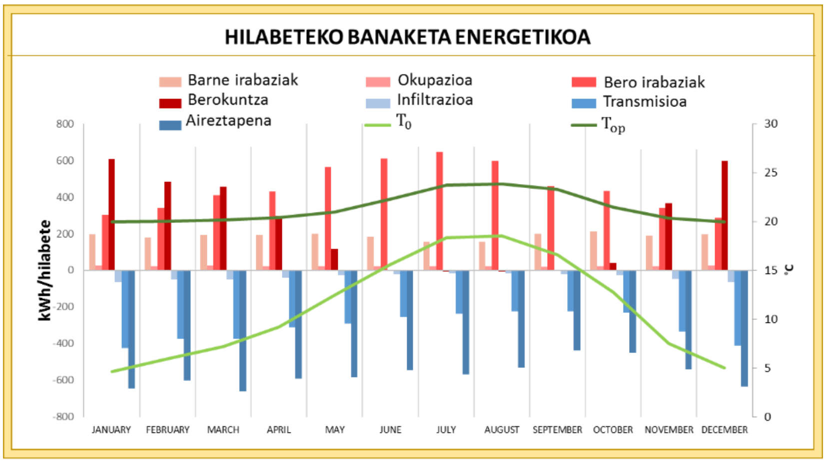
Hasteko, familia bakarreko etxearen modelo termiko dinamikoa egin zen EnergyPlus softwarearekin eta urte beteko datu monitorizatuekin kalibratu zen [38]. Bero irabaziak, aireztapena eta transmisio galerak modeloaren eta datu errealen alderaketekin zehaztu ziren. Horrela, Ek.(A. 1) jarraituz berokuntza eskaria orduz ordu lortu zen, non sarrera fluxuak irteerakoekin orekatzen diren.



Irudia A. 5 (a) Eraikinaren energia balantzea. (b) Eraikinaren exergia balantzea

Exergia bero eskaria metodo zehaztuarekin kalkulatu zen. Irudia A. 5 (a)-n urteko energia balantzearen energia pilatua erakusten da m²-ko eta (b) irudian, ordea, exergia balantzea.

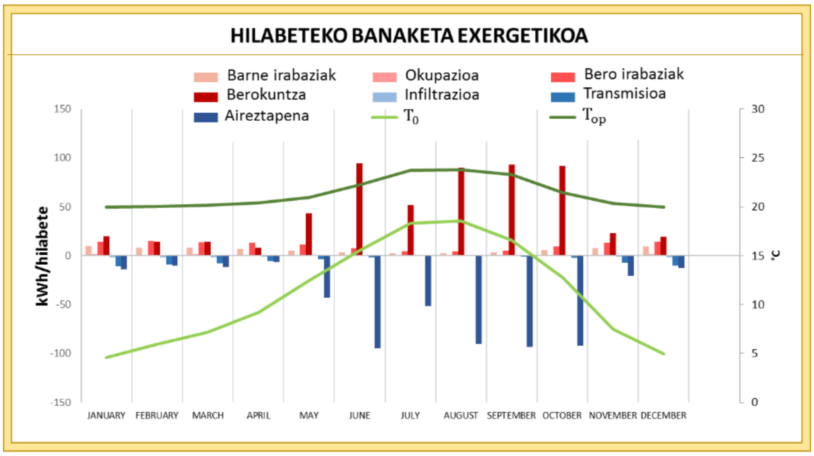
Balioen arteko alde handia eta exergia suntsiketa exergia eskari totalaren % 21 balioa nabarmendu behar dira. Beraz, suntsiketa horiek saihesteko hobekuntza nahiko gauza daitezke.



Irudia A. 6 Hilabeteko energia galerak eta irabaziak

Horrez gain, Irudia A. 6n energia irabazien eta galeren hilabeteko balioak agertzen dira eta Irudia A. 7n, aldiz, balio berdinak exergia terminoetan irudikatzen dira. Bi kasuetan kanpo airearen tenperaturaren (T_0) eta barneko tenperatura operatiboaren (T_{op}) profilak barneratzen dira eskariaren ulermena errazteko.

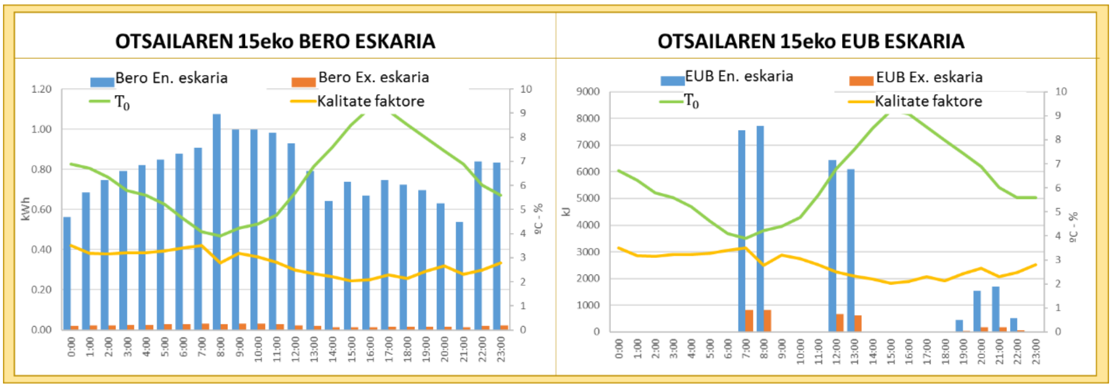
Exergia grafikoaren kWh/hilabete eskala aipatu behar da, energia baino 5 aldiz txikiagoa baita.



Irudia A. 7 Hilabeteko exergia galerak eta irabaziak

Urteko jarrera erakusteko, Irudia A. 8 (a)-n orduz ordu aurkezten dira energia eta exergia bero eskariak. Neguko ohiko egun bat hautatu zen, otsailaren 15a. Grafikoan T_0 eta exergia faktorea (exergia eta energia eskariaren arteko zatiketa) ere batu dira.

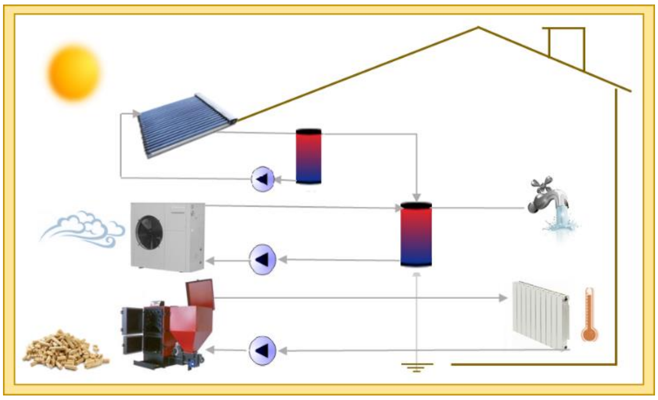
Antzeko eran, EUB eskaria orduko profil estandarrean lortu zen IEA-SHC Task26 softwarearekin [39]. Urteko EUB energia eskaria 459 kWh/urte·perts eta exergia eskaria, ordea, 46 kWh/urte·perts dira. Beraz, Irudia A. 8 (b)-n otsailaren egun berberako EUB energia eta exergia eskariak marrazten dira, gainera, hor ere kanpo tenperatura eta EUBaren exergia faktorea gehitu dira.



Irudia A. 8(a) berokuntzaren eta (b) EUBren Q eta E eskariak neguko ohiko egun batean

A.4.1.2. Eskaria hornitzeko eraikinaren sistema termikoa

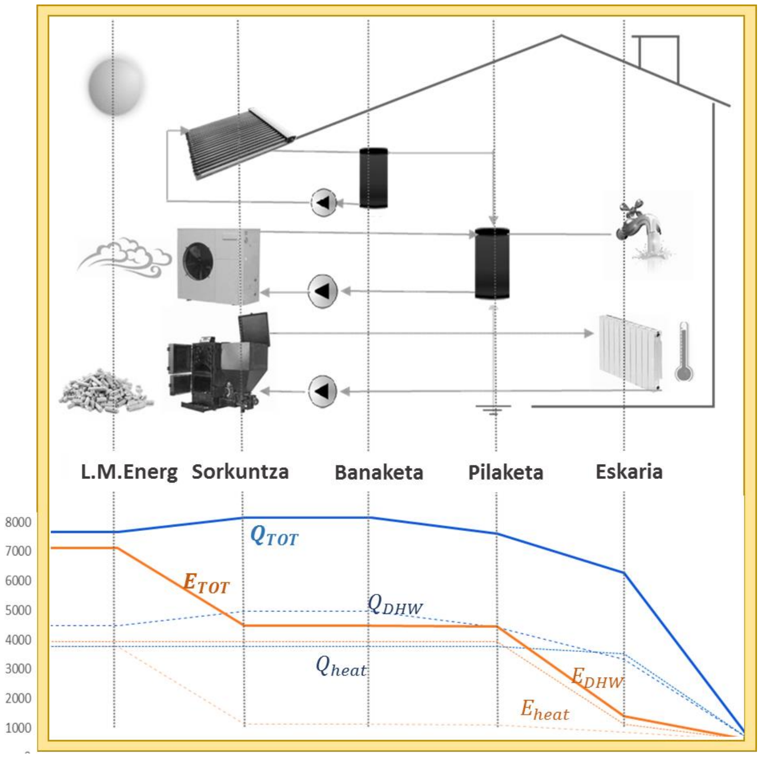
Sistema termikoak berokuntzarako biomasa galdara bat dauka (2.4 - 9 kW). EUB ura aurreberotzeko eguzki panel baten bidez (2,3 m^{2}ko moduluarekin eta biltegi batekin) eta aire-ur bero ponpa (3,6 kW) batekin asetzen da, 300 l-ko EUB biltegiarekin, ikus Irudia A. 9. Etxebizitzak bero berreskurapeneko aireztapen sistema dauka zeinek uda garaian bypasseatu eta hozkuntza aktiboa ekidin egiten duen.



Irudia A. 9 Berokuntza eta EUB hornitzeko sistemaren ikerketa kasua

A.4.1.3. Sistemaren energia eta exergia analisia

Sistema Trnsys v17 [40] programarekin simulatu zen. Ikerketa kasuko osagaiak softwarearen liburutegiko modelo sinplifikatuak aukeratuz errepresentatu ziren, ahalik eta modu zorrotzenean errealitatera hurbilduz. Gainera, EUB eta berokuntza eskarik une berean barneratu ziren. Modeloa urtebete batean simulatu zen orduko denbora tartearekin.



Irudia A. 10 Instalazio termikoaren katean zehar energia eta exergia eraldaketak

Simulazioaren ostean, fluxu bakoitzeko datu termodinamikoak lortu eta orduko energia eta exergia balioak bildu ziren. Beraz, urteko Q and E balio pilatuekin Irudia A. 10 eraiki zen non bost fase hartu ziren kontuan; baliabideen erdiespenetik produktuaren eskaintzara arte dira: lehen mailako energia, sorkuntza, banaketa, biltegiratzea eta eskaria.

Marra urdinarekin energia bihurketa katea adierazten da eta laranjarekin, aldiz, exergia eraldaketa. Gainera, marra beteek guztizko emaitzak irudikatzen dituzte (Q_{TOT} eta E_{TOT}), puntukako lerroek EUB zirkuitua (Q_{DHW} eta E_{DHW}) eta marra etenek berokuntza zirkuitua (Q_{heat} eta E_{heat}). Eskariaren energia kalitatea erdiesteko grafiko erabakigarria da hori eta, ikus daitekeen lez, exergia kurba energiarena baino nabarmen baxuagoa da.

Lehen mailako energia eta sorkuntza faseen arteko Q_{TOT} eta E_{TOT} lerroen aurkako noranzkoa arraroa gerta daiteke, lehenengo parametroa gora baitoa eta bigarrena behera. Horren arrazoia bero ponparen eraginkortasun koefizientea (COP) da. Kondensadorearen bero eskaintzaren eta elektrizitate kontsumoaren arteko lotura adierazten du. Adibidez, 3 balioko COParen arabera, 1 kW elektrizitate behar dira kondentsadorean 3 kW lortzeko. Ondorioz, beti unitatea baino altuagoa da.

Alabaina, energiaren kalitate faktorea aintzat hartuz gero (hau da, exergia), balioa errotik aldatzen da. Finean, argindarra exergia purua da eta beroaren zati bat baino ezin da lan erabilgarrian bilakatu; beraz, definizioz, exergia etekina beti da unitatea baino txikiagoa. Adibidearen arabera, nahiz eta urteko bero ponparen batez besteko COPa 2,85 izan, exergia etekina $\varepsilon_{HP} = 0{,}28$ da.

Antzeko zeozer gertatzen da biltegiekin: energia analisian kontuan hartutako galera bakarrak bero galerak direnez, etekinak % 100eko idealtasunetik gertu daude (pilaketa adiabatikoetan gertatu lez). Aitzitik, tenperatura ezberdineko fluxuen nahasketen itzulezintasunak ez dira bertan ikuskatzen, esaterako sareko ur hotzaren eta biltegiaren barneko ur beroaren arteko nahastea. Adibide honetan, EUB biltegiaren urteko batez besteko etekin energetikoa $\eta_{T1} =$ % 81 izanagatik, etekin exergetikoa $\varepsilon_{T1} =$ % 54 da.

Era berean, E_{TOT} exergia profilaren gainbegiradarekin exergia suntsiketa nagusien lekuak ikusten dira: lehen mailako energiaren transformaziotik zirkuitua berotzeko fasean eta biltegieen irteeratik azkeneko eskariaren tarteetan. Gehitzeko, energiaren eta exergiaren arteko eskala ezberdintasunak berehala antzeman egiten dira.

A.4.1.4. Emaitzen eztabaida

Urteko berokuntza eskaria $\mathrm{Q_{heat}} = 2{,}96\ \mathrm{GWh/urte}$ eta EUB eskaria $\mathrm{Q_{EUB}} = 2{,}76\ \mathrm{GWh/urte}$ dira. Exergia terminoetan eraldatuz gero, balioak $\mathrm{E_{heat}} = 0{,}56\ \mathrm{GWh/urte}$ eta $\mathrm{E_{EUB}} = 0{,}27\ \mathrm{GWh/urte}$ direnez, bien kalitate faktore baxua erraz nabarmentzen da. Bero zirkuituaren energia eraginkortasuna $\eta_{\mathrm{heat}} =$ % 93 da eta exergetikoa, ordea, $\varepsilon_{\mathrm{heat}} =$ % 17. Bestalde, EUB sorkuntza zirkuituaren etekinak $\eta_{\mathrm{EUB}} =$ % 71 eta $\varepsilon_{\mathrm{EUB}} =$ % 0,09 dira.

Labur esanda, sistema osoaren guztizko energia etekina $\eta_{TOT} =$ % 81 bada ere, etekin exergetikoa $\varepsilon_{TOT} =$ % 13 da, azkenekoan bihurketen itzulezintasunak barneratzen direlako.

Emaitza gisa, nahiz eta iEKG eraikin bat izan, energia aurrezpenerako aukerak handiak daude, betiere energia kalitateak kontuan hartuz gero, bai eraikinaren azalean bai sistema termikoan. Exergia baliabide kontsumoaren murrizketak energia kalitate gutxiagoaren beharra adierazten du, beraz, kalitate baxuko energia iturriak erabil daitezke eskariak asetzeko (hondar beroak, besteak beste). Informazio hori soilik lortzen da bigarren legea aplikatuz.

A.4.2. (ii) Eraikin birgaituaren ikerketa kasua

Ikerketa kasua lau blokeen sistema termikoan datza, denek baitute berokuntza eta EUB hornitzeko instalazio berbera. Etxebizitzak Espainiaren iparraldean daude, Bilbao, eta 70koko hamarkadan eraiki ziren; (I) blokeak 190 egoiliar dauzka, beste bi blokek (II eta III) 108 bana eta laugarrenak (IV) 160 bizilagun, ikus Irudia A. 11. Energia sistema horniketa birgaitu egin da eta, azalduko den antzera, galdarak eta zirkulazio ponpak aldatu egin dira.

Lau eraikinek antzeko egitura ezaugarriak dauzkate, ikus Taula A. 1.

Taula A. 1 Blokeen egitura ezaugarriak

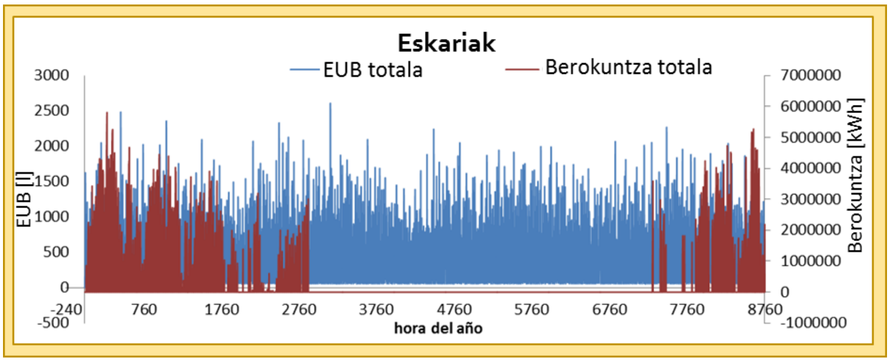
EGITURA EZAUGARRIAK		
Taldea	Deskripzioa	Trasmitantzia
Fatxadak	Adreilu bikoitzeko hormak isolakuntza barik	1.68 W/m^2K
Teilatu laua	Isolakuntza termikoarekin, kareore porlan iragazgaitzarekin	1.51 W/m^2K
Leihoak	Egurrezko marko originalak eta leiho monolotikoak. Denboran zehar zenbait ordeztu egin dira eraginkortasun altuagoko batzuekin	2.89 W/m^2K

Irudia A. 11 Lau blokeen ikerketa kasua

Eraikinaren energia erabilera Trnsys v17 software dinamikoaren bidez analizatu zen. Modeloa eremu anitzeko osagaietan oinarritu zen eta zona bakoitzean energia balantzea gauzatu zen non propietate arkitektoniko eta materialen ezaugarri termiko oro leialki adierazi ziren. Modeloaren zehaztasun matematikoak Trnsys erabiltzaile gidaliburuan daude.

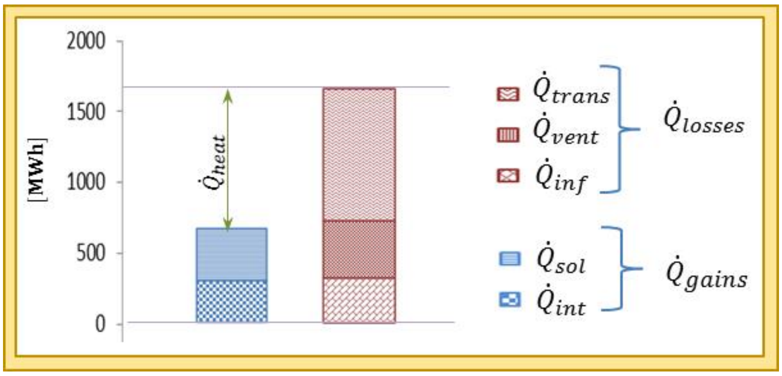
Eguraldiaren data simulazioa orduz ordu ezarri zenez, berokuntza eskaria ere orduz ordu kalkulatu zen. Bilboko klima Meteonorm softwarearekin sartu zen [41] zeinek orduko data azkeneko 30 urteen datuen batez bestekoekin ematen duen. Simulazio baldintza definitzeko (aireztapena, infiltrazioak eta irabazi termikoak), *eraikuntzaren kode teknikoaren* HE1-ko C eranskinaren balioak hartu ziren [42]. 20 °C-ko konfort termikoaren tenperatura erabili zen eta gaueko atzerapena 23:00tik 6:00ra hartu zen 4°C-ko tartearekin. Berokuntza egutegia azaroaren 1ean hasi eta apirilaren 30ean bukatzen da eta kanpo tenperatura 15 °C-tik behera badago edota azken 18 orduen batez besteko tenperatura 15 °C baino gutxiago bada berokuntza pizten da. Ondorioz, berokuntza eskariak Espainia Iparraldeko etxebizitzen ohiko eskari profila dauka [43].

EUBcalc tool erabili zen EUB [l/h] eskaria kalkulurako. Programak eskaria era estatistikoan banatzen du urtean zehar. Beraz, bloke bakoitzeko erabiltzaileak kontuan hartzen ditu eta eskaria orduz ordu banatzen du; 55 °C-tan bultzatzen da EUB iturrietara. Irudia A. 12 urteko berokuntza eta EUB eskariak irudikatzen dira.



Irudia A. 12 Guztizko berokuntza eskaria [kJ/h] eta EUB totala [l/h] urtean zehar

A.4.2.1. Energia eta exergia eskariak

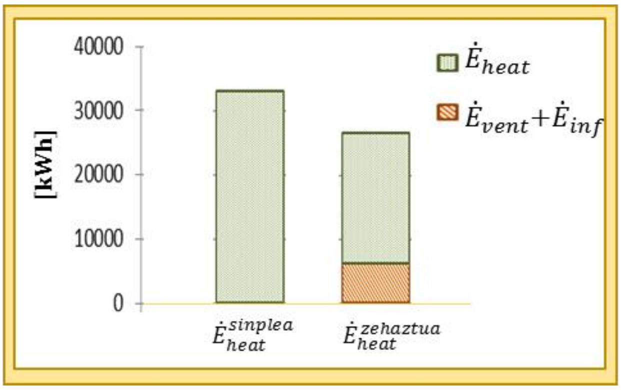


Irudia A. 13 Energia balantzea

Urteko energia balantzea Irudia A. 13n dago. Eskumako zutabeko galerak eraikinaren azalean zeharreko bero transferentziak, $\dot{Q}_{trans}$ $(965\ MWh)$; aireztapeneko bero sentikorraren galerak, $\dot{Q}_{vent}$ $(410\ MWh)$ eta zirrikituetatik kontrolatu ezinezko aire galerak $\dot{Q}_{inf}$ $(332\ MWh)$ dira. Bestalde, irabaziak eguzki irabaziak $\dot{Q}_{sol}$ $(386\ MWh)$ eta barne irabaziak $\dot{Q}_{int}$ ($312\ MWh$) dira eta Irudia A. 13 ezkerreko zatian daude. Gainera, gezi bertikal berdeak beharrezko berokuntza eskaria adierazten du ($1{,}009\ MWh$).

Berokuntza eskaria kalkulatu ostean, exergia eskaria ($\dot{E}_{heat}$) metodo sinplifikatuarekin eta zehaztuarekin lortu ziren. Bi metodoen emaitzak Irudia A. 14an erakusten dira. Erref. [36]-an gomendatu antzera, kanpoko airea hartu zen giro erreferentziatzat (T_0).

Metodo zehatzaren urteko exergia eskaria ($26{,}804\ kWh$) metodo sinplifikatuaren eskaria ($33{,}074\ kWh$) baino nabarmen baxuagoa da. Horren arrazoia da aireztapen eta infiltrazio gelerak bero eskaria baino handiagoa direla, eguzki eta barne irabaziak medio. Emaitza lez, aireztapena ez da barne tenperaturara iritsi arte aurretiaz berotu behar, orduko egoera termodinamikoaren araberako tenperatura baxuago batera baizik.



Irudia A. 14 Exergia balantzea

Horretaz gain, [36]-an justifikatu bezala, zenbat eta T_{op} tenperatura operatiboa giro tenperaturatik gertuago egon, orduan eta handiagoa izango da metodo zehaztuaren eta sinplifikatuaren arteko aldea. Beraz, metodo zehaztua aplikatuko da hemendik aurrera ikerketan.

Taula A. 2 Urteko bero eta EUB eskarien energia eta exergia pilatuak

	ESKARIA [$MWh/urte$]	
	EUB	BEROKUNTZA
Energia	284	1,009
Exergia	18	26

Taula A. 2n urteko berokuntza eta EUB eskariak agertzen dira energia eta exergia unitateetan. Energia terminoetan EUBak eskari termino totalaren % 28,1 adierazten du, baina, exergia terminoetan, % 69,2.

A.4.2.2. Eskaria hornitzeko eraikinaren sistema termikoa

Egungo eraikuntza araudien arabera, eraikinaren energia birgaitzea azaleko etekin energetikoa maximizatuz hasten da eta, ondoren, sistema termikoan barneratzen dira hobekuntzak.

Ikerketa kasu honetan, aldiz, instalazio zaharraren arazoak eta baliabideen eskasia medio, auzoko lagunek sistema termikoan berritzapenak egitea erabaki zuten. Horregatik, eraikinaren azala ez zenez hobetu, sistema termikoaren eraldaketen aurretik eta ostean berokuntza eta EUB eskariak berdin mantendu ziren. Aldakuntzak jarraian zerrendatzen dira.

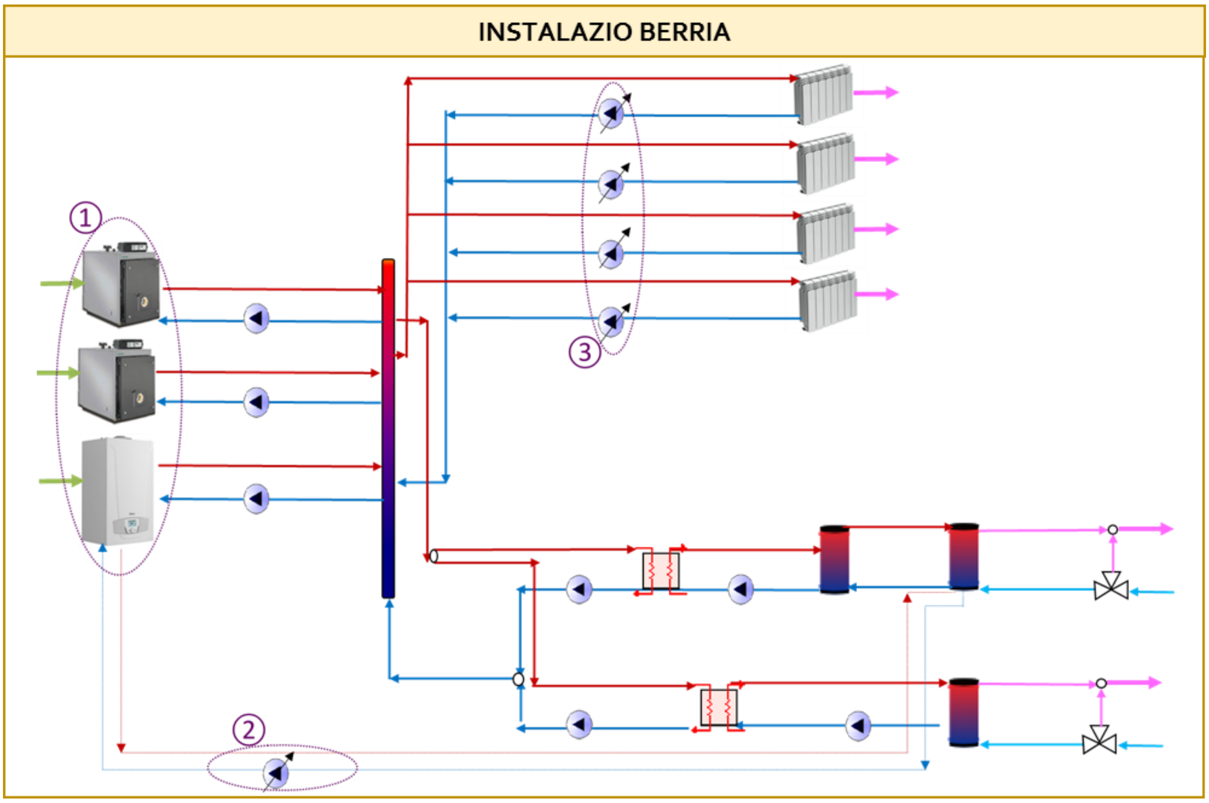
① Instalazio zaharrean hiru *fuel olio* galdara zeuden, 2325 kW-ko bi eta 1162 kW-ko bat. Horiek *gas natural*eko galdarekin ordezkatu ziren, behe tenperaturako 1900 kW-ko bi galdarekin eta 1150 kW-ko kondentsazio galdararekin ②. Azkenekoak errekuntza gasen beroaren berreskurapenerako trukagailu bat dauka.

Bi sistemen zirkuitu hidraulikoak, zaharra eta berriztatua, berdinak dira. Galdarak banaketa zirkuitura biltzaile hidrauliko baten bidez lotzen dira zeinen helburua berokuntza eta EUB zirkuituak bereiztea den. Berokuntza banaketa lau zirkuitu hidraulikoetan adarkatzen da, bloke bakoitzeko bana. EUB banaketak bi adar ditu: bat solairu baxuetara doa eta bestea goiko solairuetara. Gainera, beheko zirkuituak 3500 l-ko biltegi bi dauzka eta goikoak 4000 l-ko bat.

③ Zirkuitu zaharreko ponpak fluxu konstantekoak ziren eta berriak, aldiz, abiadura aldakorra daukate. Horren arabera, zirkuitu zaharreko berokuntza adarretan 3-bideko balbulek berokuntza tenperaturaren beharrezko set-point-ra moldatzen zuten. Sistema berriztatuak ponpen aldakuntzen abantaila duenez ez da 3-bideko balbularik behar.

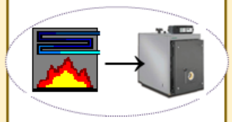
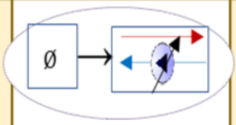
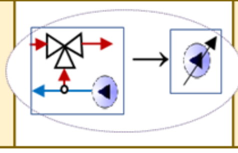
Irudia A. 15n sistema irudikatzen da zeinetan berritzapenak borobil moreekin adierazten diren; gainera,

Taula A. 3n instalazio zaharraren hobekuntzak laburtzen dira.



Irudia A. 15 Instalazio berriaren eskema. Berritzapenak borobil moreekin adierazten dira

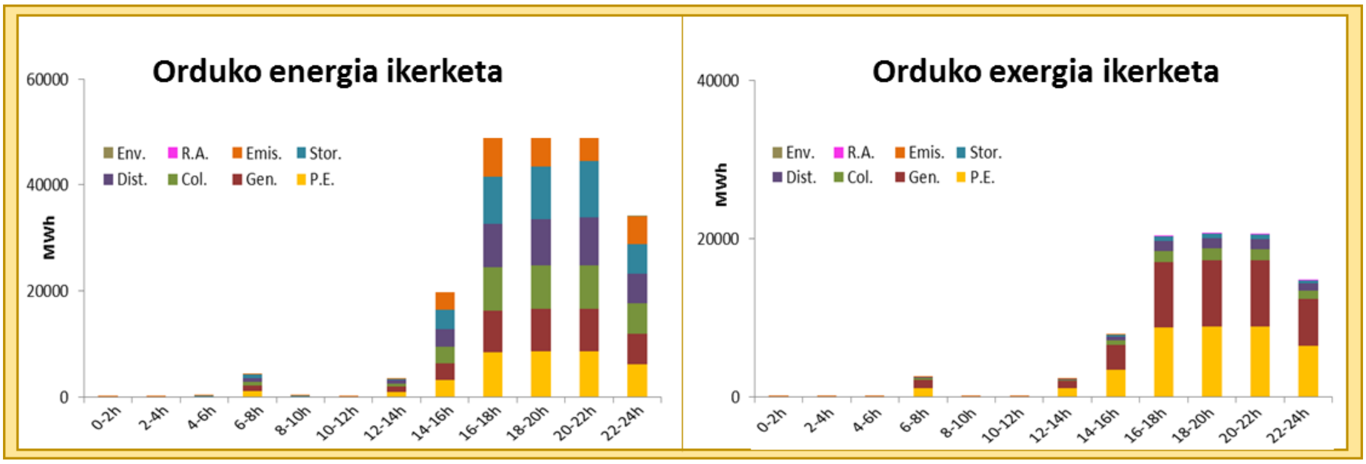
Taula A. 3 Summary of the renovations

	INSTALAZIOAN BERRIKUNTZAK		
	ZAHARRA		BERRIA
①	Fuel olio galdarak		Gas natural galdarak
②	Ø		Bero berreskurapen trukagailua
③	Berokuntzarako fluxu knteko ponpak + V3V		Abiadura aldakorreko ponpak

Sistemaren kontrola hurrengoa da: EUBak berokuntzarekiko lehentasuna dauka; EUB urtean zehar dago, berokuntza, aldiz, dagokion periodoan baino ez. Biltegiak uneoro monitorizatzen dira 60 °C-tik gorako tenperaturan egoteko. Berokuntza garaian biltzailearen tenperatura 60 °C-tik behera badoa, galdarak ur jauzi eran piztu egiten dira.

Eraikuntza energia sistemaren bihurketa faseak aurreko A.2.2 ataleko Irudia A. 3aren horiek dira, alegia: lehen mailako energia (L.M.-*P.E.*); bero sorkuntza (Sork.-*Gen.*); biltzailea (Bilt.-*Col.*); bero eta EUB banaketa (Banak.-*Dist*); bero banaketa eta EUB biltegiratzea (Pil.-*Stor.*); berokuntza igorpena eta EUBren asetzea (Igorp.-*Emis.*); barne airea (B.A.-*R.A.*) eta azala (Giro.-*Env.*).

A.4.2.3. Energia eta exergia analisia bi instalazioetan



Irudia A. 16 Otsailaren 5eko ordu orduko (a) energia bihurketa katea eta (b) exergia bihurketa katea

Bi instalazioak urte osoan zehar simulatu dira 0,5 h-ko denbora tartearekin aurreko atalean kalkulatutako eskariak kontuan hartuz, $\dot{Q}_D = \dot{Q}_{heat} + \dot{Q}_{DHW}$. Simulazio horiek fluxu energetikoak eta exergetikoak kalkulatzeko beharrezko parametro termodinamikoen bilketa ahalbidetzen dute.

Ikerketa era dinamikoan burutu zen eta, ondoren, urteko balioak bildu ziren. Hainbeste datu egoteagatik, otsailaren 5eko orduko datu energetikoak eta exergetikoak irudikatu dira Irudia A. 16n gainontzeko grafikoen egitura jarraituz.

Taula A. 4 (a)-n, instalazio zaharraren urteko lehen mailako energia zein exergia baliabide sarrera, osagai nagusien energia zein exergia sarrera, irteera eta etekina adierazten dira eta Taula A. 4 (b)-n, ordea, instalazio berriaren antzeko balioak batzen dira. Bi taulak Irudia A. 3ko geruza berdinetan banatzen dira eta sistema berriko lauki azpimarratuak kondentsazio galdararen berokuntza berreskurapenaren sarrera gehigarria adierazten du. Lehenengo mailako energiaren koefizientea 1,12 da fuel oliorako eta 1,07 gas naturalerako; eta kalitate faktoreak, aldiz, 1,07 eta 1,04.

Taula A. 4 Instalazio (a) zaharraren eta (b) berriaren urteko energia eta exergia balioak

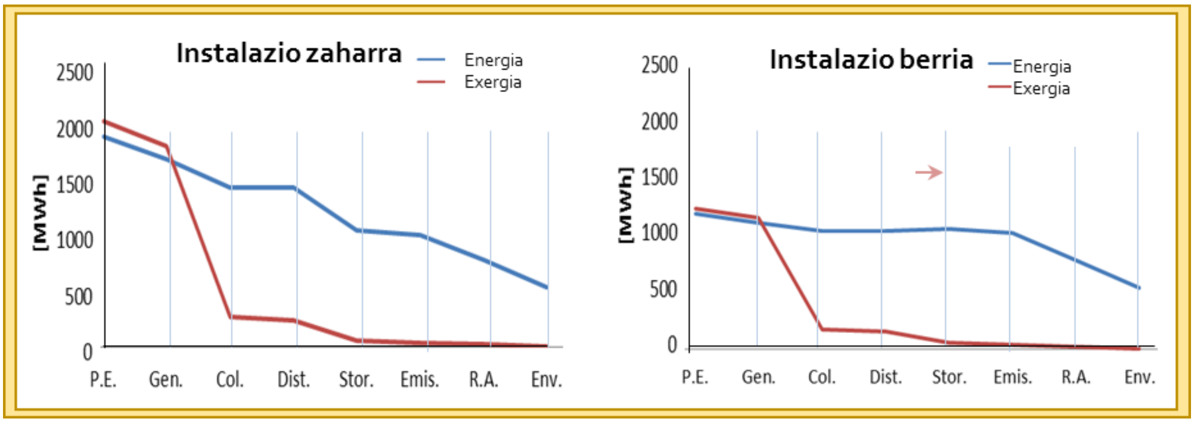
		(A) INSTALAZIO ZAHARRA					
		ENERGIA $[kWh]$			EXERGIA $[kWh]$		
		Q_{out}	Q_{in}	η %	E_{out}	E_{in}	ψ %
L.M.	B1	2108	2361	-	2255	2526	-
	B2	-	-	-	0	0	-
	B3	89	99	-	95	106	-
Sork.	B1	1791	2108	85	334	2255	15
	B2	-	-	-	0	0	-
	B3	75	89	85	13	95	14
Bilt.	C	1858	1867	100	313	347	90
Banak. bero	H1 br.	398	581	68	16	96	16
	H2 br.	142	205	69	6	34	16
	H3 br.	122	206	59	5	34	14
	H4 br.	408	546	75	16	90	18
Banak. EUB	HX1	185	185	100	26	33	80
	HX2	134	134	100	23	26	90
Pil.	T1+T2	166	185	90	14	624	2
	T3	125	134	93	12	23	52
Igorp. bero	H1	386	398	95	13	16	80
	H2	135	142	95	4	6	77
	H3	116	122	95	4	5	78
	H4	388	408	95	13	16	79
Igorp. EUB	DHW L	164	166	99	10	14	74
	DHW H	120	125	97	8	12	64
B.A.	Block I	386	386	100	10	13	83
	Block II	129	135	96	3	4	76
	Block III	111	116	95	3	4	74
	Block IV	383	388	99	10	13	83
Giro.	Heat	698	1009	69	0	27	-

		(B) INSTALAZIO BERRIA					
		ENERGIA $[kWh]$			EXERGIA $[kWh]$		
		Q_{out}	Q_{in}	η %	E_{out}	E_{in}	ψ %
L.M.	B1	271	290	-	282	302	-
	B2	124	133	-	129	138	-
	B3	1041	1113	-	1082	1158	-
Sork.	B1	255	271	94	42	282	15
	B2	117	124	94	20	129	16
	B3	1032	1041	99	174	1082	16
Bilt.	C	1344	1347	100	199	226	88
Banak. Bero	H1 br.	411	412	100	17	60	29
	H2 br.	142	142	100	6	21	29
	H3 br.	122	123	100	5	18	29
	H4 br.	408	408	100	17	59	29
Banak. EUB	HX1	127	127	100	17	19	89
	HX2	129	130	99	20	21	92
Pil.	T1+T2	164	184	89	13	28	49
	T3	121	129	94	10	20	52
Igorp. bero	H1	391	411	95	13	17	73
	H2	135	142	95	4	6	71
	H3	116	122	95	4	5	71
	H4	388	408	95	13	17	73
Igorp. EUB	DHW L	164	164	100	10	13	77
	DHW H	120	121	100	8	10	75
B.A.	Block I	386	386	99	10	13	83
	Block II	129	135	96	3	4	76
	Block III	111	116	95	3	4	74
	Block IV	383	388	99	10	13	83
Giro.	Heat	698	1009	69	0	27	-

Antzeko eran, era grafikoan aurreko taulen informazioa batzeko Irudia A. 17 eraiki da. Energia eta exergia bihurketak konparatzeko eta sistema zaharra eta berria alderatzeko laburpen bat da. Grafikoak, taulen antzera, Irudia A. 3ko geruzetan banatuta daude.

Energia jarrera instalazio zaharrean eta berriztuan alderatuz gero, datorrena ondorioztatzen da:

- % 35 energia aurrezpena lortu da birgaitzearekin, alde batetik, gas naturalak fuel olioa ordeztu duelako eta, bestetik, galdara berriek eraginkortasun hobea dutelako. Gainera, instalazio zaharra gain dimentsionatuta zegoen, bigarren galdara itzalita zegoelako beti; kasu berrian, aldiz, hirurek hartzen dute parte bero sorkuntzan (ikus L.M. lerroa tauletan).
- Bero banaketa sistemari dagokionez, instalazio zaharrean galera gehiago daude (ikus Banak. Bero.-aren eraginkortasuna Taula A. 4 (a)-n). Horren zergatia da egungo sisteman ponpak modulatzen daudelako berokuntza eskarira moldatuz. Aintzinean, ordea, 3-bideko balbulak zeuden funtzio horretarako.
- EUB biltegiaren eraginkortasuna ere hobetu egin da HR-ren bero gehiketari esker (ikus kutxa laranja Taula A. 4 (b)-n eta gezi gorria Irudia A. 17n).



Irudia A. 17 Instalazio zaharrean eta berrian energia eta exergia diagrama fluxuak

Exergia jarrera alderatzen bada bi sistemetan, datozen gogoetak egin daitezke:

- Itzulezintasun handiak daude bero sorkuntza sisteman (ikus galdaren etekin exergetiko baxua tauletan eta Sork. geruzaren balio txiki Irudia A. 17n). Ondorioz, galdaren nahasketan, errekuntzan eta bero banaketa prozesuetan atzeraezintasun handiak daude.
- Nahiz eta erradiadoreen berokuntza sistemaren etekin energetikoa % 95 izan, haren etekin exergetikoa zerbait baxuagoa da (% ~71). Logelako airean ere exergia suntsiketa nabaria dago (% ~77), finean, tenperatura operatiboa erradiadore sistemen azalera tenperatura baino askoz baxuagoa baita.
- EUB biltegien etekin exergetiko jaitsiera ere aipatu behar da; bero galerekin exergia suntsiketak lotzeaz gain, tenperatura ezberdinetako nahasketen suntsiketak ere hartzen baitira kontuan (ikus Pil. Taula A. 4 (a)-n eta (b)-n).

A.4.2.4. Emaitzen eztabaida

EUB eta berokuntza eskari energetikoak eta exergetikoak kalkulatu dira ondorioztatuz exergia eskariaren metodo zehaztua sinplifikatua baino hobea dela; aireztapenagatik eta infiltrazioagatik galera anitz baitaude.

Exergia analisiak birgaitzearen hobekuntza adierazten du, zein % 2,55 urteko batez besteko etekin exergetikotik abiatuta % 4,01 baliora heldu den (energia etekina, ordea, % 59,90 zen sistema zaharrean eta % 91,64 berrian). Pentsa zezakeen antzera, itzulezintasun handienak galdaretan daude zeintzuek exergia suntsiketa osoaren % 81 diren. Berokuntza banaketak eta igorpenak ere atzeraezintasunak dauzkate (% 11).

Beraz, berrikuntzak hainbat hobekuntza ekarri arren, etekin exergetikoan oinarrituz gero, oraindik aukera ugari daude: sorkuntza eta eskari kalitateen artean lotura hobea lortu behar da. Informazio hori bigarren legearen aplikazioarekin soilik ikus daiteke.

A.5. ONDORIOAK

Eraikuntza arloak ia mundu mailako energia kontsumo totalaren heren bat kontsumitzen du eta, horregatik, energia etekina hobetzeko giltzarria da. Beraz, azken hamarkadan energia araudietan hainbeste aurrerapen egin dituzte; gainera, 2010/31/UE Direktibak iEKG eraikinen definizioa bultzatzen du eta 2020ko abenduaren 31 epemuga lez jartzen du eraikin berri guztiak iEKG izan daitezen. Ezbairik gabe, hori da energia positiboko eraikinen aitzinako urratsa.

Horretaz gain, 2012/27/EU EEDaren esanetan, eraikin publikoak eredugarriak izan behar dira. Beraz, 2014ko urtarrilaren 1etik aurrera, eraikin publikoen azal berotuaren eta aireztatuaren % 3 izan behar da urtero birgaitua, gutxienez estatu kide bakoitzaren etekin energetiko minimoa izateko.

Testuinguru horretan autore askok egin dute lan eraikin sistema termikoen optimizazioan eta diseinuan baina, tamalez, gehiengoak ikuspegi guztiz energetikoarekin egin du.

Energia ikasketa orokorrek termodinamikaren lehenengo legean dute funtsa. Analisi mota hori energia zenbaketara mugatzen da energia sarrerak eta irteerak kuantifikatuz. Horrela, fuelen, elektrizitatearen, masa emarien, eta abarren energia amaierako produktuetan eta sasi-produktuetan agertu behar dira. Ikuspegi horren arabera, energia galerak soilik dira erabili gabeko bero fluxuak. Beraz, lehen legearen analisiaren esanetan, talde edo prozesu baten etekin galera bero xahutua baino ez da.

Zenbait modu daude lehen printzipioaren ikusmiratik sistema edo osagai baten etekin energetikoa definitzeko baina horietako batek ere ez du energiaren kalitatea aintzat hartzen. Ondorioz, etekin definizio horiekin energia mota ezberdinei pisu berdina esleitzen zaie, horien kalitatea edozein izanagatik ere. Hortaz, zenbait eragozpen daude, adibidez, Carnot taldearen etekina Carnot-faktorea izatea eta ez, aldiz, unitatea (talde idealaren etekinari legokion balioa); edota bero ponpen etekina COParen bidez adierazi beharra (unitatea baino altuagoko balioa); etab. Are gehiago, planta termoelektriko handiek, zeintzuek energia bihurketa sistemen artean onenen artean dauden, eraginkortasun baxuak dauzkate (% ~ 40-55); bestalde, ur berorako ohiko galdara indibidualak, ikuspegi termodinamikotik etekin gutxiagokoa, etekin garaiagoa dauka (%~ 90), gertakari kontraesankorra, alegia.

Exergia etekinek, alderantziz, hobe adierazten dituzte baliabideen erabilpenak eta egin daitezkeen hobekuntzen gidaliburu lez har daitezke. Exergia suntsiketa zein entropia sorkuntza baliagarriak dira prozesuaren itzulezintasuna adierazteko. Hala eta guztiz ere, entropiaren erabilpena zailagoa da atzeraezintasunen galerak irudikatzeko. Gainera, exergia metodoak prozesuaren galera errealak zuzenean zenbatesten ditu, hots, lan erabilgarriaren murrizketa ebaluatzen du bihurketen itzulezintasunak medio eta sistemen alderaketarako tresna giltzarria da. Orduan, itzulezintasunek sistemen etekina neurtzen dute eta exergia metodoak horiek kuantifikatu eta kokatzen ditu, datorren sistemaren sintesirako edo birgaitzerako.

Hortaz, exergia aplikazioaren onurak kontuan hartuz, analisia tresna egokitzat har daiteke eraikinen energia aurrezpenerako. Gainera, eta tesiaren jomuga aintzat hartuz, exergian oinarritutako ikerketa sakonagoek (termoekonomia kostu kontaketa eta diagnostikoa) puntu ahulak identifikatzeko eta horien energia erabilera hobetzeko balio dute kontsumoa zein ekonomia kostuak zein ingurugiro igorpenak murrizteko.

Hori da, preseski, termoekonomiaren analisi dinamikoa lehen aldiz eraikinetan aplikatzeko motibazioa.

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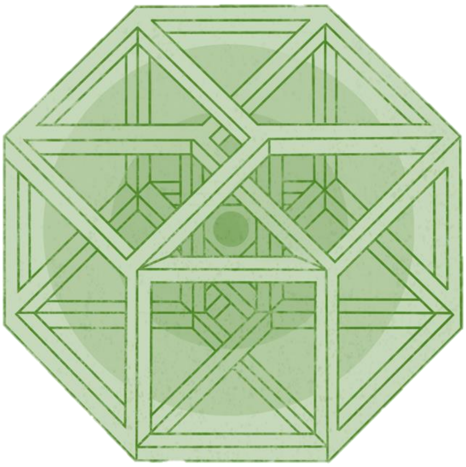


B KAPITULUA

Eraikinen adierazpen dinamikoa

eman ta zabal zazu

UPV EHU

B KAPITULUA

AZPIINDIZEAK

EUB	Etxeko ur beroa
$Heat$	Berokuntza
TOT	Totala
0	Giroa
lat	Latentea
Dep	Dependentea
Ind	Independentea

GOIINDIZEAK

Tr	Trnsys
Re	Erreala
$Calc$	Kalkulatua

SINBOLOAK

T	[ºC]	Tenperatura
$\dot{m}$	[kg/s]	Masa emaria
RH	[%]	Hezetasun erlatiboa
$\dot{Q}$	[kJ/s]	Bero fluxua
LL	[*][1]	Behe limitea
HL	[*]	Goi limite
η	[%]	Etekin energetikoa
$\bar{x}$	[*]	Operazio aldagaiak
$\bar{\tau}$	[*]	Diseinu aldagaiak

[1] [*] = units of the corresponding variable

B KAPITULUA: ERAIKINEN ADIERAZPEN DINAMIKOA

B.0. LABURPENA

Kapitulu labur hau energia sistemen modeloan oinarritzen da. Nahiz eta exergia ikuspunturik behar ez izan, modelo termikoa ezinbestekoa da bigarren legeko edozein aplikaziorako. Emaitza guztiak adierazpenaren kalitatearen araberakoak dira.

Eraikinak denboran zehar etengabean aldatzen doazelako, modelo dinamikoak nahitaezkoak dira. Bi metodo berritzaile garatzen dira ohiko bi egoera ebazteko: lehenengoa, sistema termikoen eraikuntzan datza erabiltzaileen beharren arabera. Bigarrenean, aldiz, sistemaren modeloa egiten da monitorizazio datuetatik abiatuta. Bi metodologiak adibideen bitartez garatzen dira.

Ondorioz, termoekonomia aplikaziorako lehenengo halabeharrezko urratsa modu aurrendarian ebazten da.

B.1. SARRERA

Sistema baten jarrera termodinamikoa modelo termikoaren bitartez adierazten da eta hori, batez ere, masa eta energia balantzeetatik dator. Adierazpena ikerketa termodinamikorako giltzarri izateaz gain, exergiaren kostu kontaketarako eta diagnosiaren inplementaziorako ezinbestekoa da.

HVAC&R sistemen jarrera egonkorra ez izateagatik, modelo dinamikoak behar dira zentzuzko emaitzak lortzeko. Eskakizun hori bereziki garrantzitsua da energia berriztagarriak darabilten sistemetan, biltegiratzeak beharrezkoak baitira erabiltzaileen beharrak bermatzeko iturria erabilgarri ez dagoenean. Gainera, sistemaren konfigurazioa (osagaien pizketa eta itzaltzea) etengabe aldatzen doa erabiltzaileen beharren eta kanpo giroaren aldakuntzen arabera.

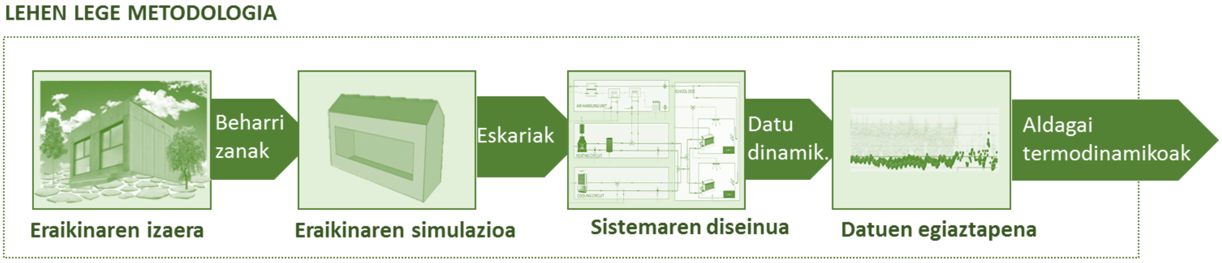
Beste batzuen artean, bi egoera nagusi bereiz daitezke: (1) sistema ez dagoenez eraiki egin behar da etxe zehatz baten eskariak asetzeko edo (2) sistema badago eta (zenbait) datu dinamiko monitorizaziotik lor daiteke. Lehenengo kasuak simulazio dinamikoaren beharra du eta bigarrenak, ordea, karakterizazio dinamikoa. Esan lez, bi kasuen emaitza modelo termikoaren adierazpena da eta bertatik, denbora tarte bakoitzean, beharrezko datu termodinamikoak lortuko dira.

B.2. ERAIKINEN SIMULAZIO DINAMIKOA

Lehenengo atalean eraiki beharreko instalazioaren lorpen dinamikoa azaltzen da. Hautabide sinplifikatua da, finean, sistemen *diseinua* arlo oso zabala baita eta ez da tesiaren helburua.

B.2.1. Simulazioaren metodologia

Irudia B. 1n aplikazioan jarraitzeko urratsak erakutsi eta jarraian garatzen dira zehaztasunak:



Irudia B. 1 Eraikinen simulazio dinamikorako metodologia

1. *Eraikinaren izaera*. HVAC&R sistemen diseinurako aurretiazko datuen jasoera lehenengo urratsa da: lekua, klima, eraikin mota, azala, erabiltzaileen jarrera, etab.
2. *Eraikinaren simulazioa*. Datu horiekin analistak eraikinaren modeloa egin eta simulazio dinamikoaren bitartez eskariak kalkulatzen ditu.
3. *Sistemaren diseinua*. Azken batean, HVAC&R sistema gai izan behar eraikinaren beharrizanak asetzeko eta, beraz, ezaugarriak eta kontrol estrategia zehaztu behar dira (berokuntzarako, hozkuntzarako eta aireztapenerako set-point-ak determinatuz)
4. *Datuen egiaztapena*. Trnsys modelo bat eginez eta simulatuz, beharrezko datuak lortu eta egiaztatzen dira.

Metodologia proposatua eraikin publiko batean aplikatuko da zeinek oso mugatuta dituen berokuntza, EUB eta hozkuntza eskariak eta zorrotz mantendu behar duen barneko aire kalitatea (IAQ). Horrela, metodoa egiaztatzen da.

B.2.2. (iii) Eskola baten ATU ikerketa kasua

Eraikina Palermoko (Italia) 6 ikasgelako eskola bat da, denak daude lurzoru solairuan, ikus Irudia B. 2. Estatuko hezkuntzarako egitura denez, IAQaz gain barneko tenperaturaren eta hezetasun erlatiboaren konforta egiaztatu behar dira. Beharrizan horietarako, aire tratamendurako unitate bat bi fan-coil terminal laguntzaileekin eraiki da.

Irudia B. 2 Ikerketa kasuaren eraikinaren irudia

B.2.2.1.1. Eraikinaren izaera

Esan lez, lehenengo urratsa eraikinaren beharrizanen kalkulua da ondoren dagokion sistema termikoa erabakitzeko.

Ondorioz, eraikinaren egitura ezaugarriak eta giro baldintza Trnsys-eko ([1] Transient System Simulation Tool) TRNBuild interfazean. Egitura simetrikoa denez, eskola bi zona termikoetan banatu zen: bakoitzak hiru ikasgela eta bolumen totalaren 6300 m³ barneratu eta 7560 kJ/K-ko kapazitantzia ditu. Gainera, leiho bana daukate: lehenengoa hegoaldera begira dago eta bigarrena, aldiz, iparraldera. Taula B. 1n hormen eta leihoen ezaugarri fisiko eta termiko nabarmenak agertzen dira.

Taula B. 1 Eraikinaren hormen eta leihoen egitura eta ezaugarri termikoak

HORMA MOTA	GERUZA	LODIERA	
Barne horma	gypsum	0.012	m
	isolakuntza	0.05	m
	Gypsum	0.012	m
	U-balioa	0.652	W/m²K
	Gainazala	210	m²
Kanpo horma	adreilua	0.24	m
	isolakuntza	0.1	m
	igeltsua	0.015	m
	U-balioa	0.339	W/m²K
	Gainazala	210	m²
Sabaia	Hormigoia	0.24	m
	isolakuntza	0.16	m
	U-balioa	0.233	W/m²K
	Gainazala	900	m²

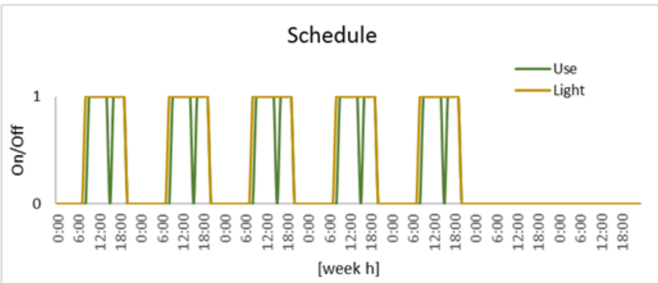
HORMA MOTA	GERUZA	LODIERA	
Lurrazala	Lurra	0.05	m
	harria	0.06	m
	silence	0.04	m
	Hormigoia	0.24	m
	isolakuntza	0.08	m
	U-balioa	0.313	W/m²K
	Gainazala	900	m²
Barne horma	Lurra	0.05	m
	harria	0.06	m
	isilaldia	0.04	m
	hormigoia	0.24	m
	U-balioa	0.834	W/m²K
	Gainazala	900	m²

LEIHOA	GERUZA	LODIERA	
Bikoitza	Zone 1	NORTH	
	Zone 2	SOUTH	
	U -value	0.4	W/m²K
	Surface	105	m²

Barne irabaziak eraikinaren erabileraren arabera barneratu ziren: argiztapena asteko egunetan zehar 8:ootatik 19:ootara piztuta dago; ikasleak (ikasgelako 25) goizeko 9:ootan iritsi, 14:oo-15:oo tartean bazkaldu eta 19:ootan bukatzen dituzte ikasgaiak; ordenadoreak (1 gelako, guztira 6) gendea barruan badago martxan jartzen dira; informazioa Taula B. 2n laburtzen da.

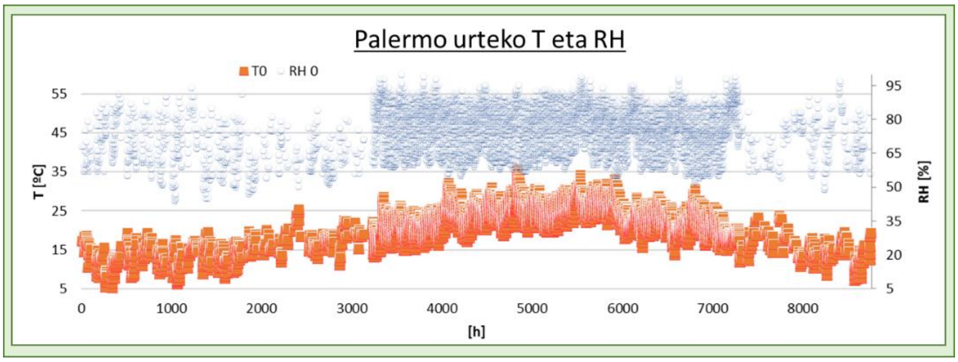
Taula B. 2 Barne irabazi mota eta ordutegia

BARNE IRABAZIAK	MOTA	ORDUTEGIA
Pertsona	ISO 7730	75 · USE
	Jesarrita, argi lausoa, tekleatzen	
Ordenadoreak	140 W PC + monitor	3· USE
Argiak	Artificial	75·LIGHT



Klima datu prozesatzaile batek Palermoko eguraldia sartzen du Meteonorm [2] softwaretik. Irudia B. 3n urte meteorologikoaren araberako hiriaren tenperatura (T) eta hezetasun erlatiboa (RH) irudikatzen dira; hala eta guztiz ere, operazio denbora tartearen balioak baino ez dira agertzen, hots, gauen edo asteburuen balioak ezabatu dira.

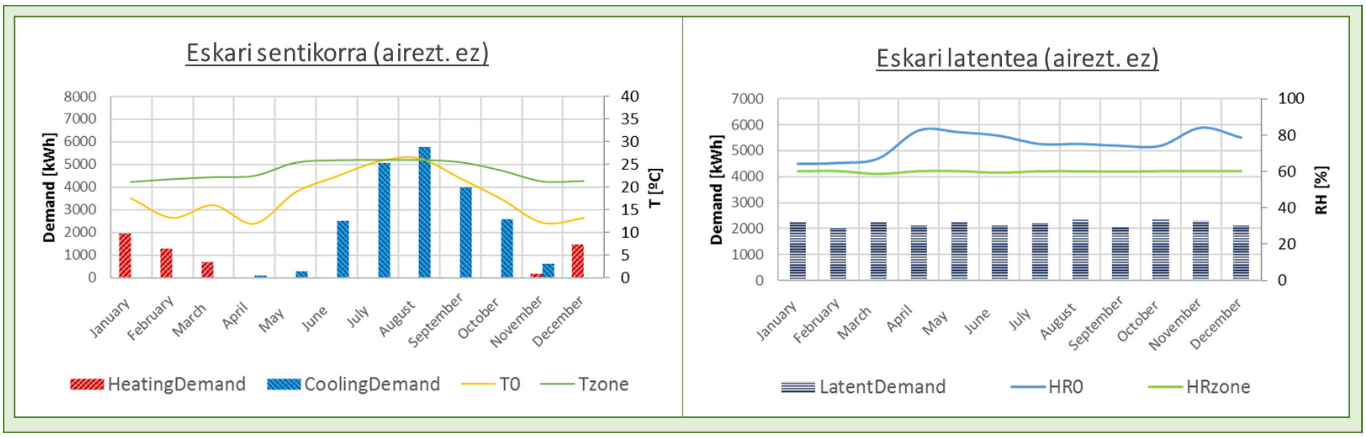
Beraz, kanpoko batez besteko tenperatura eta hezetasun erlatiboa berokuntza periodoan zehar (azaroaren 1etik maiatzaren 15era) 14 ºC eta % 68 da eta hozkuntza periodoan (maiatzaren 16tik urriaren 31ra) 23 ºC eta % 76.



Irudia B. 3 Palermoko urteko tenperatura eta hezetasun erlatiboa (Meteonorm datuak)

B.2.2.2. Eskariaren kalkulua

Edozein instalazio, talde edo kontrol barneratu baino lehen eskaria kalkulatu behar da. Hasteko, konfort termikoaren beharrak zenbatetsiko dira (bakarrik tenperaturaren eta hezetasunaren murrizpenak) eta, ondoren, bigarren simulazio batekin airearen kalitate onargarria lortzeko baldintzak barneratuko dira (alegia, aireztapen emaria minimoa).

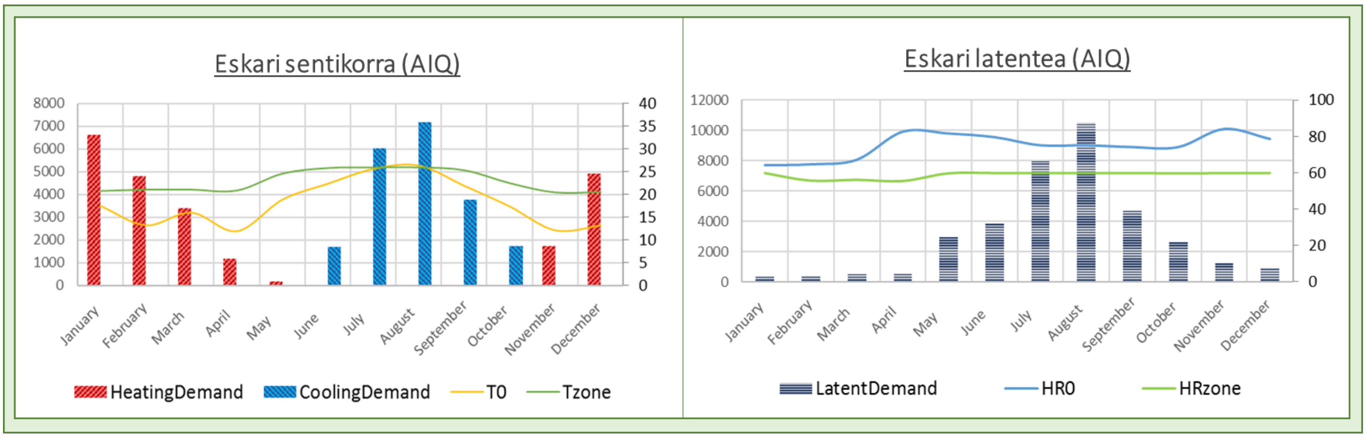


Irudia B. 4 (a) Eskolaren hilabeteko berokuntza eta hozkuntza eskaria barne tenperatura set-point-arekiko; (b) eskari latentea hezetasun set-point-arekiko

Lehenengo fasearen emaitzaren arabera, Irudia B. 4(a)-n beharrezko hilabeteko berokuntza (HeatingDemand) eta hozkuntza (CoolingDemand) eskaria agertzen da barne tenperatura neguan 21 ºC-tan eta udan 25 ºC-tan mantentzeko. Hilabeteko batez besteko tenperatura (To) eta zona bakoitzeko tenperatura (Tzone) ere barneratu dira. Antzeko moduan, hilabeteko eskari latentea (LatentDemand) Irudia B. 4 (b)-n erakusten da; barne irabaziak orekatu eta barne giroa % 60ko hezetasunean (HRzone) mantentzeko bero latenteari dagokio. Kanpoko hilabeteko batez besteko hezetasun erlatiboa ere gehitu da (HRo).

Emaitzen arabera, eta COP=4 balioko hozkailu eta η = % 90 etekineko galdara bat kontuan hartuz, hotz makinak beharrezko potentzia nominal minimoa 14 kW da eta galdarak 44 kW. Bestalde, zonako gehiegizko bero latentea $\dot{Q}_{zone_M}^{lat} = 66700\ kJ/h$ da.

Bigarren urratsa barne aire kalitatearekin (IAQ) bat dator. Kalitatea, berez, aireztapenaren bidez orduko aire aldaketa balioarekin lortzen da [3]. Bi irizpide erabaki ziren eskolaren erabilpenaren arabera: ikasleak barruan badaude, aireztapen emari minimoa 12,5 l/s·perts da eta inor ez badago baina erabilera piztuta egonik 0,83 l/s·m² baino handiagoa izan behar da.



Irudia B. 5 (a) Eskolaren hilabeteko berokuntza eta hozkuntza eskaria barne IAQarekiko; (b) eskari latentea hezetasun IAQarekiko

Premia horiek jarraituz, hurrengo simulazioak kutsatzaileak ezabatzeko aireztapen beharra kontuan hartuz kalkulatzen du eskaria, ikus Irudia B. 5.

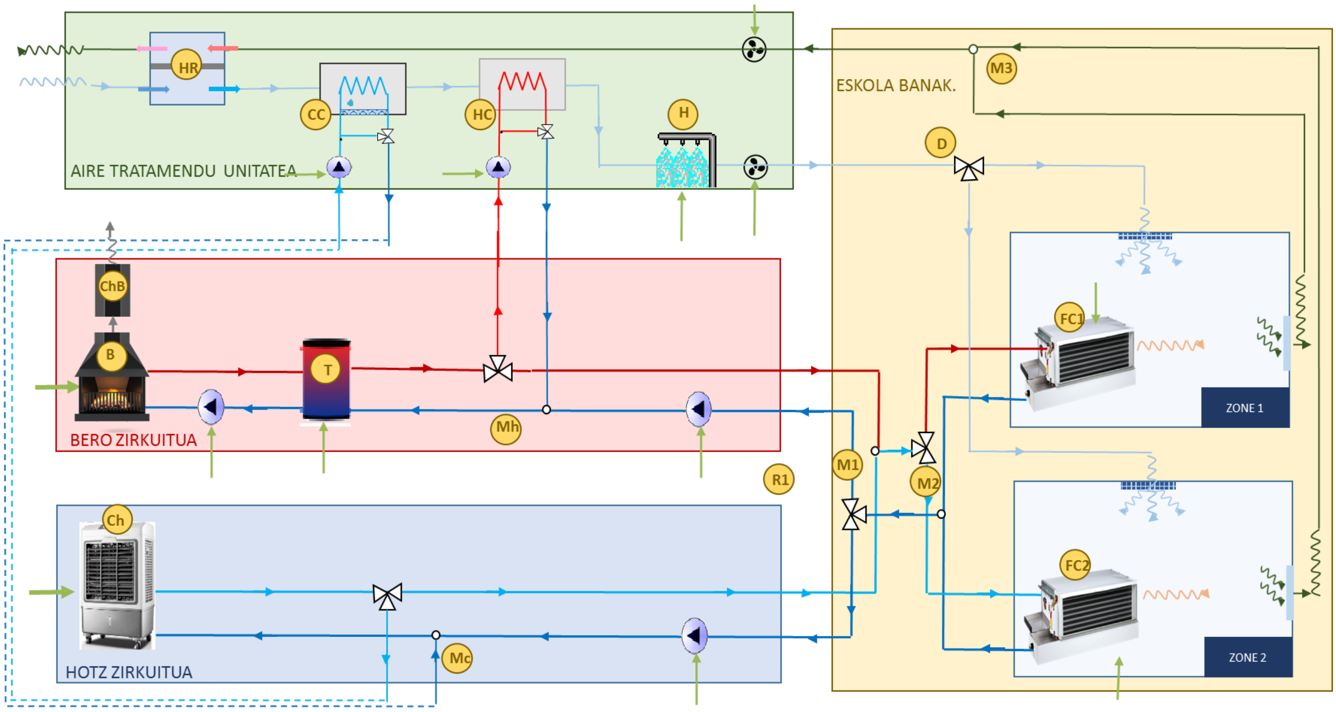
Orduan, egoera horretako hotz makinaren gutxieneko potentzia 50 kW da eta galdararen balio minimoa 77 kW.

B.2.2.3. Instalazioaren diseinua

Taula B. 3 Instalazioko osagaien izendapena eta deskripzio laburra

IZENDAPENA		DESKRIPZIOA	IZENDAPENA		DESKRIPZIOA
1	B	Galdara	9	H	Hezegailua
2	Ch	Hozkailua	10	Mc	Hotz kiribilaren V3V
3	T	Pilaketa	11	Mh	Bero kiribilaren V3V
4	FC1	Zone1 fan-coil	12	M1	H/C FC-ren V3V
5	FC2	Zone2 fan-coil	13	M2	FC1/FC2-ren V3V
6	CC	Hotz kiribila	14	M3	Aire akitu nahasgailua
7	HC	Bero kiribila	15	D	Haizagailu banatzailea
8	HR	Bero berreskuratzailea	16	Bc	Galdara tximinia

Instalazio hautatua airearen tratamendurako unitate (ATU) bat da eta bi fan-coil lagungarri ditu, ikus Irudia B. 6; osagaiak zenbakitu eta labur deskribatzen dira Taula B. 3n.



Irudia B. 6 Sistemaren eskema fisikoa

Eskeman erakutsi lez, ATUak ondorengo osagaiak dauzka: airearen bero berreskuratzailea (HR); hozkailuak edo galdarak elikatutako hotz harila (CC) eta bero harila (HC); hezedura sistema (H) eta banaketa osagaiak (D eta M3).

Bestalde, bi zirkuituk fan-coilak (FC1 eta FC2) hornitzen dituzte urtean zeharreko hozkuntzarako edo berokuntzarako.

Alde batetik, bero zirkuituak 80 kW-ko galdara bat (B) eta 2500 l-ko biltegi termiko bat (T) dauzka; ur beroa ATUra zein FCetara doa 3-bideko balbularen (Mh) modulazioaren bitartez. Beste alde batetik, hotz zirkuituak 100 kW-ko hozkailuarekin (CH) du harremana eta bere banaketa sistemarekin (Mc). Bi zirkuituen terminaletan osagai hidraulikoak daude (M1 eta M2).

B.2.2.3.1. Instalazioaren kontrola

Taula B. 4 Urteko set-point eta ordutegi nagusien zerrenda

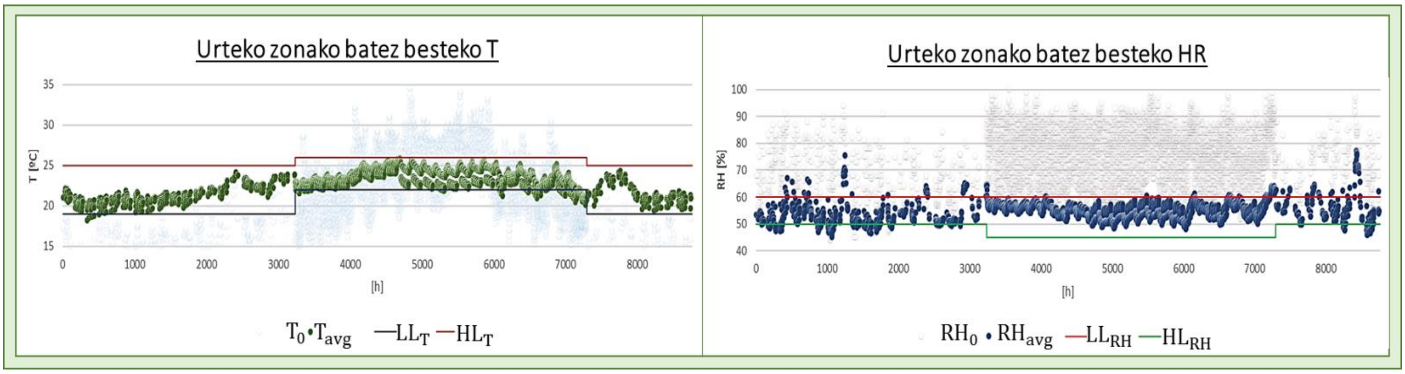
✓ $\textbf{Urteko ordutegia} = \begin{cases} Negua & (1^{st}\ Nov. - 15^{th}\ May) \\ Uda & (16^{th}\ May - 31^{st}\ Oct.) \end{cases}$ ✓ $\textbf{Airez.ordutegia} = \{ \geq \dot{m}_{vent}^{min} \quad (1^{st} Jan. - 31^{st} Dic.)$ ✓ $\textbf{Sorgailuen set.T} = \begin{cases} T_B^{out} = 60\ °C \\ T_{CH}^{out} = 7\ °C \end{cases}$	✓ $\textbf{Barne set.T} = \begin{cases} Negua & 19\ °C < T_{Zone}^{i} \leq 25\ °C \\ Uda & 22\ °C < T_{Zone}^{i} \leq 27\ °C \end{cases}$ ✓ $\textbf{Barne set.RH} = \begin{cases} Negua & 50\% < RH_{Zone}^{i} \leq 60\ \% \\ Uda & 45\% < RH_{Zone}^{i} \leq 60\ \% \end{cases}$

Eraikinaren urteko set-point-ak Taula B. 4n batzen dira non osagaien operazio moduak jarraian azaltzen diren:

- ✓ Aireztapenerako emariak ATUa zeharkatzen du airea lantzeko. Xedea IAQa eta karga latentearen kontrola direnez, eskari denbora tartearen funtzio dago:
  - *Uda* garaian, CC eta HC elkarrekin daude lanean eta H hezegailua itzalita dago. Aire tratatu kantitatea minimoa da eta CCaren helburua hezetasuna kentzea da; gero, HCak beroa 14°C-ra igotzen du aire banaketa egokia ziurtatzeko.
  - *Negu* garaian, CC beti dago itzalita eta HC lanean dago (beraz, B ere pizten da), H-k oso gutxitan hartzen du parte. Aireztapenak barneko airearen hezetasun erlatiboa kontrolatzen du. Bestalde, HCren irteerako tenperaturaren kontrola konfort baldintzak asetzeko eragiten da.
- ✓ Uneoro aire akitua eta garbia aire-aire bero berreskurapen sistematik (HR) igarotzen dira.
- ✓ Fan-coil-ak elementu lagungarriak dira beharrezko bero sentikor gehigarria jaurtitzeko.
- ✓ *Uda*ran, hozkailuak hotza barneratzen du konfort baldintzak asetzeko, *negu*an, ordea, berokuntza sistema erabiltzen da. Bero zirkuituko galdararen funtzionamendua T biltegiaren set-point-en arabera da.

B.2.2.3.2. Datuen balioztatzea

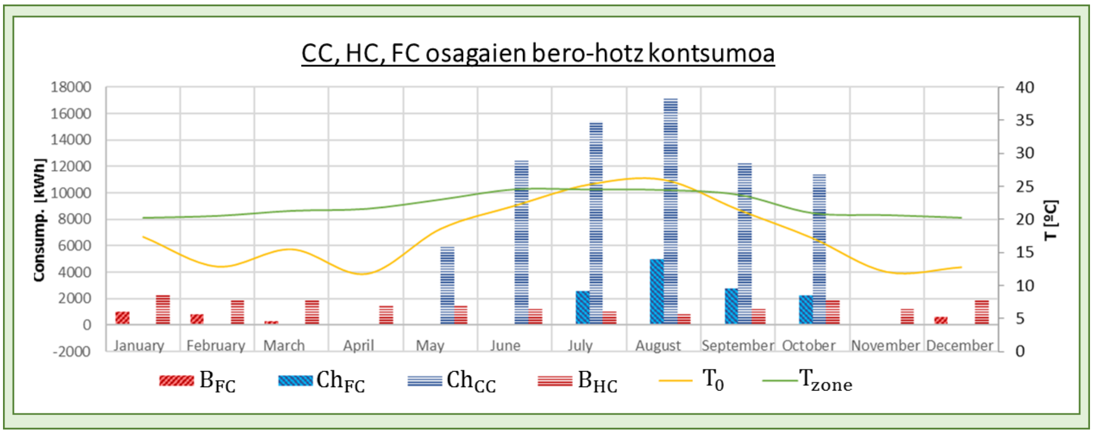
Osagai eta kontrol horiek guztiak Trnsys-en Simulation Studio-ko interfazean programatu ziren eta urteko 8760 orduetan zehar egin zen simulazioa 3 minutuko denbora tartearekin.



Irudia B. 7 (a) Urteko zonako batez besteko tenperatura, kanpo tenperatura eta konfort tartea; (b) batez besteko RH, kanpo RH eta konfort RH

Irudia B. 7 (a)-n urtean zeharreko batez besteko tenperatura erakusten da eta (b)-an, aldiz, bi zonetako RH. Gainera, kanpoaldeko baldintzak (hodei puntuak) eta konforterako mugak (lerroak) barneratzen dira; operazio tarteko balioak adierazi dira soilik, hots periodo itzaliak (gauak, asteburuak, etab.) deuseztatu dira. Ikus antzera, eremuen barneko tenperaturen % 94 dago behe eta goi limiteen (LL,HL) tartean eta RHaren % 93. Ondorioz, kontrola egoki moldatu da behar izanetara.

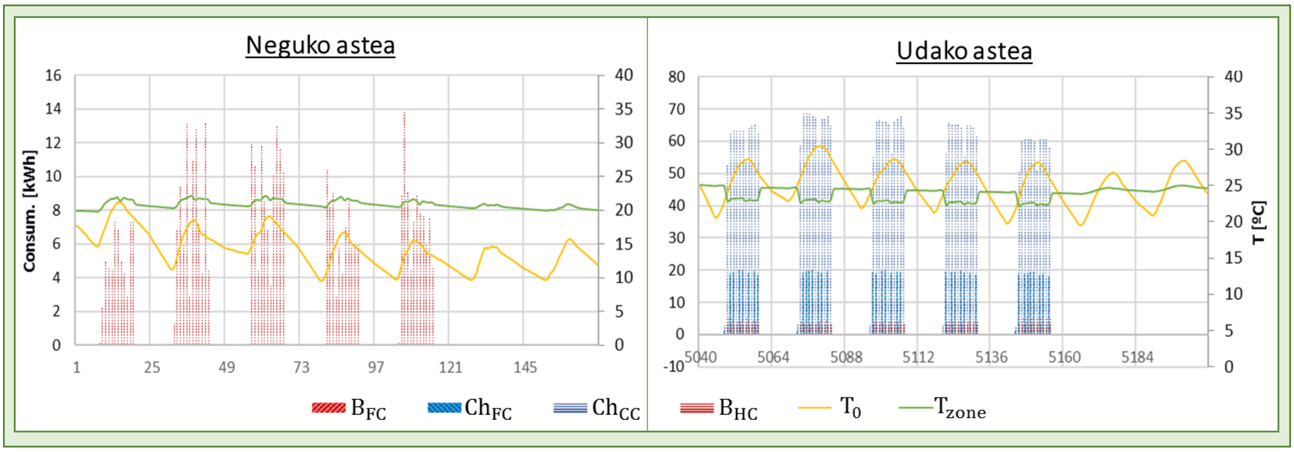
Irudia B. 8n urtean zeharreko CCaren (Ch_{CC}), HCaren (B_{HC}) zein FCen (B_{FC} eta Ch_{FC}) berokuntzarako eta hozkuntzarako kontsumoak agertzen dira dagokion elikatze osagaiaren arabera (B edo Ch). Erakutsi antzera, ez dago hotz kontsumorik berokuntza periodoan zehar eta bero kantitate txikia erabiltzen da hozkuntza tartean zehar barne aire banaketa 14 °C-tan bermatzeko; ia bero guztia CCan eta HCan erabiltzen da, FCak bigarren mailako talde laguntzaileak direlako.



Irudia B. 8 Hilabeteko CC, HC eta FC osagaien bero eta hotz kontsumoa eta kanpo eta barne batez besteko tenperatura

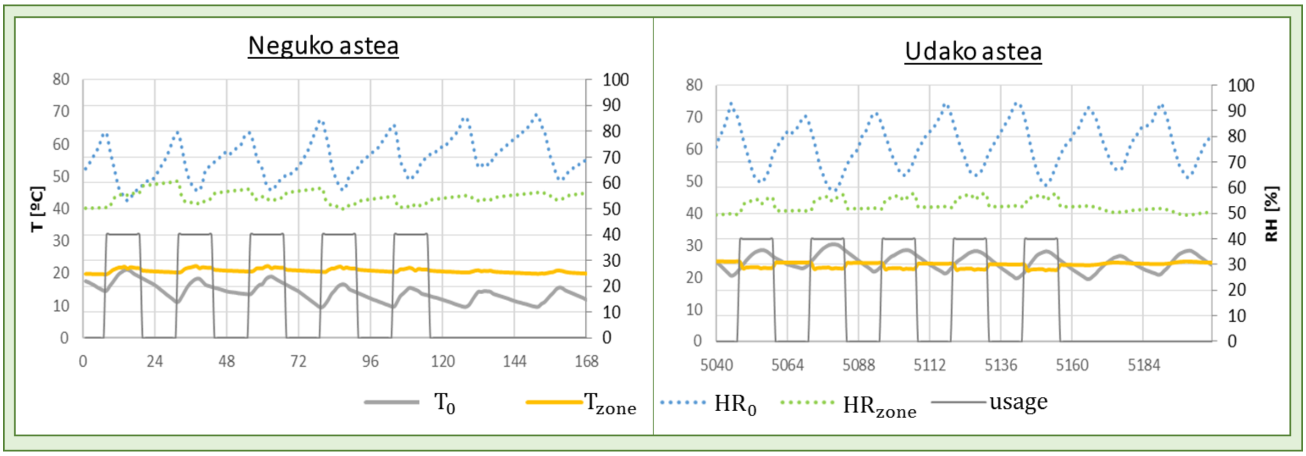
Hilabeteko balioak ez direnez adierazgarriak eta orduz orduko (edo gutxiagoko) tarteek hobe erakusten dute eskolaren erabilpena Irudia B. 9 eta Irudia B. 10ak sartu dira. Neguko (urtarrileko lehen astea) eta udako (abuztuaren lehen astea) bi aste esanguratsu adierazten dira.

Irudia B. 9 aurreko irudiaren Irudia B. 8 deskripzioa orduz ordu jarraitzen du eta bigarren grafikoak, ordea, eremuetako eta kanpoko tenperatura eta hezetasun erlatiboa irudikatzen ditu erabilera periodoaren funtzio.



Irudia B. 9 CC,HC, eta FCs orduz orduko balioak; irteera eta sarrera tenperatura (a) urtarrileko aste eta (b) abuztuko aste batean zehar

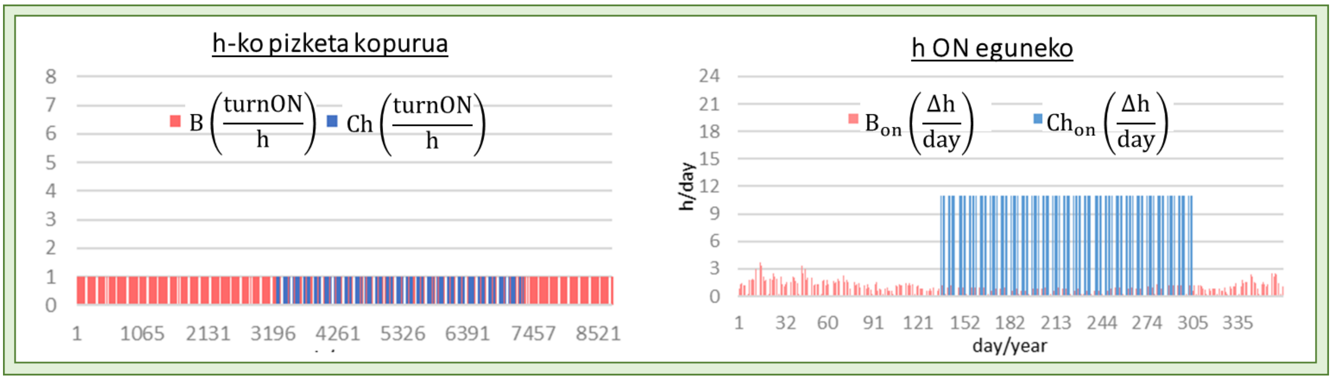
Halere, berokuntza eta hozkuntza kontsumoen arteko eskala ezberdintasuna aintzat hartzen bada, pentsa daiteke hozkuntzarako inertzia sistema bat behar dela (buffer bat adibidez) hozkailuaren pizketa eta itzaltze kantitateak murrizteko (berokuntza zirkuituan biltegi bat dagoen antzera). Hiru minutuko denbora tartea kontuan hartuz gero, sorkuntza taldeak sakonki azter daitezke eta horien funtzionamendu modua atera. Orduan, ordu bateko on-off kantitatea 8 baino altuagoa bada, sistema inertziala barneratu beharko da.



Irudia B. 10 Kanpo eta barne tenperatura eta RH erabilpenaren arabera (a) urtarrileko eta (b) abuztuko aste batean

Irudia B. 11 (a)-n galdararen eta hozkailuaren aktibazio kantitate maximoak adierazten dira urteko 8760 orduetan zehar; Irudia B. 11 (b)-k, bestalde, urteko 365 egunetan zeharreko operazio orduak erakusten ditu.

Eztabaidatu antzera, ez da inertzia sistemarik behar B-ren eta Ch-ren pizketa kantitate maximoa ordu batean 1 delako. Gainera, (b) atalean erakutsi lez, hozkailua hozkuntza periodoan 11 orduz piztuta dago, alegia, erabiltzaileen denbora tartea (aireztapena behar denean, zehatz).



Irudia B. 11 Sorkuntza taldeak (a) Urtean zeharreko pizketa kopurua (b) Urtean zehar guztizko funtzionamendu orduak

Hortaz, instalazio proposatuak egoki asetzen ditu eskolaren urtean zeharreko beharrizan dinamikoak.

B.3. ERAIKINAREN KARAKTIZAZIO DINAMIKOA

Bigarren egoera sistema monitorizatu baten datu errealen karakterizazio dinamikoan datza.

Datu esperimentaletatik modelo termodinamiko matematikorako jauziaren urratsa da. Dauden datuez baliatuz, instalazioaren osagai bakoitza zehatz eta era dinamikoan adierazi behar da errealitatea ahalik eta zintzoen erakusteko.

Eraikinaren energia sistema era xehatuan errepresentatzeko arazo bat beharrezko sarrera datuen kantitatea da [4]. Praktikan, sarrera balio batzuk ez daude edo ezin dira lortu. Beraz, karakterizazioa estuki lotuta dago datu esperimentalen eskuragarritasunarekin.

Erref. [5]-aren arabera jasotako datuen arabera bi modelo mota defini daitezke: (1) *legeek gida*tutako modeloak lege fisikoetan oinarritzen dira, esaterako, grabitate edo bero transferentzia legeak; horiek askotan gain-parametrizatuak daude, beharrezko datuak datu eskuragarriak baino gehiago direlako. Bestalde, (2) *datuak gida*tutako modeloek hasierako data gutxiago behar dituzte eta sistemaren jarrera erabiltzen dute sistemen propietateak aurreikusteko; oro har, modelo horiek sarrera balio gutxiago behar dituzte sistema adierazteko.

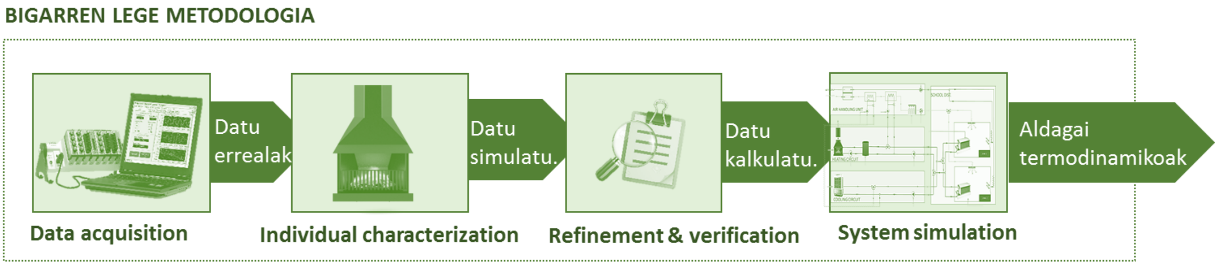
Ikasketa honetan zeharreko ikerketa kasuek bigarren modeloaren ezaugarriak dauzkate, datuak sentsore kantitate eta monitorizazio sistema mugatu batzuetatik lortzen direlako. Modelo garatua *kutxa-gris* modelo berri batean datza, metodo horren zehaztasuna eta erabilgarritasuna sistema dinamikoetan aski egiaztatuta baitago [6]; horretarako, sistemaren modelo fisikotik zenbait parametro gako identifikatu behar dira. Hainbat erreminta daude simulazio trantsitoriorako, kasurako Trnsys, zeinek osagaietan oinarrituz simulazioa egitura modularraren gisara inplementatzen duen.

Modu berdinean, identifikazio sistema erabil daiteke modelo dinamikoaren adierazpeneko parametroen estimaziorako. Modeloak sistemen jarrerak adierazteko erabiltzen direnez, inertzia bezalako aldagaiak ezaugarritu daitezke. Ondorioz, ikerketa kasua eta haren parametroen doikuntza Trnsys softwarearen osagai zehatzak Matlab System Identification Toolbox [7] programarekin batuz lor daiteke.

Sistema konplexuen adierazpena eta simulazio murrizketak zalantzan jarri daitezke trantsizioetan zehar zenbait informazioa galdu daitekeelako. Ziurgabetasunei, beraz, aipua egin behar zaie. Erref. [8]-aren arabera, identifikazio sistema, modeloen sorkuntza, zenbaki prozesaketa eta berezko eszena zenbait ezbaien iturri dira. Gainera, edozein modeloren testuinguruan, irteeren kalitatea sarrera balioen kalitatearen araberakoa da.

B.3.1. Karakterizaziorako metodologia

Irudia B. 12n eraikinen azterketa dinamikoa aplikatzeko urratsak adierazi eta jarraian zehazten dira:



Irudia B. 12 Eraikinen ezaugarriketa dinamikorako metodologia

1. *Datuen erdiespena*. Sistemaren osagaien diseinu zehatzerako lehenengo urratsa datu monitorizatuak jasotzea da (masa emariak, tenperaturak, presioak, etab.) eta osagaien berariazko ezaugarriak (edukia, bolumena, bero transferentzia koefizientea, etab.).
2. *Karakterizazio indibiduala*. Aurreko datuen arabera Trnsys liburutegiko modelo bat aukeratu eta moldatu egiten da.
3. *Fintasuna eta karakterizazioa*. Ostean, Trnsys-en irteerak datu errealekin alderatzen dira eta Matab erabiltzen da osagaiak hobetzeko eta jarrera errealak ezaugarritzeko.
4. *Sistemaren simulazioa.* Osagai indibidual denen modeloak elkarrekin lotu eta kontrola barneratzen da. Beraz, datuak atera eta egiazta daitezke.

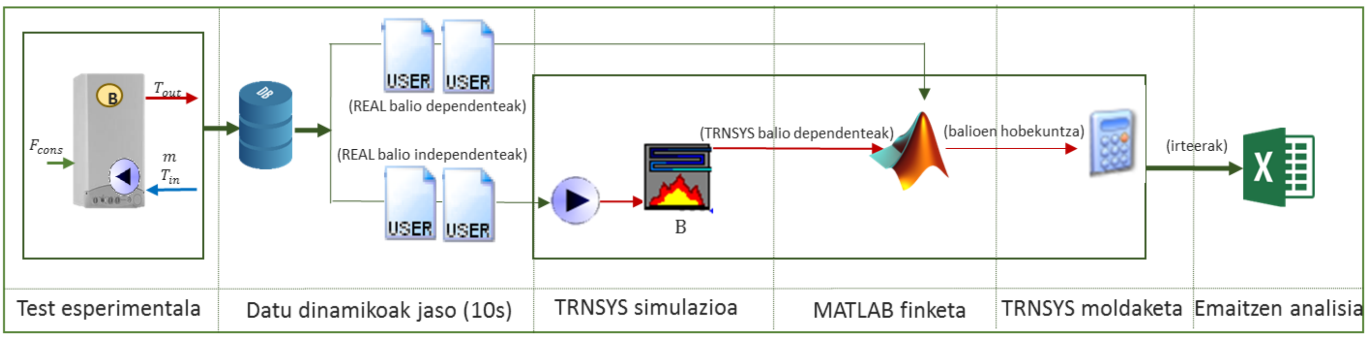
Orduan, sistema errealen karakterizaziorako metodologia berria proposatu eta sakonki garatuko da jarraian. Trnsys eta Matlab softwareen barne modeloen konplexutasunak aintzat hartuz, biltzailearen adibide erraza baino ez da erakutsiko.

B.3.1.1. Karakterizazio modeloa

Esan antzera, osagaien modeloa Trnsys-en oinarritzen da modelo matematiko trantsitorioak barneratzen baititu masa eta energia balantzeen ekuazioetatik ($\sum_k m_k = 0$ eta $\sum_k m_k \cdot h(\bar{x}) = 0$). Operazio aldagaiak ($\bar{x}$) erabiliko dira diseinu aldagaien ($\bar{\tau}$) ordez; finean, sistema aurretiaz finkatuta dagoelako (alegia, ezaugarri fisikoak zehaztuta daude).

Hortaz, saiakuntzatik datu errealak jaso eta gero, taldera gehien hurbiltzen den Type-a erabaki behar da Trnsys liburutegitik eta simulazio indibiduala gauzatu; sarrera aldagai *independenteak* (operazio aldagaiak) jarraian datu errealetatik barneratzen dira. Simulazioaren irteerak, aldagai *dependenteak*, denbora tarte orotan alderatzen dira datu esperimental errealekin doitzeko. Horrela, irteera simulatuak ber-doitu egiten dira eta efizientzia gabezi errealak eransten dira. Beste hitz batzuetan, Trnsys-en irteera balioaren $\left(T_{i_{Dep}}^{Tr}\right)$ eta modu esperimentaleko balioaren $\left(T_{i_{Dep}}^{Re}\right)$ artean desbideraketa egon daiteke Trnsys-ek ez baititu errealitatean ager daitezkeen inertzia gehigarriak kontuan hartzen. Doikuntza Matlab-en System Identification Toolbox erramintarekin egiten da inertziak eta jarrera errealak barneratuz eta Trnsys-en balioak errealitatera hurbilduz $\left(T_{i_{Dep}}^{Calc}\right)$.

Irudia B. 13n galdara karakterizatzeko urratsak adierazten dira era eskematikoan non datu errealen, Trnsys simulazioko datuen eta Matlab-en arteko loturak irudikatzen diren. Bestalde, Irudia B. 14k biltzailearen (C) eta bero trukagailuaren (HX) karakterizazio era azaltzen du Trnsys-en Simulation Studio-ko interfasean.

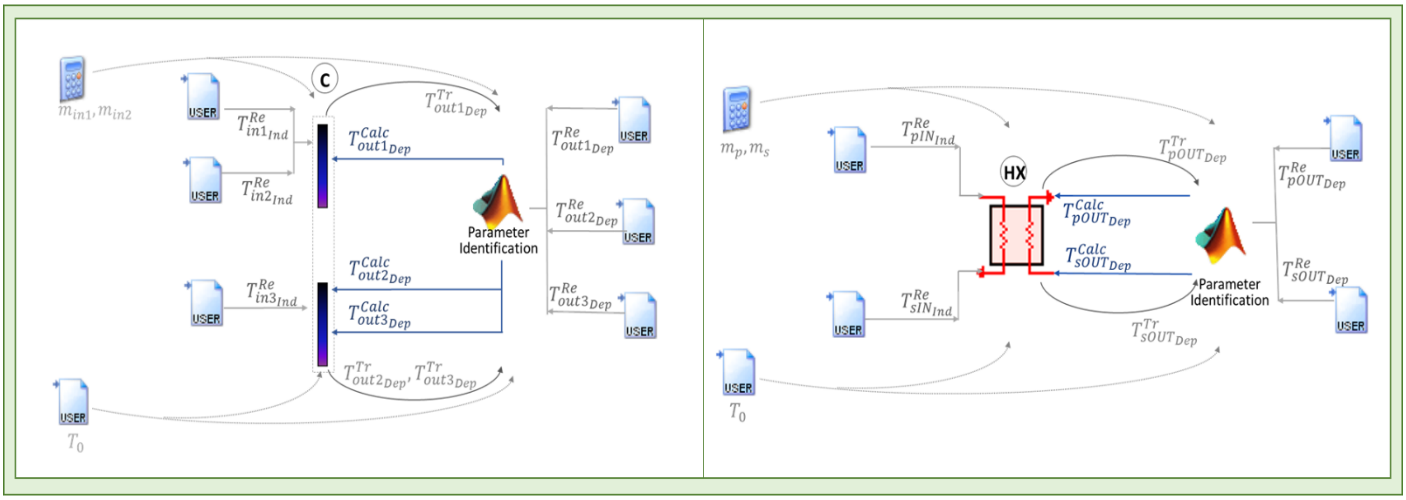


Irudia B. 13 Galdararen simulaziorako modeloa lortzeko eskema

Irudia B. 14n erakutsi antzera, modulu ezberdinek hartzen dute parte modeloen moldakuntzan eta hobekuntzan:

- Osagaia, berez, Trnsys liburutegitik hautatzen da eta erdian dago (C edo HX). Lehenengo, Trnsys-etik aukeratu eta, gero, ezaugarri errealak barneratu behar dira. Trnsys-en Type-en parametroak eraldatuz egiten da hori.

- *User* Type-ak, osagaiaren inguruan agertzen dira (T_i^{Re} izendapenarekin) eta kanpo datu esperimentalen irakurketetarako osagaiak dira. Horietan sistema errealeko datu monitorizatuak dagokien denbora tartearen arabera idazten dira. User Type kopurua sentsoreek irakurritako datu kopurua da.



Irudia B. 14 C eta HX osagaiak ezaguarritzeko eskema Trnsys-en SImulation Studio interfazean

- Bi User aldagai mota daude: independenteak $\left(T_{i_{Ind}}^{Re}\right)$ eta dependenteak $\left(T_{i_{Dep}}^{Re/Tr/Calc}\right)$, *"Ind"* eta *"Dep"* azpiindizeekin, hain zuzen. Aldagai independenteak osagaiaren sarrerak dira eta Irudia B. 14ko ezkerraldean daude. User aldagai dependenteak, ostera, esperimentuko aldagaiak dira (Trnsys-en irteera aldagaien baliokideak) eta eskumaldean daude. Horiek Trnsys-eko balioekin uneoro alderatu behar dira osagaiaren jarrera erreala ahalik eta modu leialean adierazteko. Laburtzeko, hiru aldagai *dependente* daude: Trnsys simulazioaren irteerak $\left(T_{i_{Dep}}^{Tr}\right)$, saiakerako sentsoreen aldagai baliokideak $\left(T_{i_{Dep}}^{Re}\right)$ eta Matlab-en kalkulatutakoak $\left(T_{i_{Dep}}^{Calc}\right)$. Lehenengo bi balioak ez direnez berdinak $\left(T_{i_{Dep}}^{Tr} \neq T_{i_{Dep}}^{Re}\right)$, helburua balio independenteen $\left(\sum_j T_{j_{Ind}}^{Re}\right)$ eta dependenteen arteko lotura matematiko bat lortzea da errealitatea errepresentatzeko (ikus Ek.(B. 1)). Azkenengo urrats hori Matlab-en System Identification Toolbox-arekin egiten da guztiz.

$$T_{i_{Dep}}^{Calc} = f\left(T_{i_{Dep}}^{Tr}, \sum_j T_{j_{Ind}}^{Re}\right) = T_{i_{Dep}}^{Re} + errorea \tag{B. 1}$$

- Aurreko arrazoia medio, Irudia B. 14n $T_{i_{Dep}}^{Re}$eta $T_{i_{Dep}}^{Tr}$ MatLab Type-arekin lotzen dira (*Parameter Identification* izenpean). Bi softwareen arteko lotura da eta betan aldagai dependenteen doikuntza gauzatzen da. Horretarako, datu esperimentalak Trnsys-eko datuekin konparatu egin behar dira eta Matlab-en bidez errealitatera estutu.

Horrela, sistemako osagai bakoitzaren modelo matematikoa lortzen da eta, gero, instalazio osoan barnera daitezke dagozkien loturekin eta kontrolarekin.

B.3.2. Biltzailearen ikerketa kasua

Adibide gisara, biltzailearen (C) ezaugarritze dinamikoa egingo da Eusko Jaurlaritzako Eraikinen Kalitate Kontrolerako Laborategian (EKKL) 4 egunetan zehar lortutako datuekin. Gainontzeko sistemaren osagaiekin batera monitorizatu egin zen horien arteko hartu emanak eta eraginak aztertzeko eta ezaugarritzeko.

Irudia B. 14ko C osagaiaren nomenklatura jarraituz datuak dira: nahasketarako emari masikoak (m_{in1}, m_{in2}), sarrera ($T_{in1_{ind}}^{Re}, T_{in2_{ind}}^{Re}, T_{in3_{ind}}^{Re}$) eta irteera tenperaturak ($T_{out1_{dep}}^{Re}$) eta nahasketa tenperaturak ($T_{out2_{dep}}^{Re}, T_{out2_{dep}}^{Re}$). Beraz, doitzeko aldagaiak dira: $T_{out1_{Dep}}^{Calc}, T_{out2_{Dep}}^{Calc}, T_{out2_{Dep}}^{Calc}$.

Orduan, Trnsys-eko irteerak $\left(T_{i_{Dep}}^{Tr}\right)$ datu errealen arabera zuzendu ziren Matlab System Identification Toolbox-en eskutik, alegia:

$$T_{out1_{Dep}}^{Calc}(t) = \frac{\dot{m}_{in1}(t) \cdot T_{in1_{Ind}}^{Re}(t) + \dot{m}_{in2}(t) \cdot T_{in2_{Ind}}^{Re}(t)}{\dot{m}_{in1}(t) + \dot{m}_{in2}} \tag{B. 2}$$

$$T_{out2_{Dep}}^{Calc}(t) = T_{in3_{Ind}}^{Re}(t) \tag{B. 3}$$

$$T_{out3_{Dep}}^{Calc}(t) = \begin{cases} T_{in3_{Ind}}^{Re}(t) \cdot 0.9649 & \dot{m}_{in2} = 0 \\ T_{out3_{Dep}}^{Tr}(t) & \dot{m}_{in2} \geq 0 \end{cases} \tag{B. 4}$$

Garatu antzera, ponpen pizketa eta itzaltze eraginak eta osagaien inertziak kontuan hartzen dira (ikus $\dot{m}_{in2}$-aren baldintza Ek.(B. 4)ean).

Data esperimentalaren eta simulazio emaitzen arteko errore erlatiboa, hau da, balio dependente errealen eta Trnsys-eko eta Matlab-eko balio dependente kalkulatuaren arteko ezberdintasuna $\left(T_{i_{Dep}}^{Calc} - T_{i_{Dep}}^{Re}\right)$ % ±3 baino txikiagoa da.

Ondorioz, teknika berri hau zuzen egokitzen da sistemen ezaugarritze problemak ebazteko.

B.4. ONDORIOAK

Eraikin sistemen ezaugarri nagusien artean dinamismoa dago, azken batean ezin baita egoera egonkor batekin horien eskaria ezta energia horniketa adierazi. Ondorioz, edozein kalkuluren aurretik osagai bakoitzaren eta instalazio osoaren modelo termodinamiko sinesgarria eraikitzea ezinbestekoa da.

Beste batzuen artean, bi egoera aurki daitezke: lehenengoa instalazioaren sorkuntzan datza eraikin zehatz batzuen beharrak asetzeko. Eskari oso konplexuak izanagatik ere, metodologiak gogobeteko emaitzak eskaintzen dituela frogatzen da.

Bigarren kasua datu erreal monitorizatuekin sistemaren ezaugarritze dinamikoan datza. Kutxa-gris modeloan du funtsa eta Trnsys eta Matlab programen konbinazioarekin lortzen da. Proposamen berritzaile honek ere aldeko emaitzak ematen ditu.

Bi metodologiek sistemaren fluxu bakoitzaren aldagai termodinamikoak lortzeko balio dute.

B.5. ERREFERENTZIAK

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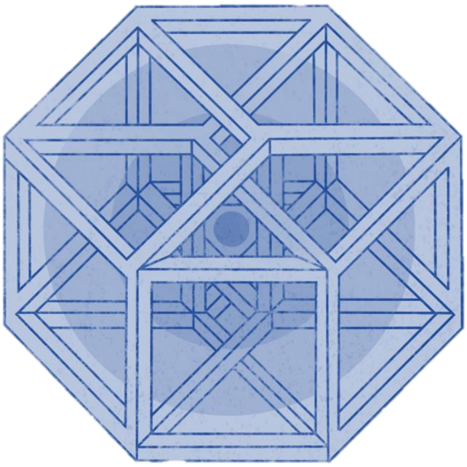


C KAPITULUA

Termoekonomia analisia eraikinetan

eman ta zabal zazu

UPV EHU

C KAPITULUA

AZPIINDIZEAK

0	Erreferentzia giroa, ingurua
T	Totala
in	Sarrera
out	Irteera
n	Sistemaren osagai kopurua
m	Sistemaren fluxu kopurua
e	Sistemaren irteerak
x	Sistemaren bidebanatzeak
r	Sistemaren birzirkulazioak
F	Fuela
P	Produktua
R	Hondakina

GOIINDIZEAK

e	Produktu erabilgarria
r	Hodakina
z	Kostu finkoak
Fix	Balio finkoak

SINBOLOAK

$\mathbf{E}$	[kJ]	Exergia fluxu bektorea $(m, 1)$
$\mathbf{E_D}$	[kJ]	Exergia suntsiketa bektorea $(m, 1)$
$\mathbf{F}^*$	[kJ]	Fuelaren kostu exergetikoa $(n, 1)$
$\mathbf{P}^*$	[kJ]	Produktuaren kostu exergetikoa $(n, 1)$
$\mathbf{R}^*$	[kJ]	Hondakinaren kostu exergetikoa $(n, 1)$
$\mathbf{k}_\mathrm{F}^*$	[kJ/kJ]	Fuelaren kostu exergetiko unitarioa $(n, 1)$
$\mathbf{k}_\mathrm{P}^*$	[kJ/kJ]	Produktuaren kostu exergetiko unitarioa $(n, 1)$
$\mathbf{C}$	[€]	Fluxuaren kostu exergoekonomikoa $(m, 1)$,
$\mathbf{C_F}$	[€]	Fuelaren kostu exergoekonomikoa $(n, 1)$
$\mathbf{C_P}$	[€]	Produktuaren kostu exergoekonomikoa $(n, 1)$
$\mathbf{Z_e}$	[€]	Taldearen inbertsioa, amortizazioa eta mantenu kostua $(n, 1)$

$\mathbf{J}$	[-]	Exergia balantzearen matrizea (n, m)
$\boldsymbol{\alpha}_\mathbf{s}$	[-]	Fluxuen irteera matrizea (s, m)
$\boldsymbol{\alpha}_\mathbf{r}$	[-]	Birzirkulazio matrizea $(m - n - s, m)$
$\mathbb{F}_\mathrm{r}$	**[kJ]**	Fuelen bektore hedatua $(m, 1)$
$\mathbb{Y}_\mathrm{s}$	[-]	Irteera bektore hedatua $(m, 1)$
$\mathbb{J}_\mathrm{r}$	**[kJ]**	$\mathbf{J_r}$ matrize hedatua (m, m)

k_j	**[kJ/kJ]**	j osagaiaren exergia kontsumo unitarioa
α_{ij}	**[-]**	Bidebanatze parametroak, *FP* adierazpena
r_{ij}	**[-]**	Birzirkulazio parametroak, *PF* adierazpena
ψ_{ir}	**[-]**	Hondakinen banaketa parametroak, *FP* adierazpena
ω_{ej}	**[kJ]**	j osagaien kanpo baliabideak, *FP* adierazpena
ω_{sj}	**[kJ]**	j osagaien kanpo produktua, *PF* adierazpena

$\langle\mathbf{FP}\rangle$	[-]	x_{ij} (n, n) banaketa parametroen matrize dependentea, *FP* adier.
$\langle\mathbf{PF}\rangle$	[-]	α_{ij} (n, n) banaketa parametroen matrize dependentea, *PF* adier.
$\langle\mathbf{KP}\rangle$	[-]	Kontsumo unitarioen matrize dependentea (n, n), *PF* adier.
$^{\mathbf{t}}\langle\mathbf{F_T F}\rangle$	[-]	Osagaien kanpo fuel bektorearen proportzio bektorea $(1, n)$
$\vert\mathbf{F}\rangle$	[-]	Operadore matriziala (n, n), *PF* adierazpena

$\|\mathbf{P}\rangle$	[-]	Operadore matriziala (n, n), *PF* adierazpena
$\|\mathbf{I}\rangle$	[-]	Operadore matriziala (n, n), *PF* adierazpena
$\|\widetilde{\mathbf{P}}\rangle$	[-]	Operadore matriziala hondakinekin (n, n), *PFR* adierazpena
$\|\widetilde{\mathbf{R}}\rangle$	[-]	Operadore matriziala hondakinekin (n, n), *PFR* adierazpena

QF	[-]	Kalitate faktorea
$\bar{\tau}$	[*][2]	Diseinu parametroak

[2] [*] = dagokion aldagaiaren unitateak

C KAPITULUA: TERMOEKONOMIA ANALISIA ERAIKINETAN

C.0. LABURPENA

Termodinamikaren bigarren legearekin termoekonomiak energia bihurketa prozesuen fisika eta ekonomia batzen ditu. Energia karga profil oso irregularrengatik eta plantaren operazio desorekatuagatik termoekonomia aplikazioa eraikinetan mugatuta dagoenez, metodoa zailtzen duen ikuspegi dinamikoa behar du horrek.

Termoekonomia sinbolikoaren (ST) garapen historikoarekin eta laburpenarekin, kapituluaren lehen atalak termoekonomiaren potentziala nabarmentzen du erabakiak hartzeko, berezko kostuen eta efizientzien arteko erlazioa azpimarratzeko gaitasunagatik. Bi ikerketa kasurekin azalduko dira STaren nondik norakoak.

Bigarren atalean aplikazioaren hobekuntza egiten da metodologian eraikinen energia sistemetan dinamismoa inplementatuz. Egitura produktiboaren gakoak ebazten dira, zehazki, horren ohikoak diren 3-bideko balbulak eta osagai inertzialak. Disipazio osagaien rola ere azaltzen da ikerketa kasuekin.

Guztira, kapitulu honek termoekonomia aplikazioaren sendotasunak eta eskasiak azpimarratzen ditu eta eraikinen erabilpenerako hobetzen da.

C.1. SARRERA

Energia sistemen bigarren legearen analisiek 60ko hamarkadaren erdialdean eragin nabarmena izaten hasi ziren, hortik aurrera egun arte, hainbeste aurreratze izan dituzte. Exergia metodoaren inplementazioaren lorpenetan nagusia, 80ko hamarkadan garatua, termoekonomiaren zientziako *exergia kostuen kalkulua* izan zen, zeinek prozesuaren itzulezintasunen arabera fluxuei kostuak lotzen dizkion. Termoekonomiak ekonomia eta termodinamika analisiak batzen ditu sistemaren produktuei prezio arrazionalak esleitzeko, efizientzia gabeziak detektatu eta horien eragin ekonomikoak zenbatesteko, diseinu aukerak ebaluatzeko, prozesuaren unitateen aldagai zehatzak optimizaziorako, etab. [1]. 90ko hamarkadan metodo bakarra ez zegoenez, teknika ezberdinak konparatu eta bateratzen ahalegindu ziren CGAM (C. Frangopoulos, G. Tsatsaronis, A. Valero eta M. von Spakovsky) problemaren bitartez, ideia nagusia exergia kostua kokatzeko bide bakarra erabiltzea zen.

Beraz, kostua exergiaren arabera kokatzen da, alegia, energia prozesuaren itzulezintasunekiko era proportzionalean. Zehazki, exergia kostuak zenbat exergia unitate behar diren produktu jakin bat sortzeko adierazten du eta hiru baldintza bete behar dira: (1) sistemaren mugak aurretiaz definitu behar dira; (2) osagaien arteko loturak ezagunak izan behar dira (*modelo termodinamikoa*) eta (3) osagai bakoitzaren produkzio helburua zehaztuta dago (*egitura produktiboa*) [2].

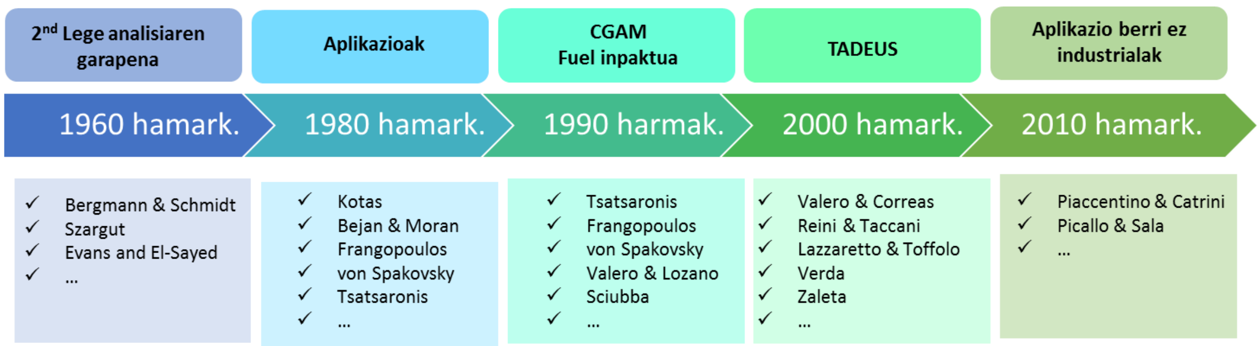
Modelo termodinamikoa osagaiaren sarrera eta irteera fluxuak determinatzeko erabiltzen da, modelo produktiboak, ordea, fluxuak fueletan (F), produktuetan (P) eta hondarretan (R) banatzen ditu [3].

Orduan, exergia balantzeaz gain osagai bakoitzean ekonomia xedea ere aitortu behar da. Izan ere, exergia fluxua egoeraren eta osaeraren araberako propietate termodinamikoa izan arren, kostua fluxua eratzeko prozesu zehatzaren funtzio da. Ondorioz, fluxu berberak osatzeko prozeduraren arabera exergia kostu ezberdinak izan ditzake [4]. Kasu horretan, exergia kostuak energia kateko puntu zehatzera iristeko bildu dituen itzulezintasunak zenbakitzen ditu. Hortaz, parametroak gainontzeko osagaien eragin zuzenak eta zeharkakoak barneratzen ditu eta baita fluxuen arteko kostu ezberdinen justifikazioa ere. Gainera, batez besteko kostuek, egitura kostuek eta kostu marginalek matematika formulazio analogoa daukate [5] (izatez, kostu marginalen eta batez besteko kostuen arteko ezberdintasuna kapitalaren amortizazio kostua baino ez da [6]).

Are gehiago, kostu exergetikoa osagaien eraginkortasun termodinamikoa eta kostuen efizientzia ebaluatzeko alternatiba da plantaren osagaientzako zein sistemen loturentzako. Tarteko eta bukaerako kostuen zehaztapena oso erabilgarria da elementuak eta ekonomia kontzeptuak erlazionatzeko.

Abantailak egonagatik ere, kostuen balioak hautatutako sistemaren limiteen eta helburuen funtzio dira; beraz, ingeniariaren xedearen eta ulermenaren arabera.

Horregatik, eta energia sistemen konplexutasuna aintzat hartuz, zenbait proposizio garatu ziren teknikaren mekanizaziorako eta fintasunerako. Besteen artean, *ekonomia exergetikoaren ikuspegia* (EEA), [7]; *lehen exergoekonomia ikuspegia* (FEA), [8]; *Termoekonomia funtzionalaren analisia*, (TFA), [9]; *ingeniaritzaren analisi funtzionala* (EFA), [10]; *azkenekoa sartu hasierako irten ikuspegia* (LIFOA), [11]; *teoria estrukturala*, [12]; *kostu exergetikoaren zenbaketa* (SPECO), [13]; etab. zerrenda daitezke. Kapitulu honetan zehar *termoekonomia sinbolikoa* (ST) [14] garatzen da zein ekuazio matrizial orokorrekin kostuen balioak ebazten dituen; **E Kapitulua**n, bestalde, *exergia analisi garatua* (AEA) [15] aztertzen da zeinek analisia bestelako ikuspuntu batetik egiten duen.



Irudia C. 1 Bigarren legearen garapenaren eskema

2000 urteetan zehar, termoekonomia *diagnosi* helburuetarako aplikatu zen eta TADEUS ikerketa taldea (*Thermoeconomic Approach to the Diagnosis of Energy Utility Systems*) sortu zen. Diagnosiaren aplikazioa arlo ez industrialetan (eraikinen energia sistemetan, esaterako) ez zen 2010ko hamarkadara arte aztertu, ikus Irudia C. 1. Bibliografia garapenaren datu zehatzak [16] eta [6] erreferentzietan agertzen dira.

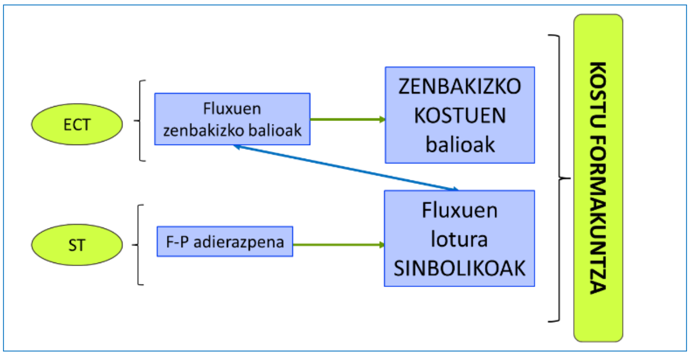
Termoekonomia industria mailan bai [17] baina eraikin giroan hainbeste ez erabiltzearen arrazoiak dira, besteak beste, energia fluxuak energia plantetan baino baxuagoak direla. Gainera, analisiak sail elektrikoko eta kimikoko kontzeptuetatik eta definizioetatik datozelako, eraikuntza arloan aplikatu ahal izateko eraldatu behar dira. Are gehiago, maila termikoak oso baxuak dira eta, beraz, giro baldintzen erabakiak eragin handia dauka exergiaren balioetan [18]. Haatik, gero eta lan gehiago hari dira eraikinetan gauzatzen [19], [20].

Bestalde, aplikazioa tresna gakoa bilakatzen hasi da eraikinen sistema termikoetan (adibidez, eguzkien berokuntza sistemetan [21], HVAC sistemetan [22], aire girotze sistemetan [23], [24], hotz xurgatzaile sistemetan [25], lurreko baliabide sistemetan [26], etab.) edo osagai indibidualen karakterizazioetan (esaterako, mikro-trigenerazio taldeetan [27], lurreko eta aireko bero ponpetan [28],[29], bero trukagailuetan [30], energia termiko biltegietan [19] etab.). Horri ere eraikinen birgaitzerako integrazioa gehitu behar zaio (kasurako, gas naturaleko kogenerazio sistemaren berritzapena [32] edo eraikinen energia birgaitzerako diseinu ezberdinen alderaketa).

C.2. TERMOEKONOMIA SINBOLIKOA

C.2.1. Eraikinetan termoekonomia sinbolikoaren analisia

Termoekonomia sinbolikoa (ST) *egitura produktiboa*ren analisirako eta baliabide naturalen kontsumorako metodologia bat da kostu formakuntzen zergatiak identifikatzeko. Exergia kostuen teorian (ECT) du funtsa eta ekuazio orokorrak lortzea baimentzen du; horiek energia sistema baten guztizko eraginkortasuna beste aldagai termodinamiko batzuekin, hala nola, fuela, kostu exergetikoa, etab. eta osagai bakoitzaren etekinekin lotzea baimentzen du. Azken batean, kostu kontaketarako metodologiak (ECT bezala) zenbakizko teknikak dira eta ekuazio linealen sistemak ebatziz kostuen kalkulu zehatza ahalbidetu arren, ez dute kostuen formakuntza prozesuaren kausa identifikatzen. ECT eta konputazio sinbolikoa nahastuz gero (konputazio sinbolikoaren paketeen bitartez, adibidez, *Mathematika* edo *Matlab*), edozein energia sistemaren formulazioa lor daiteke, ikus Irudia C. 2.



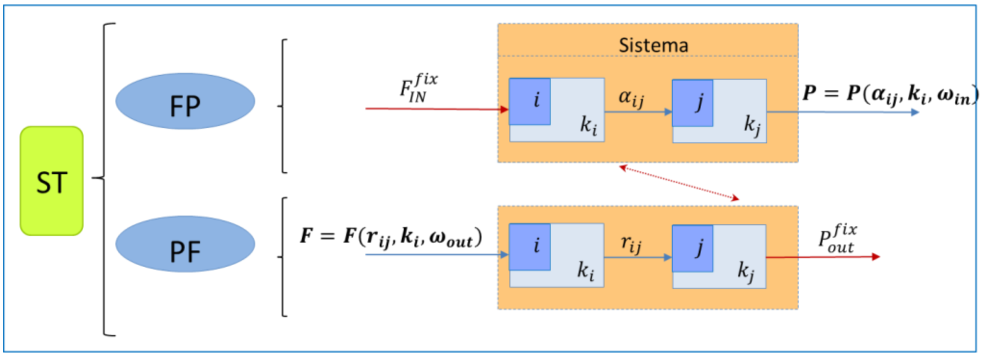
Irudia C. 2 Metodoaren deskripzio orokorra

STaren helburua osagaien arteko loturak eta produkzio prozesua adieraztea da fuel-produktu adierazpenaren bitartez. Horretarako, sistemako elementu bakoitza kutxa beltzat hartu eta sarrera-irteera parametroekin ezaugarritzen da zentzuei Fuela eta Produktua deritze. Adierazpen horrekin edozein osagaiaren aldaketak plantan zelan eragiten duen ikus daiteke. Gainera, kostuak eta sistemaren osagai askeen arteko adierazpen analitikoak lortzen dira, Horregatik, STarekin sistema baten edozein egoera determinatzeko emaitza orokorrak lortzen dira.

Labur esanda, ekuazio orokorrekin lan egiten bada arazo jeneralen emaitza orokorrak lortzen dira. Beraz, ST kostu zenbaketarako erraminta sendoa da.

Industria prozesuetan eta planta termikoetan STaren aplikazioa aski ezaguna izanagatik ere [34], eraikinetan STaren aplikazioa askoz eskasagoa da. Alabaina, azken urteotan zenbat lan argitaratu dira, besteak beste, kontrol estrategientzako aireportuen HVAC sistemen lanak [35], gas hedapenen sistemak hozkuntza planta konbentzionalean [37], etab. Azkenekoak matematika tresna sofistikatuen beharrik ez dagoela azpimarratzen du, tratamendu metrikoak egin baitaitezke.

STarekin lan egitean bi egoera ager daitezke, ikus Irudia C. 3. Batetik, baliabideen kontsumoa ezarrita egon daiteke (F_{IN}^{fix}) eta, orduan, produktuak plantaren egituraren arabera aldatuko dira. Hori banaketa koefizientekin (α_{ij}), osagaien efizientziekin -edo horien alderantzikoagatik, kontsumo exergetikoekin (k_i)-, eta sarrera ezaugarriekin (ω_{in}) osatzen da: $P = P(\alpha_{ij}, k_i, \omega_{in})$. Horri FP adierazpena edo horniketak sustatutako modeloa deritzo.



Irudia C. 3 Horniketak sustatutako eta eskariak sustatutako modeloen eskema

Bestetik, beste egoera batean produktua finko egon daiteke (P_{OUT}^{fix}). Adibidez, berokuntza eta EUB sistemak hornitu behar du berokuntza eta EUB, aire girotuko sistemak hozkuntza eskaria eman behar du, etab. Beraz, beharreko baliabidea plantaren egituraren araberakoa da eta birzirkulazio koefizienteekin (r_{ij}), exergia kontsumoarekin (k_i) eta kanpo ezaugarriekin (ω_{out}) deskribatzen da: $F = F(r_{ij}, k_i, \omega_{out})$. Formulazio hori PF adierazpena edo eskariak sustatutako modeloa bezala ezagutzen da.

STak termoekonomia propietateak bi adierazpenen aldagai kanonikoen menpe lortzea ahalbidetzen du, esaterako, exergia eta kostuak. Bi errepresentazioak, jakina, estuki lotzen direnez batetik besterako jauzia egin daiteke. STa energia sistemen diseinurako tresna baliagarria da eta sistema konplexuen simulazioen edo ohiko optimizazioen teknikak osatzen ditu.

C.2.1.1. STaren laburpena eskariak sustatutako modeloan

Sistemak eskaria hornitzeko beharrezko baliabideak era sinbolikoan lortuko dira (PF modeloa). Beraz, sarrerak plantaren egituraren funtzio izango dira, alegia, *birzirkulazio koefizienteak*, osagaien *exergia kontsumo unitarioak* eta *amaierako irteera produktuak*.

C.2.1.1.1. Egitura fisikoa

Bedi energia sistema bat n osagaiz eta m masa edo energia fluxuen loturez osaguta. Fluxuen eta osagaien arteko erlazioak $\mathrm{A}\,(n,m)$ intzidentzia matrizearekin adierazten dira. Horrek masa, energia, exergia eta kostu balantzeak modu matrizialean ebazten ditu. Zenbat eta agregazio maila txikiagoa izan orduan eta zehatzagoa izango da intzidentzia matrizea eta, beraz, kostuak eta efizientzia gabeziak hobe egongo dira definituak; baina, datu kantitate gehiago beharko denez, instrumentazioaren kalitatea altuagoa izan beharko da.

Egitura fisikoa definitu osteko urratsa egitura produktiboaren determinazioa da azpisistema bakoitzaren baliabideak eta produktuak adierazteko. Fluxuak osagai bakoitzaren fueletan eta produktuetan taldekatu behar dira. Horrela, fuelen A_F eta produktuen A_P intzidentzia matrizeak eraikitzen dira. $\mathbf{k_D}$ bada osagaien kontsumo unitarioaren matrize diagonala (n,n) eta exergia balantzeari dagokionez, idazten da:

$$(\mathbf{A_F} - \mathbf{k_D} \cdot \mathbf{A_P}) \cdot \mathbf{E} = \mathbf{0} \qquad \text{(C. 1)}$$

non $(\mathbf{A_F} - \mathbf{k_D} \cdot \mathbf{A_P})$ eta $\mathbf{J}$ deritzon.

ECT proposizioekin $(m-n)$ ekuazio gehigarri lortzen dira. s bada amaierako produktuen kantitatea, orduan, s ekuazio gehigarri izango dira irteera fluxuak, $\boldsymbol{\alpha}_\mathbf{s} \cdot \mathbf{E} = \mathbf{E_s}$ eta $(m-n-s)$ ekuaziok birzirkulazioak adieraziko dituzte, $\boldsymbol{\alpha}_\mathbf{r} \cdot \mathbf{E} = \mathbf{0}$. Horregatik, $\mathbb{J}_\mathrm{r}$ matrize hedatua (m,m) eta $\mathbb{F}_\mathrm{r}$ bektore hedatua $(m,1)$ eraiki daitezke. Azkeneko bektoreak produktu totalen exergia fluxuak barneratzen ditu $[\mathbf{0}_{(n,1)}; \mathbf{E_s}_{(s,1)}; \mathbf{0}_{(r,1)}]$, eta egiaztatzen da:

$$\mathbb{J}_\mathrm{r} \cdot \mathbf{E} = \mathbb{F}_\mathrm{r} \qquad \text{(C. 2)}$$

$\mathbb{J}_\mathrm{r}$ matrize erregularra denez alderantzizkoa dauka. Modu horretan, exergiaren adierazpenak lortzen dira $\mathbf{E}$ modeloari dagozkion aldagai kanonikoen arabera, alegia, kontsumo exergetiko unitarioaren, birzirkulazio koefizienteen eta sistemaren produktuen menpe.

C.2.1.1.2. Egitura produktiboa

Nahiz eta ECTak fluxuen kostuak eta fuelen zein produktuen kostuak kalkulatzen dituen, Fuel-Produktu errepresentazioarekin adierazpen zuzenagoak lortzen dira. Egitura produktiboa Fuel/Produktu taula edo diagramarekin adieraz daiteke eta estuki lotzen da Leontief-en sarrera-irteera ekonomia analisiarekin, halere, fluxuak exergia balioetan daude. Horren arabera, osagai bakoitza kutxa beltz lez adierazten da F sarrerarekin eta P irteerarekin. Zenbait konponente birtual gaineratzen dira baturak (zirkunferentziak) eta banaketak (diamanteak) irudikatzeko.

Birzirkulazioak i produktutik datorren j osagaiko baliabideen (F_j) proportzioa dira:

$$r_{ij} = \frac{E_{ij}}{F_j} \qquad \text{(C. 3)}$$

Osagai baten produkzioa beste osagai baten fuela (E_{ij}) edo plantaren amaierako produkzioa ($E_{i,e}$) izan daiteke:

$$P_i = E_{i,e} + \sum_{j=1}^{n} r_{ij} \cdot F_j \qquad , \qquad i = 1, \ldots, n \qquad \text{(C. 4)}$$

eta plantaren fuel totala da**:**

$$F_T = \sum_{j=1}^{n} r_{e,j} \cdot F_j \qquad \text{(C. 5)}$$

Aurreko Ek.(C. 4) matrize eran adierazten da:

$$\mathbf{P} = \mathbf{P_s} + \langle \mathbf{PF} \rangle \cdot \mathbf{F} \qquad \text{(C. 6)}$$

$\mathbf{P_s}$-k amaierako produktuen exergia balioak barneratzen ditu eta $\langle \mathbf{PF} \rangle$ (n, n) dimentsioko matrizea da zeinen elementuak birzirkulazio koefizienteak (r_{ij}) diren. κ_{ij} exergia kontsumo marginalak dira, alegia, i osagaitik datorren baliabide kantitatea (E_{ij}) j osagaiaren produktuaren (P_j) unitate bat lortzeko eta k_j j osagaiaren exergia kontsumo unitatea da:

$$\kappa_{i,j} = \frac{E_{i,j}}{P_j} = \frac{r_{i,j}.F_j}{P_j} = r_{i,j} \cdot k_j \qquad \text{(C. 7)}$$

Osagaien exergia kontsumo marginalen arteko gehiketa kontsumo exergetiko unitarioaren berdina da:

$$\sum_{i=0}^{n} \kappa_{i,j} = k_j \qquad \text{(C. 8)}$$

$\langle \mathbf{F_T F} \rangle$ $(1, n)$ dimentsioko bektorea da eta kanpo baliabideetatik datorren osagaiaren fuel proportzioa adierazten du:

$$^{\mathbf{T}}\langle \mathbf{F_T F} \rangle = {}^{\mathbf{T}}\mathbf{u} \cdot (\mathbf{U_D} - \langle \mathbf{PF} \rangle) \qquad \text{(C. 9)}$$

Bedi $\langle \mathbf{KP} \rangle$ matrizea κ_{ij} elementuekin:

$$\langle \mathbf{KP} \rangle = \langle \mathbf{PF} \rangle \cdot \mathbf{k_D} \qquad \text{(C. 10)}$$

non, esan antzera, $\mathbf{k_D}$ osagai bakoitzaren kontsumo unitarioko matrize diagnonala den.

Beraz, osagai bakoitzeko fuela, produktua eta itzulezintasuna da:

$$\mathbf{P} = |\mathbf{P}\rangle \cdot \mathbf{P_s} \quad , \quad |\mathbf{P}\rangle = (\mathbf{U_D} - \mathbf{KP})^{-1} \qquad \text{(C. 11)}$$

$$\mathbf{F} = |\mathbf{F}\rangle \cdot \mathbf{P_s} \quad , \quad |\mathbf{F}\rangle = \mathbf{k_D} \cdot |\mathbf{P}\rangle = \mathbf{k_D} \cdot (\mathbf{U_D} - \mathbf{KP})^{-1} \qquad \text{(C. 12)}$$

$$\mathbf{I} = |\mathbf{I}\rangle \cdot \mathbf{P_s} \quad , \quad |\mathbf{I}\rangle = (\mathbf{k_D} - \mathbf{U_D}) \cdot |\mathbf{P}\rangle = (\mathbf{k_D} - \mathbf{U_D}) \cdot (\mathbf{U_D} - \mathbf{KP})^{-1} \qquad \text{(C. 13)}$$

Plantaren baliabide totalak dira:

$$F_T = \sum_{j=1}^{n} \kappa_{ej} P_j \qquad \text{(C. 14)}$$

eta matrize eran:

$$\mathbf{F_T} = {}^{\mathbf{T}}\mathbf{k_e} \cdot |\mathbf{P}\rangle \cdot \mathbf{P_s} \qquad \text{(C. 15)}$$

non ${}^{\mathbf{t}}\mathbf{k_e} = (\kappa_{e1}, \kappa_{e2}, \dots, \kappa_{en})$ $(n, 1)$ dimentsioko bektorea den kanpo sarreren kontsumo exergetiko unitarioekin.

$$\mathbf{k_e} = \langle \mathbf{F_T F} \rangle \cdot \mathbf{k_D} \qquad \text{(C. 16)}$$

Sistemaren exergia kontsumo unitarioaren formula unibertsala (efizientziaren alderantzizkoa), sistemaren konplexutasuna edozein izanagatik, da:

$$k_T = \frac{F_T}{P_T} = \frac{{}^{\mathbf{T}}\mathbf{k_e} \cdot |\mathbf{P}\rangle \cdot \mathbf{P_s}}{{}^{\mathbf{t}}\mathbf{u}\ \mathbf{P_s}} \qquad \text{(C. 17)}$$

C.2.1.1.3. Kostu zenbaketa

Osagai bakoitzaren fuel eta produktu kostu exergetikoen eta exergoekonomikoen ekuazioak lortuko dira jarraian. Ek.(C. 4)-aren adierazpen baliokidea lor daiteke exergia kostuentzako eta, ECT arauak kontuan hartuz, datozen ekuazioak lortzen dira:

$$k_{P_i}^* - \sum_{j=1}^{n} \kappa_{ji} \cdot k_{P_j}^* = k_{e_i}^* \qquad , \qquad i = 1, \dots, n \qquad \text{(C. 18)}$$

Aitzinako adierazpenak produktuen kostu exergetiko unitarioa ($k_{P_i}^*$) osagai bakoitzaren kontsumo exergetiko marginalarekin ($\kappa_{ji} \cdot k_{P_j}^*$) lotzen du eta matrize eran:

$$\mathbf{k_P^*} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{k_e^*} \qquad \text{(C. 19)}$$

Kanpo baliabideen exergia kostu unitarioa $\mathbf{k_e^*} = \langle \mathbf{F_T F} \rangle$ da.

Osagai bakoitzaren fuel kostua da:

$$k_{F_i}^* = r_{ei} + \sum_{j=1}^{n} r_{ji} \cdot k_{P_j}^* \qquad \text{(C. 20)}$$

eta era matrizialean:

$$\mathbf{k_F^*} = \mathbf{k_e^*} + {}^{\mathbf{T}}\langle \mathbf{PF} \rangle \cdot \mathbf{k_P}^* \qquad \text{(C. 21)}$$

$\mathbf{k_F^*} = \mathbf{H_D} \cdot \mathbf{k_P^*}$ adierazpena aintzat hartuz non $\mathbf{H_D}$ efizientzia energetikoen matrize diagonal den, operadore lineal bat defini daiteke:

$$|\mathbf{k_F^*}\rangle = (\mathbf{U_D} - {}^{\mathbf{t}}\langle \mathbf{PF} \rangle \cdot \mathbf{k_D})^{-1} \qquad \text{(C. 22)}$$

Orduan, fuelen exergia kostu unitarioen eta kanpo baliabideen kontsumo unitarioen harremana da:

$$\mathbf{k_F^*} = |\mathbf{k_F^*}\rangle \cdot \mathbf{k_e^*} \tag{C. 23}$$

Fluxu baten exergia kostua hori lortzeko beharrezko baliabide kopurua da eta, beraz, ez dauka zentzurik plantako produktuen funtzioan jartzeak. Osagaien produktuen kostuak, antzeko eran:

$$\mathbf{k_P^*} = |\mathbf{k_P^*}\rangle \cdot \mathbf{k_e^*} \tag{C. 24}$$

eta $|\mathbf{k_P^*}\rangle$ operadorea da:

$$|\mathbf{k_P^*}\rangle = (\mathbf{H_D} - {}^{\mathbf{T}}\langle\mathbf{PF}\rangle)^{-1} \tag{C. 25}$$

Ikas bitez, orain, kostu exergoekonomikoak. Ek.(C. 22)-aren antzera esan daiteke:

$$\mathbf{c_F} = \mathbf{c_e} + {}^{\mathbf{T}}\langle\mathbf{PF}\rangle \cdot \mathbf{c_P} \tag{C. 26}$$

non $c_{e,i}$ i osagaieko kanpo baliabideen kostu unitarioa den. Aurreko adierazpenetik lortzen da:

$$\mathbf{c_F} = \mathbf{H_D} \cdot (\mathbf{c_P} - \mathbf{z_p}) \tag{C. 27}$$

non $\mathbf{z_P}$ $(n, 1)$ dimentsioko bektorea den produktu unitateko amortizazio, mantenu eta operazio kostuekin, beraz:

$$\mathbf{c_F} = |\mathbf{k_F^*}\rangle \cdot \mathbf{c_e} + (|\mathbf{k_F^*}\rangle - \mathbf{U_D}) \cdot \mathbf{z_F} \tag{C. 28}$$

orduan:

$$\mathbf{c_P} = |\mathbf{k_P^*}\rangle \cdot \mathbf{c_e} + (|\mathbf{k_F^*}\rangle - \mathbf{U_D}) \cdot \mathbf{z_P} \tag{C. 29}$$

Operadore horrekin fuelen eta produktuen kostu exergetiko unitarioak lotzen dira kanpo baliabideen kostu exergetikoekin. Ikus antzera, produktuen kostu exergoekonomikoak bi osagaiekin osatzen dira: batek kanpo baliabideen kostu unitarioekin harremana du ($|\mathbf{k_P^*}\rangle \cdot \mathbf{c_e}$) eta besteak amortizazio kostu unitarioekin ($(|\mathbf{k_F^*}\rangle - \mathbf{U_D}) \cdot \mathbf{z_P}$).

C.2.1.2. Hondakinen barneraketa

ST laburpenean fluxuak fueletan edo produktuetan sailkatu dira. Alabaina, prozesu produktiboetan jarioen artean hondakinak deritzen materia edo energia fluxu gehigarriak ager daitezke. Egitura produktiboari dagokienez ez daukate erabilgarritasunik baina horien inpaktua murrizteko energia eskatzen dute. Edozein energia sisteman osagai produktiboaz gain disipazio osagaiak ere badaude zeintzuen helburua nahi ez diren fluxuak guztiz edo hein batean ezabatzea den.

Hondakinen kostu kokapenaren problema konplexua da fluxuen nortasunaren araberakoa eta eraketa formaren funtzio baita. Hondakinen kostuen loturak hainbat modutan ebatz daitezke [38], [39], [40]. Ikerketa honetan zehar Erref.[41]-ko egitura matematikoa hondakinen zein horien eraginen kostuak kalkulatzeko hautatu da.

Hondakinen kostu exergetikoa (formazio kostua) eta horien garbiketarako baliabideen kostua (murriztapen kostua) sorkuntza unitate produktiboan kokatu behar da eta baita ere plantaren amaierako produktuetan. Hondakinak identifikatu ostean, bakoitzaren formakuntza prozesua jarraitu eta horien jatorria zehaztu behar da.

Kostu exergoekonomikoak ikertuko dira. Hondakina r osagaiean disipatzen bada eta beste zenbaitetan badu jatorria, hondakinaren kostua banatu egiten da talde sortzaileen artean:

$$P_r^* = \sum_{i\epsilon produk} P_{r,i}^* \tag{C. 30}$$

Beraz, hondakinen kostua i osagai produktiboan da:

$$R_i^* = \sum_{\substack{r\epsilon disipazio\ osag. \\ i\epsilon produktiboa}} P_{r,i}^* \tag{C. 31}$$

orduan:

$$P_i^* = F_i^* + R_i^* \tag{C. 32}$$

eta kasu horretan disipazio unitateen hondarren kostuak hori sortzeko osagai produktiboan kokatzen dira.

$P_{r,i}^*$ balioak determinatzeko, kostu banaketa ratio bat ($\psi_{i,r}$) definitzen da, hau da:

$$P_{r,i}^* = \psi_{i,r} \cdot P_{r,e}^* \qquad , \qquad \sum \psi_{i,r} = 1 \tag{C. 33}$$

Kokapen hori zenbait modutan egin daiteke hondakinaren nortasunaren arabera eta ez dago irizpide orokorrik. r disipazio unitatearen kostua da:

$$P_r^* = E_{e,r} + \sum_{i=1}^{n} k_{P_i}^* \cdot E_{i,r} \tag{C. 34}$$

i osagai produktiboan kokatutako hondakinaren kostua da:

$$\psi_{i,r} = \frac{k_{P_i}^* \cdot E_{i,r}}{k_{P_r}^* - k_{e,r}^*} \tag{C. 35}$$

$\langle \mathbf{KR} \rangle$ (n, n) matrize berria barneratzen bada $\rho_{r,i}$ osagaiekin:

$$\rho_{r,i} = \frac{k_{P,i}^{e*} \cdot \kappa_{i,r}}{k_{P,r}^{e*} - k_{e,r}^*} \cdot \frac{P_r}{P_i} \qquad , \qquad i \in produk\ ;\ r \in disipa \tag{C. 36}$$

Kokapen horren hondar ekarpenaren bide laburra hartzen du aintzat. Halaber, metodo konplexuagoak daude kostu produkzioaren katea osatzeko [39].

Orduan, kostu exergetiko unitarioa bi ekarpenekin lotu daiteke: kanpo baliabideekin ($\mathbf{k_P}^{\mathbf{e},*}$) eta hondakinekin ($\mathbf{k_P}^{\mathbf{r},*}$). Hortaz:

$$\mathbf{k_P}^* = \mathbf{k_P}^{\mathbf{e}*} + \mathbf{k_P}^{\mathbf{r}*} \tag{C. 37}$$

$$\mathbf{k_P^{e,*}} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{k_e^*} \quad , \quad |\mathbf{P}\rangle = (\mathbf{U_D} - \mathbf{KP})^{-1} \tag{C. 38}$$

$$\mathbf{k_P^{r,*}} = {}^{\mathbf{T}}|\widetilde{\mathbf{R}}\rangle \cdot \mathbf{k_p^{e,*}} \quad , \quad |\widetilde{\mathbf{R}}\rangle = (\mathbf{U_D} - |\mathbf{R}\rangle)^{-1} - \mathbf{U_D} \quad , \quad |\mathbf{R}\rangle = \langle \mathbf{KR} \rangle \cdot |\mathbf{P}\rangle \tag{C. 39}$$

$$\mathbf{k_P}^* = {}^{\mathbf{T}}|\widetilde{\mathbf{P}}\rangle \cdot \mathbf{k_e^*} \quad , \quad |\widetilde{\mathbf{P}}\rangle = (\mathbf{U_D} - \langle\mathbf{KP}\rangle - \langle\mathbf{KR}\rangle)^{-1} \tag{C. 40}$$

Jarraian kostu exergoekonomikoak aztertuko dira. Ek.(C. 37)-aren antzera, produkzio kostua ekarpen ezberdinen funtzio bana daiteke: kanpo baliabideen kostuei ($\mathbf{c_P^e}$), taldeen inbertsio kostuei ($\mathbf{c_P^z}$) eta hondakin sorkuntza kostuei ($\mathbf{c_P^r}$) dagozkionak. Produkzio kostuak honela adierazten dira:

$$\mathbf{c_P} = \mathbf{c_P^e} + \boldsymbol{c_P^z} + \boldsymbol{c_P^r} \tag{C. 41}$$

$$\mathbf{c_P^e} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{c_e} \tag{C. 42}$$

$$\mathbf{c_P^z} = {}^{\mathbf{T}}|\mathbf{P}\rangle \cdot \mathbf{z_p} \tag{C. 43}$$

$$\mathbf{c_P^r} = {}^{\mathbf{T}}|\widetilde{\mathbf{R}}\rangle \cdot \mathbf{c_P^e} \tag{C. 44}$$

Produktuen kostuen ostean fuelen kostuak kalkula daitezke:

$$\mathbf{c_F} = \mathbf{c_e} + {}^{\mathbf{T}}\langle\mathbf{PF}\rangle \cdot \mathbf{c_P} \tag{C. 45}$$

STaren moldagarritasuna kontuan hartuz, kostu formakuntzaren zehaztapena handitzen da instalazioaren azpisistema kantitatea handitu heinean. Beste hitz batzuetan, zenbat eta zehaztasun gehiago izan azpisistemetan orduan eta ulermen handiagoa egongo da kostuen formakuntza prozesuan.

C.2.2. Ikerketa kasua

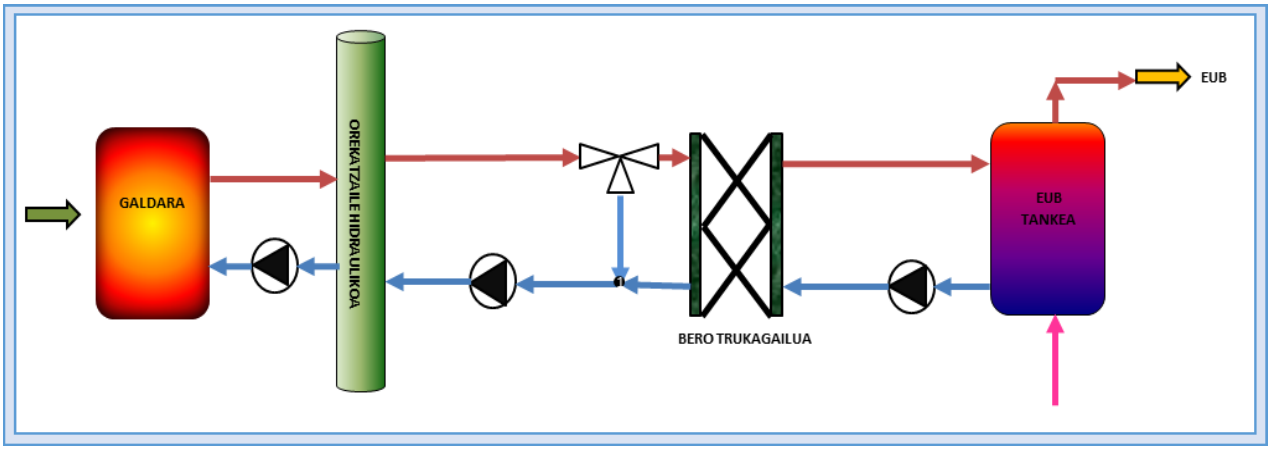
Aurreko teoria sakontzeko bi adibide garatuko dira:

Lehen adibidearen jomuga laburpen gisa eta modu konpaktuan ST metodologia aurkeztea da, aldagai termoekonomikoen adierazpen orokorrak barneratuz osagaien kontsumo unitateen, birzirkulazio koefizienteen eta amaierako produktuen menpe, alegia, eskariak sustatutako metodoaren arabera. Adibide sinplea bilatu denez, ikerketa kasua EUB instalazio soil bat da.

Bigarren adibidearen helburua STaren moldagarritasuna eta kostuen kontaketarako eraginkortasuna azpimarratzea da. Aurreko **A Kapitulu**ko (ii) *Birgaitze ikerketa kasua* hartuko da non bi sistema termiko konparatzen diren eta bertatik berrikuntzak dakartzan onura ekonomikoak nabarmenduko dira STaren aplikazioarekin.

C.2.2.1. (iv) EUB instalazio sinplea

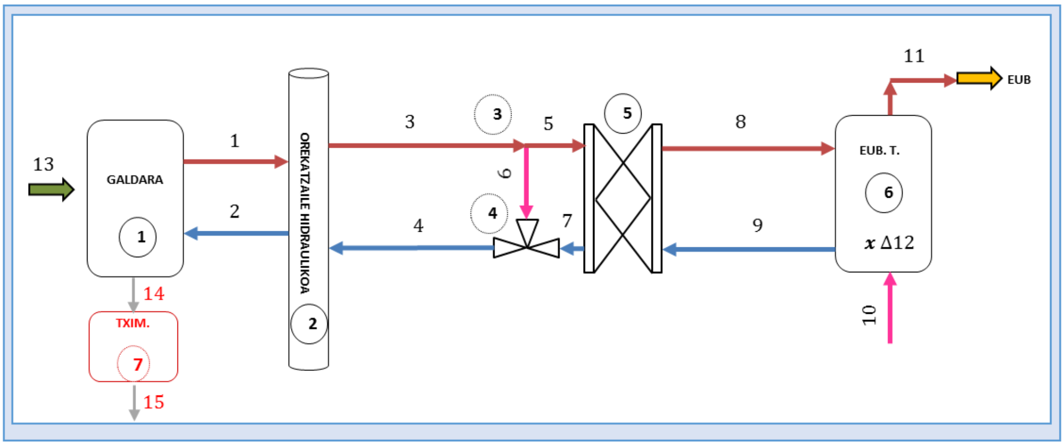
Energia horniketa sistemak 20 familientzako EUB eskaria asetzen du, Bilbon (Espainiako iparraldean) 28 kW-ko potentzia nominaleko gas kondentsazio galdararekin. Sistemak orekatzaile hidrauliko bat, eskariaren araberako 3-bideko balbula, bero trukagailua eta EUB biltegi bat ditu. Gainera, bi zirkulazio ponpa daude, zirkuitu primarioan bat eta bestea sekundarioan (ikus Irudia C. 4) 7 osagai eta 15 fluxu kontuan hartu ziren analisian (ikus Irudia C.



Irudia C. 4 EUB sorkuntzarako instalazioaren eskema

5).

Ikusi lez, disipazio osagai bat izendatu zen, tximinia (eta fluxu erlazionatuak gorriz azpimarratu dira). Gainera, bi zirkulazio ponpak ez dira kontuan hartu horien potentzia txikia medio. Beraz, exergia fluxuen kalkuluek ez dute presioen eraginik kontuan hartzen.



Irudia C. 5 Fluxuen eta osagaien zenbaketa

C.2.2.1.1. Adierazpen sinbolikoak

Taula C. 1 (a)-n egitura produktiboaren analisia batzen da. Taula honetan osagai bakoitzaren fuela zein produktua, exergia kontsumo unitatea, plantaren kanpo produktua eta hondakinak daude[3]. Soilik 14 fluxua da hondakina zein galdararen tximinia irteerako errekuntza gasekin lotzen den eta, beraz, 15 garbiketaren ondoriozko hondakina da.

Taula C. 1 (a) F/P/R Taula eta osagai bakoitzaren exergia kontsumo unitarioa (b) bidebanatze ratioak

	n	FUELA	PRODUKTU	HOND.	k	P_s	R_s
①	Galdara	$\dot{E}_{13}$	$\dot{E}_1-\dot{E}_2$	$\dot{E}_{14}$	$\frac{(\dot{E}_1-\dot{E}_2)+\dot{E}_{14}}{\dot{E}_{13}}$	0	-
②	Orekatzaile hidraulikoa	$\dot{E}_1-\dot{E}_2$	$\dot{E}_3-\dot{E}_4$	-	$\frac{\dot{E}_3-\dot{E}_4}{\dot{E}_1-\dot{E}_2}$	0	-
③	Banatzailea	$\dot{E}_3$	$\dot{E}_5+\dot{E}_6$	-	$\frac{\dot{E}_5+\dot{E}_6}{\dot{E}_3}$	0	-
④	V3V	$\dot{E}_6+\dot{E}_7$	$\dot{E}_4$	-	$\frac{\dot{E}_4}{\dot{E}_6+\dot{E}_7}$	0	-
⑤	HX	$\dot{E}_5-\dot{E}_7$	$\dot{E}_8-\dot{E}_9$	-	$\frac{\dot{E}_8-\dot{E}_9}{\dot{E}_5-\dot{E}_7}$	0	-
⑥	Tankea	$(\dot{E}_8-\dot{E}_9)+\Delta\dot{E}_{12}$	$\dot{E}_{11}-\dot{E}_{10}$	-	$\frac{\dot{E}_{11}-\dot{E}_{10}}{(\dot{E}_8-\dot{E}_9)+\Delta\dot{E}_{12}}$	$\dot{E}_{11}$	-
⑦	Tximinia	$\dot{E}_{14}$	$\dot{E}_{15}$	-	$\frac{\dot{E}_{15}}{\dot{E}_{14}}$	0	$\dot{E}_{15}$

n	BIDEBANATZE RATIOAK	α_r
①	$r_1=\frac{\dot{E}_2}{\dot{E}_1}$	$\dot{E}_2-\dot{E}_1\cdot r_1=0$
②	$r_2=\frac{\dot{E}_4}{\dot{E}_3}$	$\dot{E}_4-\dot{E}_3\cdot r_2=0$
③	$r_3=\frac{\dot{E}_7}{\dot{E}_6}$	$\dot{E}_7-\dot{E}_6\cdot r_3=0$
④	$r_4=\frac{\dot{E}_9}{\dot{E}_8}$	$\dot{E}_9-\dot{E}_8\cdot r_4=0$
⑤	$r_5=\frac{\dot{E}_{10}}{\dot{E}_{11}}$	$\dot{E}_{10}-\dot{E}_{11}\cdot r_5=0$
⑥	$r_6=\frac{\dot{E}_8-\dot{E}_9}{\Delta\dot{E}_{12}}$	$(\dot{E}_8-\dot{E}_9)-\Delta\dot{E}_{12}\cdot r_6=0$

Taula horretatik fuel $\mathbf{A_F}$ eta produktu $\mathbf{A_P}$ matrizeak berehala lortzen dira. EUB biltegian fuel gehigarritzat hartu da simulazio periodoko exergia igoera ($\Delta\dot{E}_{12}$).

Taula C. 1 (b)-en, α_r matrizea sortzeko bidebanatze ekuazioak agertzen dira. Instalazioaren produktuak bi direnez, α_s (2,7) matrizea eraikitzen da.

Amaitzeko, $\mathbb{J}_r$ matrizea ($\mathbf{J}\equiv\mathbf{A_F}-\mathbf{k_D}\cdot\mathbf{A_P}$, $\boldsymbol{\alpha_s}$ eta $\boldsymbol{\alpha_r}$ matrizeen konposaketa) eta $\mathbb{Y}_\mathbf{S}$ bektore hedatua lortzen dira, ikus Taula C. 2.

Ek.(C. 2)-ko ekuazio matriziala ebatziz eta $\mathbf{J_r}$ matrizearen alderantzizkoarekin, fluxu bakoitzaren adierazpen sinbolikoak lortzen dira, exergia kontsumo unitarioaren, birzirkulazio koefizienteen eta plantaren irteeren arabera, ikus Taula C. 3.

[3]Lan honetan zehar E_i exergia fluxu oro parametro dependentetzat hartu behar da $E_i(\bar{x})$: aldagai estentsiboekin (m) eta intentsiboekin (γ, T, ...) osatua. Leku arrazoiengatik E_i erabiltzen da $E_i(\bar{x})$-ren beharrean.

Taula C. 2 J_R eta Y_s matrize hedatuak

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
J=	$-k_1$	k_1	0	0	0	0	0	0	0	0	0	0	1	$-k_1$	0
	1	-1	$-k_2$	k_2	0	0	0	0	0	0	0	0	0	0	0
	0	0	1	0	$-k_3$	$-k_3$	0	0	0	0	0	0	0	0	0
	0	0	0	$-k_4$	0	1	1	0	0	0	0	0	0	0	0
	0	0	0	0	1	0	-1	$-k_5$	k_5	0	0	0	0	0	0
	0	0	0	0	0	0	0	1	-1	k_6	$-k_6$	1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	1	$-k_7$
α_s=	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
α_r=	$-\frac{\dot{E}_2}{\dot{E}_1}$	1	0	0	0	0	0	0	0	0	0	0	0	1	0
	0	0	$-\frac{\dot{E}_4}{\dot{E}_3}$	1	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	$-\frac{\dot{E}_7}{\dot{E}_6}$	1	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	$-\frac{\dot{E}_9}{\dot{E}_8}$	1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	1	$-\frac{\dot{E}_{10}}{\dot{E}_{11}}$	0	0	0	0
	0	0	0	0	0	0	0	1	-1	0	0	$-\frac{(\dot{E}_8-\dot{E}_9)}{\Delta\dot{E}_{12}}$	0	0	0
$^t\mathbb{Y}_s$=	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1

Plantaren exergia kontsumo unitario totala (exergia efizientziaren alderantzizkoa) da:

$$k_T = \frac{F_T}{P_T} = \frac{\Delta\dot{E}_{12} + \dot{E}_{13}}{(\dot{E}_{11} - \dot{E}_{10})} = \frac{k_1 \cdot k_7 \cdot \dot{E}_{s_{15}} + k_6 \cdot \frac{\dot{E}_{s_{11}}}{1 + r_6} \cdot \left[1 + r_6 \cdot k_1 \cdot k_5 \cdot \frac{k_2 \cdot k_3 \cdot (1 - r_2)}{(1 - k_3 \cdot k_4 \cdot r_2)}\right]}{\dot{E}_{s_{11}}}$$

Formula horrekin instalazioko osagaien exergia kontsumo unitarioak erlazionatzen dira egitura parametroekin eta kanpo produktuekin. Formula unibertsala denez, koefizienteen eta kontsumoen balio ezberdinetarako plantaren kontsumo unitario totala edozein egoeran lortzen da.

C.2.2.1.1.1. Kostu exergetikoa

Unitate bakoitzeko fuelen eta produktuen kostuak kalkulatzeko, $\langle\mathbf{FP}\rangle$, $\langle\mathbf{KP}\rangle$ eta $\langle\mathbf{KR}\rangle$ matrizeak behar dira, Ek.(C. 7), (C. 10) eta (C. 36) ekuazioen menpe. Emaitzak Taula C. 4n erakusten dira.

Taula C. 3 Fluxu bakoitzaren adierazpen sinbolikoak

	FLUXUEN ADIERAZPEN SINBOLIKOAK
1.	$\dot{E}_1 = r_6 \cdot k_2 \cdot k_3 \cdot \frac{(1-r_2)}{(1-r_1)} \cdot \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
2.	$\dot{E}_2 = r_1 \cdot r_6 \cdot k_2 \cdot k_3 \cdot \frac{(1-r_2)}{(1-r_1)} \cdot \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
3.	$\dot{E}_3 = r_6 \cdot k_3 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
4.	$\dot{E}_4 = r_2 \cdot r_6 \cdot k_3 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
5.	$\dot{E}_5 = r_5 \cdot \frac{[k_3 \cdot k_4 \cdot r_2 - (1+r_3)] \cdot k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_3) \cdot (1+r_6)}$
6.	$\dot{E}_6 = r_2 \cdot r_6 \cdot k_3 \cdot k_4 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_3) \cdot (1+r_6)}$
7.	$\dot{E}_7 = r_3 \cdot r_2 \cdot r_6 \cdot k_3 \cdot k_4 \frac{k_5 \cdot k_6}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_3) \cdot (1+r_6)}$
8.	$\dot{E}_8 = r_6 \cdot k_6 \cdot \frac{\dot{E}_{s_{11}}}{(1-r_4) \cdot (1+r_6)}$
9.	$\dot{E}_9 = r_4 \cdot k_6 \cdot \frac{\dot{E}_{s_{11}}}{(1-r_4) \cdot (1+r_6)}$
10.	$\dot{E}_{10} = r_5 \cdot \frac{\dot{E}_{s_{11}}}{1-r_5}$
11.	$\dot{E}_{11} = \frac{\dot{E}_{s_{11}}}{1-r_5}$
12.	$\Delta\dot{E}_{12} = k_6 \cdot \frac{\dot{E}_{s_{11}}}{1+r_6}$
13.	$\dot{E}_{13} = k_1 \cdot k_7 \cdot \dot{E}_{s_{15}} + r_6 \cdot k_1 \cdot k_5 \cdot k_6 \cdot \frac{k_2 \cdot k_3 \cdot (1-r_2)}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot \frac{\dot{E}_{s_{11}}}{(1+r_6)}$
14.	$\dot{E}_{14} = k_7 \cdot \dot{E}_{s_{15}}$
15.	$\dot{E}_{15} = \dot{E}_{s_{15}}$

Matrize horiekin produktuen kostu exergetikoak lortzen dira (C. 38) eta (C. 39) ekuazioen bitartez, ikus Taula C. 5.

Beraz, produktuen kostu unitario totala da: $\mathbf{k_P}^* = \mathbf{k_P}^{\mathbf{e}*} + \mathbf{k_P}^{\mathbf{r}*}$Ek.(C. 37).

Osagai bakoitzaren fuelen kostu unitarioa kalkulatzeko Ek.(C. 21) aplikatu eta emaitzak Taula C. 7n agertzen dira.

Taula C. 4 $\langle \mathbf{FP} \rangle$, $\langle \mathbf{KR} \rangle$, $\langle \mathbf{KR} \rangle$ matrizeak bidebanatze koefizienteen menpe

$^{t}\langle \mathbf{F_T F} \rangle =$	1	0	0	0	0	$\frac{1}{1+r_6}$	0
$\langle \mathbf{FP} \rangle =$	0	1	0	0	0	0	1
	0	0	$1-r_2$	0	0	0	0
	0	0	0	1	1	0	0
	0	0	r_2	0	0	0	0
	0	0	0	0	0	$\frac{r_6}{(1+r_6)}$	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

$\mathbf{k_e}^{\mathbf{T}} =$	k_1	0	0	0	0	$\frac{k_6}{1+r_6}$	0
$\langle \mathbf{KP} \rangle =$	0	k_2	0	0	0	0	κ_7
	0	0	$k_3 \cdot (1-r_2)$	0	0	0	0
	0	0	0	k_4	k_5	0	0
	0	0	$k_3 \cdot r_2$	0	0	0	0
	0	0	0	0	0	$\frac{k_6 \cdot r_6}{(1+r_6)}$	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

$\langle \mathbf{KR} \rangle =$	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	$\frac{\dot{E}_{15}}{(\dot{E}_1 - \dot{E}_2) + \dot{E}_{14}}$	0	0	0	0	0	0

Taula C. 5 Produktuen kostu exergetiko unitarioa (a) kanpo baliabideen eta (b) hondakinen menpe

	P. KOSTU EXERGETIKO UNITARIOA KANPO BALIABIDE. LOTUA
①	$k_{p_1}^{e,*} = k_1$
②	$k_{p_2}^{e,*} = k_2 \cdot k_1$
③	$k_{p_3}^{e,*} = \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1$
④	$k_{p_4}^{e,*} = k_4 \cdot \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1$
⑤	$k_{p_5}^{e,*} = k_5 \cdot \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1$
⑥	$k_{p_6}^{e,*} = \frac{k_6 \cdot r_6}{(1+r_6)} \cdot k_5 \cdot \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot k_1 + \frac{k_6}{(1+r_6)}$
⑦	$k_{p_7}^{e,*} = k_7 \cdot k_1$

	PRODUKTUEN KOSTU EXERGETIKO UNITARIOA HODARREKIN LOTUA
①	$k_{p_1}^{r,*} = \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
②	$k_{p_2}^{r,*} = k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
③	$k_{p_3}^{r,*} = \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
④	$k_{p_4}^{r,*} = k_4 \cdot \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
⑤	$k_{p_5}^{r,*} = k_5 \cdot \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
⑥	$k_{p_6}^{r,*} = \frac{k_6 \cdot r_6}{(1+r_6)} \cdot k_5 \cdot \frac{(1-r_2) \cdot k_3}{(1-k_3 \cdot k_4 \cdot r_2)} \cdot k_2 \cdot \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$
⑦	$k_{p_7}^{r,*} = \frac{\rho_{7,1}}{(1-\rho_{7,1} \cdot k_7)} \cdot k_{p_7}^{e,*}$

Taula C. 7 Fuelen kostu exergetiko unitarioak

	FUELEN KOSTU EXERGETIKO UNITARIOA
①	$k_{F_1}^* = 1$
②	$k_{F_2}^* = \frac{k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
③	$k_{F_3}^* = \frac{(1-r_2)}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
④	$k_{F_4}^* = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
⑤	$k_{F_5}^* = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
⑥	$k_{F_6}^* = 1-\frac{k_6\cdot r_6}{(1+r_6)}-\frac{k_6\cdot r_6}{(1+r_6)}\cdot\frac{(1-r_2)\cdot k_3\cdot k_5}{(1-k_3\cdot k_4\cdot r_2)}\cdot\frac{k_2\cdot k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$
⑦	$k_{F_7}^* = \frac{k_1}{(1-\rho_{7,1}\cdot k_{d_7})}$

Taula C. 6 Produktuen eta fuelen kostu exergoekonomiko unitarioak

	P. KOSTU EXERGOEKONOMIKO UNITARIOA KANPO KOSTUEKIN LOTUA
①	$c_{p_1}^z = z_1$
②	$c_{p_2}^z = k_2\cdot z_1 + z_2$
③	$c_{p_3}^z = \frac{z_3 + k_3\cdot(1-r_2)\cdot(k_2\cdot z_1 + z_2 + r_2\cdot z_4)}{(1-k_3\cdot k_4\cdot r_2)}$
④	$c_{p_4}^z = \frac{z_4 + k_4\cdot(1-r_2)\cdot(k_2\cdot k_3\cdot z_1 + k_3\cdot z_2 + z_3)}{(1-k_3\cdot k_4\cdot r_2)}$
⑤	$c_{p_5}^z = z_5 + \frac{\kappa_5\cdot(1-r_2)\cdot(\kappa_2\cdot\kappa_3\cdot z_1 + \kappa_3\cdot z_2 + z_3 + r_2\cdot\kappa_3\cdot z_4)}{(1-k_3\cdot k_4\cdot r_2)}$
⑥	$c_{p_6}^z$ $= z_6 + \frac{\kappa_6\cdot r_6}{(1+r_6)}$ $\cdot\frac{z_5 + \kappa_{d5}\cdot(1-r_2)\cdot(\kappa_2\cdot\kappa_3\cdot z_1 + \kappa_3\cdot z_2 + z_3 + r_2\cdot\kappa_3\cdot z_4)}{(1-k_3\cdot k_4\cdot r_2)}$
⑦	$c_{p_7}^z = \kappa_7\cdot z_1$

	P. KOSTU EXERGOEKONOMIKO UNITARIOA HONDARREKIN LOTUA
①	$c_{p_1}^r = \frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
②	$c_{p_2}^r = k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
③	$c_{p_3}^r = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
④	$c_{p_4}^r = k_4\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
⑤	$c_{p_5}^r = k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
⑥	$c_{p_6}^r = \frac{k_6\cdot r_6}{(1+r_6)}\cdot k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot\frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot k_7)}\cdot k_1\cdot c_{NG}$
⑦	$c_{p_7}^r = \frac{\beta_{7,1}}{(1-\beta_{7,1}\cdot\kappa_7)}\cdot k_1\cdot c_{NG}$

	P. KOSTU EXERGOEKONOMIKO UNITARIOA KANPO BALIABIDEEKIN LOTUA
①	$c_{p_1}^e = k_1\cdot c_{NG}$
②	$c_{p_2}^e = k_2\cdot k_1\cdot c_{NG}$
③	$c_{p_3}^e = \frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG}$
④	$c_{p_4}^e = k_4\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG}$
⑤	$c_{p_5}^e = k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG}$
⑥	$c_{p_6}^e = \frac{k_6\cdot r_6}{(1+r_6)}\cdot k_5\cdot\frac{(1-r_2)\cdot k_3}{(1-k_3\cdot k_4\cdot r_2)}\cdot k_2\cdot k_1\cdot c_{NG} + \frac{k_6}{(1+r_6)}\cdot c_w$
⑦	$c_{p_7}^e = k_7\cdot k_1\cdot c_{NG}$

	F. KOSTU EXERGOEKONOMIKO UNITARIOA
①	$c_{F_1} = c_{NG}$
②	$c_{F_2} = c_{P_1}$
③	$c_{F_3} = (1-r_2)\cdot c_{P_2} + r_2\cdot c_{P_4}$
④	$c_{F_4} = c_{P_3}$
⑤	$c_{F_5} = c_{F_3}$
⑥	$c_{F_6} = \frac{1}{(1+r_6)}\cdot c_w + \frac{r_6}{(1+r_6)}\cdot c_{P_5}$
⑦	$c_{F_7} = c_{P_1}$

C.2.2.1.1.2. Kostu exergoekonomikoa

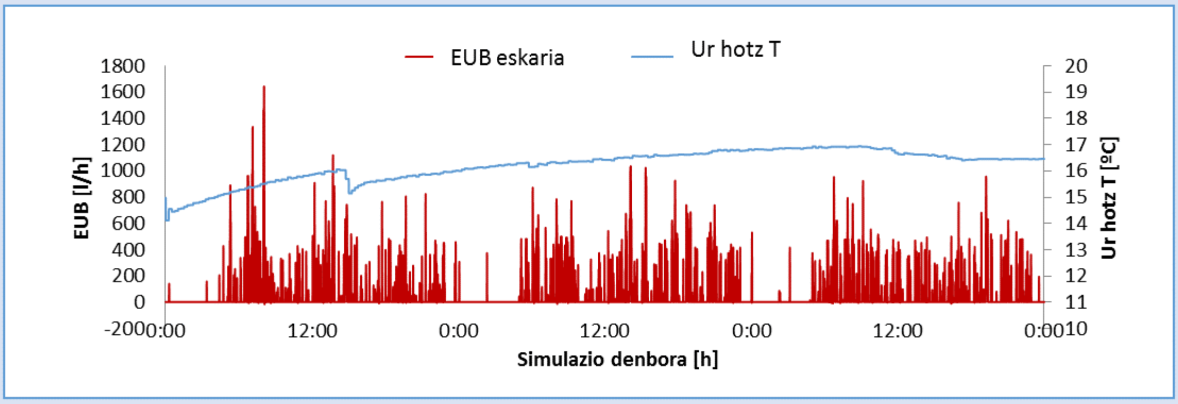
Kostu exergoekonomikoei dagokieenez, hiru osagai bereizten dira: lehenengoa kanpo baliabideekin lotzen da, bigarrena amortizazio eta mantenu kostuekin eta hirugarrenak hondakinekin du harremana. (C. 42), (C. 43) eta (C. 44) ekuazioekin, produktuen kostuak lortzen dira eta Taula C. 6n batu. Produktuen kanpo kostuen arabera, z_i osagai bakoitzaren produktu unitateko amortizazio eta mantenu kostua da, hots, $z_1 = \frac{Z_1}{P_1} = \frac{Z_1}{(\dot{E}_1 - \dot{E}_2) + \dot{E}_{14}}$, etab. Gainera, c_{NG} gas naturalaren exergia unitateko kostua da eta c_w, ordea, sareko ur hotzaren kostu unitarioa.

Orduan, produktuaren kostu ekonomiko unitario totala da: $\mathbf{c_P} = \mathbf{c_P}^{\mathbf{e}} + \mathbf{c_P}^{\mathbf{z}} + \mathbf{c_P}^{\mathbf{r}}$, Ek.(C. 41).

Produktuen kostuak lortu eta gero, fuelen kostuak lortzen dira Ek.(C. 45)-tik, emaitzak Taula C. 6n daude.

C.2.2.1.2. Zenbakizko emaitzak

Modelo termikoa lortzeko aldagaiak Trnsys-en simulazio dinamikoarekin lortzen dira. Eraikinaren erabiltzaileez eta erabileraz gain, kokapena, klima eta sareko tenperatura kontuan hartzen ditu [42]. EUB eskarirako banaketa estandarraren probabilitate Gaussiar eta eskailera funtzioak erabiltzen dira [43]. Sareko ur tenperaturaren eta EUB eskariaren profilak simulazioaren hiru egunetarako Irudia C. 6n daude.



Irudia C. 6 EUB eta ur hotzaren tenperatura profilak hiru egunetan zehar

Taula C. 8n fluxu bakoitzeko exergia balio pilatuak daude periodoaren amaieran.

Taula C. 8 fluxu bakoitzeko exergia balio pilatuak hiru egunetan zehar

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\frac{kW.h}{3\ egun}$	109.07	72.19	112.80	83.12	91.42	21.38	61.73	106.73	82.02	0	18.50	3.30	293.72	1.11	1.11

Taula C. 9n, fuelen, produktuen eta hondarren balioak daude. Hiru eguneko periodoaren bukaeran pilatutako exergia kontsumo unitarioa eta produkzio totala ere barneratu dira.

Taula C. 9 F/P/R balio pilatuak hiru egunetan zehar

		FUELA	PRODUKTUA	HONDAKINA	k	P_s
①	Galdara	293.72	36.88	1.1	7.96	-
②	Oreka. H	36.88	29.69	-	1.24	-
③	Banatza.	112.80	112.80	-	1	-
④	V3V	83.12	83.12	-	1	-
⑤	HX	29.69	24.71	-	1.20	-
⑥	Tankea	28.01	18.50	-	1.51	18.5
⑦	Tximinia	1.11	1.11	-	1	1.1

C.2.2.1.2.1. Kostu exergetikoa

⟨FP⟩, ⟨KP⟩ eta **⟨KR⟩** matrizeekin osagai bakoitzeko produktuen exergia kostu unitarioak kalkulatzen dira. Taula C. 10 (a)-n balio horiek bi osagaietan banatzen dira ($k_{P_i}^{e,*}, k_{P_i}^{r,*}$) eta Taula C. 10 (b)-n, aldiz, fuel eta produktu kostu exergetiko unitarioak adierazten dira ($k_{F_i}^{*}, k_{P_i}^{*}$), ondorioz, EUBaren kostu unitarioa.

Taula C. 10(a) Kostu unitariko desagregatuak (b) Fuelen eta Produktuen kostu unitarioak

	$k_p^{e,*}$	$k_p^{r,*}$
Galdara	7.73	0.23
Oreka. H	9.61	0.29
Banatza.	9.61	0.29
V3V	9.61	0.29
HX	11.54	0.35
Tankea	15.59	0.46
Tximinia	7.73	0.23

	k_f^{*}	k_p^{*}
Galdara	1	7.96
Oreka. H	7.96	9.89
Banatza.	9.89	9.89
V3V	9.89	9.89
HX	9.89	11.72
Tankea	10.60	17.46
Tximinia	7.96	7.96

C.2.2.1.2.2. Kostu exergoekonomikoa

Kostu exergoekonomikoak kalkulatzeko beharrezko informazioa hiru eguneko periodoaren amortizazio zein mantenu kostuak eta gas naturalaren zein ur hotzaren kostu unitarioa dira. Informazio hori Taula C. 11n dago.

Taula C. 11 Kostu exergoekonomikoen kalkulurako datuak

		Erosketa kostua (I_i) [€]	Urteko kostu finkoa (CF_i) [€/ urte]	Operation Time [min/ 3egun]	Urteko oper. Denb.(OP_{year}) [h/urte]	$Z_i = \frac{CF_i}{OP_{year}}$ [€/h]	Z_i [€/3egun]
①	Galdara	1100	152.14	748	1516.78	0.10	7.22
②	Oreka. H	900	124.48	748	1516.78	0.08	5.91
③	Banatza.	-	-	748	1516.78	-	-
④	V3V	100	13.83	748	1516.78	0.01	0.66
⑤	HX	795	109.96	1112	2254.89	0.05	3.51
⑥	Tankea	1200	165.97	1663	3372.19	0.05	3.54
⑦	Tximinia	-	-	-	-	-	-

Info. orokorra	
Erosketa totala (I_T)	4095
Mantenu eta operazioa (MO)	300

Formula erabilgarriak	
Bizitza erabilgarria (n)	30 years
Urteko interesa (i)	0.05
$FR = i \cdot (1+i)^n$	0.07
Kostu finko totalak (CF_T)	$(MO + I_T \cdot FR)$
Urteko kostu finkoak (CF_i)	$\frac{CF_T}{I_T} \cdot I_i$

Sarrera kostu unitarioak	
$c_{NG}\left[\frac{€}{kWh_{ex}}\right]$	0.05
$c_w\left[\frac{€}{kWh_{ex}}\right]$	0.12

Azkenik, Taula C. 12 (a)-n produktuen kostu exergoekonomiko unitarioa hiru osagaietan banatua dago ($c^e_{P_i}, c^r_{P_i}, c^z_{P_i}$) eta Taula C. 12 (b)-n, bestalde, osagai bakoitzaren fuel eta produktu kostu exergeokonomiko unitarioa (c_{F_i}, c_{P_i}).

Taula C. 12 (a) P-ren kostu exergoekonomiko unitarioa hiru osagaietan banatua (b) F eta P kostu exergoekonomiko unitarioak

	c^e_P [€/kWh_{ex}]	c^r_P [€/kWh_{ex}]	c^z_P [€/kWh_{ex}]
Galdara	0.42	0.01	0.19
Oreka. H	0.53	0.02	0.44
Banatza.	0.53	0.02	0.46
V3V	0.53	0.02	0.47
HX	0.63	0.02	0.69
Tankea	0.87	0.03	1.12
Tximinia	0.42	0.01	0.19

	c_F [€/kWh_{ex}]	c_P [€/kWh_{ex}]
Galdara	0.05	0.63
Oreka. H	0.63	0.98
Banatza.	1.00	1.00
V3V	1.00	1.00
HX	1.00	1.34
Tankea	1.20	2.01
Tximinia	0.63	0.63

Energiaren menpe jarri ahal dira adierazpenak energia/exergia koefizienteengatik biderkatuz gero. Taula C. 13n osagai bakoitzaren produktuen kostu unitarioa eta hiru egunetako totala dago (c_{P_i}, C_{P_i}).

Taula C. 13 Osagai bakoitzeko produktuaren kostu energetiko unitarioa eta totala

	c_P $[€/kWh_{en}]$	C_P $[€/3egun]$
Galdara	0.06	23.80
Oreka. H	0.07	29.02
Banatza.	0.03	112.76
V3V	0.03	83.74
HX	0.03	33.19
Tankea	0.07	37.12
Tximinia	0.06	0.69

C.2.2.1.3. Emaitzen eztabaida

Termoekonomiaren gaineko zentzua eta metodologiaren helburua kostu formakuntza prozesuaren lorpena da. ST tresnari esker osagaien arteko loturak lortzen dira sistemaren egitura produktiboan oinarrituz eta era sinbolikoan erakutsiz. Beraz, plantaren guztizko etekina parametro baten aldakuntzak zelan eragiten duen ikustea erraza da. ECTarekin elkartzen denez, kostuaren aldaketa parametro baten eraldaketaren bidez ere aztertzen da.

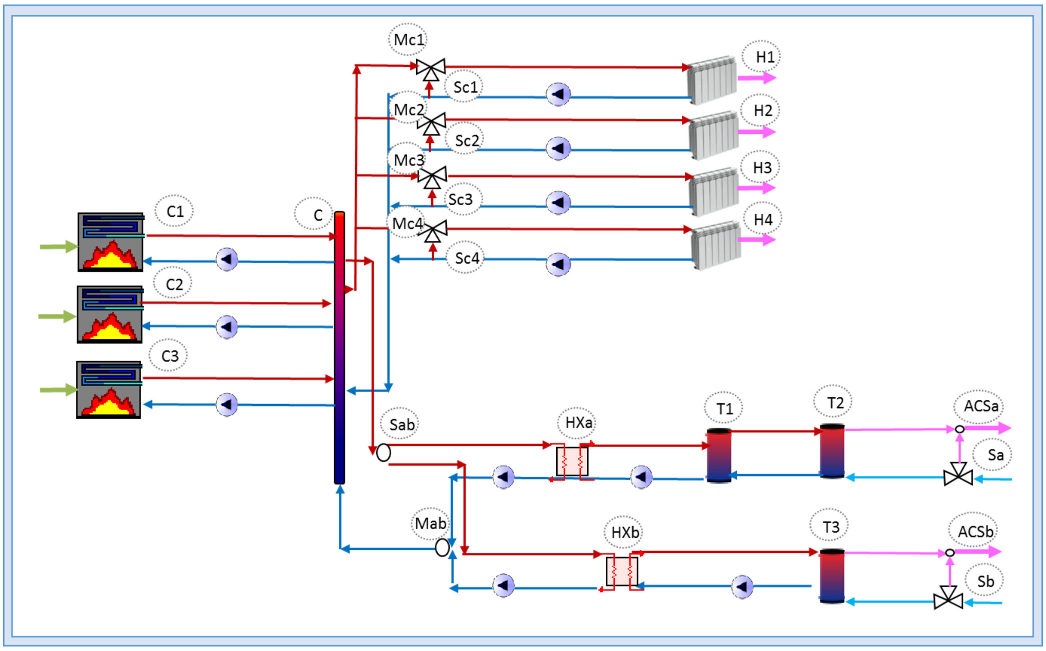
STak adierazpen orokorrak baimentzen ditu eta ondorengoko edozein egoeratan fuelen, produktuen, kostuen eta abarren zenbakizko balioak lortzeko erabil daitezke. Formulan balioak barneratzeko fluxuen datuak behar dira. Presioa, tenperatura, masa emarien balioak, etab. modelo termikorako bildu behar dira eta, gero, aldagai termoekonomikoak kalkulatu behar dira plantaren edozein egoerarako.

Emaitzen arabera, zeinbait taldeen kanpo baliabideekin lotutako kostua handiena da, adibidez galdaran (0.42 $[\frac{€}{kWh_{ex}}]$); bestalde, mantenuarekin eta amortizazioarekin erlazionatutako kostua da beste osagai batzuetan garaiena, esaterako, biltegian (1.12 $[\frac{€}{kWh_{ex}}]$).

Hondakinen arazo konplexua ere hartu da kontuan. Hondakinen kostuak (errekuntza gasak) talde sortzailean kokatu dira, sorkuntza prozesuan parte hartu duten taldeei kostua esleitzearen irizpidea aintzat hartuz. Osagai batzuetan, kasurako galdaran, kostuan hondakinen eragina murritza da (0.01 $[\frac{€}{kWh_{ex}}]$); beste batzuetan, ordea, biltegietan adibidez, efektua hirukoizten da kate energetikoaren kokapenaren eraginez (0.03 $[\frac{€}{kWh_{ex}}]$).

C.2.2.2. (ii) Eraikin birgaituaren ikerketa kasua

Adibidea hau A Kapituluko (ii) ikerketa kasuaren jarraipena da non instalazio zahar eta berritu bat konparatzen diren. Beraz, bi sistema daude bi egitura produktiborekin. Esan lez, kostu formakuntzaren zehaztasuna taldeen aukeraketaren arabera dago.



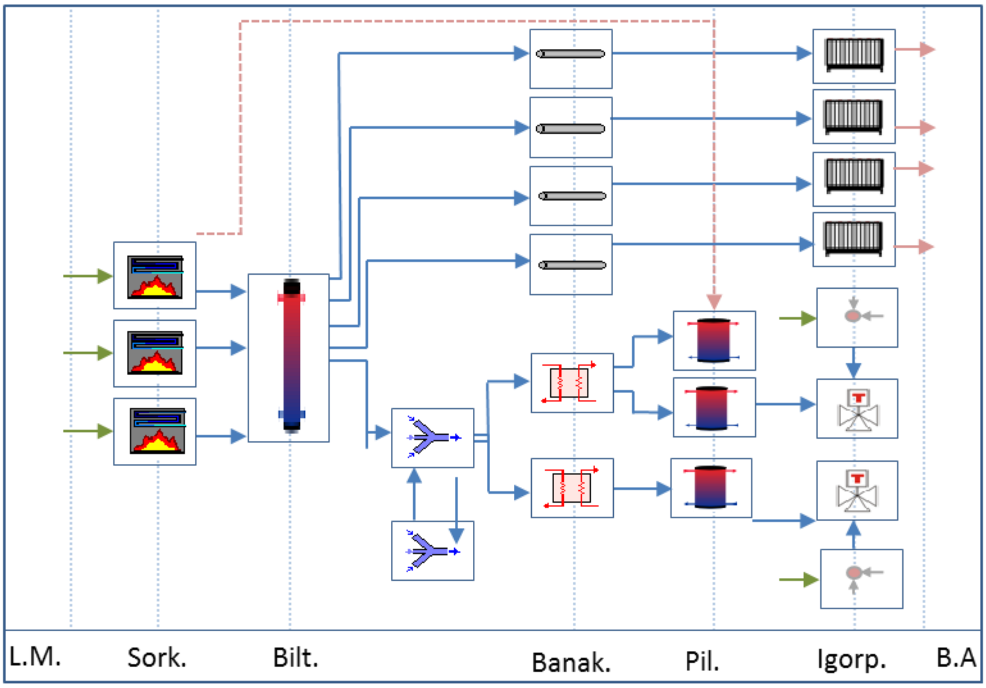
Irudia C. 7 Instalazio zaharraren eskema fisikoa

Instalazio zaharra 27 azpisistemetan, 70 fluxuetan eta 7 irteeretan banatzen da (4 berokuntza irteera eta 2 EUB txorrota; osagai hautatuak Irudia C. 7n daude). Instalazio berria, ordea, 20 azpisistemekin, 62 fluxurekin eta 7 irteerekin adierazten da.

Taula C. 14 Analisirako instalazioen talde amankomunak

INSTALAZIOAREN TALDE KOMUNAK			
Group	**Description**	**Group**	**Description**
B1	1 galdara + 1 galdara ponpa	T1	1 tankea + 6 EUB behe ponpa
B2	2 galdara + 2 galdara ponpa	T2	2 tankea + (7 berreskiratze ponpa)
B3	3 galdara + 3 galdara ponpa	T3	3 tankea + 8 EUB goi ponpa
C	Biltzailea	DHW L	EUB beheko solairuetan
H1 br.	I Bero banaketa adarra	DHW H	EUB goiko solairuetan
H2 br.	II Bero banaketa adarra	H1	I Blokearen igorpen sistema + 9 ponpa BI
H3 br.	III Bero banaketa adarra	H2	II Blokearen igorpen sistema + 10 ponpa BII
H4 br.	IV Bero banaketa adarra	H3	III Blokearen igorpen sistema + 11 ponpa BIII
HX1	Behe HX + 4 HX behe ponpa	H4	IV Blokearen igorpen sistema + 12 ponpa BIV
HX2	Goi HX + 5 HX goi ponpa		

Nahiz eta egitura sinboliko ezberdinak izan, azpisistemak talde berdinak sortzeko konbinatu ziren instalazioen arteko alderaketa gauzatzeko. Analisian erabilitako taldeen zerrenda Taula C. 14n dago non izendapena eta bakoitzaren deskripzio laburra dagoen.



Irudia C. 8 Productive model of both facilities

Modelo produktiboa, bi instalazioentzat amankomuna, Irudia C. 8n erakusten da. Gezi gorriek barne girorako sistemaren produkzioa seinalatzen dute (B.A.) eta gezi berdeek, aldiz, sarrera baliabideak, alegia, galdaren erregaia (marra zuzenak), ponpen elektrizitatea (marra puntu-etenak) eta sareko ur hotza (marra etena). Gainera, marra eten gorri bat dago instalazio berriaren kondentsazio galdararen eta berreskuratzailearen eraginez sarrera gehigarria zeinek adierazten duen. Sarrera-irteera analisi tipikoa sekuentziala egin daiteke ia osagai denetan 3-bideko balbulan izan ezik (auzi hori ondoren garatuko da C kapituluan).

C.2.2.2.1.1. Kostu exergetikoa

Azpisistema bakoitzaren fuelen eta produktuen kostu unitarioa ($\mathbf{k}_\mathbf{F}^*$ eta $\mathbf{k}_\mathbf{P}^*$) talde amankomunen arabera kalkulatu eta bateratu egin zen. Taula C. 15k instalazio zaharraren eta berrituaren kostu exergetiko unitarioak jasotzen ditu. Azpisistema bakoitzaren itzulezintasuna adierazten da fuelaren eta produktuaren kostuen arteko diferentziarekin.

Kutxa urdinek EUBaren goi eta behe planten kostu exergetiko unitarioa erakusten dute. Era berean, kutxa gorriek berokuntza zirkuituen kostuak erakusten dituzte. Berokuntza igorleak bero katearen azken tokian egoteagatik itzulezintasun asko jaso eta kostu altuak dauzkate.

Instalazio zaharra eta berria alderatzen badira, bai berokuntzan bai EUB zirkuituan aurrezpenak daude. Hasierako instalazioan berokuntzaren batez besteko exergia kostu unitarioa 47,8 zen eta berrian, aldiz, 25,3. Antzeko moduan, EUBaren batez besteko exergia kontsumo unitarioa 22,7 zen eta sistema berrituan, ordea, 20,2. Taula C. 15 (b)-ko kostuaren aurrezpena ere T2-aren bero berreskuratzailean datza, zeren $\mathrm{k}_{\mathrm{F}_{\mathrm{T2}}}^{*,\mathrm{new}} = 7{,}02$ baxuagoa da $\mathrm{k}_{\mathrm{F}_{\mathrm{T2}}}^{*,\mathrm{old}} = 9{,}46$ baino kondentsazio galdararen sarrera gehigarria medio.

Taula C. 15 F eta P kostu exergetiko unitarioak (a) instalazio zaharrean eta (b) berrian

INSTALAZIO ZAHARRA [-]						INSTALAZIO BERRIA [-]					
n	k_F^*	k_P^*	n	k_F^*	k_P^*	n	k_F^*	k_P^*	n	k_F^*	k_P^*
B1	1	6.76	T1	9.19	14.72	B1	1.00	6.69	T1	7.66	12.69
B2	-	-	T2	9.46	19.88	B2	1.00	6.36	T2	7.02	17.26
B3	1	7.20	T3	8.27	16.30	B3	1.00	6.23	T3	7.74	15.44
C	6.77	7.50	DHW L	17.48	22.34	C	6.33	7.20	DHW L	15.56	20.15
H1 br.	22.37	23.12	DHW H	16.17	22.97	H1 br.	6.74	6.74	DHW H	15.30	20.27
H2 br.	22.87	23.36	H1	23.12	46.22	H2 br.	6.43	6.43	H1	6.74	25.41
H3 br.	26.64	27.36	H2	23.36	46.63	H3 br.	6.33	6.33	H2	6.43	25.19
H4 br.	21.26	21.98	H3	27.36	55.24	H4 br.	6.73	6.73	H3	6.33	25.20
HX1	7.45	9.46	H4	21.98	43.07	HX1	6.93	8.25	H4	6.73	25.37
HX2	7.36	8.40				HX2	6.89	7.99			

C.2.2.2.1.2. Kostu exergoekonomikoa

Bi osagaiek kostu exergoekonomikoan hartzen dute parte: kanpo baliabideekin lotzen da bat (c_e) eta bestea unitateen amortizazio eta mantenu kostuekin (z_i). Kanpo fuelen kostu exergoekonomikoa horien merkatu prezioen bitartez lortzen da, non $c_{e_{FO}}^{zahar} = 8{,}52\ c€/kWh_{ex}$ fuel olioaren, $c_{e_{NG}}^{berri} = 4{,}75\ c€/kWh_{ex}$ gas naturalaren eta $c_{e_{elek}} = 12{,}21\ c€/kWh_{ex}$ argindarraren kostu unitarioak diren. Sareko ur hotzaren kostua ez dago exergiarekin erlazionatuta eta balioa $51{,}97 c€/m^3$ da.

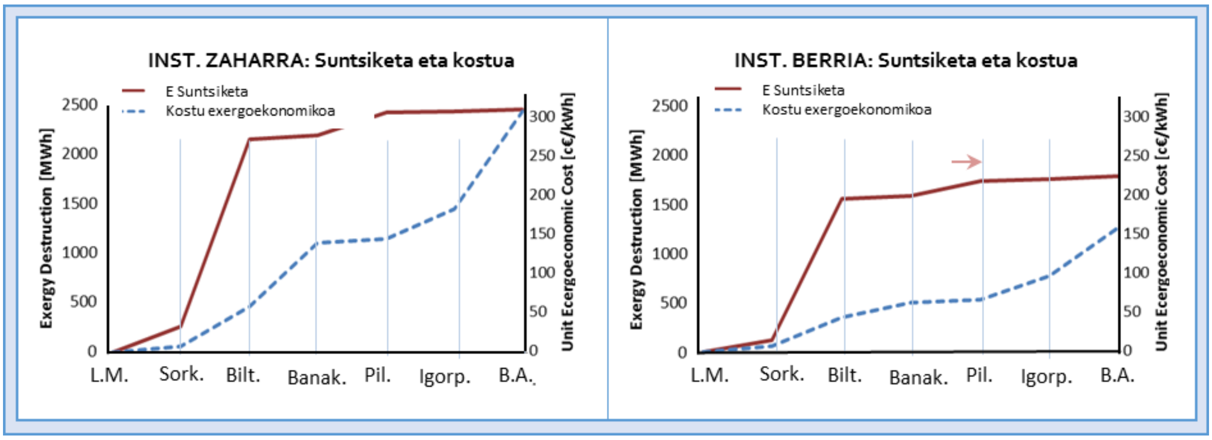
Bi instalazioen kostuak alderatzeko kanpo baliabideen kostuak baino ez dira kontuan hartuko. Sistemen produktu nagusiekin erlazionatutako balioak (EUB eta berokuntza) Taula C. 16n daude.

Taula C. 16 Produktuen kostue exergetiko unitarioak (a) instalazio zaharrean eta (b) berrian

INST. ZAHARRA $[c€/kWh_{ex}]$		INST. BERRIA $[c€/kWh_{ex}]$	
n	c_P	n	c_P
DHW L	190.87	DHW L	98.35
DHW H	196.47	DHW H	99.04
H1	395.22	H1	123.55
H2	399.73	H2	124.08
H3	473.44	H3	124.63
H4	368.45	H4	123.43

Ikus antzera, fuelen prezio ezberdinak eta birgaitzeak dakartzan itzulezintasun murrizketak medio, nabaria da instalazio berriaren aurrezpen ekonomikoa (jakina, taldeen inbertsio kostuak aintzat hartu gabe). Berokuntzaren kostu exergoekonomiko unitarioa instalazio berrian zaharrean baino % 69 baxuagoa da (ikus lauki gorriak) eta EUBarena, ordea, ia erdira jaitsi da (ikus lauki urdinak).

Energia katearen gainontzeko emaitzak grafika baten batu dira Irudia C. 9n joerak erakusteko. Kostu exergoekonomikoaz gain, exergia suntsiketaren pilaketa marraztu da instalazio zaharrean eta berrituan.



Irudia C. 9 Exergia suntsiketa eta kostu exergoekonomiko unitarioa (a) instalazio zaharrean eta (b) berrian

C.2.2.2.2. Emaitzen eztabaida

Analisi exergetikoak energia fluxuak homogeneizatzen ditu energia kalitatearen arabera eta sistemen eta osagaien alderaketa baimentzen du. Horregatik birgaitze sistemen aurrezpenak ikertzeko giltzarria da. Gainera, exergia kostu termoekonomikoa esleitzeko oinarrizko parametroa da sistema baten puntura arteko itzulezintasun pilaketen arabera. Exergia kostua STarekin konbinatzen bada, metodo moldagarri mekanikoa lortzen da.

Adibidearen helburua energia sistema zahar eta berritu baten arteko konparaketa da. Beraz, bi instalazioen egitura produktiboa eta azpisistema multzo berdinak definitu ostean, fluxu bakoitzaren kostu exergetikoa eta exergoekonomikoa kalkulatu dira. Amaierako produktuei dagokionez, berokuntzarako balioak 47,8 eta 25,3 dira eta EUBerako 22,7 eta 20,2. Horien arabera hobekuntza adierazten da. Antzeko moduan, kostu exergoekonomikoen balioak (inbertsio kostuak saihestuz) 15,93 $c€/kWh_{en}$ eta 5,21 $c€/kWh_{en}$ dira berokuntzarako eta 10,04 $c€/kWh_{en}$ eta 4,87 $c€/kWh_{en}$ EUBrako; bertan ere nabarmentzen dira fuelei dagozkion aurrezpen handiak instalazio birgaituan.

C.3. ST ERAIKINEN SISTEMA DINAMIKOETAN

B Kapituluan esan gisa, eraikinen beharrizanak etengabean aldatzen doaz erabiltzaileen eta ingurugiroaren lotura estuagatik. Ondorioz, eraikinen energia instalazioek uneoro aldatzen dituzte funtzionamendu moduak (piztuz, itzaliz eta modulatuz) kontsumitzaileen beharretara moldatzeko. Horregatik, konfigurazio fisikoa eta egitura produktiboa aldatzen doazelako, sistema super-egitura baten lez har daiteke osagaien (i, j) eta giroaren (e) arteko elkarrekintzen bitartez.

Eraikinen jarrera dinamikoa aintzat hartuz (eta beraz, egitura produktiboaren dinamismoa), ST sistematika hauta daiteke kostu exergetikoa modu orokorrean ebazteko.

Helburua super-egitura bat sortzea da konfigurazio guztiak barneratuz. Horrela, denbora tarte bakoitzean egitura produktibo espezifikoa aktibatuta egongo da zein baldintza partikularretara egoki moldatuko den. Berez, super-egituraren azpi-konbinaketa bakoitzak kostu formakuntza ezberdina izango du osagaien nahasketa ezberdina egongo delako.

Atal honetako ekarpenaren berrikuntza egoera dinamikoentzako kostu termoekonomikoen aplikazio dinamiko berritzailea da. Oinarria eraikinen jarrera dinamikoaren konplexutasuna da zeinek, aldi berean, kostu kapitalen eta eraginkortasunaren arteko harremana anitz zailtzen duen.

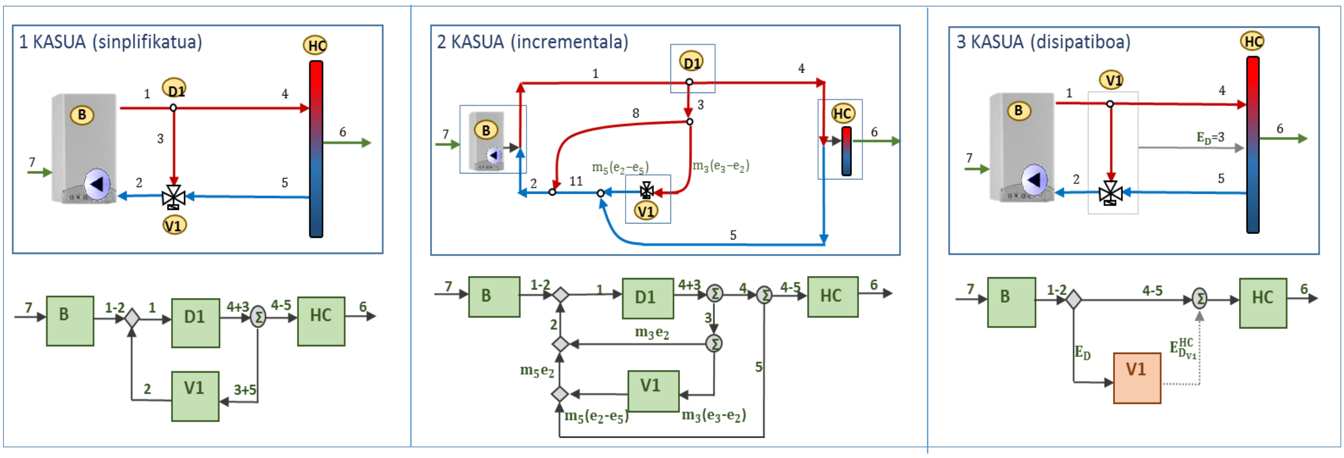
Gainera, erabilgarritasun nabarmenagatik, bi osagai sakonki ikertuko dira, alegia, 3-bideko balbulak eta biltegi inertzialak.

C.3.1. Osagaien modelo produktiboen sakonketa

Egitura produktiboa horren estu ikasita dagoelako, atal hau 3-bideko balbulen (V3V) eta osagai inertzialen aurkezpen termoekonomikoan oinarrituko da; azken batean, HVAC&R sistemetan ezinbesteko elementuak dira eta ikasketa arretatsua merezi dute. Biak hartu behar dira osagai dinamikotzat eta horien egitura produktiboa sistemaren beharrizanen arabera aldatuz joango da.

C.3.1.1. V3V egitura dinamikoa

V3Varen modelo produktiboa zenbait eretan uler daiteke; oro har, oinarria nahasketa atalean dago tenperatura ezberdineko fluxuak elkartzean exergia suntsiketa baitago.



Irudia C. 10 V3V osagaiarentzako egitura produktiboaren interpretazio ezberdinak

Irudia C. 10n eraikin bateko kasu sinple ohikoa agertzen da zein galdara (B) batek orekatzaile hidraulikoa (HC) elikatzen duen eta 3-bideko balbularekin modulatzen den. Hiru konfigurazio aztertuko dira hiru egitura produktiboekin; horien izendapenak dira: *sinplifikatua*, *inkrementala* eta *disipatiboa* (ulermena errazteko, produktu nagusia fluxu bakartzat hartu da 6) Osagai bakoitzaren F eta P dagozkien fluxu zenbakien arabera definitu dira eta Irudia C. 1oren azpiko atalean daude.

Lehenengo kasua sinplea da zeinetan 3-bideko balbula banagailuan (D1) eta nahasgailuan (V1) bereizi den eta zeinen fuela eta produktua dagozkion sarrera eta irteera fluxuak diren, [44]an egin lez. Bigarren kasuan, V1en fuela fluxu beroaren eta nahastuaren arteko exergia tartea da eta produktua, aldiz, nahasketaren eta fluxu hotzaren arteko jaitsiera [13]. Azkeneko kasuak V3Va modu konpaktuan ikertzen du eta disipazio elementutzat hartu; hau da, helburu produktiborik gabeko elementutzat hartzen da (exergia suntsitzen du soilik) eta beharrezkoa da sistemaren eragiketa egokirako. Kasu horretan, exergia suntsiketa zerbitzatzen duen osagai produktiboan kokatu behar da [39].

1 KASUA	2 KASUA	3 KASUA
BALANTZEA • $c_7E_7 + c_2E_2 = c_1E_1$ → $c_7 = 1$ • $c_1E_1 = c_3E_3 + c_4E_4$ → $c_3 = c_4$ • $c_3E_3 + c_5E_5 = c_2E_2$ • $c_4E_4 = c_5E_5 + c_6E_6$ → $c_4 = c_5$	**BALANTZEA** • $c_7E_7 + c_2E_2 = c_1E_1$ → $c_7 = 1$ • $c_1E_1 = c_3E_3 + c_4E_4$ → $c_3 = c_4$ • $c_4E_4 = c_5E_5 + c_6E_6$ → $c_4 = c_5$ • $c_5E_5 + c_{10}E_{10} = c_{11}E_{11}$ • $c_3E_3 = c_8E_8 + c_9E_9$ → $c_8 = c_9$ • $c_8E_8 + c_{11}E_{11} = c_2E_2$ • $c_9E_9 + c_{10}E_{10}$	**BALANTZEA** • $c_7E_7 + c_2E_2 = c_1E_1$ → $c_7 = 1$ • $c_1E_1 + c_5E_5 = c_2E_2 + c_3E_3 + c_4E_4$ → $c_3 = \frac{c_4(E_4-E_5)}{E_3}$ • $c_4E_4 + c_3E_3 = c_5E_5 + c_6E_6$ → $c_4 = c_5$
KOSTU UNITARIOA ✓ $c_1 = \frac{E_7(E_3+E_4)}{E_1(E_4-E_5)}$ ✓ $c_2 = \frac{-E_7(E_3+E_5)}{E_2(E_4-E_5)}$ ✓ $c_3 = \frac{E_7}{E_4-E_5} = c_4 = c_5$ ✓ $c_6 = \frac{E_7}{E_6}$ ✓ $c_7 = 1$	**KOSTU UNITARIOA** ✓ $c_1 = \frac{E_7(E_3+E_4)}{E_1(E_4-E_5)}$ ✓ $c_2 = \frac{-E_7(E_3+E_5)}{E_2(E_4-E_5)}$ ✓ $c_3 = \frac{E_7}{E_4-E_5} = c_4 = c_5$ ✓ $c_6 = \frac{E_7}{E_6}$ ✓ $c_7 = 1$ ✓ $c_8 = \frac{E_7E_3}{(E_8+E_9)(E_4-E_5)} = c_9$ ✓ $c_{10} = \frac{E_7E_3E_9}{E_{10}(E_8+E_9)(E_4-E_5)}$ ✓ $c_{11} = \frac{E_3E_9+E_5(E_8+E_9)}{E_{11}(E_8+E_9)(E_4-E_5)}$	**KOSTU UNITARIOA** ✓ $c_1 = \frac{E_7}{(E_1-E_2)} = c_2$ ✓ $c_3 = \frac{E_7}{2E_3}$ ✓ $c_4 = \frac{E_7}{2(E_4-E_5)} = c_5$ ✓ $c_6 = \frac{E_7}{E_6}$ ✓ $c_7 = 1$

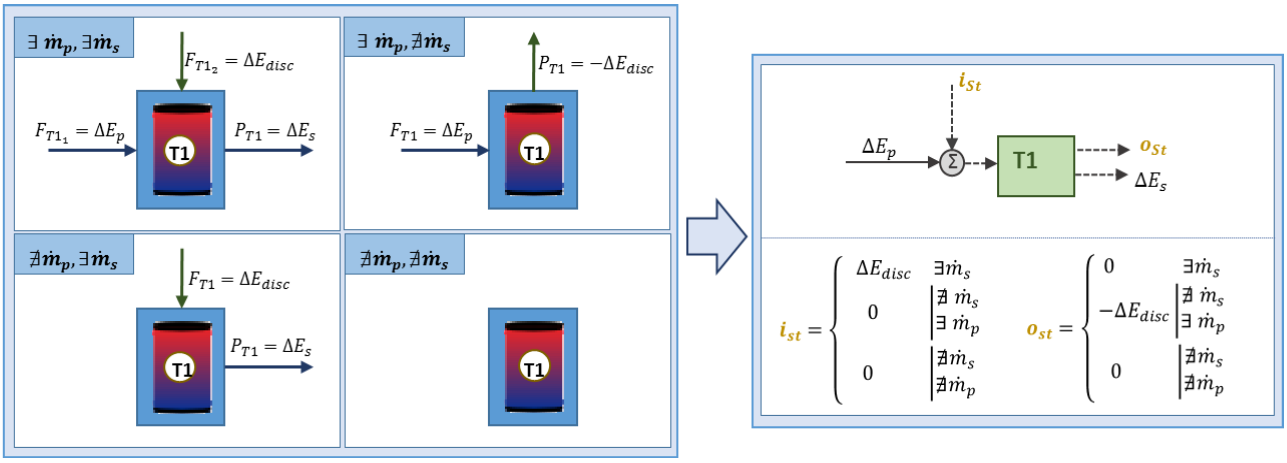
Irudia C. 11 Dagozkien exergoekonomia kostuen balantzeak eta kostu unitarioen emaitzak

Exergia balantze bat eta F zein P proposizioak barneratzen badira osagai bakoitzean, fluxuen exergia kostu unitarioak lortzen dira; balantzeak, proposizioen aplikazioa eta ebazpena Irudia C. 11n dago. Jakina, kasu orotan, produktuaren c_6 kostua berdina da eta E_7/E_6 balioa du; 1. kasuaren eta 2. kasuaren tarteko fluxuen kostuak berdintsuak dira, 3. kasuak, ordea, ebazpen guztiz ezberdinak ditu.

C.3.1.2. Tanke inertzialen egitura dinamikoa

Osagai inertzialek eztabaida sor dezakete jarrera dinamikoagatik. Irudia C. 12n adierazi antzera, produktu eta fuel ezberdinak defini daitezke tankean (T1) primarioko eta sekundarioko masa emarien baldintzen arabera ($\dot{m}_p, \dot{m}_s$). Adibidean, $\Delta E_p, \Delta E_s$ eta ΔE_{disc} hautatu dira sarrerako, irteerako eta denbora tartearen deskarga exergiak adierazteko.

Beraz, egitura produktiboan aukera denak era globalean barneratzeko, i_{st} eta o_{st} fluxuak barneratu dira (ikus Irudia C. 12**¡Error! No se encuentra el origen de la referencia.**ko eskumako atala non fluxuak definitzen diren).



Irudia C. 12 T1 tankearen aukerazko konfigurazioak masa emari eta egitura produktiboaren arabera

C.3.2. Ikerketa kasua

Bi ikerketa kasu garatuko dira aurreko ideiak indartzeko:

Lehenengoa eguzki energiako biltzaileen instalazioari dagokio. Egitura produktiboa urratsez urrats definituko da eta V3Varen 1. eta 2. kasuen adierazpenak erabiliko dira. Termoekonomia analisia era dinamikoan irudikatuko da.

Bigarren adibidea **B Kapitulu**aren (iii) *Eskola baten ATU ikerketa kasua*ren jarraipena da. Helburua exergia eta termoekonomia aplikazio zehatza egitea da IAQ eta konfort termikoa asetzeko sistema konplexu batean. Aireztapen helburua medio, disipazio osagaiak giltzarria dira; gainera, V3Varen 3. kasuko adierazpena erabiliko da. Izan ere, egileak dakiela, orain arte ez da inoiz ATU baten ikasketa termoekonomikorik egin.

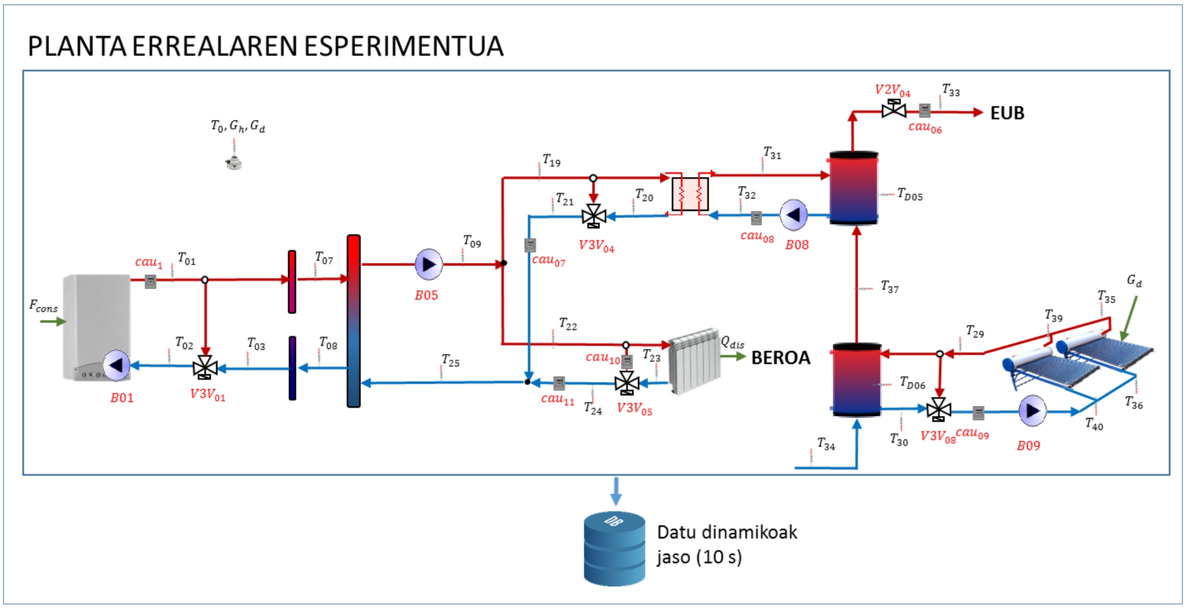
C.3.2.1. (v) Eraikinean eguzki sistemaren ikerketa kasua

Eusko Jaurlaritzaren eraikinen kontrol kalitaterako laborategian (EKKL) egokitu zen instalazio esperimentala zeinek etxe familia-anitzerako EUBren eta berokuntzaren eskariak asetzen dituen.

BaxiRoca 24 BIOS galdara bat da 28 kW termikoekin eta fabrikatzaileen arabera % 97ko efizientziarekin (behe bero ahalmenean oinarritua); eguzki biltzaile sistema lagungarria dauka 2,5 m²-ko gainazaleko seriezko panelekin. Eguzki zirkuituak Roca 500-E 500 litroko biltegia dauka eta 2,8 kW-ko elektrizitate erresistentzia du zeinek beharrezko inertzia eragiten duen eguzki moduluen sarrera uraren tenperatura konstante mantentzeko. EUB zirkuituak 95 cm-ko diametroko eta 2,25 m-ko altuerako Lapesa CV-1000RB 1000 litroko biltegi bat ere badu. Bero disipazioa 5RYardi HP 250 fan-coil bateria batekin eta 2 tutuko sistemarekin egiten da. Gainera, tarteko 3-bideko balbulak, bero trukagailuak eta orekatzaile hidraulikoak daude beroa banatzeko.

Kontrolak galdara pizten du bero eskaria badago edota EUB biltegiaren tenperatura 62 ºC-tik behera badoa legionala bakteria saihesteko. Kasu horretan, EUB pilaketa sistema martxan jartzen da bero trukagailuaren primarioko sarrera tenperaturaren eta tankearen batez besteko tenperaturaren artean 7 ºC baino gehiago badago. Eguzki biltegia, antzeko eran, eguzki panelen eta tankearen batez besteko tenperaturen artean 7 ºC edo gehiago badago piztuko da.

Esperimentua hiru egunetan zehar egin zen eta datuak 10 segundoko jaso ziren monitorizazio eta kontrolaren inplementazio zehatzari esker; 120 sentsore baino gehiago baitaude instalazioan zehar. Irudia C. 13n eskema printzipala irudikatzen da eta sisteman zeharreko sentsoreak adierazten dira.



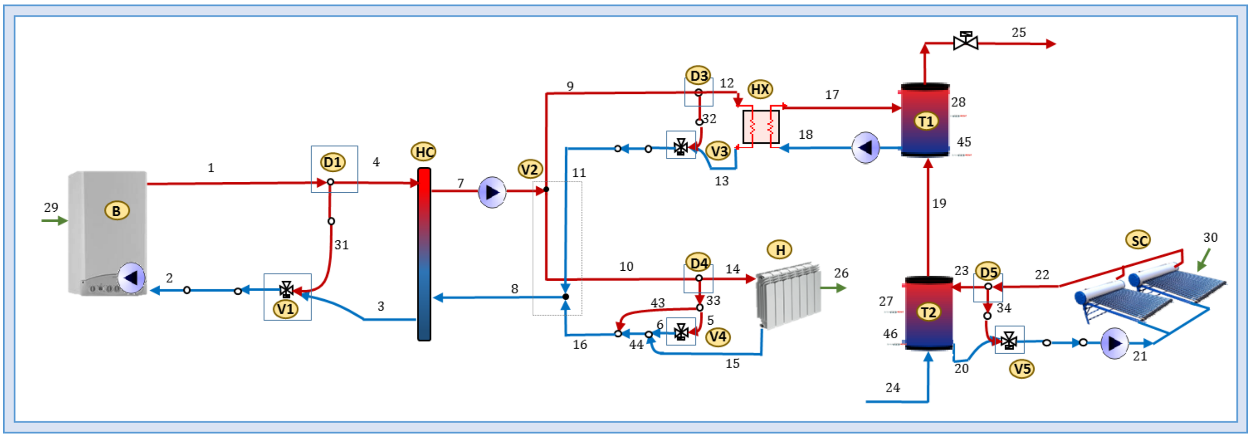
Irudia C. 13 Berokuntza eta EUB instalazioaren eskema printzipala eta horren sentsoreak

Banaketarako 3-bideko balbulek (V3V) jarrera ezberdina daukate helburuaren arabera: berokuntza sistemako balbula eskaria asetzeko modulatu egiten da. Bero trukagailuaren aurrekoa dena-ezer ez balbula da, beraz, dena pasarazten utzi edo bypaseatzen du. Galdarako eta eguzki zirkuituko V3Vak segurtasun arrazoiengatik barneratu direnez (edota bestelako operazio moduentzako) ez dute horien egoera aldatzen.

C.3.2.1.1. Jarrera errealaren karakterizazioa

B Kapituluan aipua egin antzera, sistemaren modelo termikoa giltzarria da. Instalazioaren modelizazioa osagaien karakterizazio indibidualarekin hasten da, datu esperimentalen arabera, Matlab [45] eta Trnsys [42] softwareen nahasketarekin. Elementu ororen simulazioa egin eta gero, horien arteko loturak eta kontrola inplementatzen dira. Ondorioz, simulazio dinamikoa 10 segundoko egin zen datu errealen bitartez.

C.3.2.1.2. Termoekonomiaren modelo dinamikoa



Irudia C. 14 Instalazioaren deskripzioa V3V-ren egitura produktibo zehatzarekin

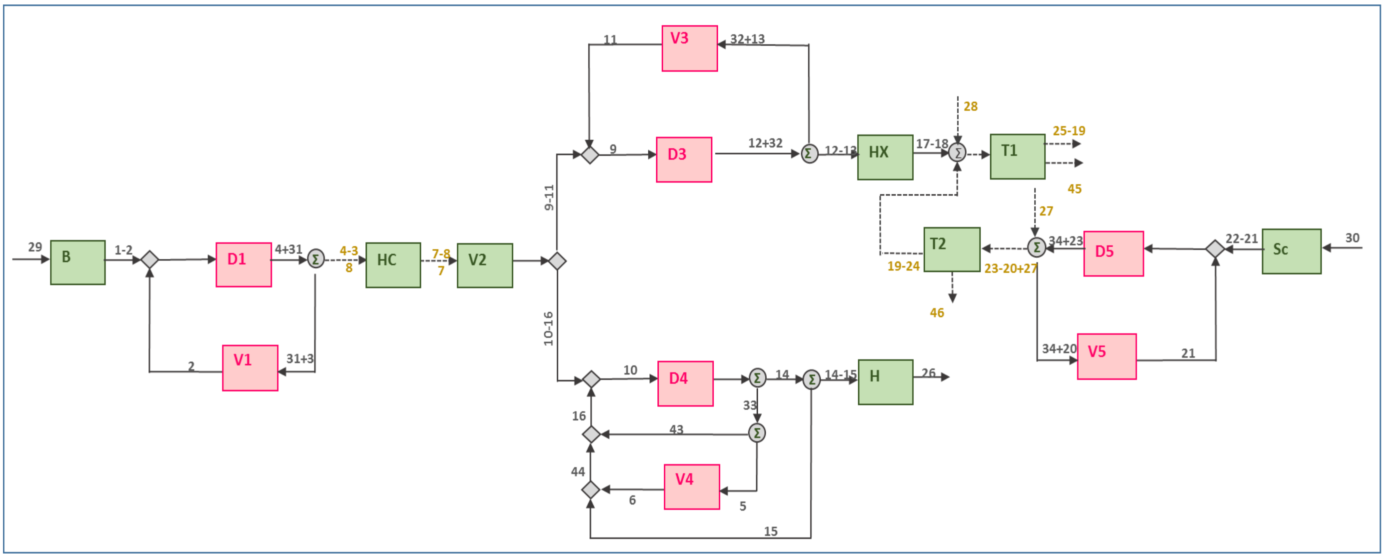
Irudia C. 14n ikerketan zehar erabilitako zenbaketa eta nomenklatura erakusten dira. Ikusi antzera, V3Varen adierazpen ezberdinak medio, 1. eta 2. kasuak hautatu ziren: lehenengoa guztia-ezer ez egoerari dagokio (V1,V2,V3,V5) eta bigarrena modulazio balbulari (V4). Are gehiago, biltegiak (T1 eta T2) modu globalean deskribatu ziren dagozkien konfigurazio ororen arabera (ikus i_{st}=E_{27}, E_{28} eta o_{st}=E_{45}, E_{46} fluxu birtualak Irudia C. 14n).

Taula C. 17 Ekuazio orokorrak eta termoekonomia modeloaren egitura produktibo "estatikoa" nomic model

		EKUAZIO OROKORRAK		EGITURA PRODUKTIBOA	
		KOSTU BALANTZEAK	PROPOSIZIOAK	FUELA	PRODUKTUA
①	B	$c_{29}E_{29} + c_2E_2 = c_1E_1$	$c_{29} = 1$	E_{29}	$E_1 - E_2$
②	D1	$c_1E_1 + c_{31}E_{31} = c_4E_4$	$c_4 = c_{31}$	E_1	$E_4 + E_{31}$
③	V1	$c_{31}E_{31} + c_3E_3 = c_2E_2$		$E_{31} + E_3$	E_2
④	HC	$c_4E_4 + c_8E_8 = c_3E_3 + c_7E_7$	$c_4 = c_3$	$E_4 - E_3$ or E_8	$E_7 - E_8$ or E_7
⑤	V2	$c_7E_7 + c_{11}E_{11} + c_{16}E_{16} = c_8E_8 + c_9E_9 + c_{10}E_{10}$	$c_7 = c_8$ $\frac{E_9^* - E_{11}^*}{E_9 - E_{11}} = \frac{E_{10}^* - E_{16}^*}{E_{10} - E_{16}}$	$E_7 - E_8$	$E_{10} - E_{16} + E_9 - E_{11}$
⑥	V3	$c_{13}E_{13} + c_{32}E_{32} = c_{11}E_{11}$		$E_{13} + E_{32}$	E_{11}
⑦	D3	$c_9E_9 = c_{12}E_{12} + c_{32}E_{32}$	$c_{12} = c_{32}$	E_9	$E_{12} + E_{32}$
⑧	V4	$c_5E_5 = c_6E_6$		E_5	E_6
⑨	D4	$c_{10}E_{10} = c_{14}E_{14} + c_{33}E_{33}$	$c_{14} = c_{33}$	E_{10}	$E_{14} + E_{33}$
⑩	HX	$c_{12}E_{12} + c_{18}E_{18} = c_{13}E_{13} + c_{17}E_{17}$	$c_{12} = c_{13}$	$E_{12} - E_{13}$	$E_{17} - E_{18}$
⑪	H	$c_{14}E_{14} = c_{15}E_{15} + c_{26}E_{26}$	$c_{15} = c_{14}$	$E_{14} - E_{15}$	E_{26}
⑫	T1	$c_{17}E_{17} + c_{19}E_{19} + c_{28}E_{28} = c_{18}E_{18} + c_{25}E_{25} + c_{45}E_{45}$	$c_{28} = 1$. $c_{17} = c_{18}$ $\frac{E_{25}^* - E_{19}^*}{E_{25} - E_{19}} = c_{45}$	$E_{28} + E_{17} - E_{18} + E_{19} - E_{24}$	$E_{45} + E_{25} - E_{19}$
⑬	T2	$c_{24}E_{24} + c_{27}E_{27} + c_{20}E_{20} = c_{19}E_{19} + c_{23}E_{23} + c_{46}E_{46}$	$c_{27} = 1$. $c_{23} = c_{20}$ $\frac{E_{19}^* - E_{24}^*}{E_{19} - E_{24}} = c_{46}$	$E_{27} + E_{23} - E_{20}$	$E_{46} + E_{19} - E_{24}$
⑭	V5	$c_{20}E_{20} + c_{34}E_{34} = c_{21}E_{21}$		$E_{34} + E_{20}$	E_{21}
⑮	D5	$c_{22}E_{22} = c_{23}E_{23} + c_{34}E_{34}$	$c_{23} = c_{34}$	E_{22}	$E_{34} + E_{23}$
⑯	SC	$c_{30}E_{30} + c_{21}E_{21} = c_{22}E_{22}$	$c_{30} = 1$	E_{30}	$E_{22} - E_{21}$

Beraz, modelo termoekonomiko “estatiko” bat eraiki zen aukera dinamiko denak barneratzeko. Osagai nagusi ororen kostu balantzea eta dagozkion ekuazio gehigarriak Taula C. 17ren ezkerreko partean batu dira. Taula C. 17ren eskumako atalak, aldiz, osagai bakoitzaren fuela eta produktua deskribatzen ditu; Irudia C. 14ko izendapenak erabili dira. Areago, kanpoko sarrera globalak gas naturala zein exergia irradiazioak (E_{29}, E_{30}) eta tankeen deskarga (E_{27}, E_{28}) dira; irteera totalak, ordea, EUB eta berokuntza exergia eskariak ($E_{25} - E_{29}, E_{26}$) eta tankeen pilaketa dira $\dot{m}_s$ ez badago (E_{45}, E_{46}).

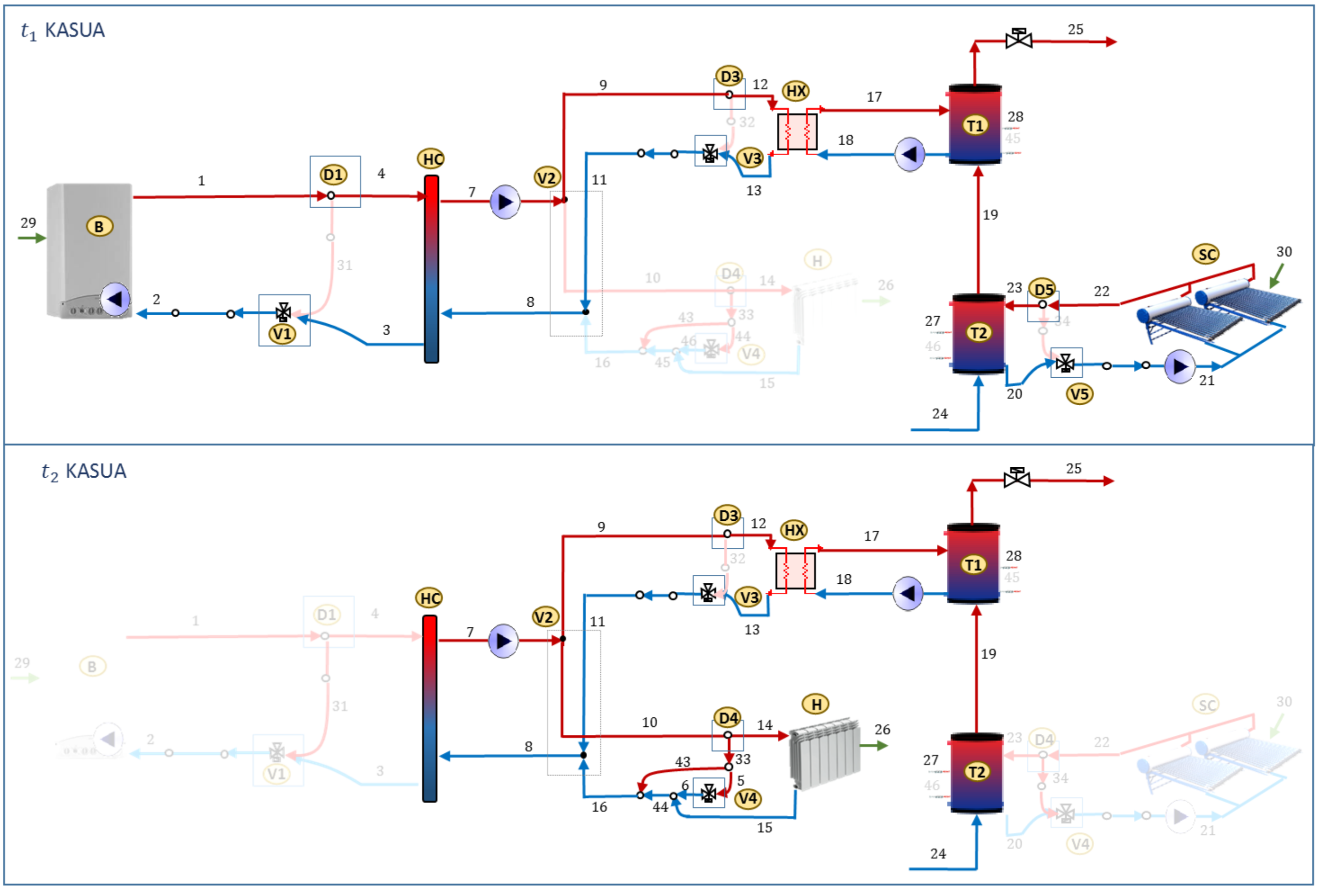
Irudia C. 15n egitura produktiboa erakusten da (Fuel/Produktu diagrama) zeinek aukera guztiak dituelako, programatzen erraza den.



Irudia C. 15 Instalazioaren egitura produktibo orokorra

Ondorioz, denbora tarte bakoitzeko egitura produktibo dinamikoa soilik parte hartzen ez duten fluxuak zeroz biderkatuz lortzen da; Irudia C. 16ak t_1 eta t_2 kasuak erakusten ditu. Lehenengoan, E_5, E_6, E_{10}, E_{14}, E_{15}, E_{16}, E_{26}, E_{31}, E_{32}, E_{33}, E_{34}, E_{43}, E_{44}, E_{45}, E_{46} fluxuak 0 dira eta bigarrenean, bestalde, E_1, E_2, E_4, E_3, E_{20}, E_{21}, E_{22}, E_{23}, E_{29}, E_{30}, E_{31}, E_{32}, E_{34}, E_{45}, E_{46} fluxuak. Dagozkien ekuazioak eta egitura produktiboak Irudia C. 17 - Taula C. 18 eta Irudia C. 18 - Taula C. 19an daude.

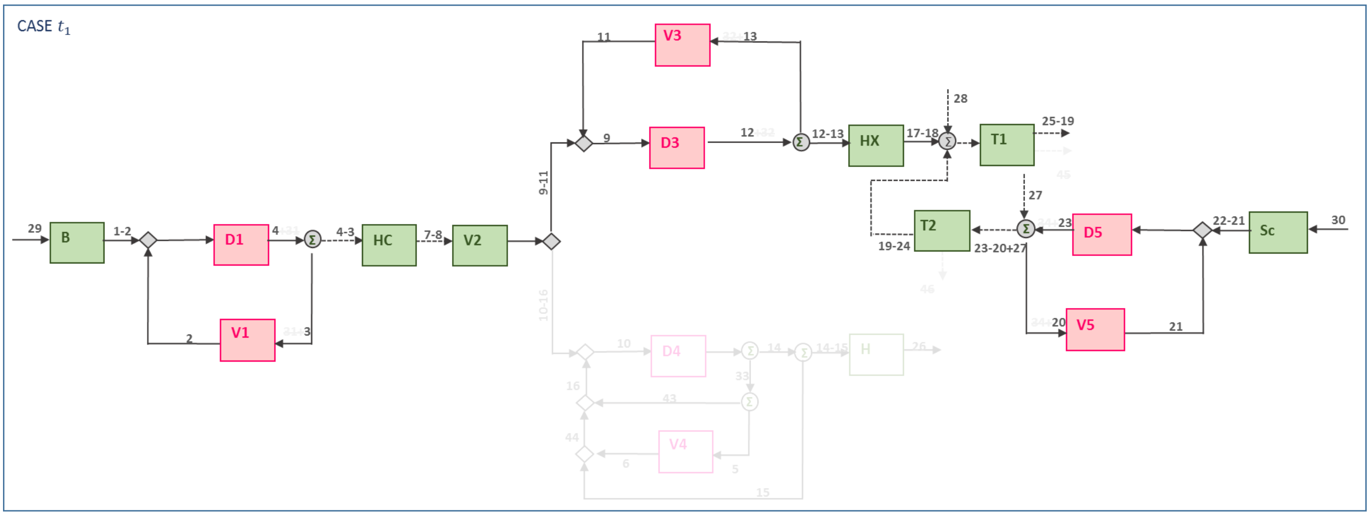
Hori dela eta, sistemaren termoekonomia analisia denbora tarte bakoitzean aplikatzen da; horrela, kostu zenbaketa dinamikoaren lehen helburua lortzen da.



Irudia C. 16 Bi funtzionamendu kasu t_1 eta t_2 denbora tartearen arabera

Taula C. 18 t_1 kasuaren termoekonomia modelorako ekuazioak eta egitura produktiboa

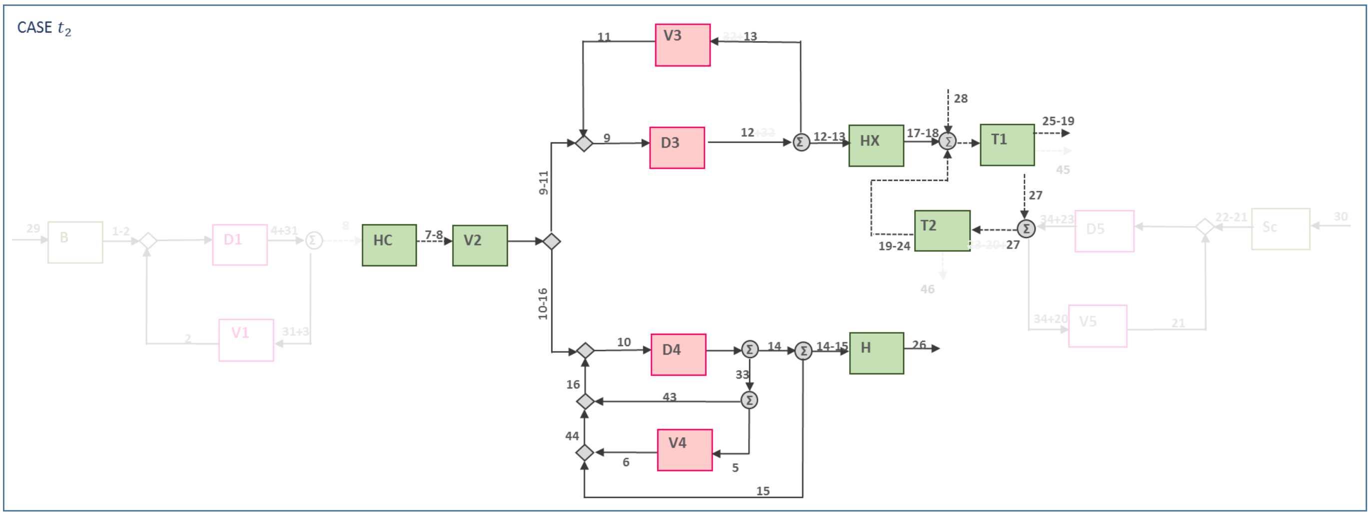
		t_1 KASU DINAMIKOA			
		EKUAZIO OROKORRAK		EGITURA PRODUKTIBOA	
		KOSTU BALANTZEAK	PROPOSIZIOAK	FUELA	PRODUKTUA
①	B	$c_{29}E_{29} + c_2E_2 = c_1E_1$	$c_{29} = 1$	E_{29}	$E_1 - E_2$
②	D1	c_1E_1 ~~$+ c_{31}E_{31}$~~ $= c_4E_4$	~~$c_4 = c_{31}$~~	E_1	E_4 ~~$+ E_{31}$~~
③	V1	~~$c_{31}E_{31} +$~~ $c_3E_3 = c_2E_2$		~~$E_{31} +$~~ E_3	E_2
④	HC	$c_4E_4 + c_8E_8 = c_3E_3 + c_7E_7$	$c_4 = c_3$	$E_4 - E_3$ ~~or E_8~~	$E_7 - E_8$ ~~or E_7~~
⑤	V2	$c_7E_7 + c_{11}E_{11}$ ~~$+ c_{16}E_{16}$~~ $= c_8E_8 + c_9E_9$ ~~$+ c_{10}E_{10}$~~	$c_7 = c_8$ ~~$\frac{E_9^* - E_{11}^*}{E_9 - E_{11}} = \frac{E_{10}^* - E_{16}^*}{E_{10} - E_{16}}$~~	$E_7 - E_8$	~~$E_{10} - E_{16} +$~~ $E_9 - E_{11}$
⑥	V3	$c_{13}E_{13}$ ~~$+ c_{32}E_{32}$~~ $= c_{11}E_{11}$		E_{13} ~~$+ E_{32}$~~	E_{11}
⑦	D3	$c_9E_9 = c_{12}E_{12}$ ~~$+ c_{32}E_{32}$~~	~~$c_{12} = c_{32}$~~	E_9	E_{12} ~~$+ E_{32}$~~
⑧	V4	~~$c_5E_5 = c_6E_6$~~		~~E_5~~	~~E_6~~
⑨	D4	~~$c_{10}E_{10} = c_{14}E_{14} + c_{33}E_{33}$~~	~~$c_{14} = c_{33}$~~	~~E_{10}~~	~~$E_{14} + E_{33}$~~
⑩	HX	$c_{12}E_{12} + c_{18}E_{18} = c_{13}E_{13} + c_{17}E_{17}$	$c_{12} = c_{13}$	$E_{12} - E_{13}$	$E_{17} - E_{18}$
⑪	H	~~$c_{14}E_{14} = c_{15}E_{15} + c_{26}E_{26}$~~	~~$c_{15} = c_{14}$~~	~~$E_{14} - E_{15}$~~	~~E_{26}~~
⑫	T1	$c_{17}E_{17} + c_{19}E_{19} + c_{28}E_{28} = c_{18}E_{18} + c_{25}E_{25}$ ~~$+ c_{45}E_{45}$~~	$c_{28} = 1, c_{17} = c_{18}$ ~~$\frac{E_{25}^* - E_{19}^*}{E_{25} - E_{19}} = c_{45}$~~	$E_{28} + E_{17} - E_{18} + E_{19} - E_{24}$	~~$E_{45} +$~~ $E_{25} - E_{19}$
⑬	T2	$c_{24}E_{24} + c_{27}E_{27} + c_{20}E_{20} = c_{19}E_{19} + c_{23}E_{23}$ ~~$+ c_{46}E_{46}$~~	$c_{27} = 1, c_{23} = c_{20}$ ~~$\frac{E_{19}^* - E_{24}^*}{E_{19} - E_{24}} = c_{46}$~~	$E_{27} + E_{23} - E_{20}$	~~$E_{46} +$~~ $E_{19} - E_{24}$
⑭	V5	$c_{20}E_{20}$ ~~$+ c_{34}E_{34}$~~ $= c_{21}E_{21}$		~~$E_{34} +$~~ E_{20}	E_{21}
⑮	D5	$c_{22}E_{22} = c_{23}E_{23}$ ~~$+ c_{34}E_{34}$~~	~~$c_{23} = c_{34}$~~	E_{22}	~~$E_{34} +$~~ E_{23}
⑯	SC	$c_{30}E_{30} + c_{21}E_{21} = c_{22}E_{22}$	$c_{30} = 1$	E_{30}	$E_{22} - E_{21}$



Irudia C. 17 t_1 kasuaren egitura produktiboa

Taula C. 19 t_2 kasuaren termoekonomia modelorako ekuazioak eta egitura produktiboa

		DYNAMIC CASE t_2			
		GENERIC EQUATIONS		PRODUCTIVE STRUCTURE	
		COST BALANCES	PROPOSITIONS	FUEL	PRODUCT
①	B	~~$c_{29}E_{29}+c_2E_2=c_1E_1$~~	~~$c_{29}=1$~~	~~E_{29}~~	~~E_1-E_2~~
②	D1	~~$c_1E_1+c_{31}E_{31}=c_4E_4$~~	~~$c_4=c_{31}$~~	~~E_1~~	~~E_4+E_{31}~~
③	V1	~~$c_{31}E_{31}+c_3E_3=c_2E_2$~~		~~$E_{31}+E_3$~~	~~E_2~~
④	HC	~~c_4E_4+~~ $c_8E_8=$ ~~c_3E_3+~~ c_7E_7	~~$c_4=c_3$~~	~~E_4-E_3 or~~ E_8	~~E_7-E_8 or~~ E_7
⑤	V2	$c_7E_7+c_{11}E_{11}+c_{16}E_{16}$ $=c_8E_8+c_9E_9+c_{10}E_{10}$	$c_7=c_8$ $\frac{E_9^*-E_{11}^*}{E_9-E_{11}}=\frac{E_{10}^*-E_{16}^*}{E_{10}-E_{16}}$	E_7-E_8	$E_{10}-E_{16}+E_9-E_{11}$
⑥	V3	$c_{13}E_{13}$ ~~$+c_{32}E_{32}$~~ $=c_{11}E_{11}$		$E_{13}+E_{32}$	E_{11}
⑦	D3	$c_9E_9=c_{12}E_{12}$ ~~$+c_{32}E_{32}$~~	~~$c_{12}=c_{32}$~~	E_9	E_{12} ~~$+E_{32}$~~
⑧	V4	$c_5E_5=c_6E_6$		E_5	E_6
⑨	D4	$c_{10}E_{10}=c_{14}E_{14}+c_{33}E_{33}$	$c_{14}=c_{33}$	E_{10}	$E_{14}+E_{33}$
⑩	HX	$c_{12}E_{12}+c_{18}E_{18}=c_{13}E_{13}+c_{17}E_{17}$	$c_{12}=c_{13}$	$E_{12}-E_{13}$	$E_{17}-E_{18}$
⑪	H	$c_{14}E_{14}=c_{15}E_{15}+c_{26}E_{26}$	$c_{15}=c_{14}$	$E_{14}-E_{15}$	E_{26}
⑫	T1	$c_{17}E_{17}+c_{19}E_{19}+c_{28}E_{28}$ $=c_{18}E_{18}+c_{25}E_{25}$ ~~$+c_{45}E_{45}$~~	$c_{28}=1$; $c_{17}=c_{18}$ ~~$\frac{E_{25}^*-E_{19}^*}{E_{25}-E_{19}}=c_{45}$~~	$E_{28}+E_{17}-E_{18}+E_{19}-E_{24}$	~~$E_{45}+$~~ $E_{25}-E_{19}$
⑬	T2	$c_{24}E_{24}+c_{27}E_{27}$ ~~$+c_{20}E_{20}$~~ $=c_{19}E_{19}$ ~~$+c_{23}E_{23}+c_{46}E_{46}$~~	$c_{27}=1$ ~~; $c_{23}=c_{20}$ $\frac{E_{19}^*-E_{24}^*}{E_{19}-E_{24}}=c_{46}$~~	E_{27} ~~$+E_{23}-E_{20}$~~	~~$E_{46}+$~~ $E_{19}-E_{24}$
⑭	V5	~~$c_{20}E_{20}+c_{34}E_{34}=c_{21}E_{21}$~~		~~$E_{34}+E_{20}$~~	~~E_{21}~~
⑮	D5	~~$c_{22}E_{22}=c_{23}E_{23}+c_{34}E_{34}$~~	~~$c_{23}=c_{34}$~~	~~E_{22}~~	~~$E_{34}+E_{23}$~~
⑯	SC	~~$c_{30}E_{30}+c_{21}E_{21}=c_{22}E_{22}$~~	~~$c_{30}=1$~~	~~E_{30}~~	~~$E_{22}-E_{21}$~~



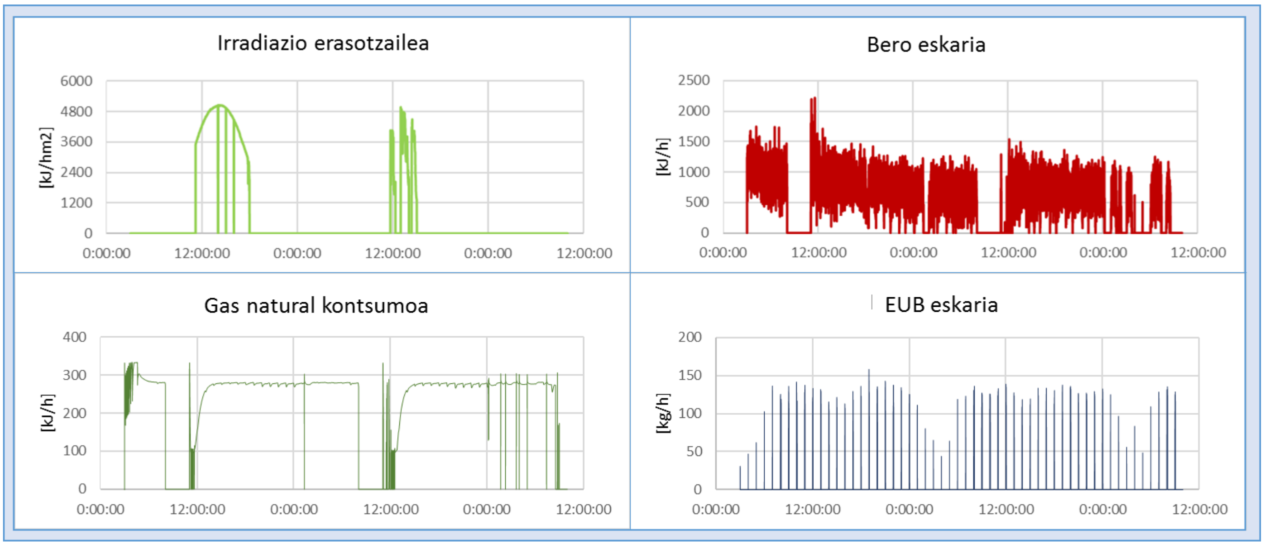
Irudia C. 18 t_2 kasuaren egitura produktiboa

C.3.2.1.3. Zenbakizko emaitzak

Aurretiaz esan antzera, 3 eguneko azterketa egin zen EKKLko instalazio esperimentalean. 30 Pt 100 1/10DIN sentsore termiko erabili ziren ± 0.15 °C –ko ziurgabertasunarekin eta 7 Siemens SITRANS FM emari kontagailu elektromagnetiko % $\pm$ 0.1-ko ziurtasunarekin; halaber, 1 Itron Gallus Class 1.5 gas neurgailu batek galdararen fuel kontsumoa neurtzen du eta 3 piranometro erabili ziren erradiazio lauso eta global horizontala zein bertikala neurtzeko. Datuak 10 segundoko batu ziren.

C.3.2.1.3.1. Proba eta datuak

Irudia C. 19n erradiazio erasotzailea, gas natural kontsumoa eta berokuntza zein EUB eskariak agertzen dira.

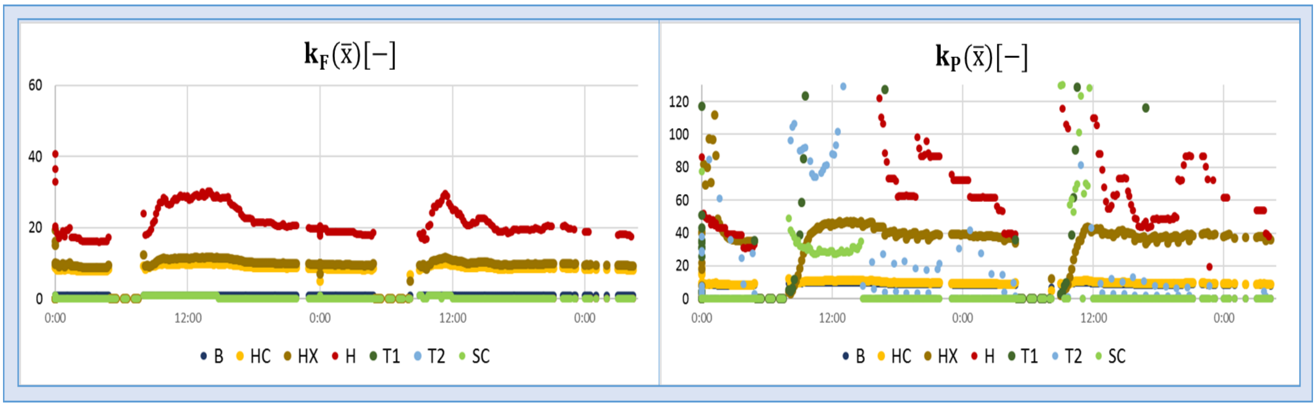


Irudia C. 19 Irradiazio, gas kontsumo, berokuntza eta EUB eskarien datuak esperimentuan zehar

Azaldu gisa, lehenengo urratsa osagai errealen karakterizazio matematikoan datza horien modelo termikoa eraikitzeko. Ostean, osagaiak lotu eta kontrola inplementatzen da Trnsys-en Simulation Studio-an. Beraz, instalazio osoaren modelo dinamikoa lortzen da.

Gero, Irudia C. 14**¡Error! No se encuentra el origen de la referencia.**ko fluxu bakoitzaren aldagai termodinamikoak (masa emariak, tenperaturak, etab.) 10 segundoko lortzen dira eta dagokien fluxu exergetikoak kalkulatzen dira formularen arabera [7].

C.3.2.1.3.2. Analisi termoekonomikoa



Irudia C. 20 Osagai nagusien fuel eta produktu kontsumo exergetiko unitario dinamikoa

Analisi termoekonomiko dinamikoa fluxuen aldagai termodinamikoak (eta, ondorioz, exergiak) ezagutu ostean egin zen. Taula C. 17ko adierazpen orokorrak programatuz eta 10 minutuko balio pilatuak kontuan hartuz kostuak kalkulatu ziren. Osagai nagusien fuelen eta produktuen kontsumo exergetiko unitarioak Irudia C. 20n erakusten dira eta, Taula C. 20k, aldiz, ikasketa periodoaren batez besteko balioak barneratzen ditu (jakina, batez besteko balioen esanahia ez da guztiz zehatza eta ezin da oinarritzat erabili, finean, osagaien pizketa eta itzaltze egoeren araberakoa baita; halere, erreferentziatzat har daiteke).

Taula C. 20 Osagai nagusien batez besteko fuel eta produktu kontsumo exergetiko unitarioa

	$k^*_F(\bar{x})[-]$	$k^*_P(\bar{x})[-]$		$k^*_F(\bar{x})[-]$	$k^*_P(\bar{x})[-]$
B	1.00	8.78	**D4**	21.52	21.52
D1	8.78	8.78	**HX**	10.10	38.22
V1	8.78	8.78	**H**	21.55	112.02
HC	8.78	9.75	**T1**	36.87	107.72
V2	9.75	10.10	**T2**	21.57	55.39
V3	10.10	10.10	**V5**	47.45	47.45
D3	10.10	10.10	**D5**	50.70	50.70
V4	21.44	45.97	**SC**	1.00	30.94

Analisi termoekonomikoak sisteman zeharreko kostuek kokapen argazkia eskaintzen du. Batetik, produktuen eta fuelen kostu exergetiko unitarioen arteko aldeak $(k^*_{p,i}(\bar{x}) - k^*_{F,i}(\bar{x}))$ i osagaiaren itzulezintasunak adierazten ditu; alegia, beharrezko balioen eta lortutako produktuaren arteko energia narriadura. Ondorioz, itzulezintasun handieneko osagaia hobekuntzaren ikuspuntu izan behar da; adibidez, H elementuaren suntsiketak nabariak dira energia kalitate altua erabiltzen delako giro baldintzetatik gertuko gela bat berotzeko; are gehiago, oso aldakorra da.

Beste alde batetik, fuelen exergia kostu unitarioak $(k^*_{F,i}(\bar{x}))$, i osagaira heldu arteko itzulezintasun pilatuak adierazten ditu. Hori dela eta, balibaideen kostu unitarioa sistema osoaren konfigurazioaren araberakoa da eta bertara iritsi arteko energia narriadura oro barneratzen ditu. Beraz, aldagai horrek osagaiak non eta zelan dauden elkar eraginda erakusten duenez, kontrolaren hobekuntza bideratzen du. Horregatik, esaterako, EUB biltegiak fuelaren exergia unitatean suntsiketa anitz jasotzen ditu, azken batean, hara iristeko atzeraezintasun ugari batu baititu.

C.3.2.1.4. *Emaitzen eztabaida*

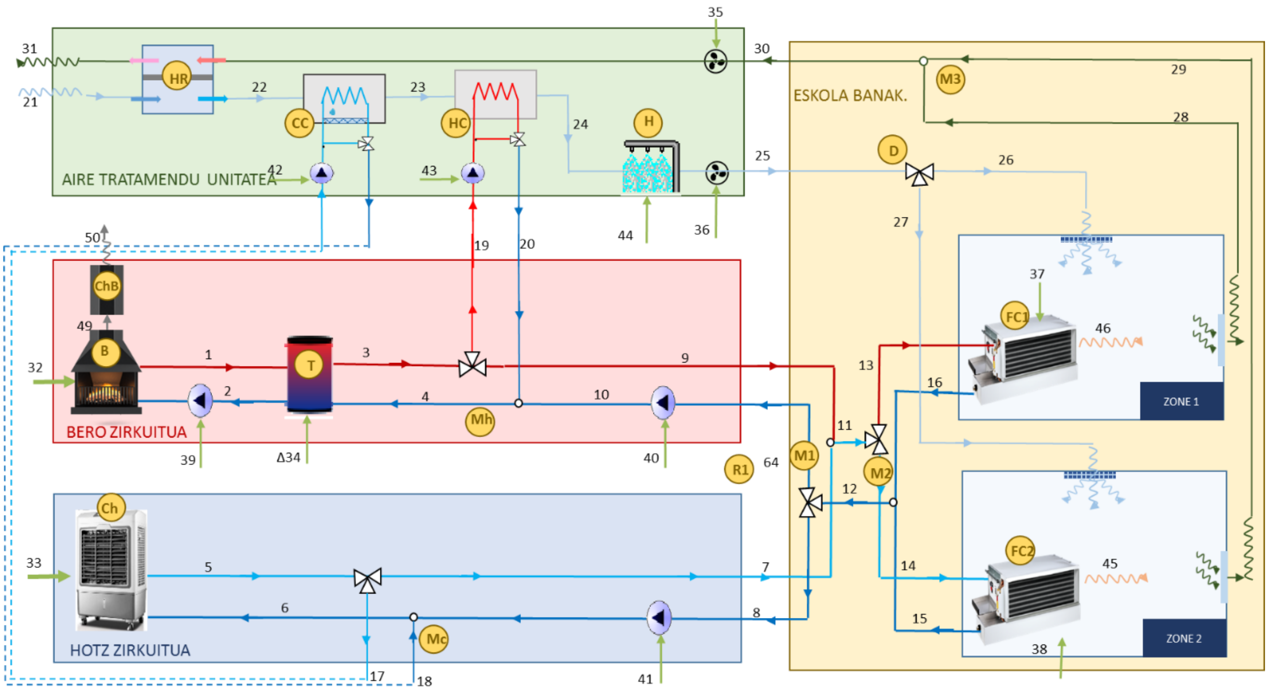
Eraikuntza sistema baldintza aldakuntzen oso menpekoa izateagatik, ST era dinamikoan aplikatu behar da. Hortaz, modelo termikoak uneoro aldatzeaz gain, fluxuen kostuak etengabe aldatzen doaz. Adibidearen helburua egitura produktiboarekin lotutako arazoak era globalean ebaztea zen.

Horretarako, V3Vak ikuspegi sinpletik eta inkrementaletik ikasi dira: konfigurazio sinplea dena-ezer ez balbulak adierazteko erabili zen eta bigarren adierazpena, ordea, modulazio balbulentzako. Gainontzeko osagaien konfigurazio aukerak super-egituran barneratzen dira.

Emaitza gisa, berogailua oso osagai itzulezina da eta kostuen aldakuntza nabarmena du giro baldintzen menpekotasun handia medio. Horrela kostu dinamikoen esleipena justifikatzen da: osagai bakoitzaren fuelen eta produktuen kostu exergetiko unitario aldakari hori ikerketa periodoan zehar 10 minutuko kalkulatu zen.

C.3.2.2. **(iii) Eskola baten ATU ikerketa kasua**

Adibide hau **B Kapitulu**ko (iii) ikerketa kasuaren jarraipena da non Palermoko eskola baten bero sistema garatzen den berokuntza, hozkuntza, aireztapena eta EUB eskariak asetzeko. Eskema fisikoa eta dagokion fluxuen eta osagaien izendapena Irudia C. 21n adierazten dira.



Irudia C. 21 Instalazioaren eskema fisikoa

Termoekonomia aplikatzeko, azpisistema bakoitzaren exergia fluxuak (guztira 50, ikus Irudia C. 21) kalkulatu behar dira urteko 8760 orduetan zehar. ATUrekin udaran (edo neguan) airea hoztu eta hezetasuna kentzen (edo berotu eta hezetasuna gehitu) zaionez, *exergia kimikoa* gehitu da analisian [46].

*Exergia fisikoa*ri dagokionez, zati termikoak baino ez ziren aintzat hartuz, atal mekanikoekin lan egiteak fluxuen bikoizketa dakarrelako [47]. Edozein kasutan ere, termikoaren ehunekoa nabari altuagoa denez, zati mekanikoa deusezta daiteke. Nahiz eta horren ezabatzeak ponpak eta haizagailuak era indibidualean ez hartzea eragiten duen, horien kontsumo elektrikoak zirkuituaren osagai nagusien barnean hartu ziren kontuan.

Gainera, R fluxuak giltzarri dira osagaien nortasuna adierazteko disipazio elementuak talde produktiboekin lotzen baitira. Disipazio elementuak bi konfigurazioetan ager daitezke: *sistema-giroa* edo *sistema-sistema*. Ondorioz, alde batetik, disipazio osagaiak R ingurugirora jaurti baino lehen koka daitezke eta oro har legeekin eta araudiekin erlazionatzen dira. Adibidez, galdararen tximiniako irteera gasak iragazteko (Bc) non keak garbitzeko ($R_{Bc} = E_{47}$) kostua galdarari lotzen zaion.

Beste alde batetik, disipazio elementuak tartekoak izan daitezke eta sistemaren barnean daude energia zikloa ixteko. Oro har beharrizan termodinamikoekin bat datoz. Kasurako, 3-bideko balbulen 3. kasuko adierazpena (Mh, Mc, M1, M2, M3): exergia suntsiketa bat dago ($R_{M_i} = E_{D_{Mi}}$) tenperatura ezberdineko fluxuak nahasten direlako; alabaina, exergia suntsiketaren minimizazio nahi bada, kontrol sistema baten bitartez itzulezintasun horiek guztik ekidin daitezke.

Datorren Taula C. 23an batzen dira osagai produktiboak.

C.3.2.2.1. *Temoekonomiaren modelo dinamikoa*

Jomuga nagusia urtean zeharreko super-egitura dinamikoarentzako prozedura orokor bat sortzea da.

Kasu honetan era *PF formulazioa* erabili zen STaren garapenerako (eskariak sustatutako modeloa). *PF* adierazpena baita egokiena sistema baten produkzio zehatzerako beharrezko baliabideak zenbatzeko eta kanpo fuelen kostu unitarioen araberako kostuak lortzeko.

Baina, sinplifikazio arrazoiak medio, $\langle \mathbf{PF} \rangle$ matrizea *FP* (eskariak sustatutako modeloa) eta *PF* adierazpenen arteko harremanetatik lortu zen. Azken finean, $\langle \mathbf{FP} \rangle$ matrizea eraikitzea franko errazagoa da eta esanahi fisikotik gertuago dago. Beraz, ikerketa *PF modeloa* erabiliz egin arren, sarrera aldagai independenteak ① kanpo baliabideak E_e; ② bidebanatze eta banaketa parametroak α_{ij}, ψ_{ij} (izendapenak argiago egiteko $\alpha\,^i_j$ eta $\psi\,^i_j$ erabili ziren aitzinakoen ordez); eta, ③ osagaien exergia kontsumo unitarioak k_i izan ziren. Horren ostean, *PF adierazpena* bi modeloen arteko loturengatik lortu zen.

① Lehenengo E_e aldagaiak dira: galdararen gas naturala (E_{32}) eta hozkailuaren elektrizitatea (W_{33}); (ΔE_{34}); haizagailuen (W_{35}, W_{36}) eta ponpen ($W_{39} \dots W_{43}$) elektrizitatea; eta hezetasun sistemaren (W_{44}) eta fan-coil-en (W_{45}, W_{46}) elektrizitate elikadura.

② Bigarren α^i_j adierazlea bat dator irteera bat baino gehiagoko osagai produktiboekin. Taula C. 21n definitzen dira (eta adibide bat Taula C. 22n dago).

Taula C. 21 α^i_j bifurkazio parametroak

α^i_j bifurkazio parametroak	
$\alpha^B_{Cb} = \frac{E_{49}}{P_B}$	$\alpha^B_T = 1 - \alpha^B_{Cb}$
$\alpha^T_{HC} = \frac{E_{19}-E_{20}}{P_T}$	$\alpha^T_{FC} = \frac{E_9-E_{10}}{P_T}$
$\alpha^{Ch}_{CC} = \frac{E_{17}-E_{18}}{P_{Ch}}$	$\alpha^{Ch}_{FC} = \frac{E_7-E_8}{P_{Ch}}$
$\alpha^{TOT}_{FC1} = \frac{E_{13}-E_{16}}{P_{FC_{TOT}}}$	$\alpha^{TOT}_{FC2} = \frac{E_{14}-E_{15}}{P_{FC_{TOT}}}$
$\alpha^{Dem1}_{HR} = \frac{E_{28}}{P_{Dem1}}$	$\alpha^{Dem1}_{Z1} = 1 - \alpha^{Dem1}_{HR}$
$\alpha^{Dem2}_{HR} = \frac{E_{29}}{P_{Dem2}}$	$\alpha^{Dem2}_{Z2} = 1 - \alpha^{Dem2}_{HR}$
$\alpha^{H-C}_{H} = \frac{P_T}{P_T+P_{Ch}}$	$\alpha^{H-C}_{H} = 1 - \alpha^{H-C}_{c}$

non:

- $P_{FC_{TOT}} = E_{11} - E_{12}$
- $P_{Dem1} = E_{26} + E_{46}$
- $P_{Dem2} = E_{27} + E_{45}$
- *rest P_i is in Table C. 23*

Oharra:

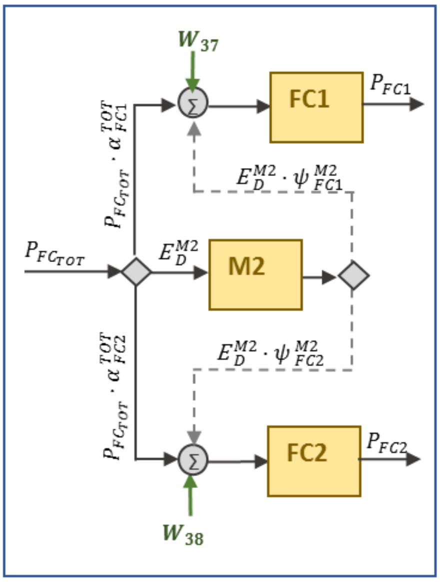
- $\alpha^T_{HC} + \alpha^T_{FC} \leq 1$
- $\alpha^{Ch}_{CC} + \alpha^{Ch}_{FC} \leq 1$
- $\alpha^{TOT}_{FC1} + \alpha^{TOT}_{FC2} \leq 1$

Bestalde, ψ^i_j parametroak R irteera bat baino gehiagko disipazio osagaiekin bat datoz eta, kasuan, 3-bideko balbulekin lotzen dira (Mh, Mc, M1 and M2).

Taula C. 22 E^{Mi}_D eta ψ^i_j + M2/FC1/FC2 osagaien adibidea

$E^{Mh}_D = (E_9 - E_{10}) + (E_{19} - E_{20}) - (E_3 - E_4)$
$E^{Mc}_D = (E_9 - E_{10}) + (E_{19} - E_{20}) - (E_3 - E_4)$
$E^{M1}_D = (E_9 - E_{10}) + (E_7 - E_8) - (E_{11} - E_{12})$
$E^{M2}_D = (E_{11} - E_{12}) - (E_{13} - E_{16}) - (E_{14} - E_{15})$
$E^{M3}_D = E_{28} + E_{29} - E_{30}$

$\psi^{Mh}_{HC} = \frac{E_{19}-E_{20}}{(E_{19}-E_{20})+(E_9-E_{10})}$	$\psi^{Mh}_{FC} = 1 - \psi^{Mh}_{HC}$
$\psi^{Mc}_{CC} = \frac{E_{17}-E_{18}}{(E_{17}-E_{18})+(E_7-E_8)}$	$\psi^{Mc}_{FC} = 1 - \psi^{Mh}_{HC}$
$\psi^{M2}_{FC1} = \frac{E_{13}-E_{16}}{(E_{13}-E_{16})+(E_{14}-E_{15})}$	$\psi^{M2}_{FC2} = 1 - \psi^{M2}_{FC1}$



Ondorioz, E_D^{Mi} balbularekin lotutako j osagai produktiboa $E_{D_j}^{Mi} = E_D^{Mi} \cdot \psi_j^{Mi}$ terminoaz zigortzen da non ψ_j^{Mi} banaketa koefizientea den. Definizio horiek Taula C. 22n daude eta eskumako aldean M2/ FC1/ FC2 osagaien adibidea irudikatzen da.

Adibide horren arabera (3-bideko balbulen 3. kasuari dagokio, alegia), M2 disipazio osagai bat da zeinek beroa/hotza banatzen eta nahasten dituen FC1 eta FC2 osagai produktiboentzako. Nahasketa bitartean, E_D^{M2} hondakina sortzen da eta FC1 zein FC2-ri lotzen zaie ψ_{FCi}^{M2} pisuaren arabera. Gainera, $P_{FC_{TOT}}$ bero/hotz erabilgarria FC-etan banatzen da α_{FCi}^{TOT} parametroaren bidez.

③ Azkeneko k_i-aren kalkulua fuelaren eta produktuaren arteko zatiketa lez kalkulatzen da. Taula C. 23k osagaien sistema produktiboa dauka eta horien fuela, produktua eta hondakina adierazten dira.

Taula C. 23 Osagai produktiboen egitura

Osagaia	FUELA	PRODUKTUA	HONDARRA
B	E_{32}	$(E_1 - E_2)$	E_{47}
Ch	$W_{33} + E_{41}$	$(E_5 - E_6)$	
T	$(E_1 - E_2) + \Delta E_{34} + W_{39} + W_{40}$	$(E_3 - E_4)$	
FC1	$(E_{13} - E_{16}) + W_{37}$	E_{46}	$E_{D_{FC1}}^{Mh} + E_{D_{FC1}}^{Mc} + E_{D_{FC1}}^{M1} + E_{D_{FC1}}^{M2}$
FC2	$(E_{14} - E_{15}) + W_{38}$	E_{45}	$E_{D_{FC2}}^{Mh} + E_{D_{FC2}}^{Mc} + E_{D_{FC2}}^{M1} + E_{D_{FC2}}^{M2}$
CC	f^{CC}	p^{CC}	$E_{D_{CC}}^{Mh} + E_{D_{CC}}^{Mc}$
HC	$(E_{19} - E_{20}) + W_{43}$	p^{HC}	$E_{D_{HC}}^{Mh} + E_{D_{HC}}^{Mc}$
HR	$(E_{30} - E_{31}) + W_{35}$	$(E_{22} - E_{21})$	$E_{D_H}^{M3}$
H	f^H	p^H	
D	E_{25}	$E_{26} + E_{27}$	

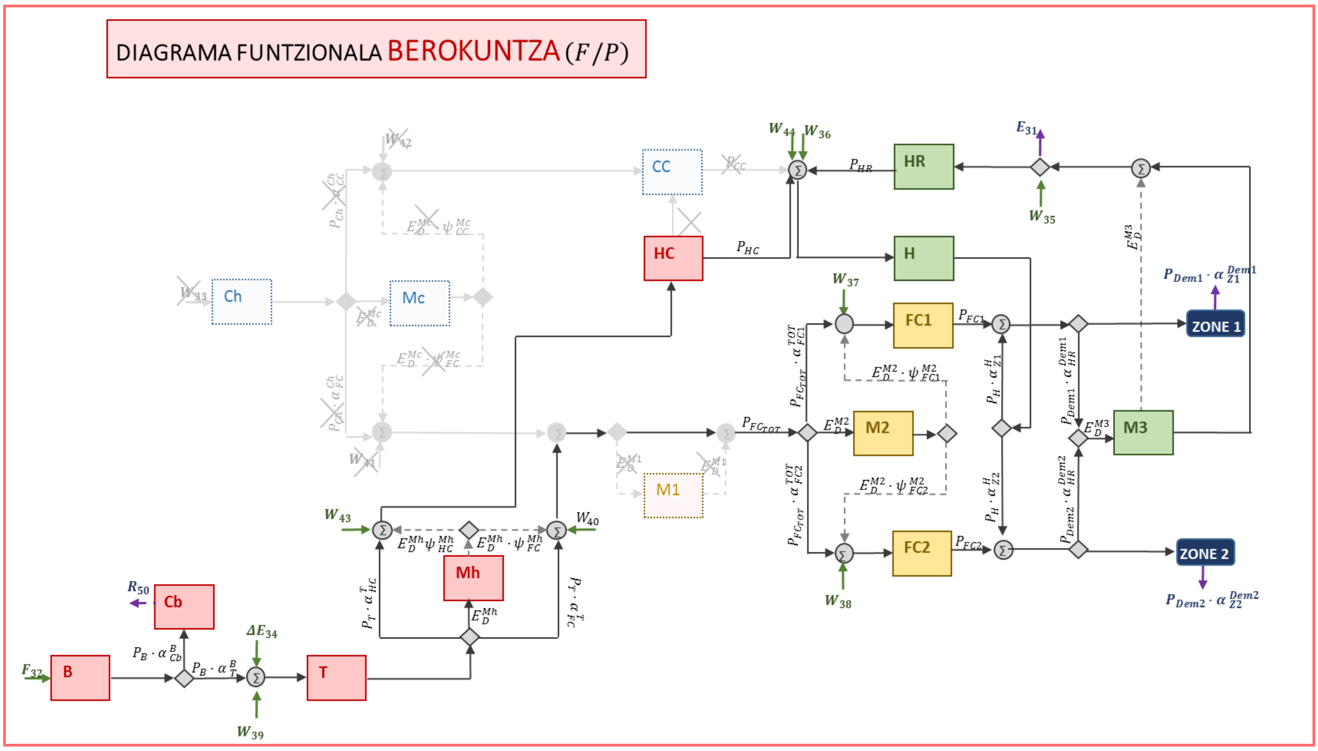
f^C	Berokuntza F $((E_{17} - E_{18}) + W_{42} + E_{23})$; Hozkuntza F $((E_{17} - E_{18}) + W_{42} + (E_{24} - E_{23}))$
p^C	Berokuntza P (E_{22}); Hozkuntza P $(E_{24} - E_{22})$
p^{HC}	Berokuntza P $(E_{23} - E_{24})$; Hozkuntza R $(E_{24} - E_{23})$
f^H	Berokuntza F $(E_{44} + W_{36})$; Hozkuntza F $E_{44} + W_{36} + E_{24}$
p^H	Berokuntza P $(E_{25} - E_{24})$; Hozkuntza P (E_{25})
$E_{D_j}^{Mi}$	j osagaiean hondarraren lekukotzea Mi nahasgailuaren exergia suntsiketagatik

Helburua urtean zehar lan egiteko formula orokor eta dinamiko bat lortzea izan arren (nahiz eta kontrola etorkizunean aldatu), zenbait fuel eta produktu (eta baita hondakin) definizio lotu zaizkio osagai batzuei hozkuntza edo berokuntza periodoen arabera (f^{CC}, p^{CC}, p^{HC}, f^H, p^H); jarraian azalduko dira.

Hasteko, HCaren helburu produktiboa neguan zehar sarrera airea berotzea da beharrezko set-point-era arte. Era horretan, exergia termikoa igo egiten da sarrera eta irteera airearen artean ($\Delta E_{air}^{HC} = E_{24} - E_{23}$). Udan, aldiz, helburua exergia suntsitzea da 14°C-ko set-point tenperatura lortzeko; azken batean, irteera fluxua sarrerako hura baino gertuago dago giro baldintzetatik, ($E_{24} - E_{23} < 0$). Beraz, HCa disipazio osagaiaren lez egiten du lan $\Delta E_{air} < 0$-ko jomugarekin. Orduan, $|\Delta E_{air}^{HC}|$ CCarekin lotu behar da CCaren lan baldintzekin estuki lotzen delako.

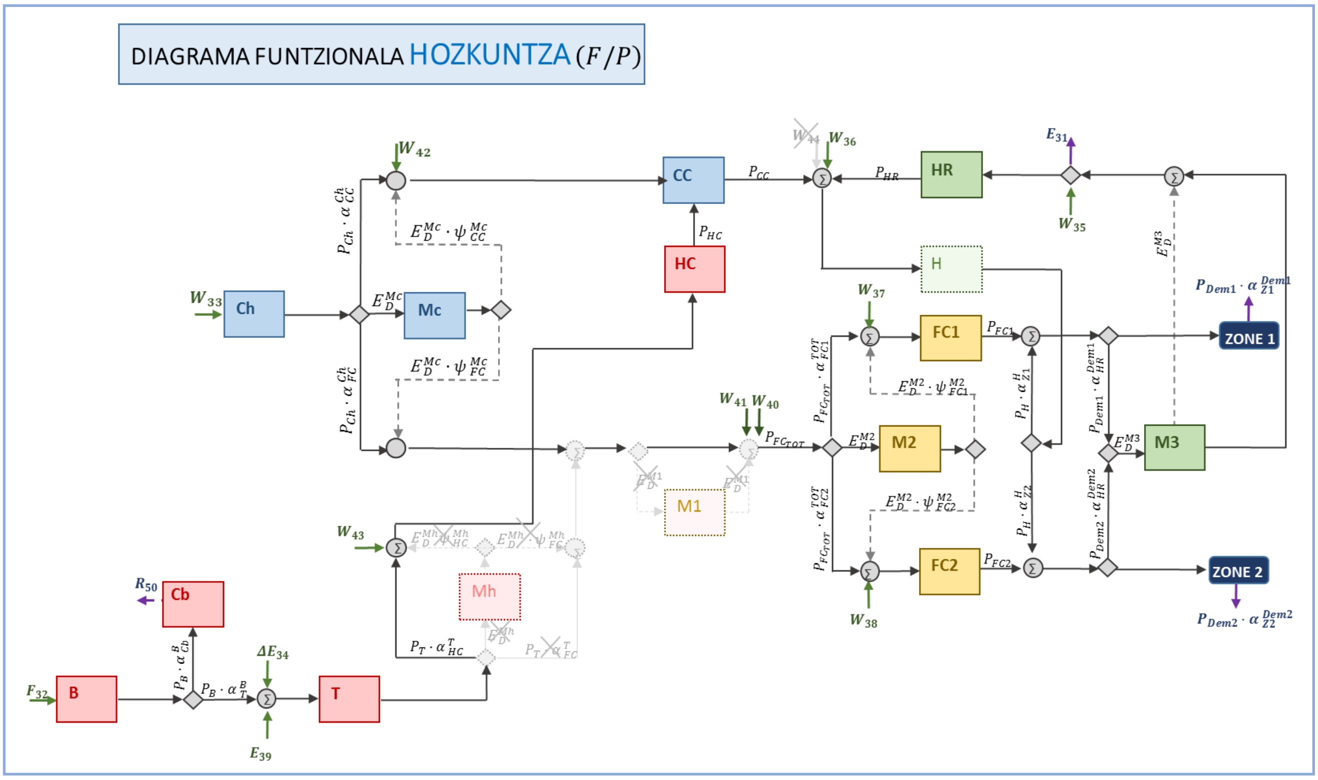
Behaketa horien arabera, batetik, CCaren baliabidea hotz periodoan, hozkailuaren sarrerarekin batera$|\Delta E_{air}^{HC}|$ da airearen baldintza eraldatzeko ($\Delta E_{air}^{CC} = E_{24} - E_{22}$). Beste alde batetik, kontrol espezifikoa aintzat hartuz, CCak berokuntza periodoan ez du parterik hartzen. Beraz, ez dago hotz sarrerarik ($(E_{17} - E_{18}) + W_{42} = 0$) eta aireztapen fluxuak osagaia bypaseatzen du inolako aldakuntzarik gabe ($E_{23} = E_{22}$).

Hezegailuarekin (H) antzeko zeozer gertatzen da uda garaian: aire fluxuak osagaia zeharkatzen du. Hala eta guztiz ere, haizagailuaren elektrizitate elikadura W_{36} kontuan hartzen da.



Irudia C. 22 Berokuntza periodoan diagram funtzionala dagokion kontrolarekiko

Irudia C. 22n eta Irudia C. 23n hozkuntza eta berokuntza periodoen egitura produktiboa irudikatzen da; itzalitako osagaiak lauso marraztu eta parte hartu gabeko fluxuak gurutzatu dira. Horrela, super-egituraren diagrama funtzional orokorra interpretatzen da.



Irudia C. 23 Hozkuntza periodoan diagram funtzionala dagokion kontrolarekiko

Diagrama funtzionaletan, bi osagai berri barneratu dira ZONE1 eta ZONE2. Ez dira errealak baina eskolako produktu nagusiak irudikatzeko jarri dira: $P_{Dem1} \cdot \alpha_{Z1}^{Dem1}$ eta $P_{Dem2} \cdot \alpha_{Z2}^{Dem1}$. Eraikinaren exergia eskariarekin bat datoz eta ikur positiboa zein negatiboa izan ditzakete.

Batetik, $P_{Demi} \cdot \alpha_{Zi}^{Dem1} > 0$ eraikinaren beharrak asetzeko exergia esan nahi du. Bestetik, $P_{Demi} \cdot \alpha_{Zi}^{Dem1} < 0$ guztiz nahi ez den egoera adierazten du sartu baino exergia gehiago kendu dela adierazten duelako; edo, beste modu batean esanda, gunea exergia suntsiketarako osagai lez lan egiten duela (disipazio elementu bezala).

C.3.2.1.3.3. Kostuen zenbaketa

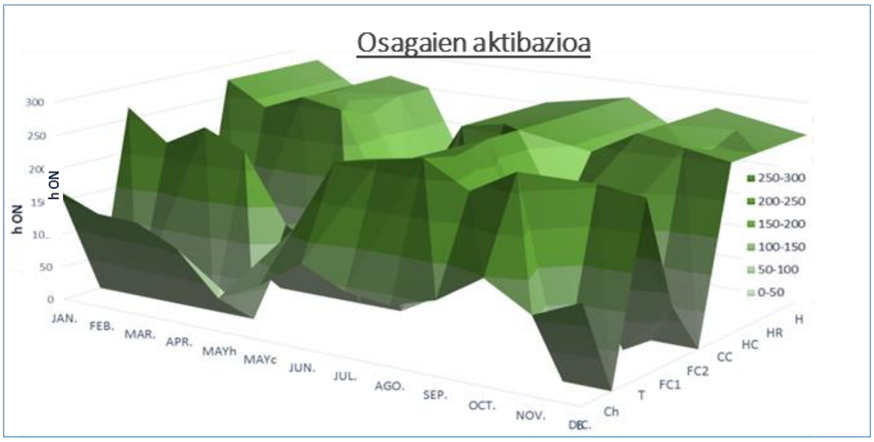
Egitura produktibo dinamiko horrekin denbora tarte bakoitzeko $\langle \mathbf{KP} \rangle$ eta $\langle \mathbf{KR} \rangle$ matrizeak kalkulatzen dira. Ekuazio matrizialen ebazpenekin, osagai bakoitzaren fuelen eta produktuen kostu exergetiko zein exergoekonomiko unitarioak eta kostu totalak kalkulatzen dira. Are gehiago, produktuen kostua helburu produktiboaren c_P^e, hondakin formakuntzaren c_P^r eta kostu finkoen c_P^z arabera banatzen da.

Energia denez parametro orokorra eta emaitzak unitate horretan eman nahi badira, fuelaren eta produktuaren kalitate faktoreaz biderkatuz lortzen da $(F_i^{En}/F_i^{Ex}$ and $P_i^{En}/P_i^{Ex})$. Haatik, negu garian energia eta exergia fluxuak norazko berdina badute ere, udaran, aldiz, aurkakoa daukate. Beraz, F_i^{En} eta P_i^{En} definizioetan kontuan hartu beharreko baldintza da

C.3.2.1.4. Emaitza numerikoak

Trnsys simulazioaren bitartez, fluxuen datu termodinamikoak 3 minutuko lortu ziren eta orduko pilatu ziren urteko 8760 orduetan zehar.

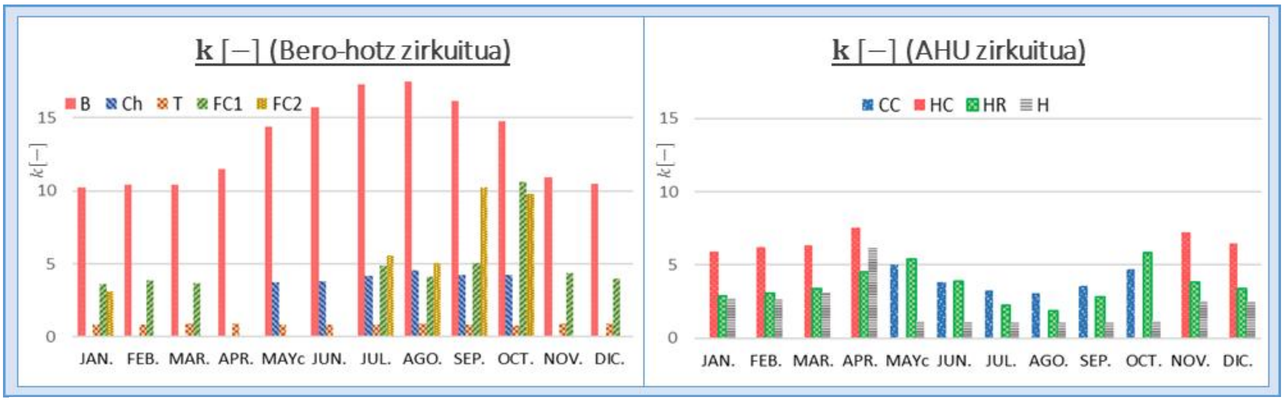
Irudia C. 24n osagai produktiboen hilabeteko pizketa orduak irudikatzen ditu (B, Ch, T, FC1, FC2, CC, HC, HR, H). Gainera "May" bitan banatu da (MAYh eta MAYc) berokuntza periodoaren lehenengo hamabostaldia eta hozkuntzaren gainontzeko egunak bereizita erakusteko (ikus kontrolaren baldintzak B.2.2.2.1 atalean).



Irudia C. 24 Sistemako osagaien pizketa eta itzaltzea urtean zehar

Osagai produktibo bakoitzaren k_i balioa kalkulatu ondoren Irudia C. 25n batzen da. Ezkerreko grafikoan sorkuntza eta fan-coil laguntzaile taldeak batzen dira (B, Ch, FC1, FC2) *Bero-hotz zirkuitua* izendapenarekin; bestalde, eskumako grafikoan aire tratamendurako unitateak daude (CC, HC, HR eta H) zeintzuek *AHU zirkuitua* izenpean dauden.

Orduan, periodo bakoitzeko osagai aktiboak erraz azter daitezke (esaterako, orientazioa dela eta, FC2 ia ez dago neguan piztuta eta HC, ordea, disipazio osagaia da uda garaian).



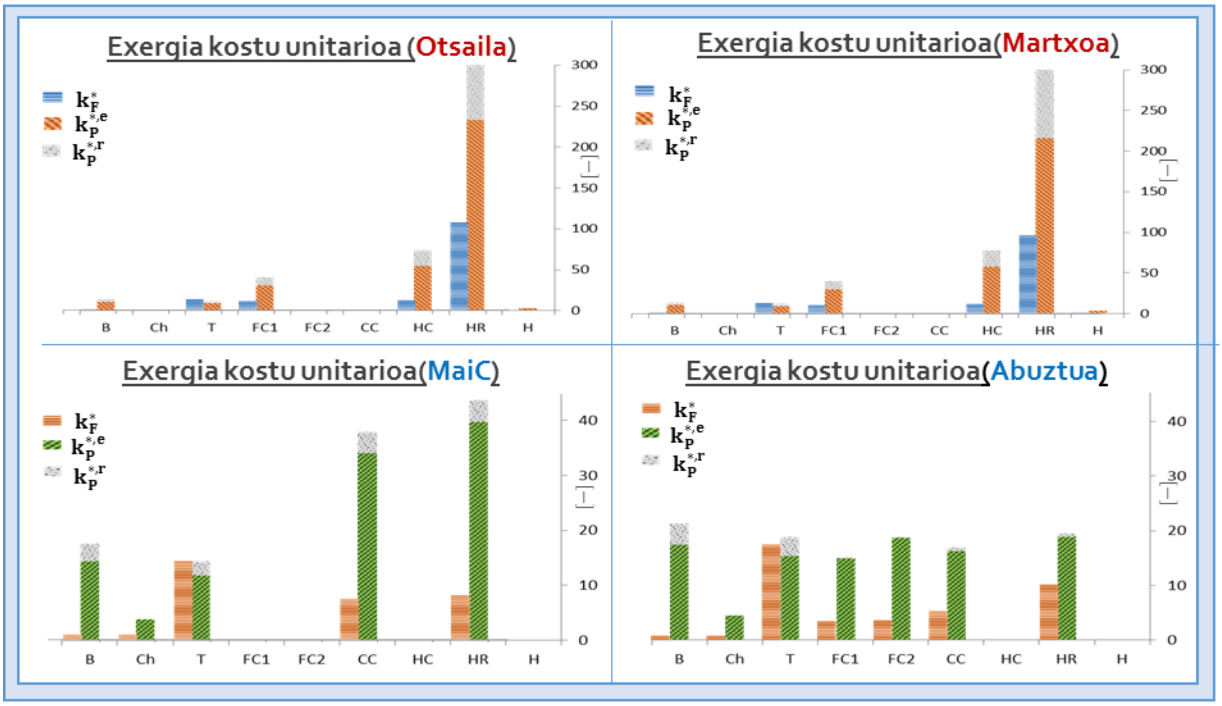
Irudia C. 25 Urtean zeharreko hilabeteko batez besteko kontsumo unitarioa

Hilabeteko batez besteko kostu exergetikoaren balioa baldintza dinamikoen arabera aldatzen doa. Azken finean, k_i osagaien parametro estatikoez gain (bero transmisio koefizientea, biltegiaren bolumena, etab.) termodinamika aldagai aldakorren (pilatze tenperatura, galdararen karga partziala, etab.) zein kanpo baldintzen arabera ere baitago (tenperatura eta hezetasuna). k_B-ren arabera, adibidez, galdarak kontsumoa handitzen du hozkuntza periodoan Bren itzulera tenperatura gertuago baitago bultzatze tenperaturatik T_B^{out}, nahiz eta etekin energetikoa konstante mantendu.

Tamalez, k_i kurba ez konstanteek *funtzio-oker induzituak* deitutako efektuak eragiten dituzte eta funtzionamenduan aldaketak eragin ditzakete. Termoekonomia aplikazioetan aintzat izan behar dira horiek, kasurako, diagnosian edo sistemen optimizazioan.

Gainera, sorkuntza taldeekin bat datozen itzulezintasun handiak ikus daitezke: nahiz eta Baren etekin energetikoa % 95 baliotik gertu egon, exergetikoa % 12 baino baxuagoa da barne errekuntzaren energia narriadurak tartean. Era berean, Ch-aren etekin energetikoa unitatea baino handiagoa izan arren (EER > 4), etekin exergetikoa % 30 baliotik gertu dago kalitate altuko elektrizitatea erabili baita kalitate baxuko bero fluxua lortzeko.

C.3.2.1.4.1. Kostu exergetikoak



Irudia C. 26 Kostu exergetiko unitarioak udarako eta neguko hilabete esanguratsuetan

Irudia C. 26n osagai produktiboen kostu exergetiko unitarioak agertzen dira berokuntza eta hozkuntza periodoko bi hilabeteetan zehar. Gainera produktuen kostua $k_{P_i}^{*,e}$eta $k_{P_i}^{*,r}$ balioetan banatu da.

Esan lez, osagaiaren produktuaren eta fuelaren kostu unitarioaren aldeak ($k_{P_i}^* - k_{F_i}^*$) muga teknikoen eta efizientzia gabezien itzulezintasunak adierazten ditu (beraz, bakoitzaren k_i kontsumoarekin lotzen da). Bestalde, fuelen kontsumo unitarioak ($k_{F_i}^*$) osagai bakoitzaren kokapen erlatiboarekin bat dator gainontzeko sistemen itzulezintasunak barneratuz (hortaz, beste osagaien kanpo efinzientzia gabeziekin lotzen da). Orduan, kostua energia katearen eraldaketen arabera garatzen doa.

Berokuntza periodoko emaitzak konparatzean datozen gogoetak egiten dira:

- ✓ Kostu formakuntza prozesuak joera berdina jarraitzen du periodo horretan.
- ✓ HR, ikuspegi exergetikotik aztertuta, itzulezintasun handiko osagaia da (k_{HR}~3) produktuaren kostu unitarioa $k^*_{P_{HR}}$ fuelaren kostua baino ia 3 aldiz handiagoa baita $k^*_{F_{HR}}$.
- ✓ HR produkzio katearen amaierako elementutzat har daiteke aire akitua botatzea baita horren helburua eta aire garbia sartzea. Beraz, gainontzeko osagaien itzulezintasunak barneratzen dituenez $k^*_{F_{HR}}$ balio altua dauka.
- ✓ Bigarren legearen ikuspegitik, HRren erabilpena negu garaian kostu exergetikoan igoera nabaria dakar.

Emaitzak *hozkuntza* garaian ebaluatuz gero ikusten da:

- ✓ Kostu formakuntza prozesua oso sentikorra da hozkuntzako hilabeteekiko.
- ✓ Hozkuntzarako uraren kostu unitarioa $k^*_{P_{Ch}}$ maiatzetik abuztura igotzen da k_{Ch}-ren igoera medio (exergia etekinaren jaitsiera). Kostu hori $k^*_{F_{CC}}$ formakuntzaren arduraduna ere bada.
  Gainera, $k^*_{F_{CC}}$ balioan parte hartzen dute: CCaren ponpa elikatzeko elektrizitateak eta HCaren exergia suntsiketa (zein k_B-arekin lotzen den). Halaber, $k^*_{P_{CC}}$ lotuta dago k_{CC}-arekin eta abuztuan jaitsi egiten da.
- ✓ FCen hotz produkzioaren kostuak ($k^*_{P_{FC1}}, k^*_{P_{FC2}}$) ATUaren produkzio kostuen antzekoak dira k_{FC} balio altuengatik. Hortaz, bigarren legearen ikusmiratik, FCaren erabilpena sorkuntza laguntzaile gisa ez da aukerarik egokiena.

C.3.2.1.4.2. Kostu exergoekonomikoak

Analisi exergoekonomikorako datu ekonomikoak behar dira. Taula C. 24n taldeen erosketa prezioak agertzen dira eta baita baliabideen kanpo kostu unitarioak ere.

Taula C. 24 Kanpo datuak: osagaien erosketa kostua eta datu ekonomikoak

Osagaia	Erosketa kostua
B	7,934 €
Ch	44,062 €
T	7,137 €
FC1	693 €
FC2	693 €
CC	1,040 €
HC	600 €
HR	3,023 €

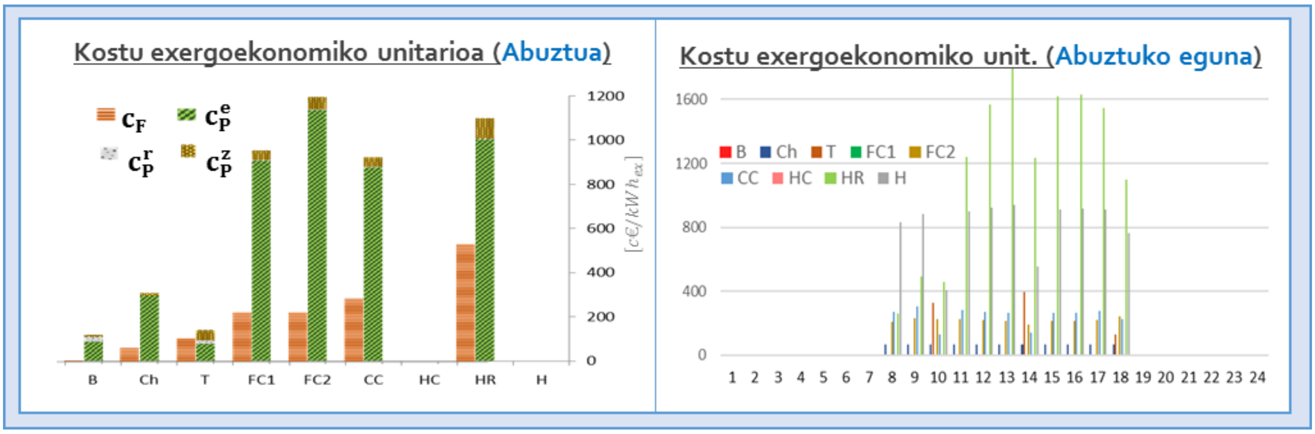
Osagaia	Erosketa kostua
H	4,252 €
Mc	187 €
Mh	114 €
M1	114 €
M2	187 €
M3	114 €
D	100 €
Bc	200 €

Datu ekonomikoak	
Urteko interes efektiboa i	0.05
Bizitza erabilgarria (urteak)	20

Baliabidea	$[c€/kWh_{en}]$
Elektrizitatea	21.81
Gas naturala	5.27

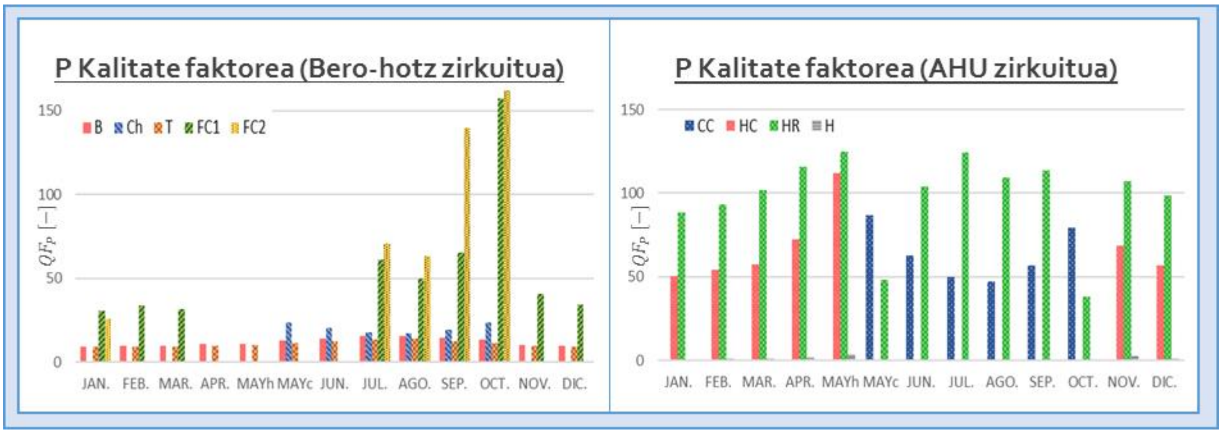
Hozkuntza periodoko hilabetearen (abuztua) emaitzak Irudia C. 27n daude non produktuen kostu unitarioa formakuntza prozesuaren arabera banatu den: $c^{e}_{P_i}$ produktu erabilgarriaren, $c^{r}_{P_i}$ hondakinen eta $c^{z}_{P_i}$ kanpo baliabideen formakuntza kostuan, hain zuzen.

Kostu exergoekonomiko unitarioaren joera (c€/kW$_{ex}$) eta kostu exergetikoaren joera (kW$_{ex}$ /kW$_{ex}$) berdintsuak dira nahiz eta itzulezintasunen kostu kokapenaz gain datu ekonomikoak erabili (€) diren c kalkuluentzako. Irudia C. 27n c_{F_i}-aren orduko kostu exergoekonomikoak barneratu ziren termoekonomiaren moldagarritasuna adierazteko asmoz.



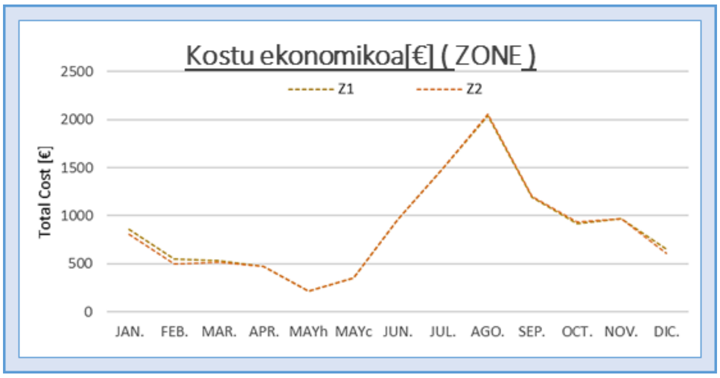
Irudia C. 27 Batez besteko eta orduko kostu Exergoekonomikoa hozkuntza periodoan

Emaitzak energia terminoetan emateko, Irudia C. 28n hilabeteko batez besteko kalitate faktoreak erakusten dira. ATU eraldaketa katearekin kalitate oso baxuak lotzen dira: berokuntzaren batez bestekoa $QF^{Heat}_{P,AHU}$, 57,84 da eta hozkuntzaren balioa $QF^{cool}_{P,AHU} = 51{,}18$.



Irudia C. 28 Urtean zeharreko batez besteko kalitate faktorea

Amaierako produktuen hilabeteko kostu ekonomiko totala (Zone1 eta Zone2-ko eskariak) Irudia C. 29n batzen dira eta horien zenbakizko datuak Taula C. 25n daude.



Irudia C. 29 Amaierako produktuaren batez besteko kostu totala urtean zehar

Jakina denez, laburbilduz, "hotza beroa baino garestiagoa da".

Taula C. 25 Hilabeteko kostu totala produkzioarekin eta hondar sorkuntzarekin zein kostu finkoekin lotua

		Hilabeteko guztizko kostu ekonomikoa [€]												
		URT.	OTS.	MAR.	API.	MAlh.	MAlc	EKA.	UZT.	ABU.	IRA.	URR.	AZA.	ABE.
Z.1	C_P^{e+r}	638 €	401 €	370 €	356 €	182 €	347 €	955 €	1,482 €	2,032 €	1,180 €	901 €	473 €	463 €
	C_P^z	221 €	146 €	159 €	113 €	31 €	6 €	10 €	6 €	7 €	9 €	21 €	497 €	187 €
Z.2	C_P^{e+r}	599 €	367 €	357 €	356 €	182 €	347 €	955 €	1,487 €	2,051 €	1,196 €	916 €	473 €	436 €
	C_P^z	207 €	135 €	154 €	113 €	31 €	6 €	10 €	6 €	7 €	9 €	21 €	496 €	177 €

C.3.2.2.2. *Emaitzen eztabaida*

Termoekonomia analisiak energia sistema baten kostu formakuntza prozesua ulertzen laguntzen du. Exergia parametro arrazional gisa erabiltzen da eta kostua itzulezintasunen arabera kokatzen da.

Ikerketa egin aurretik exergia balio totalekin ikasketa egingo den edota, alderantziz, exergiaren atal kimikoan, termikoan eta mekanikoan bereiztuko den erabaki behar da. Banaketak emaitzak hobetzen ditu baina esfortzua askotan handiagoa da ebazpenen aurreratzea baino. Beraz, kasu horietan ondorioak antzekoak dira eta ez dago konplexutasuna gehitzeko arrazoirik.

Adibide honetako (iii) ikerketa kasuan, metodo sistematiko eta zalantzarik gabekoa garatu da lehen aldiz Palermoko (Italia) eskola bateko ATU sistemetan termoekonomia dinamikoaren azterketa aplikatzeko; sistemak konfort termikoa asetzen baitu barneko aire kalitatea eta tenperatura eta hezetasun baldintzak kontuan hartuz.

Proposamen orokorra ematen zaio ST aplikazioari. Super egitura batekin operazio baldintza dinamiko guztiak jasotzen dira (nahiz eta kontrola etorkizunean aldatu). Zenbait osagaiek horien egitura produktiboa aldatzen dutenez urtearen periodoaren arabera (baita osagai produktibo izatetik disipazio elementura igaro ere) zenbait doikuntza egin dira. Horrela, osagai bakoitzeko kostu exergetiko eta exergoekonomiko unitarioak erraz kalkulatzen dira dagokion denbora tarteko egitura produktiboaren arabera. Zenbait gako ematen dira bigarren legearen moldagarritasunari eta aplikazioari dagokionez. Sistema osoaren kanpo baliabideen kontsumoarengatik urteroko kostua 19.502 € da eta inbertsio, mantenu eta operazio kostuen balioa 2.785 € da.

C.4. **ONDORIOAK**

Exergiaren metodo arruntak ez du baliabide osotasunarentzako osagaien itzulezintasunen araberako eragina adierazten, hau da, ez da gai kostuaren zein zati dagoen talde bakoitzaren exergia suntsiketarekin lotuta ebaluatzeko. Helburu hori betetzeko, ordea, termoekonomia sortu zen termodinamikaren bigarren legea ekonomia kontzeptuekin batzeko. Beraz, kostu exergetikoak itzulezintasun bakoitzari sistemaren osotasunaren arabera pisu bat emateko erabiltzen da eta, exergia kostuak ikasteko, instalazioaren egitura produktiboa eraiki behar da. Termoekonomia sinbolikoak (ST) analisi hori baimentzen du eta guztiz egokia da eskala handiko instalazioentzat.

Izatez, kostuak sistemaren energia bihurketen eraginkortasunak estuki lortzen ditu; beraz, plantan zeharreko kostuen mapak ahalbidetzen ditu puntu kritikoen zehaztapenak eta premia handieneko hobekuntza estrategikoentzako identifikazioak. Giltzarria kostuaren definizioan datza eta ikerketa hori exergian oinarritzen da.

Orduan, edozein prozesuko itzulezintasuna (E_D) sistemaren sarreraren eta irteeraren arteko exergiaren aldea lez kalkulatzen denez sistema termodinamikoaren baldintza *fisiko*ekin estuki lortzen da.

Bestalde, kostu exergetikoak prozesu *produktibo*an du funtsa eta ez baldintza termikoetan, beraz, prozesuaren perfekzio mailaren araberakoa da. Hortaz, egitura fisiko bakar batek *egitura produktibo* ezberdinak dauzka F-ren eta P-ren definizioa eztabaidagarria izan daitekeelako. Orduan, analistaren helburuaren eta irizpidearen arabera moldatzen da. Hori da, preseski, termoekonomiaren arazoetan handienetako bat.

Horretaz gain, **B Kapitulu**an esan antzera, masa eta energia balantzeak nahikoak dira energia sistema bat diseinatzeko, optimizaziorako eta diagnosirako. Exergia balantzea berez beharrezkoa ez izan arren, informazio gehigarria ematen du fluxu bateko lan erabilgarriaren arabera. Erabilgarritasunaren kontzeptua erabiliz (ikuspegi ekonomikoa barneratuz, alegia), sisteman zehar energia narriadura prozesuaren arabera kostu exergetikoaren banaketa irudia lortzen da.

Lortutako aurrerapenak aintzat hartzeagatik ere, datorren galdera sortzen da: zergatik da erabilgarria edo beharrezkoa sistema baten jarrera dinamikoaren irudi exergoekonomiko bat izatea? Erantzuna eztabaidagarria da zeren, azken batean, helburua diseinua hobetzea izaten ohi da (diseinurik egokienak bizitzan zeharreko *kostuak* minimizatzen ditu) eta, horretarako, diseinu aldagaiak ($\bar{\tau}$) moldatu behar dira. Jakina denez, exergia zenbait parametro intentsiboekin eta estentsiboekin eraikitzen da. Bestalde, diseinuaren optimizazioa prozesu iteratiboa da eta optimo global bat lortu arte errepikatu behar da; beraz, exergoekonomiari dagokionez, egiazko optimo bat ezin da exergien loturen ondorioz lortu ($E_1 = f(\bar{\tau}), E_2 = f(\bar{\tau}), E_1 = f(E_2)$).

Hala eta guztiz ere, exergia analisiak fluxuak homogeneizatzen ditu energiaren kalitatearen arabera eta osagaien eta sistemen arteko alderaketa egokiagoa ahalbidetzen du. Beraz, *exergia kostua* minimizatzea helburutzat hartu behar da, baina, bidea diseinu parametroen $\bar{\tau}$ eraldaketa izan behar da.

Eraikinaren energia sistemaren kudeaketak jarrera dinamikoa eskatzen du etengabeko eraldaketengatik. Horregatik, STaren prozedura dinamiko bat garatu da, non era globalean ebazten dituen egitura produktibo aldakorraren gakoak (gainera, termoekonomiaren aplikazio dinamikorako software bat **Annex**-ean garatzen da).

Halaber, arreta berezia eman zaie 3-bideko balbulei eta inertzia osagaiei. V3Vak hiru ekonomia ikuspuntutik ikasi dira: sinplea, inkrementala eta disipazio ikuspegitik, eta, konfigurazio horiek ikerketa kasu ezberdinetan aplikatu dira. Era berean, inertzia osagaiak adierazteko egitura produktiboa garatu da i_{st} eta o_{st} fluxuen bitartez.

Nahiz eta aldakuntza dinamikoak konplexutasunak barneratu, beharrezkoa da eraikinekin lan egin nahi bada. Beraz, oso ikerketa kasu zaila analizatu da metodoaren aplikazio gida izan dadin non osagai batzuen jarrera produktiboa edo disipatiboa urtearen periodoaren araberakoa den.

Exergia oinarri berdinetan du *exergoinguru* zientzia arloak zeinek ingurugiro inpaktuak itzulezintasunen arabera zenbakitzen dituen. Biek, exergoekonomiak zein exergoinguruak energia auditoretzetan erabil daitezke galera lekuak identifikatzeko eta kostu ekonomikoen zein inguru kostuen arabera sailkatzen dituen etorkizuneko hobekuntzak egiteko. Gainera, sintesirako eta diagnosirako inplementa daitezke, kostu formakuntza prozesuaren informazioa eta termodinamika, ekonomia zein ingurugiro inpaktuen parametroen arteko loturak eta osagaien zein sistemen arteko elkarrekintzak ematen dituelako.

Beraz, termoekonomia metodologiaren helburua hobekuntza sustatzea da eraginkortasuna igotzeko, gastuak murrizteko eta kutsatzaile igorpenak jaisteko. Tamalez, teoria ez dago guztiz osatua iragarpen estatistikoetan, erabaki eztabaidagarrietan, kostu estimazioetan, eta abarretan oinarritzen delako. Halere, bigarren legearen aplikazioa mundu mailan ospea hartzen ari da eta erabakiak hartzeko tresna baliotsua da. Horri esker, energia aurrezpenaren eta ingurugiro zainketaren helburuak pixkanaka lortzen hasi dira.

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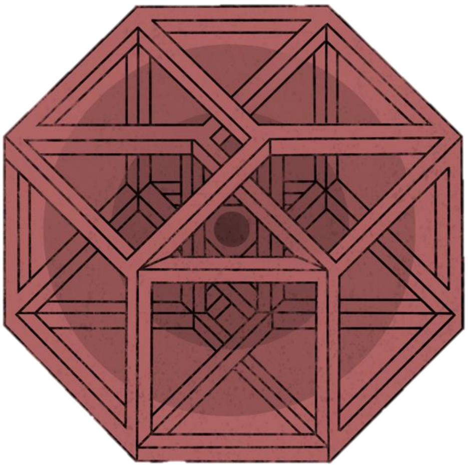


D KAPITULUA

Eraikinetan diagnosi termoekonomikoa

eman ta zabal zazu
UPV EHU

D KAPITULUA

AZPIINDIZEAK

T	Totala
e	Sistemako sarrerak
s	Sistemako irteerak
n	Osagai kopurua
m	Sistemaren fluxu kopurua

GAININDIZEAK

o	Erreferentzia
ref	Erreferentzia
$real$	Egoera erreala
$free$	Baldintza askea
$control$	Kontrol sistemaren esku sartzea
$anom$	Anomaliak

SINBOLOAK

T	[ºC]	Tenperatura
$\dot{m}$	[kg/s]	Masa emaria
c_P	[kJ/kgK]	Bero ahalmena
UA	[W/K]	Guztizko bero transferentzia koefizientea
$\dot{H}$	[kW]	Entalpia fluxua
$\dot{Q}$	[kW]	Bero fluxua
$\mathbf{F}$	[kJ]	Fuel bektorea $(n, 1)$
$\mathbf{P}$	[kJ]	Produktu bektorea $(n, 1)$
$\mathbf{I}$	[kJ]	Itzulezintasun bektorea $(n, 1)$
$\mathbf{R}$	[kJ]	Hondakin bektorea $(n, 1)$
ΔF_T	[kJ]	Fuel inpaktua
$\mathbf{k}_F^*$	[kJ/kJ]	Fuelen koste exergetiko unitario bektorea $(1, n)$
$\mathbf{k}_P^*$	[kJ/kJ]	Produktuen koste exergetiko unitario bektorea $(1, n)$
$\mathbf{c}_F$	[kJ/kJ]	Fuelen koste exergoekonomiko unitario bektorea $(n, 1)$
$\mathbf{MF}$	[kJ]	Funtzio-oker bektorea $(n, 1)$
$\mathbf{DF}$	[kJ]	Disfuntzio bektorea $(n, 1)$
$\mathbf{MF}^*$	[kJ]	Funtzio-okerren kostu bektorea $(n, 1)$
$[\mathbf{MF}]$	[kJ]	Funtzio-oker matrizea (n, n)
$[\mathbf{DF}]$	[kJ]	Disfuntzio matrizea (n, n)
κ_{ij}	[kJ/kJ]	Exergia kontsumo marginala
$\psi_{MF_i^*}$	[kJ/kJ]	Funtzio-okerren inpaktu adierazlea
$\langle\mathbf{PF}\rangle$	[kJ]	Banaketa matrizea r_{ij} (n, n) *PF* adierazpena
$\langle\mathbf{KP}\rangle$	[kJ]	Kontsumo unitarioen banaketa matrizea (n, n), *PF* adierazpena
${}^t\langle\mathbf{F_T F}\rangle$	[kJ]	Osagaien kanpo baliabideen proportzio bektorea $(1, n)$
$\lvert\mathbf{I}\rangle$	[kJ]	Operadore matriziala (n, n), *PF* adierazpena
$\lvert\mathbf{P}\rangle$	[kJ]	Operadore matriziala (n, n), *PF* adierazpena
$\lvert\mathbf{R}\rangle$	[kJ]	Operadore matriziala (n, n), *PF* adierazpena
π	[*][4]	Prozesua ezagutarazteko aldagaia

[4] [*] = dagokion aldagaiaren unitateak

ξ	[*]	Karakterizazio aldagaiak
k_j	[kJ/kJ]	j osagaiaren kontsumo exergetiko unitarioa
x	[*]	Aldagai independenteak

D KAPITULUA: ERAIKINETAN TERMOEKONOMIA DIAGNOSTIKOA

D.0. LABURPENA

Kapitulu honen helburua HVAC&R sistemetan diagnostiko termoekonomikoaren problema zuzena ebaztea da. Ideia nagusia irakurleei teoriaren onurak eta desabantailak adieraztea da ikuspegi kritikoa emateko. Azken batean, kapitulu honetan zeharreko ikuspegi zorrotzak eta garapenak ahalbidetzen baitu diagnosirako erabakia egitea.

Lehenengo atalean, fuel inpaktu metodologia aztertzen da eta bi adierazle berri proposatzen dira osagai bakoitzaren funtzio-oker kostua zenbatzeko. Gainera, adierazpen berriak ondorioztatzen dira anomalien eta kontrol sistemaren esku hartzearen kostu ekonomikoa kalkulatzeko. Halere, fuel inpaktu metodologia ez da guztiz eraginkorra anomalien sorburua identifikatzeko.

Bigarren sekzioan, fuel inpaktu formula nolakotasun kurbekin lotzen da aurreko anbiguetateak konpontzeko. Aurkikuntzaren gakoa bi metodologiatik bat ere ez dela hobeagoa da, biak osagarriak direlako. Bi teoriak batuz gero, anomalia bakoitzaren fuel inpaktua kalkula daiteke diagnostikoa modu errepikakorrean aplikatuz.

Azkeneko alderdian, diagnosiaren aplikazio errealerako bidea definitzen da aitzinako metodologia hobetuz. Prozedura zuzena eta argia garatzen da diagnostikoa eraikinen sistema energetikoetan era mekanikoan aplikatuz.

D.1. SARRERA

Instalazio bat ikuspegi ekonomikotik zein gizarte edo giro ikuspuntutik optimizatzen denean, prozesuko fase guztiak kontu handiz aztertu behar dira: talde egokien hautaketa, kontrol onenaren aplikazioa eta mantenu optimoa. Egoera errealean anomalia bat balego, erreferentziazko operazioa erraz zapuztu daiteke fuel kontsumoa igoz eta, ondorioz, operazio kostuak.

Sistemak oro har eskas mantentzen dira eta eraginkortasunaren narriadura lazgarria jasaten dute urteak aurrera joan ahala eta funtzio-okerren edo akatsen eragina medio [1]. Anomalia horiek ez dute funtzionamendua gelditzen baina plantaren etekinean degradazioa eragiten dute eta nahi ez diren eragin induzituen iturri izateaz gain, operazio nominalaren baldintza larriki kaltetu dezakete.

Definizioz, diagnostikoak gaixotasun edo arazo baten natura identifikatzeko zientzia da horren sintomak aztertuz. Beraz, termoekonomia diagnostikoa operazioa analizatzeko bigarren legeen oinarritutako teknika da. Jomuga anomalia (*funtzio-oker*) batek eragindako osagaiaren identifikazioa du exergia etekinen aldakuntzen analisiaren bitartez (edo horren alderantzizkoarekin, kontsumo exergetiko unitarioaz, k). Sistemaren energia berreskurapenaren potentziala kuantifikatzea ere du asmoa, egungo (operazio) eta egoera idealaren (erreferentzia) arteko baliabide kontsumo gehigarria ebaluatuz. Nahiz eta (erakutsiko den antzera) anomalien detekzioak ez duen termoekonomiaren beharrik, diagnostiko termoekonomikoaren funtsezko ideia da osagai ezberdinetan itzulezintasun aldakuntza berdina gertatu arren, produktu berdina mantentzeko baliabide gehigarrian eragin ezberdina daukala kokapenaren arabera [2]. Are gehiago eta beste metodologiak ez bezala, exergia eta termoekonomia analisiak teknika sistematikoak direnez edozein sistemetan aplika daitezke [3]; beraz, termoekonomia diagnostikoak anomalia guztietarako errepikapena ahalbidetzen du eta, horregatik, metodologia orokorra da.

Alderdi positiboak egonagatik ere, zenbait ahuldura dauzka diagnostiko termoekonomikoak. A.1.2 Atalean adierazi lez, exergiak termodinamikaren informazio sintetikoa erakusten duenez osagaien arteko harremanak aztertzeko ez da tresnarik egokiena. Osagaien arteko elkarreragiketa fisikoak oso konplexuak dira eta anomaliak kuantifikatzeko eta kokatzeko jarduera gai korapilatsuagoa da [4], zeinek exergia kontsumo unitarioaren konparaketa baino gehiago behar duen (beste hitz batzuetan, ezagutza termodinamiko gehigarria behar da). Hortaz, diagnostiko termoekonomikoaren aplikazioak, zenbaitetan, matematika ikuspegitik ahultasunak izan ditzake [2]. Halaber, efizientzia gabezien zergatiek ez dutenez zertan itzulezintasunen kokapenekin bat egin [5], ondorengo pausu bat behar da. Gainera, diagnosi termoekonomikoaren teoria batez besteko kostuetan oinarritzen da eta horiek ez dira diagnostiko helburuetarako balore objektiboak: alde batetik, batez besteko kostuek ez dute etorkizunean espero gabeko eraginen informaziorik ematen eta, beste batetik, ez dute sortutako lehenengo eta azkenengo produktuaren artean bereizten. Izatez, optimizazioa ere inplementatu nahi bada, kostu marginalak erabili behar dira.

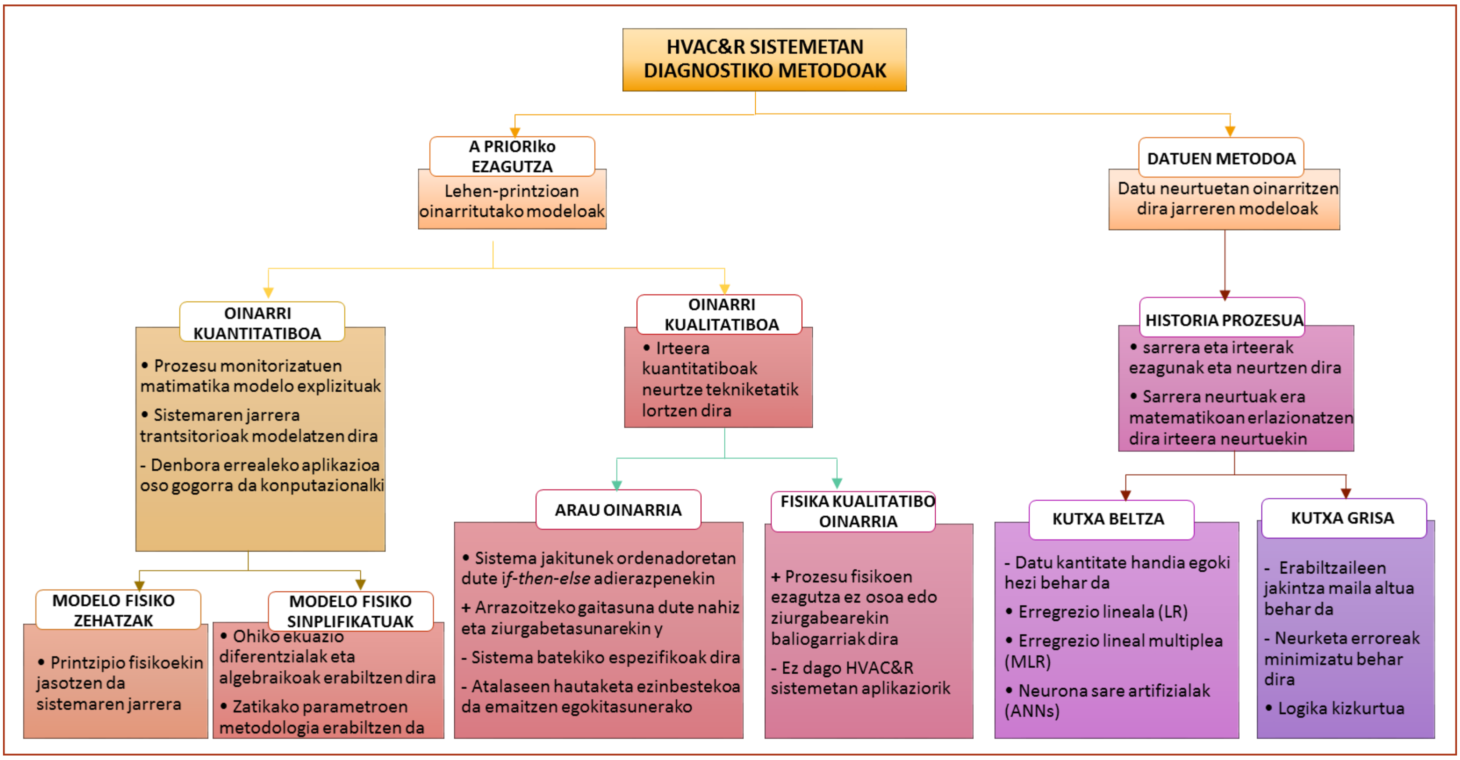
Ondorioz, termoekonomia adierazleen aplikazioak beti direnez subjektiboak [6], diagnostiko termoekonomiko klasikoa ikuspegi termodinamikotik aplikazio egokirako moldatu egin behar da eta hori da, preseski, kapitulu honen helburua.

D.1.1. Diagnostikoa aplikazio ez industrialetan

C.1 Atalean aipatu antzera, diagnostiko termoekonomikoaren garapena batez ere industrian izan da. Berez, energia plantetan akatsen detekzioa eta diagnostikoa ondo egonkortuta badago ere, haurtzaroan dago berokuntza, aireztapen, aire girotu eta hozkuntza (HVAC&R) sistemetan. Izatez, ikerketa ez zen 80ko hamarkadaren bukaerara eta 90oko hamarkadaren hasierara arte hasi [7], beste gauza askoren artean, datozen arrazoiak medio:

- Orokorrean, eraikin gehiengoen HVAC&R sistemek sentsore kantitate mugatua daukate (kontrol helburuetarako beharrezkoak soilik daude) eta prognosia, ordea, sistemaren operazioa uneoro monitorizatuz lortzen da.
- Eraikin askoren eraginkortasun arazoak kontrolaren oreka automatikoarekin berdintzen direnez, erabiltzailerik ez dute deskonforta somatzen, nahiz eta energia kontsumoa eta operazio kostua igo [8].
- Diagnosirako edo detekziorako metodoak hautatu aurretik, akatsen aurre ulermen sakona beharrezkoa da. Tamalez, metodo oso gutxik diagnostika dezakete akats baten sintoma ezberdinak denbora tarte ezberdinetan eta sistemaren operazioaren dinamismoaren arabera daude.
- Aldibereko akats anitzek kausak eta eraginak determinatzeko zailtasunak barneratzen dituzte.

Mugak egon arren, zenbait diagnostiko metodo eta mota garatu ziren HVAC&R sistemetarako azken hamarkadetan eta Irudia D. 1n batzen dira (berrikusketa sakona Erref. [9]-an dago). Alabaina, metodologia horiek akats jakinak identifikatu arren, ez dute (1) akatsak larriak edo



Irudia D. 1 HVAC&R sistemetan diagnosi metodoen deskripzio laburra

mesprezagarriak diren adierazten, ezta (2) akatsaren eraginez sistemaren eraginkortasunaren narriadura era kuantitatiboan ebaluatzen.

Bestalde, aurreko *metodologia termoekonomikoek* (1) diseinuz kanpoko operazio baldintzak analizatu, (2) aldi baterako akatsak identifikatu (banakakoak edo anitzak) eta (3) akats bakoitzaren "fuel inpaktua" neurtzen dute ohiko diagnosi metodoarekin bi operazio baldintzak alderatuz [10]. Aitzitik, ez dute akatsek bultzatutako eraginkortasun ezak murrizteko estrategiarik eskaintzen [11].

Hala eta guztiz ere, eta bigarren legeko aplikazioetan oinarrituz gero, zenbait termoekonomia diagnostiko aplikatu ziren HVAC&R sistemetan 2010ko hamarkadan eta, kapituluaren helburua aintzat hartuz, aipamen berezia behar dute.

Termoekonomiaren aplikazio konbentzionala egin zen aire giroturako sistema batean [12] non, energia plantetan ez bezala, amaierako produktuan aldakuntza dagoen. Gainera, sistemaren produkzio egituraren definizioan arazoak zeuden. Finean, anbiguotasun kontzeptualak zeudelako bereziki *kondentsadore*an (disipazio osagaia) eta *itotze balbula*n (zeinek exergia mekanikoaz elikatu eta hozkarian exergia termikoaren igoera eragiten duen) [13]. Halere, soluzioak eskaini ziren, alde batetik, akatsak eragindako disipazio unitatetako exergia suntsiketaren aldakuntza kokatuz eta, bestetik, exergia fisikoa zati termikoan eta mekanikoan bereiztuz [1].

Are gehiago, zenbait hobekuntza metodologiko barneratu ziren diagnostiko termoekonomikoa inplementatzeko: (1) fikziozko osagaien distortsioak horiek egitura produktibotik ezabatuz saihestu ziren, (2) amaierako produktuaren aldakuntza nulua onartu zen exergia fluxu oro *hozkuntza ahalmen faktore* batekin biderkatuz [12] eta (3) hozkariaren eragin gutxietsiak iragazi ziren. Gainera, diagnosi teknikaren sentikortasun analisia eztabaidatu zen [13] eta Erref.[1]-n funtzio-okerrak bereizteko beste aukera bat eskaini zen. Ikerketa kasu berbera [14] lanean erabili zen baina kasu horretan, ordea, egitura produktibo aldatuaren metodoarekin.

Erref.[8]-an, bestalde, fuel inpaktuaren (F_T) eta nolakotasun kurben (CC) diagnostiko termoekonomikoaren metodoak ebaluatu ziren (zeintzuek sakon garatuko diren kapituluan zehar) hozkuntzarako sistema komertzial batean adierazle amankomun batekin.

Zoritxarrez, zerrendatutako aplikazio denetan operazio baldintza bakarra ikertu zenez *egoera egonkorrean* ez ziren karga maila ezberdinen etekinak aintzat hartu.

Gainera, diagnostiko termoekonomikoaren erronkarik handiena *problema zuzena*ren ebazpena da zeinen helburua anomaliak hauteman eta kokatzea den. Eginkizun zaila da eta emaitzen fidagarritasuna ez da oraindik baliotu [15]. Memento honetara arte, soilik diagnosiaren *alderantzizko problema* ebatzi da, hots, osagai zehatzen anomalia jakinen *ezagutza*rekin horien eraginen kuantifikazioa termino termoekonomikoetan, esaterako, fuel inpaktua eta funtzio-okerrak.

D.1.2. Orokortasunak

Diagnostiko termoekonomikoaren lehenengo urratsak eta horien garapena [16]-n daude. Esan moduan, diagnostikoaren prozedurak sistemaren bi lan baldintzen alderaketan oinarritzen dira: *erreferentzia* operazio egoera, anomaliarik gabe (o azpiindizearekin adierazten da eta oro har diseinu baldintza da) eta operazio egoera *erreala* (plantaren momentuko egoerari dagokio eta, orokorrean, guztizko efizientzia txikiagoa dauka gutxienez akats bat duelako). Beste hitz batzuetan, anomalia edo *funtzio-oker intrintseko* batek operazio egoeran aldakuntzak eragiten ditu erreferentzia baldintzarekin alderatuz bero, zenbait parametro konstante mantentzean; adibidez, produkzio berbera mantentzen bada, baliabide kontsumoa erreferentzia egoeraren ezberdina izango da osagai batzuen funtzio-oker intrintsekoek $\Delta k = k - k^0$ bat eragingo dutelako.

Lan baldintza biak sistema berberari dagozkionez, egitura sinboliko berbera daukate [17]. Diagnostikoa gai izan behar da etekinaren desbideraketak antzemateko, zergatien sustraiak kokatzeko eta horien eraginak kontsumo gehigarrian edo inpaktu ekonomikoan adierazteko. Alabaina, diagnostikoa aplikatzean, analistak ez daki zenbat anomalia dauden ezta horien kokapena ere; halaber, itzulezintasunen kokapenak ez du kausalitatearekin bat egiten.

Diagnostiko termoekonomikoa aplikatzeko aurretiazko zenbait eskakizun daude:

- Erreferentzia egoeraren definizio egokia behar da.
- Operazio eta erreferentzia baldintzak aski gertu egon behar dira modelo lineala egiaztatzeko (perturbazio txikien hipotesia) [4].
- Diagnostikoaren xederako, kontrol bolumen definizio zehatza eta egitura produktiborako fluxuen zehaztapena behar dira. Hori ezin da exergia balantze soilekin lortu eta **C. Kapitulu**ko bi termoekonomia kontzeptu behar dira: egitura produktiboa eta kostu exergetikoa.

D.2. FUEL INPAKTUAREN DIAGNOSI METODOLOGIA

Plantaren fuel kontsumo totalaren aldakuntzan osagai funtzio-okerraren ekarpena *fuel inpaktu formula*rekin lortzen da, zein lehenengoz Erref.[6]-n aurkeztu zen. Fuel inpaktua operazio errealeko baliabide kontsumoaren (F_T) eta erreferentzia baldintzen (F_T^0) arteko aldea da:

$$\Delta F_T = F_T - F_T^0 \tag{D. 1}$$

Adierazpena bi eretan irakur daiteke eta berehala garatuko dira.

D.2.1. Fuel inpaktua

Fuel inpaktua espero gabeko anomaliek eragindako itzulezintasun aldakuntza eta baliabide kontsumo gehigarriak bultzatutako amaierako produktuaren aldaketa gehituz lortzen da, alegia:

$$① \quad \Delta F_T = {}^{\mathbf{t}}\mathbf{u} \cdot [\boldsymbol{\Delta}\mathbf{I} + \boldsymbol{\Delta}\mathbf{P_S}] \tag{D. 2}$$

Produkzio aldakuntzan operazio eta erreferentzia baldintzen arteko aldea da:

$$\boldsymbol{\Delta}\mathbf{P} = \mathbf{P} - \mathbf{P^0} \tag{D. 3}$$

Itzulezintasun hazkundea ($\boldsymbol{\Delta}\mathbf{I}$) da:

$$\boldsymbol{\Delta}\mathbf{I} = \left((\mathbf{K_D} - \mathbf{U_D}) \cdot \mathbf{P}\right) - \left(\left(\mathbf{K_D^0} - \mathbf{U_D}\right) \cdot \mathbf{P^0}\right) = \boldsymbol{\Delta}\mathbf{K_D} \cdot \mathbf{P^0} + (\mathbf{K_D} - \mathbf{U_D}) \cdot \boldsymbol{\Delta}\mathbf{P} \tag{D. 4}$$

Beraz, itzulezintasunen igoera bi osagaietan banatzen da; lehenengoa, osagaien berezko exergia kontsumo unitarioaren aldakuntzagatik dator eta, bigarrena, osagai bakoitzak produkzioan eragin beharreko aldakuntzan oinarritzen da operazio egoera berdinera moldatzeko. Lehenengo osagaiari *funtzio-oker* deritzo, $\mathbf{MF}$:

$$\mathbf{MF} = \boldsymbol{\Delta}\mathbf{K_D} \cdot \mathbf{P^0} \tag{D. 5}$$

Bigarren osagaia *disfuntzioa* da $\mathbf{DF}$ eta osagaietan sortzen da beste taldeen funtzio-okerrengatik. Osagaiaren itzulezintasun aldakuntza da beste sistemen funtzio okerrek eragindako lekuko produkzio ezberdinagatik [18]:

$$\mathbf{DF} = (\mathbf{K_D} - \mathbf{U_D}) \cdot \boldsymbol{\Delta}\mathbf{P} \tag{D. 6}$$

Ondorioz, fuel inpaktua honela adieraz daiteke:

$$① \quad \Delta F_T = {}^{\mathbf{t}}\mathbf{u} \cdot [\mathbf{MF} + \mathbf{DF} + \boldsymbol{\Delta}\mathbf{P_S}] \tag{D. 7}$$

D.2.1.1. MF eta DF analisia

Analisi sakonerako edo diagnosiaren ulermena hedatzeko, Ek.(D. 4)-a beste modu batean adierazi daiteke funtzio-oker eta disfuntzio matrizeen bitartez. Antolaketa horrek fuel inpaktuaren jatorria erakusten du, hau da, osagai baten kontsumoaren aldaketa justifikatzeko arrazoiak ahalbidetzen ditu bertako anomaliarengatik ($\mathbf{MF}$ bektorearen bidezko informazioa) eta beste taldeen anomaliengatik ($[\mathbf{DF}]$ matrizetik informazio eratorria).

Hain zuzen, $\mathbf{MF}$ bektorea kanpo funtzio-okerren bektorean ($\mathbf{MF_e}$) eta barne funtzio-okerren bektorean (${}^{\mathbf{t}}\mathbf{u} \cdot [\mathbf{MF}]$) bana daiteke. Lehenengo terminoa kanpo baliabideen kontsumo exergetiko marginalaren aldakuntzak eragiten du (alegia, inguruarekin lotutako fluxuak), bigarren terminoa, ordea, $[\mathbf{MF}]$ matrizearen eta bektore unitario irauliaren arteko biderketarekin lortzen da zeinek osagaien exergia kontsumo marginalaren aldakuntza adierazten duen berezko etekinen narriadurengatik:

$$ {}^{\mathbf{t}}\mathbf{MF} = {}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k_e} \cdot \mathbf{P_D^0} + {}^{\mathbf{t}}\mathbf{u} \cdot \left(\boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0}\right) \tag{D. 8} $$

$$ \mathbf{MF_e} = {}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k_e} \cdot \mathbf{P_D^0} \tag{D. 9} $$

$$ [\mathbf{MF}] = \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0} \tag{D. 10} $$

Era berean, $\mathbf{DF}$ bektorea ere deskonposa daiteke kanpo baliabide kontsumoen disfuntzioan ($\mathbf{DF}_{\boldsymbol{e}}$) eta beste osagaien jarrera degradatuak eragindako disfuntzioan zein $[\mathbf{DF}]$ matrizearen eta unitate bektorearen arteko biderketa den ($[\mathbf{DF}] \cdot \mathbf{u}$).

Alegia, disfuntzioa honela banatzen da:

$$ \mathbf{DF} = |\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\mathbf{P_s} + \left(|\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0}\right) \cdot \mathbf{u} \tag{D. 11} $$

$$ \mathbf{DF_e} = |\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\mathbf{P_s} \tag{D. 12} $$

$$ [\mathbf{DF}] = |\mathbf{I}\rangle \cdot \boldsymbol{\Delta}\langle\mathbf{KP}\rangle \cdot \mathbf{P_D^0} \tag{D. 13} $$

Ek.(D. 12)-ko DF_{ie} osagaiak amaierako produktuaren disfuntzio kuota adierazten du $DF_{ie} = \sum_{h=1}^{n} \theta_{ih} \Delta P_s$. Bestalde, $[\mathbf{DF}]$ matrizearen DF_{ij} osagaiak taldeko itzulezintasun aldakuntza adierazten du beste j osagaiaren funtzio-okerraren eraginez: $DF_{ij} = \sum_{h=1}^{n} \theta_{ih} \Delta\kappa_{hj}\, P_j^0$, non θ_{ij} funtzio-oker efektuaren pisua den (hots, j osagaian sortutako itzulezintasuna i-ren produktu unitate bat lortzean).

Disfuntzio eta funtzio-oker matrizearen arteko harremana da:

$$ [\mathbf{DF}] = |\mathbf{I}\rangle \cdot [\mathbf{MF}] \tag{D. 14} $$

Horren arabera, produktu aldakuntzaren eragina adierazteko disfuntzioa funtzio-oker batek sortzen du. Beste hitz batzuetan, osagaien narriadura ez dago soilik berezko itzulezintasunen gehikuntzen menpe, aurreko osagaien funtzio ere baizik [18]. Amaierako produktua konstante izan behar bada, osagai akastuan baliabide gehiago beharko dira produktu berbera lortzeko eta, beraz, uretan gorako osagaiek lekuko baliabide gehiago sortu beharko dituzte. Orduan, disfuntzioa ezin da berez konpondu soilik funtzio-oker sortzailearen murrizketarekin.

D.2.1.2. Funtzio-okerren kostua

i osagaiaren funtzio-oker kostua (MF_i^*) beharrezko kanpo fuel kontsumo gehigarria da i taldearen funtzio-okerra medio. Fuel inpaktua kanpo kontsumo exergetiko marginalaren aldaketaren eta produktuen aldakuntzaren gehiketaren bitartez adieraz daiteke:

$$ ② \quad \Delta F_T = \left({}^{\mathbf{t}}\mathbf{k}_{\mathrm{e}} \cdot \mathbf{P}\right) - \left({}^{\mathbf{t}}\mathbf{k_e}^{\mathbf{0}} \cdot \mathbf{P^0}\right) = {}^{\mathbf{t}}\boldsymbol{\Delta}\mathbf{k}_{\boldsymbol{e}} \cdot \mathbf{P^0} + {}^{\mathbf{t}}\mathbf{k_e} \cdot \boldsymbol{\Delta}\mathbf{P} \tag{D. 15} $$

$\mathbf{k_P^*}$ balioa gehituz:

$$\Delta F_T = \left({}^{t}\mathbf{\Delta k}_e + {}^{t}\mathbf{k}_P^* \cdot \mathbf{\Delta}\langle\mathbf{KP}\rangle \right) \cdot \mathbf{P^0} + {}^{t}\mathbf{k}_P^* \cdot \mathbf{\Delta P_s} \qquad \text{(D. 16)}$$

Beraz, fuel inpaktua bi osagaietan banatzen da: lehenengoa funtzio okerraren kostua da kontsumo exergetiko marginal unitarioaren aldakuntzaren ondorioz zeinek baldintza errealetan kontsumitutako baliabide gehigarriak kontuan hartzen dituen. Beraz, $\mathbf{MF}^*$ bektore esleitua da:

$${}^{t}\mathbf{MF}^* = \left({}^{t}\mathbf{\Delta k}_e + {}^{t}\mathbf{k}_P^* \cdot \mathbf{\Delta}\langle\mathbf{KP}\rangle \right) \cdot \mathbf{P_D^0} \qquad \text{(D. 17)}$$

Eta bigarrena, kanpo produktuaren aldakuntzagatik sortutako funtzio-oker kostua da eta $\mathbf{MF}_e^*$ bektorearekin adierazten da:

$$\mathbf{MF_e^*} = \mathbf{k}_{\mathbf{P_D}}^* \cdot \mathbf{\Delta P_s} \qquad \text{(D. 18)}$$

orduan:

$$② \quad \Delta F_T = {}^{t}\mathbf{u} \cdot (\mathbf{MF}^* + \mathbf{MF_e^*}) \qquad \text{(D. 19)}$$

Fuel inpaktu erlazioa diagnosirako tresna lez erabiltzean zenbait alderdi izan behar dira kontuan [5]:

- Osagaiak funtzio-okerrik ez badu eta gainontzeko osagaietan disfuntziorik induzitzen ez baditu, haren funtzio-oker kostua nulua da.
- Osagai bakoitzaren funtzio-oker kostua berdina da osagaiak baldintza errealetan behartzen duen fuel kontsumo gehigarriarekin.
- Kanpo produktuaren aldakuntza badago, aldaketa horrek eragindako fuel inpaktu proportzioa aintzat izan behar da.

Ondorioz, i osagaiaren funtzio-oker kostuak MF_i^* exergia aurrezpen potentziala erakusten du osagai horretan erreferentzia egoera berrezarri egiten bada; eta produkzio kostuaren $MF_{e,i}^*$ informazioa da nahi gabeko amaierako produkzio gehigarriak eragindako kostu saihetsezina zein funtzio-okerra zuzenduz soilik aurreztu daitekeen.

Guztizko fuel inpaktuarekiko funtzio-oker kostuaren eta osagai bakoitzaren produkzio kostuaren esanahiak ulertzeko, bi ψ adierazle proposatzen dira:

$$\psi_{MF_i^*} = \frac{MF_i^*}{\Delta F_T} \qquad \text{(D. 20)}$$

$$\psi_{MF_{e,i}^*} = \frac{MF_{e,i}^*}{\Delta F_T} \qquad \text{(D. 21)}$$

Baliabide kontsumo gehigarri gehiena eragiten duena$\psi_{MF_i^*}$ adierazlerik handieneko osagaia izango da, beraz, akastun nagusia.

Fuel inpaktuaren bukaerako laburpena lez, bi ikuspegi daude. Alde batetik,①-en osagai bakoitzaren itzulezintasunaren aldakuntza da osagai bakoitzaren anomaliek eragindako funtzio-okerren eta disfuntzioen arteko gehiketa eta, hortaz, plantaren fuel inpaktu totala da osagai bakoitzaren itzulezintasunaren aldakuntza gehi plantaren produktu totalaren aldaketa. Beste alde batetik,② ikuspuntutik, osagai bakoitzaren fuelaren inpaktu totala da osagai horretako kontsumo exergetiko unitarioaren aldakuntzarekin lotutako itzulezintasun kuotaren eta amaierako produktuen aldakuntzaren eragin induzituen gehiketa.

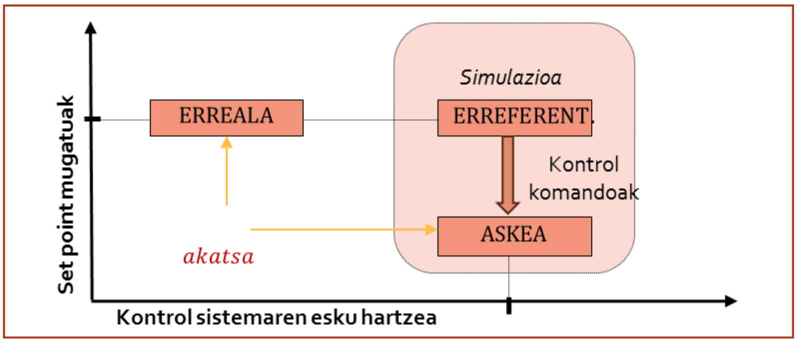
Irakurleak diagnosiaren sustraiak sakondu eta matematika adierazpenak garatu nahi baditu, [19] eta [15] erreferentziak dauzka.

D.2.2. Nahi gabeko eraginen iragazkiak

Baldintza errealen eta erreferentziaren arteko alderaketa baliagarria egiteko, zenbait eragin aurretiaz hartu behar dira kontuan [20]: *kontrol sistema esku-hartzearen eragina* eta *amaierako produkzioaren eragina*.

D.2.2.1. Kontrol sistemaren eragina

Adierazpen orokortzat, instalazio baten kontrol sistema osagai jakinen aldagaien set-point-etan oinarritzen da, esaterako, tenperaturak. Tenperatura horien balioak sistemaren egoera termodinamikoaren araberakoak dira. Anomalia batek gorabeherak sortzen ditu baloreetan eta kontrol sistemaren esku-hartzea dakar zeinek erreferentzia baldintzak aldatu eta funtzio-okerraren hedapenak saihesten dituen. Kontrol eragin hori iragazi egin beharko da erreferentzia eta operazio baldintzak ahalik eta hoberen konparatzeko eta jarrera baliokidea izateko. Baldintza artifizial bat lortzen da egoera errealetik erregulazio berdina inposatuz zeini *baldintza askea* deritzon eta era birtualean lortu behar den. Horrela, diagnosia baldintza askearen eta erreferentziaren arteko alderaketarekin egingo da eta, hortaz, funtzio-okerrak ez du erregulazio sisteman eragingo. Baldintza askeak baldintza errealeko akats (anomalia) berberak dauzka, baina kontrolaren komandoak erreferentziarekin bat datoz.



Irudia D. 2 Baldintza askea lortzeko era

Aitzinako lanetan, baldintza askea ikuspegi *matematikotik* lortzen zen [20]. Anomaliak aski txikiak izateagatik, egoera erreala eta erreferentzia gertu daude eta erregulazio parametro bakoitzaren eragina linealtzat har daiteke. Parametro bakoitzaren erregulazio ekuazioak idatzi ostean eta kontrol sistemarekin bat datozen Lagrange biderkatzaileak kalkulatu eta gero, planta modelatu egiten da egoera askearen balioak lortuz.

Halere, kapitulu honetan erregulazio sistemaren eragina iragazteko metodo berria aurkezten da. Matematika garapenaren ordez, baldintza askean simulazioaren bidez lortzen da zuzenean; egoera artifizial hori lortzeko erreferentzia baldintzatik hasi eta operazio baldintzan inposatzen da haren kontrola. Irudia D. 2n hiru baldintzak laburtzen dira: erreferentzia, erreala eta askea.

D.2.2.2. Guztizko produkzioaren eragina

Aurreko lanetan, diagnosia kanpo aldakuntzarik gabeko sistemetan aplikatzen zen [21]. Are gehiago, Erref. [6]-an diagnosia definitzen da anomaliak kokatzeko eta horiek eragindako kontsumo gehigarriak kalkulatzeko metodologia lez amaierako produktuaren ezaugarriak eta kantitateak konstante mantenduz gero.

Alabaina, arestiko zenbait lan argitaratu dira amaierako produktu bakarraren aldakuntzarekin, adibidez [13], non aldakuntza bakarra era errazean iragazi egiten den. Hala eta guztiz ere, eraikinen energia horniketa sistemetan, oro har, amaierako produktu nagusi bat baino gehiago dago, besteak beste, berokuntza, hozkuntza edo EUB eskariak. Irteera anitzak medio, produkzio aldakuntzaren eragina ($\mathbf{\Delta P_S}$) kontuan izan behar da.

D.2.3. Inpaktu ekonomikoa

Fuel inpaktu formula kostu exergetikoen terminoez gain *kostu exergoekonomiko* unitateen menpe idatzi nahi bada, datorren garapena jarraitu behar da: inpaktu ekonomikoa baldintza errealen fuel kostu totalaren eta erreferentzia baldintzaren arteko aldea da:

$$\Delta C_{F_T} = C_{F\,T} - C_{F\,T}^{\,0} \tag{D. 22}$$

Kontrol sistemaren esku-hartzearen ($\Delta C_{F_T}^{control}$) eta anomalien kostu ekonomikoak kalkulatzeko (diagnostikotik dator, $\Delta C_{F_T}^{anom}$) Ek.(D. 22) bi osagaietan banatzen da:

$$\Delta C_T = \left(C_{F_T} - C_{F_T}^{free}\right) + \left(C_{F_T}^{free} - C_{F_T}^{0}\right) = \Delta C_{F_T}^{control} + \Delta C_{F_T}^{anom} \tag{D. 23}$$

Orduan, inpaktu ekonomikoa Irudia D. 3n bezala laburtzen da:

Irudia D. 3 Inpaktu ekonomikoa zelan lortu

Kontrol sistemaren operazio kostua kalkulatzeko adierazpena da:

$$\Delta C_{F_T}^{control} = C_{F\,T} - C_{F\,T}^{\,free} = {}^{t}\mathbf{c_F} \cdot \mathbf{F_T} - {}^{t}\mathbf{c_F}^{\mathbf{free}} \cdot \mathbf{F_T^{free}} \tag{D. 24}$$

$\mathbf{c_F}$ izanik fuelen kostu ekonomiko unitarioa baldintza bakoitzean.

Anomalien kostu ekonomikoa aurreko prozeduraren antzekoa da:

$$\Delta C_{F_T}^{anom} = {}^{t}\mathbf{c_F}^{\mathbf{free}} \cdot \mathbf{F_T^{free}} - {}^{t}\mathbf{c_F}^{\mathbf{0}} \cdot \mathbf{F_T^0} = \mathbf{\Delta c_{F_e}} \cdot \mathbf{P^0} + \mathbf{c_{F_e}} \cdot \mathbf{\Delta P} \tag{D. 25}$$

$\mathbf{\Delta P}$ aldagaia barneratzen bada baldintza askean eta erreferentziaren artean, lortzen da:

$$\Delta C_{F_T}^{anom} = \left(\mathbf{\Delta c_{F_e}} + \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \mathbf{\Delta\langle KP\rangle}\right) \cdot \mathbf{P^0} + \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \mathbf{\Delta P_s} \tag{D. 26}$$

Anomalien inpaktu ekonomikoa ere banatzen da baldintza askearen eta erreferentziaren arteko funtzio-okerren kostu exergoekonomiko gehigarrian ($\mathbf{C_{MF^*}}$) eta kanpo produktuen aldakuntzen kostu exergoekonomikoan ($\mathbf{C_{MF_e^*}}$).

$$ {}^{t}\mathbf{C_{MF^*}} = \left(\Delta\mathbf{c_{F_e}} + \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \Delta\langle\mathbf{KP}\rangle\right) \cdot \mathbf{P^0} \quad \text{(D. 27)} $$

$$ {}^{t}\mathbf{C_{MF_e^*}} = \mathbf{c_{F_e}} \cdot |\mathbf{P}\rangle \cdot \Delta\mathbf{P_{s_D}} \quad \text{(D. 28)} $$

D.2.4. Ikerketa kasua

Esan antzera, nahiz eta diagnosiaren helburu erreala problema zuzenaren ebazpena izan, ikerketa kasuak aurkako bidea jarraitzen du teoria aplikatzeko eta interpretatzeko.

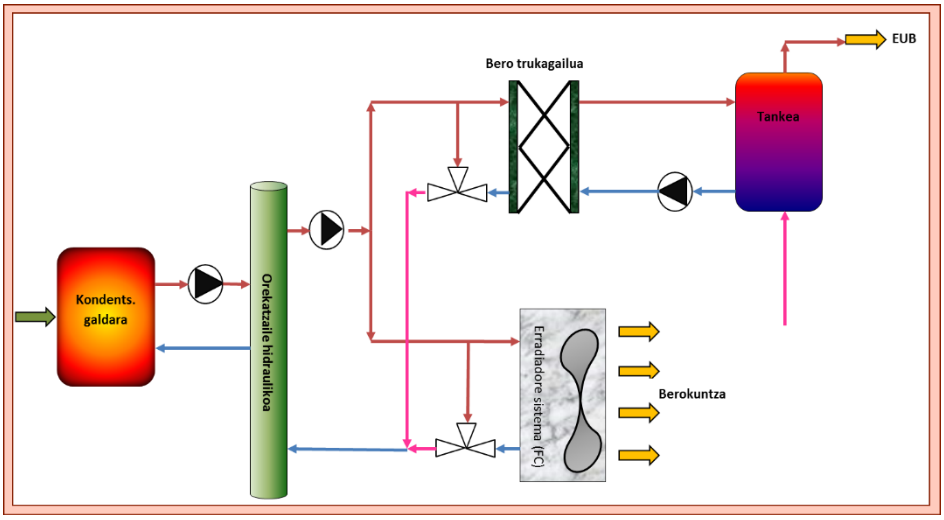
Beraz, datorren prozedura jarraituko da: instalazioa era dinamikoan modelatuko da Trnsys v17 programarekin [22] eta simulazio bikoitza gauzatu. Simulazio batek erreferentzia baldintza adierazten du eta besteak, aldiz, operazio baldintza anomaloa. Azkenekoak akats ezagun bat izango du osagai zehatz batean. Ondorioz, sortutako narriadura fuel eta ekonomia inpaktuen, funtzio-okerren, disfuntzioen eta funtzio-oker kostuen bidez ikasiko dira emaitza orokorrak era zorrotzean eta kritikoan ebaluatzeko.

Gainera, diagnostiko prozedurak kontrol sistemaren eraginak kontuan izango ditu horiek iragaziz. Diagnosi metodologiaren ekarpen berritzaile bat erakusten da non erregulazio sistemaren eraginak saihesteko bidea erakusten den. Baldintza askea garapen matematikotik lortu ordez, simulazioz lortzen da.

Are gehiago, amaierako produktuaren aldakuntza kontuan hartuko denez fuel inpaktua lotzen da anomalien itzulezintasun handitzearekin eta amaierako produktuaren aldaketarekin.

D.2.4.1. (vi) Berokuntza eta EUB sistemaren ikerketa kasua

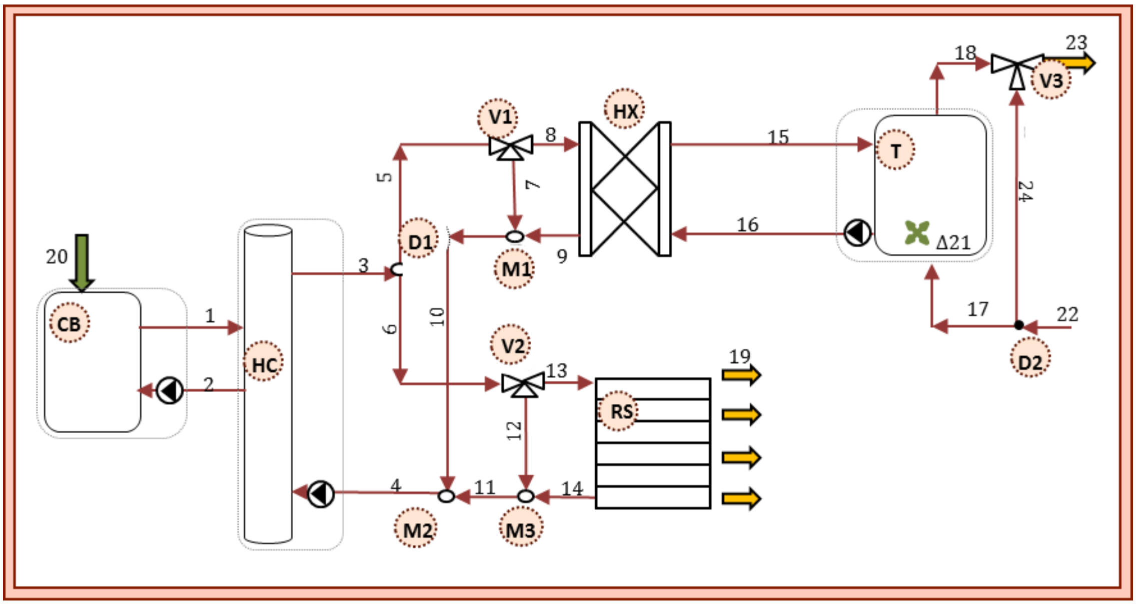
Ikerketa kasua Bilboko (Espainiaren iparraldea) 16 bizilagunentzako etxebizitzaren berokuntza eta EUB sistemaren instalazioari dagokio. Sistema hori Euskadiko ohiko berokuntza instalazioa da [23]. Energia horniketa sistema BaxiRoca 24 BIOS/82F markako kondentsazio galdara da.



Irudia D. 4 Ikerketa kasuaren instalazioaren eskema

Tenperatura altuan lan egitean, katalogoaren arabera 28 kW potentziara irits daiteke % 97-ko etekinarekin (% 17-ko etekin exergetikoarekin). Instalazioko gainontzeko osagaiak orekatzaile hidrauliko bat, 3-bideko balbulak, bero trukagailu bat eta 1000 litroko EUB biltegi bat dira. Horretaz gain, hiru ponpa hidrauliko daude, bat sorkuntza zirkuituan, bestea banaketa zirkuituan eta azkenekoa EUB sorkuntza zirkuituan, ikus Irudia D. 4. Berokuntza eskaria disipaziorako erradiadore sistemaren eta 3-bideko balbularen bitartez adierazten da. EUB biltegitik lortzen da eta 3-bideko balbula batek ziurtatzen du ur beroa tenperatura konstantean.

Esan antzera, analisia Trnsys v17-arekin egin zen. Berokuntza eskariak Espainia Iparraldeko eraikinen ohiko profila jarraitzen du [24], zein Trnsys-eko type 56-aren bitartez estimatu zen ordu bateko denbora tartearekin; EUB Task 26 Domestic Hot Water calculator programarekin kalkulatu zen [25]. Bi eskariak orduko biltegiratu ziren kanpo artxiboetan eta gero diagnosi simulazioan inplementatu. Ikerketa kasuko osagaiak Trnsys liburutegiko modelo sinplifikatuekin simulatu ziren.



Irudia D. 5 Fluxuen zenbaketa eta sistemaren osagaien izendapena

13 osagai eta 24 fluxu hartu ziren analisian, ikus Irudia D. 5. Bi kanpo sarrera hartu ziren kontuan: gas naturala ($\dot{E}_{20}$) eta tankearen ekarpena ($\Delta\dot{E}_{21}$), zein periodoko hasierako eta bukaerako exergia aldakuntzaren berdina izan eta gezi berdeekin adierazten den. Gezi horiek sistemaren irteerak adierazten dituzte, EUB ($\dot{E}_{23}$) eta berokuntza ($\dot{E}_{19}$).

Ikusi lez, hiru zirkulazio ponpak ez dira kontuan hartu horien potentzia txikia medio. Analisi zehatz eta erreal baterako, osagaien exergia alderdi termikoan eta mekanikoan banatu beharko da. Berez, anomaliak emari masikoa aldatzen badu, sistemaren guztizko etekina jaitsiko zen [26] eta orduan ponpak disfuntzioen edo eragin induzituen iturri izango ziren; aitzitik, gehiegizko nomenklaturarekin nahasketak saihesteko, ez dira kontuan hartu. Beraz, kalkuluek ez dute ur emariaren exergia adierazpenean presioaren eragina barneratu.

Analisirako osagaien zerrenda Taula D. 1n dago non zenbaketa eta laburpena adierazten diren.

Taula D. 1 Osagaien deskripzioaren laburpena

	OSAGAIA	IKURRA
①	Kondentsazio galdara	CB
②	Orekatzaile hidraulikoa	HC
③	Bero eta EUB banatzailea	D1
④	EUB 3-bideko balbula	V1
⑤	EUB nahasgailua	M1
⑥	Bero trukagailua	HX
⑦	Berok. 3-bideko balbula	V2
⑧	Bero eta EUB nahasgailua	M2
⑨	Berokuntza nahasgailua	M3
⑩	Erradiadore sistema	RS
⑪	EUB tankea	T
⑫	EUB 3-bideko balbula	V3
⑬	EUB banatzailea	D2

Plantaren *kontrola*ren arabera, EUBak lehentasuna dauka berokuntzarekiko. Unitateak aktibatu eta itzali egiten dira batez ere biltegiaren tenperaturaren (T_{19}) eta berokuntza profilaren arabera. Pilaketa tenperatura 62 ºC-ren azpitik badoa, galdara aktibatu egiten da 70 ºC-tara iritsi arte. Bero trukagailuaren sarrera tenperaturaren eta biltegi tenperaturaren arteko aldea 7 ºC baino altuagoa bada, EUB sorkuntza pizten da; aldea 4 ºC baino gutxiago bada, 3-bideko balbulak (bero trukagailutik uretan gora kokatua) beroa orekatzaile hidraulikoarekin bypasseatzen du.

Berokuntza eskaria kanpo tenperaturaren eta ordutegi finko baten arabera piztu egiten da. Beraz, berokuntza profila medio ($\dot{Q}_{heat}$), galdararen itzulera tenperatura (T_2) jaitsi egiten da eta 60 ºC-tik behera joanez gero, galdara piztu egiten da.

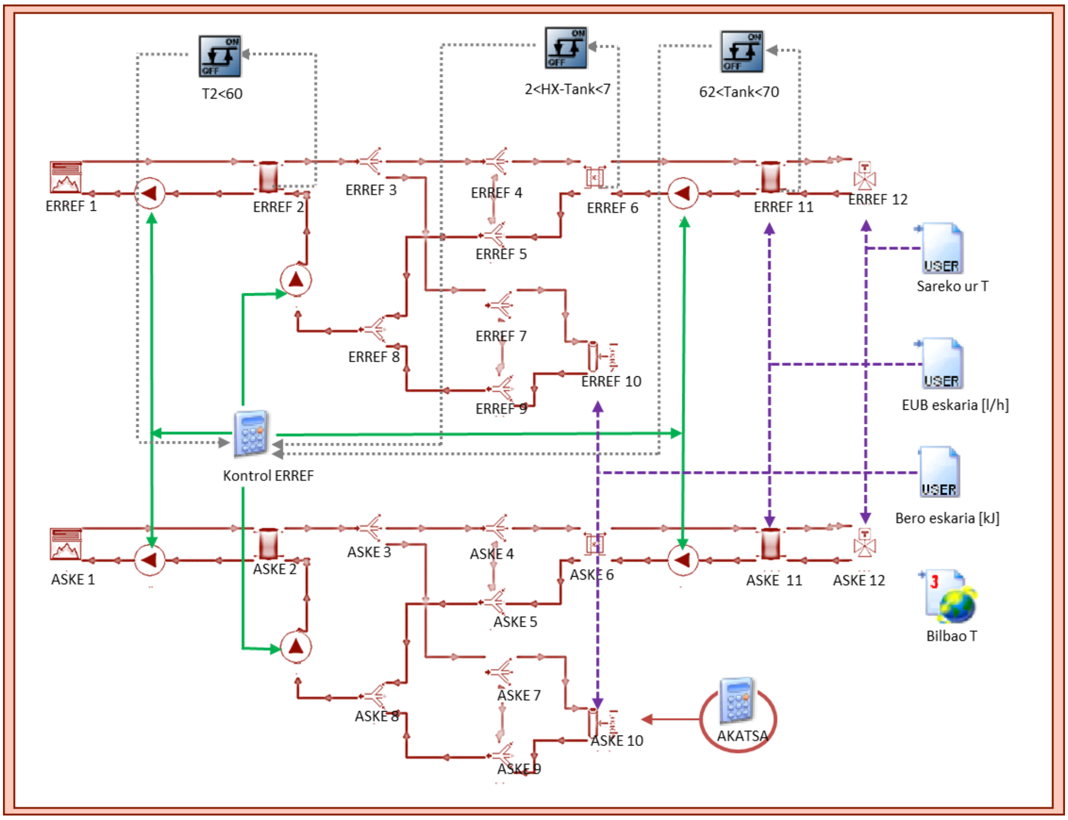
EUB irteeraren 3-bideko balbula ur beroa ($\dot{m}_{DHW}$) T_{DHW} =55 ºC tenperaturan emateko moldatu egiten da.

D.2.4.1.1. Akatsa

Edozein osagai aukera daiteke akatsa barneratzeko eta eraginak egitura produktiboan kokapenaren arabera egongo dira. Kasuan, akatsa nahita sartu da *erradiadore sisteman* (RS) % 10-eko energia etekinaren murrizketaren bitartez (alegia, erradiadore sistemaren bero erabilgarriaren eta berokuntza uraren sarrera eta irteera entalpia aldearen arteko zatiketa).

D.2.4.1.2. Kontrol sistemaren eraginaren iragazketa

Aitzinako arrazoiak medio, kontrol sistemaren esku-sartzea ekidin behar da baldintza askearen bitartez. D.2.2.1 Ataleko urratsak jarraituz, Irudia D. 6n Trnsys v17-aren interfazea erakusten da non baldintza erreala eta askea simulazio berean lortzen diren. ER*REF* adierazlearekin erreferentzia baldintza ezagutarazten da eta *ASKE* izenarekin, ordea, baldintza askea (ikus *AKATSA* Irudia D. 6aren azpialdean). Irudian kontrola eta osagaien loturak ere adierazten dira. Kontrola erreferentzia sistemaren goialdean dagoenez (ikus goiko aldeko kontroladore diferentzialen ikurrak) osagaien pizketa zein itzaltze eta erregulazio komandoak agintzen ditu set-point-en arabera (ikus *ERREF* instalazioko gezi gris etenak eta *Kontrol ERREF*-etik *ERREF* sistemara doazen gezi berdeak). Modu berean, komando horiek operazio baldintzako instalazioan barneratzen dira (ikus gezi berdeak *Kontrol ERREF*-etik *ASKE* sistemara) hasi-amatatu aginte berberak jasotzeko (espazio arrazoiengatik eta irudia argi erakusteko, ponpen komandoak baino ez dira marraztu eta 3-bideko balbulen komandoak ez daude ikusgai).



Irudia D. 6 Baldintza askearen lorpena Trnsys interfasean

Kasuan, aurretiaz esan antzera, bero eskaria bero eskari balio diskretuekin adierazi da (ikus *Bero eskaria [kJ]* User sinboloa). EUB eskaria 3-bideko balbularen modulazioaz definitzen da zeinek sareko ur hotza (ikus *Sareko ur T* User ikonoa) eta tankearen irteerako EUB emaria (ikus *EUB eskaria [l/h]* ikonoa) batzen dituen. Beraz, bi baldintzek eskari eta giro baldintza dokumentu berberak banatzen dituzte (ikus gezi moreak eta *Bilbao T* type).

D.2.4.1.3. Produkzio totalaren eragina

Instalazioan bi irteera nagusi daude: berokuntza eta EUB eskariak. Berokuntza erabiltzaileen araberako energia denez, bai baldintza askean bai erreferentzian berbera da ($\dot{Q}_{heat} = \dot{Q}^0_{heat}$); giro baldintzak berdin mantentzen direlako $\Delta P_{s_{heat}} = 0$. Bestalde, EUB ur emari eskariarekin

($\dot{m}_{DHW}$) eta tenperatura zehatzarekin ($T_{DHW} = 55$ °C) adierazten da. Hori (V3) 3-bideko balbula termostatikoaren modulazioaren bitartez lortzen da zeinek sareko ur hotza ($\dot{m}_{cold}$ emaria T_{net} tenperaturan) biltegiaren barneko beroarekin batzen dituen ($\dot{m}_{hot}$ emaria T_{18} balioan). Orduan, EUBaren energia honela kalkulatzen da:

$$\dot{Q}_{DHW} = \dot{m}_{DHW} \cdot c_P \cdot (T_{DHW} - T_{net}) = \dot{m}_{hot} \cdot c_P \cdot (T_{18} - T_0) + \dot{m}_{cold} \cdot c_P \cdot (T_{net} - T_0) = \dot{H}_{18} + \dot{H}_{24} \quad \text{(D. 29)}$$

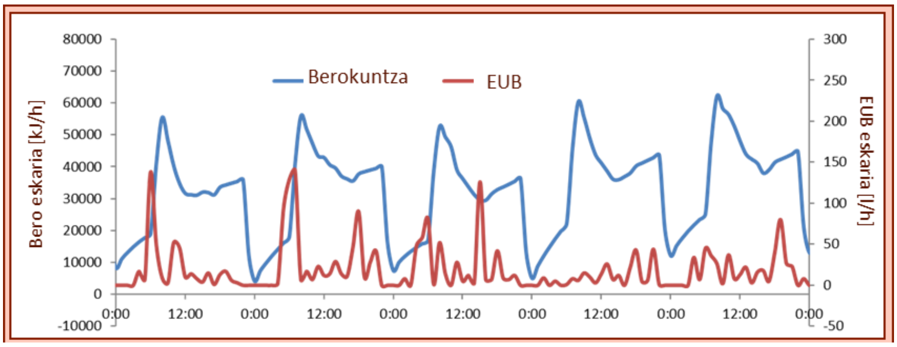
non $\dot{H}_{18}$ biltegiaren irteerako entalpia fluxua eta $\dot{H}_{24}$ sareko fluxu sarrera diren.

Baldintza askea lortzeko kontrolaren iragazpena medio, V3-ak bi instalazioetan berdin eragiten du: $\dot{m}_{hot} = \dot{m}_{hot}^0$ eta $\dot{m}_{cold} = \dot{m}_{cold}^0$. Halere, tankearen irteera tenperatura biltegiaren araberakoa izateagatik ($T_{18} = T_{18}(T_{21})$) eta akatsa kontuan hartuz, aldiuneko biltegiratze tenperatura ezberdina da: $T_{18} \neq T_{18}^0$. Hortaz, $\dot{H}_{18} \neq \dot{H}_{18}^0$ denez, kanpo produkzioaren aldakuntza ekidin ezina da, hots, $\Delta P_{s_{DHW}} \neq 0$.

Azaldu lez, diagnostikoaren teoria ulerterraza da amaierako produktua bi baldintzetan berdin mantenduz gero, fuel inpaktua anomalien kontsumo gehigarriarekin baino ez delako lotuko. Alabaina, bi irteera nagusietatik soilik bat da saihesgarria, EUB zuzenki lotzen baita akatsarekin.

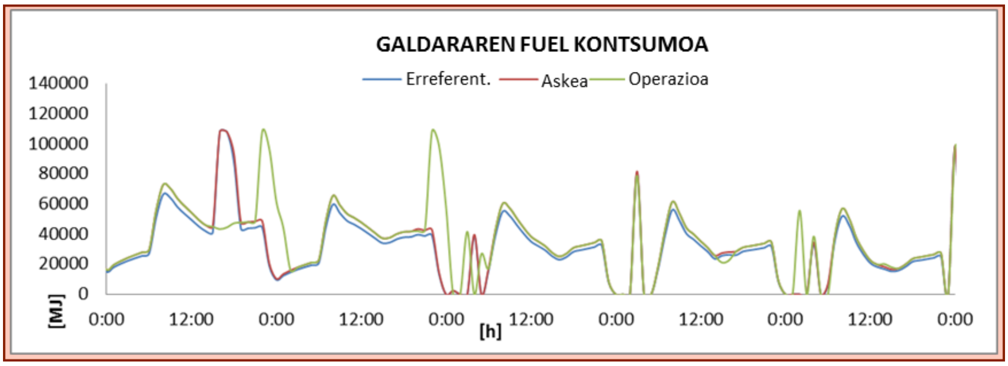
D.2.4.1.4. Zenbakizko adibidea

Erreferentziazko eta baldintza askea berokuntza garai osorako simulatu ziren, alegia, azaroaren 1etik apirilaren 30era, 30 segunduko denbora tartearekin. Berokuntza periodo osoaren irudia ikuskatzen gatza izateagatik, urtarrileko bost eguneko profilak baino ez dira marraztu Irudia D. 7n.



Irudia D. 7 Urtarrilaren 5 egunetan zehar berokuntza eta EUB eskariak

Behin hiru simulazioak eginik eta beharrezko datuak jasoz, denbora tarte bakoitzeko fluxuen exergiak kalkulatu ziren. Grafikoak argi irudikatzeko, Irudia D. 8k urtarrilaren 5 eguneko CBaren gas natural exergia kontsumoa erakusten du. Ikus antzera, marra urdinak eta gorriak erreferentzia eta baldintza askea adierazten dituzte eta ixa ardatzean memento berberean piztu eta itzaltzen dira. Marra berdeak, aldiz, operazio baldintza adierazten du eta denboran zehar une ezberdinetan hartzen du parte, haren kontrol sistemak eragitean hain zuzen.



Irudia D. 8 Urtarrilaren 5 egunetan zehar galdararen operazio, erreferentzia eta baldintza askea

Berokuntza amaieran fluxu bakoitzeko exergia pilatua hiru baldintzetan kalkulatu egin zen: erreferentzian, egoera askean eta errealean, ikus Taula D. 2ko balioak. Exergia balioak kalkulatu ondoren termoekonomia diagnostikoa aplikatzen da.

Taula D. 2 Exergia balio pilatuak erreferentzia, operazio eta baldintza askean $[GJ_{ex}]$

$[MJ]$	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}
ERREFERENT.	29.1	23.4	102.4	97.4	13.4	89.0	11.1	2.3	1.8	12.9	84.5
ASKE	29.1	22.9	85.8	80.3	13.1	72.7	10.9	2.2	1.8	12.7	67.7
OPERAZIOA	29.1	23.0	101.7	96.3	17.0	84.7	15.3	1.7	1.3	16.6	79.7

E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}	E_{19}	E_{20}	ΔE_{21}	E_{22}	E_{23}	E_{24}
54.6	34.5	30.0	2.2	1.7	0.0	0.4	1.0	34.2	0.0	0.0	0.3	0.0
38.7	34.0	29.1	2.2	1.7	0.0	0.4	1.0	37.2	0.0	0.0	0.2	0.0
52.3	32.3	27.5	1.6	1.3	0.0	0.4	1.0	36.0	0.0	0.0	0.3	0.0

D.2.4.1.4.1. MF eta DF analisia

Taula D. 3n diagnostikoaren emaitzak agertzen dira Ek.(D. 7) ikuspegitik. Zutabeetan amaierako produktuaren aldakuntza ($\mathbf{\Delta P_s}$), funtzio-okerra $\left(MF_{e,i} + MF_i\right)$ eta disfuntzio $\left(DF_{e,i} + DF_i\right)$ balioak agertzen dira osagai bakoitzerako. Azkeneko lau zutabeen gehiketak itzulezintasunaren igoera adierazten du ($\mathbf{\Delta I}$), hau da, fuel inpaktuaren kuota anomaliaren ondorioz.

F_T^0 eta F_T^{free} balioek instalazioaren erreferentziako eta baldintza askeko fuel kontsumoa adierazten dute, preseski. Bi balioen arteko aldea eta baita Taula D. 3ko gelaxka guztien batura ere, anomalien fuel inpaktua da $[\Delta F_T^{anom} = 3010\ MJ]$.

Emaitzak analizatzean datozen puntuak nabarmentzen dira:

- RS osagaiaren $\Delta \mathbf{P_s}$ balioa $[\Delta P_{s_{10}} = 0\ MJ]$ nulua da eta M4-aren amaierako produktua negatiboa da $[\Delta P_{s_{12}} = -105\ MJ]$. Emaitza horrek berokuntza sorkuntzaren produktu konstantea eta EUBaren murrizketa azpimarratzen ditu.
- $\mathbf{MF}$ funtzio-oker bektorea aintzat hartuz gero, pentsa daitekeen lez, RSak eraginik handiena dauka [MF_{10}=382 MJ], halere, CBren eragina nabaria da [MF_1=147 MJ]. Gertakari hori ulertzeko, **MF** osagaia exergia kontsumo aldakuntzaren MF_i eta kanpo

baliabide kontsumo aldakuntzaren $MF_{e,i}$ osagaietan banatu behar da. CBa hein handian kanpo baliabideen kontsumoaz eraginda dago [$MF_{e,1}$=147 MJ].

- Anomaliaren uretan gorako osagaiek (HC [MF_2=-12MJ], M2 [MF_8=39 MJ] eta M3 [MF_9=59 MJ]) ere funtzio-okerrak dauzkate. Funtzio-oker mota horiei *funtzio-oker induzituak* deritze ez baitute akatsik jasotzen.

Taula D. 3 Diagnositikoa $\Delta\mathbf{I} + \Delta\mathbf{P_S}$ [$\boldsymbol{MJ_{ex}}$] adierazpenarekin

		$\Delta\mathbf{P_s}$	$\Delta\mathbf{I}$			
			MF		**DF**	
			$\mathbf{MF_e}$	$\mathbf{MF_i}$	$\mathbf{DF_e}$	$\mathbf{DF_i}$
①	CB	-	147	-	-1250	3640
②	HC	-	-	-12	-26	78
③	D1	-	-	-	-	-
④	V1	-	-	-	-	-
⑤	M1	-	-	2	-	-
⑥	HX	-	-	-	-	-
⑦	V2	-	-	-	-	-
⑧	M2	-	-	39	-2	-9
⑨	M3	-	-	59	-5	-29
⑩	RS	-	-	382	-	-
⑪	T	-	-	-	-29	29
⑫	V3	-105	-	180	-77	-
⑬	D2	-	-2	-	-	-
			F_T^0 [MJ]=		34174	
			F_T^{free} [MJ]=		37184	

- Beste osagaien funtzio-okerrez eraginik gehiengo osagaia energia bihurketa kateko lehenengoa da, alegia, CB [DF_1 = 2390 MJ].

- Zenbait osagaiek disfuntzio balio negatiboak dauzkate, adibidez, M3 [DF_9 = -5 MJ] edo V3 [DF_{12} = -77 MJ] eta amaierako produktu murrizketarekin erlazionatu daude; azken fintzean, disfuntzio guztiak ez baitituzte funtzio-okerrek eragiten, $\Delta\mathbf{P_s}$-ak ere baizik,

Taula D. 4 DF matrizea [$\boldsymbol{MJ_{ex}}$]

	$\mathbf{DF_e}$	[DF]												
①	-1250	-	-61	-330	-	12	2	-	204	345	2240	-6	1234	-
②	-26	-	-	-7	-	-	-	-	4	7	48	-	26	-
③	-	-	-	-	-	-	-	-	-	-	-	-	-	-
④	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑤	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑥	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑦	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑧	-2	-	-	-16	-	-	-	-	-	1	4	-	2	-
⑨	-5	-	-	-42	-	-	-	-	-4	2	10	-	5	-
⑩	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑪	-29	-	-	-	-	-	-	-	-	-	-	-	29	-
⑫	-77	-	-	-	-	-	-	-	-	-	-	-	-	-
⑬	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	⓪	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬

$\mathbf{DF_e}$ bektorearen bidez. Orduan, disfuntzio horiek ez dute berezko eragin negatiborik, amaierako guztizko produktuaren aldakuntzarekin harremana baitute.

Analisi sakonerako eta diagnosia hobeto ulertzeko, disfuntzioak adierazteko aukera Ek.(D. 13)-ko matrizea da eta Taula D. 4n dago. Horren arabera datozen gogoetak egiten dira:

- $\sum_j DF_{ij}$ lerroaren gehikuntza i osagaiaren disfuntzio totala da eta Taula D. 3ren i osagaiaren balioarekin bat dator. Adibidez, $\left[\sum_j DF_{1j} = 3640\ MJ\right]$ CB-ren disfuntzioak dira eta Taula D. 3ren $[DF_1 = 3640\ MJ]$ balio berbera dute.
- Taula horren bitartez j-tan funtzio-oker bat egoteagatik i osagaiaren eragin induzituak ikuskatzen dira. Esaterako, $\left[DF_{1,8} = 204\ MJ\right]$ M2-ren funtzio-okerrak CB-an induzitutako disfuntzioa da.

D.2.4.1.4.2. Funtzio-oker kostua

Taula D. 5k diagnostikoa beste ikuspegi batetik adierazten du, Ek.(D. 19). Azkeneko bi zutabeek *adierazle giltzarriak* erakusten dituzte fuel inpaktuaren eta funtzio-oker kostuaren arteko harremana nabarmentzeko. Zenbait gertakarik D.2.1.2 Ataleko gogoetak egiaztatzen dituzte:

Taula D. 5 Funtzio-oker kostuen gehikuntzarekin diagnostikoa $[\boldsymbol{MJ_{ex}}]$

		MF^*	MF_e^*	ψ_{MF^*}	$\psi_{MF_e^*}$
①	CB	147	-	5%	-
②	HC	-73	-	-2%	-
③	D1	-396	-	-13%	-
④	V1	-	-	-	-
⑤	M1	-	-	-	-
⑥	HX	-	-	-	-
⑦	V2	-	-	-	-
⑧	M2	244	-	8%	-
⑨	M3	413	-	14%	-
⑩	RS	2683	-	89%	-
⑪	T	-	-	-	-
⑫	V3	1481	-1487	49%	-50%
⑬	D2	-2	-	-	-
		$\Delta F_T^{Anom}\ [MJ] =$		3010	

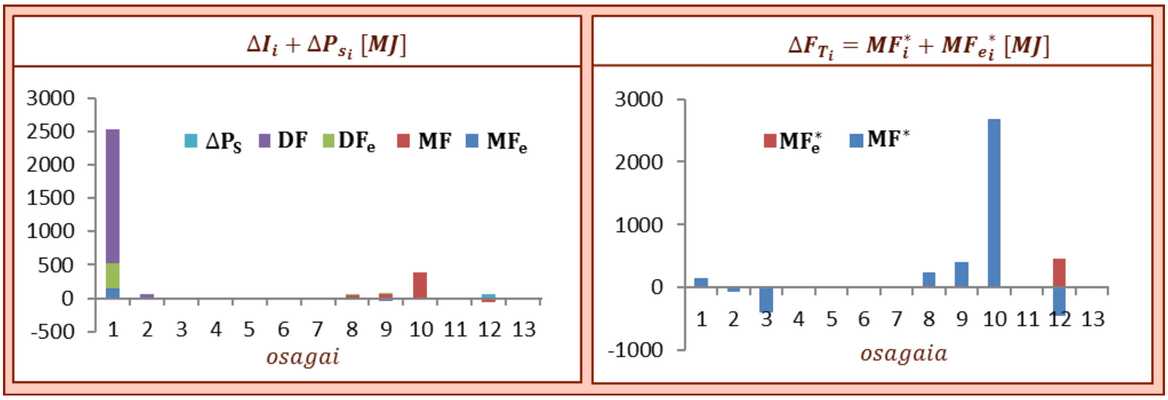
- Funtzio-oker kosturik nabarmena RSan dago $[MF_{10}^* = 2683\ MJ]$. Horrek eragindako itzulezintasun oro jasotzen baita terminoan. Beste hitz batzuetan, MF_{10}^* RSarekin lotutako funtzio-okerrak eta disfuntzioak balioak barneratzen ditu eta berdina da RSk eragindako fuel kontsumo (Taula D. 3ko MF_{10} gehi Taula D. 4ko $\sum_i DF_{i,10}$ zutabea).

- Funtzio-okerrik gabeko eta beste osagaietan disfuntzioaren eraginik gabeko osagaien funtzio-okerren kostua zero da.
- Funtzio-okerren zenbait kostu negatiboak dira $[MF_2^* = -73\ MJ]$ eta $[MF_3^* = -396\ MJ]$ disfuntzio induzituak gainontzeko osagaietan negatiboak direlako; horregatik, erreferentzia baldintzarekin alderatuz gero osagaien lekuko produkzioan murrizketa eragiten dute. Beraz, disfuntzio negatiboa eratzen dute (ikus $\sum_i DF_{i,2}$ eta $\sum_i DF_{i,3}$ zutabeak Taula D. 4n).

- V3ak funtzio-oker kostua dauka eta amaierako produktu aldakuntzari dagokio [$MF^*_{e,12} = -1487\ MJ$] eta funtzio-oker induzituarekin ia guztiz orekatzen da [$MF^*_{12} = 1481\ MJ$]. Beraz, 12 osagaiak eragin eskasa dauka.

ψ_{MF^*} (Ek.(D. 20)) eta $\psi_{MF^*_e}$ (Ek.(D. 21)) adierazleak osagai bakoitzerako kalkulatu dira horien funtzio-oker kostuaren eragina diagnostikoko fuel inpaktuaren arabera kalkulatzeko. Guztien gehiketak % 100 ematen du.

- $\psi_{MF^*_i}$ adierazlerik handieneko osagaia RS da $[\psi_{MF^*_{10}} = \%\ 89]$. Beraz, erradiadore sistemaren anomaliak erregai kontsumo igoeraren % 89 eragiten du eta, orobat, beste osagaietan kontsumoaren igoera dakar [% 5 CB-n, % 8 M2-n, % 14 M3-n eta % 49 V3-n] eta beste batzuetan, aldiz, murrizketa [% -2 HC, % -13 D1], eragin induzituak medio. Balore negatiboak aurrezpena adierazten du disfuntzio negatiboen eraginez.
- Halaber, V3-ak kontsumoaren % 50eko murrizketa eragiten du [$\psi_{MF^*_{0,12}} = \%\ -50$]. Finean, erragaiaren kontsumo gehigarriak baldintza askearen produkzioan murrizketa bat eragiten baitu.



Irudia D. 9 (a) Osagaien MF eta DF analisia (b) Osagaien funtzio oker kostuen analisia

Taula D. 4ren eta Taula D. 5ren emaitzak era grafikoan aurkezten dira Irudia D. 9 (a) eta (b)n. Lehenengoak funtzio-okerrak, disfuntzioak eta produktu totalaren aldakuntza erakusten du erreferentzia eta baldintza askeen artean. CB-a disfuntziorik handieneko osagaia da. Bigarren irudiak fuel inpaktuko funtzio-okerren kostuak erakusten ditu eta erregaiaren kontsumo gehigarriaren arduradun nagusia RS da.

D.2.4.1.4.3. Inpaktu ekonomikoa

Fuel inpaktu ikerketa osatzeko, Taula D. 6n anomaliekin lotutako kostu ekonomikoa erakusten da ($\Delta C^{anom}_{F_T}$) funtzio-okerrari dagokion kostu ekonomikoan ($\mathbf{C_{MF^*}}$) eta baldintza askearen eta erreferentziaren arteko amaierako produktu aldakuntzaren kostu ekonomikoan ($\mathbf{C_{MF^*_e}}$) bananduta. Datozen gogoetak egiten dira:

Taula D. 6 Diagnostikoaren inpaktu ekonomikoa

		C_{MF^*} [€]	$C_{MF_e^*}$ [€]
①	CB	[€] 8	-
②	HC	-4	-
③	D1	-22	-
④	V1	-	-
⑤	M1	-	-
⑥	HX	-	-
⑦	V2	-	-
⑧	M2	13	-
⑨	M3	23	-
⑩	RS	147	-
⑪	T	-	-
⑫	V3	81	-82
⑬	D2	-	-
		$\Delta C_{F_T}^{Anom}$ =164 €	

- Nabaria zenez, anomaliako RS osagaia funtzio-okerraren kostu exergoekonomiko altueneko osagaia da $[C_{MF_{11}} = 147\ €]$.
- Anomaliaren presentziaren kostu ekonomikoa berokuntza periodoan $[\Delta C_F = 164\ €]$ da. Hori osagai bakoitzaren ekarpenaren gehiketa da eta ψ_{MF^*} adierazlearen arabera dago, alegia, 8 € CB-ren funtzio-oker induzituagatik, -22 € D1-en eta 23 € M3-n induzituagatik.

D.2.4.1.5. Kontrol sistema operazioaren kostua

Ek.(D. 23)-aren bidez operazio baldintza errealaren eta baldintza askearen arteko kostua kalkulatzen da. Emaitzak Taula D. 7n jasotzen dira.

Taula D. 7 Guztizko ekonomia inpaktua [€]

$\Delta C_{F_T}^{kontrol}$	$\Delta C_{F_T}^{anom}$	ΔC_{F_T}
-64 €	164 €	**102 €**

Datozen gertakariak daude:

- Baldintza askea lortzeko erreferentziazko kontrol operazioa baldintza errealetan aplikatzean kostua igotzen da. Beraz, kontrol sistemaren jarrerak inpaktu negatiboa dauka kostuan [-64€]. Azken finean, operazio baldintza errealetan set-point-ak kontrol sistemak kontrolatu eta aldagiak balio tarte baten barruan mantentzen ditu (hots, galdararen itzulera tenperatura minimoa, tankearen biltegiratze tenperatura, etab.). Baldintza askean, ordea, balore horiek ez dute mugarik. Ondorioz, galdarak beharrezko sarrera askoz baxuagoa da (ikus E_2 eta E_{20} balioak Taula D. 2n).
- Emaitza gisa, *erradiadore sistema*ren % 10eko energia etekinaren narriadurak eragindako kostu gehigarri totala 102€ da.

D.2.4.2. Emaitzen eztabaida

Termoekonomia metodologia oso erabilgarria da funtzio-okerren eraginak kuantifikatzeko. Hala eta guztiz ere, Lazzaretto-k [6] nabarmendu antzera, MF_i gaiek ez dute soilik *funtzio-oker intrintsekoen* eragina erakusten, kontsumo exergetiko unitarioaren aldakuntza gorabehera induzituek ere sor ditzaketelako. Emaitzek erakutsi bezala, osagai anomaloak (RS) funtzio-oker kostua izateaz gain, gainontzeko osagai gehienek ere dute kostua (CB, HC, D1, M2, M3, V3, D2).

Osagaien etekinak lan egoeraren oso menpekoak dira; beraz, funtzio-oker intrintsekoa askotan lotzen da funtzio-oker induzituekin eta, osagaiek egitura produktiboaren arabera erlazio estua dutenez, sisteman zehar eragin induzituak nabarmen hedatzen dira. Ondorioz, DF_{ij} osagaien informazioa *eragin induzitu* totalen zati bat baino ez da.

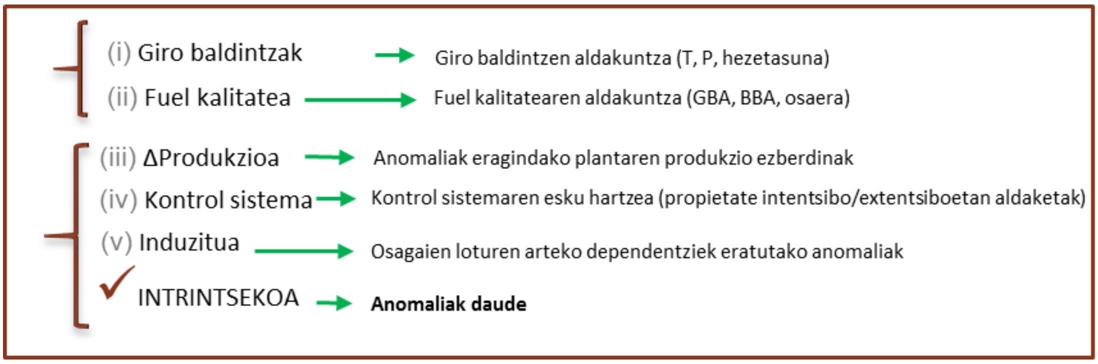
Orduan, lan honetako metodologia anomalien iturria identifikatzeko ez da eraginkorra, soilik kontsumo gehigarri gehiengoa eragiten duen osagaia hautemateko, $\psi_{MF_i^*}$ adierazle handieneko elementua hain zuzen (baina ezin da jakin osagai horrek anomalia duen).

Berez, zenbait eragin induzitu ager daitezkelako, ψ_{MF^*} adierazleak zerotik balio ezberdina izan dezake nahiz eta anomalia intrintsekorik ez izan. Haatik, bi aukera daude: 1) soilik ψ_{MF^*} zutabeko elementu batek dauka zeroren balio ezberdina edo 2) gainontzeko gaiek antzeko ψ_{MF^*} balioa dute. Lehenengo kasuan, diagnostikoaren problema guztiz ebatzita dago. Anomalia bakarra dago plantan eta, beraz, baldintza askearen eta erreferentziaren arteko fuel inpaktu dena horren menpe dago. Akats hori guztiz konpontzen bada lortuko den energia aurrezpena fuel inpaktuaren balio bera da. Bigarren kasuan, ezin da aurretiaz problema ebatzi eta instalazioaren modelo matematikoa behar da [21]. Azken finean ψ_{MF^*} metodoak exergia kontsumo unitarioaren araberako adierazlea erabiltzen baitu eta aldagai termodinamikoen arteko egiazko dependentzia ezkutatzen da horrela, esaterako, tenperaturen, presioen, masa emarien eta osaeraren arteko harremanak. Aldagai independenteen arteko metodo matematikoa behar da.

D.2.5. Fuel inpaktu diagnostikoaren mugak

Aurreko eztabaida aintzat hartuz eta laburbilduz, MF eta DF analisian bakarrik oinarritutako funtzio-okerrak baliagarriak dira baldin eta: (1) i osagaiaren produktua lekuko aldagaia da eta erreferentziazko baldintzetan askatasun gradu bakarra dauka eta (2) k_{ij} balioa ez dago produktuaren menpe [5]. Aurreikusi daitekeen lez, baldintza horiek ez dira errealistak eta exergia kontsumoen arteko loturak askotan nabarmenak dira. Kasu horietan gainezartze printzipioak ere ez du funtzionatzen, operazio baldintzen fuel inpaktua ezberdina baita anomalia indibidualek eragindako fuel inpaktuen gehiketarekin [27].

Beraz, ΔF_T fuel inpaktu formula ez da nahikoa aldagai independenteen arteko eraginen jarrerak kontrolatzeko. Horiei funtzio-oker induzituak deritze zeintzuen ezagutza diagnostikoaren inplementaziorako ezinbesteko urratsa den [28]. Besteen artean, funtzio-oker induzitu ezberdinak daude (mota bakoitza Irudia D. 10on izendatu eta labur azaltzen da): (i) inguru baldintzen aldaketek eragin ditzakete, (ii) fuel kalitate aldaketek, (iii) plantaren produkzio ezberdinek, (iv) kontrol sistemaren esku hartzeak edota (v) barne esku-sartze termodinamikoek eragin ditzakete.



Irudia D. 10 Funtzio-okerren sailkapena

Ondorioz, funtzio-okerren eta disfuntzioen analisiak ez duenez eragin induzituen eta intrintsekoen artean bereizten, ezin da guztiz baliagarritzat hartu. Azken batean, soilik sistemaren aldagai exergetikoak erabiltzen badira, aldagai termodinamikoen arteko hartu eman errealak (tenperaturen, osagaien, emari masikoen eta abarren arteko erlazioak) ezkutatuta daude.

Metodologiaren arazo horiei aurrea emateko aukera berriak sortu ziren. Besteak beste, [27] lanean barne eraginei pisua emateko era berri bat garatu zen iragazi progresiboen bitartez: esan antzera, kontrol ekintzak ekidin egin egiten dira *baldintza askea*ren bitartez eta *etekin kurben* linealtasun gabeziak iragazi egiten dira. Halere, baldintza askea ez da beharrezkoa funtzio-okerren zergatia aurkitzeko baina egokia da kontrol sistemaren fuel inpaktua estimatzeko [2].

Linealtasun gabeziak kalkulatzeko, aldiz, anamnesia erabiltzen da: analisia plantaren bizitza erabilgarrian zehar errepikatzen da eta emaitzak konparatu egiten dira. Anomalia errealen eta osagaien ez linealtasunek eragindako "istiluen" artean bereizmena [29] plantaren analisi historikoa erabiltzen da. Erref. [27]-eko lanean, modelo hori neurona sarearekin egiten da eta operazio baldintzen datu baliagarri anitz behar dira. Iragazpen horien ostean, hondar anomalia intrintsekoekin eraginak zuzenean lotzen dira.

Eragin induzituak bereizteko beste aukera bat aldagai termodinamikoen arteko harreman funtzionalak kontuan hartzea da osagaien *nolakotasun kurbe*kin CC [2]. Balio exergetikoek ez dutenez beharrezko aldagai independenteen kopuru jakina ahalbidetzen, horiek bigarren urrats batean kalkulatzen dira eta lan erabilgarriaren homogeneotasuna alderaketak egiteko erabiltzen da [10]. CCen aplikazio matematikoa eta grafikoa Erref. [30]-n erakusten da. CCaren ahuldura da osagaiaren CC ezagutu ezean moduren batean bere jarrera simulatu behar dela. Halaber, funtzio-okerreko osagaiak azpimarratzeko balio badu ere, osagai bakoitzaren fuel inpakturik ez du azaltzen; teoria modu indibidualean aplikatu eta ikuspegi orokorra galtzen baita (halere, potentzialitatea kontuan hartuz, datorren atalean metodologia hau garatu egiten da).

Aipatutakoez gain, *funtzio-oker aldagaien adiskidetze metodologia* RMV [31] garatu egin zen eta ondoren Erref.[32]-an hedatu egin zen analisiaren konplexutasuna murriztuz. Ikuspegi termoekonomikotik haratago, eta horren mugak aintzat hartuz, bestelako diagnostiko termodinamikoak garatu ziren; esaterako: logika kiribildua [33], analisi kuantitatibo kausala, erregresio lineala, algoritmo genetikoen metodoa [34], funtzio-okerren hatz-aztarna [35], etab. Zenbait metodoen alderaketa [36] lanean egiten da.

D.3. NOLAKOTASUN KURBEN DIAGNOSIAREN METODOLOGIA

Ahalmena medio, atal hau osagaien nolakotasun kurbetan [2] oinarritzen da.

i osagaiaren nolakotasun kurba π_i termodinamika kantitate bat adierazteko erlazio multzoan oinarritzen da zeinek osagaiaren jarrera operazio aldagai funtzioen (ξ_i) bitartez adierazten diren. Erreferentzia operazio baldintzarekin lotzen den nolakotasun kurba orokorrak Ek.(D. 30)-ren itxura hartzen du eta kurbaren barneko lan puntu zehatz bateko (R) adierazpena Ek.(D. 31)-arekin idazten da:

$$\pi_i^0 = f^0(\xi_i^0) \tag{D. 30}$$

$$\pi_i^{0,R} = f^0(\xi_i^{0,R}) \tag{D. 31}$$

Osagaia adierazteko (π_i) aldagai termodinamikoa ezberdina izan daiteke irizpidearen arabera. Toffolo-k eta Lazzaretto-k [37] *itzulezintasuna* erabiltzea gomendatu zuten, horrek balio estuki positiboa hartzen baitu anomalia bat badago. Halere, aurreko alderaketa egin ahal izateko, (k_i) exergia kontsumo unitarioa erabiliko da aldagai termodinamiko dependente gisara. Hautatutako ξ_i aldagaiak emari masikoak, tenperaturak eta presioak dira eta operazio aldagai independente deritze x_i. Orduan, erreferentzia baldintza adierazteko formula orokorra eta (R) puntu zehatz bateko adierazpenak dira:

$$k_i^0 = f^0(x_i^0) \tag{D. 32}$$

$$k_i^{0,R} = f^0(x_i^{0,R}) \tag{D. 33}$$

Demagun eragin induzituak uretan behera igortzen direnez, $x_i^{0,R}$ balioak osagaiaren muga fisiko inposatuengatik $x_i^{0,A}$ balioetara doazela. Beraz, osagaia (A) operazio baldintza puntu berrian egongo da lanean, baina, puntu hori oraindik egongo da erreferentzia kurbaren gainean (f^0):

$$k_i^{0,A} = f^0(x_i^{0,A}) \tag{D. 34}$$

Are gehiago, bedi egoera berri bat non osagaiak anomalia duen, beste hitzetan, funtzio-oker intrintsekoa dauka. Kasu horretan ere, osagaia beste (B) baldintza puntu batean egongo da lanean aldagai independente balio ezberdinekin (x_i^B). Baina, i osagaiak akatsik ez duenez, akats baldintzara lotutako nolakotasun kurba (f) erreferentziaren ezberdina izango da (f^0):

$$k_i^B = f(x_i^B) \tag{D. 35}$$

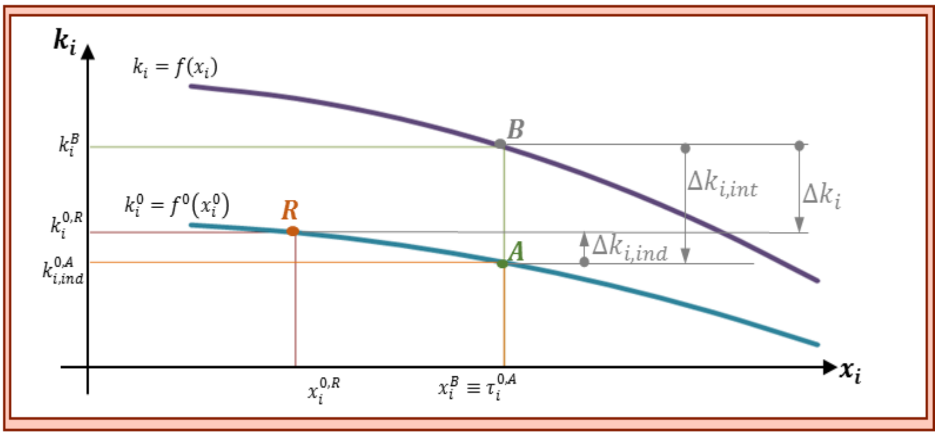
D.3.1. Nolakotasun kurbak

Ikasketa hori osagai bakoitzean era independentean aplikatu behar da. Esan bezala, i osagai orokorrak bi balio izango ditu exergia kontsumo unitariorako, lehenengoa erreferentzia egoerarekin (k_i^0) lotuko da eta bigarrena, aldiz, egoera akastuarekin (k_i).

Orduan, osagaia anomaliarik ez izan arren, erreferentzia baldintzako aldagai termiko independenteak ($x_i^{0,R}$) ezberdinak izango dira akats egoerarekin alderatuta (x_i^B) eragin induzituak medio. i osagaiak akatsa badu, akats egoeraren nolakotasun kurba (f) erreferentzia kurbaren (f^0) ezberdina izango da. Kasu horretan, exergia kontsumo unitario balio berria kalkula daiteke; hori era matematikoan lortzen da akats egoeraren balore independenteak erreferentzia kurban ezarriz:

$$k_{i,ind}^0 = f^0\left(x_i^{o,A}\right) \tag{D. 36}$$

Irudia D. 11n hiru kasuak marrazten dira.



Irudia D. 11 Erreferentzian eta operazioan kontsumo exergetiko unitarioa

Emaitza gisa, exergia kontsumo unitarioaren aldakuntza (Δk_i) exergia kontsumo aldaketa induzituan eta intrintsekoan bana daiteke ($\Delta k_{i,ind}$, $\Delta k_{i,int}$) jarraian adierazi antzera:

$$\Delta k_{i,ind} = k_{i,}^0\left(x_i^A\right) - k_i^0\left(x_i^R\right) \tag{D. 37}$$

$$\Delta k_{i,int} = k_i\left(x_i^B\right) - k_i^0\left(x_i^A\right) \tag{D. 38}$$

Orduan, osagai bakoitzaren funtzio-okerra adierazten da funtzio-oker intrintsekoen eta induzituen arteko gehiketarekin:

$$MF_i = MF_{i,int} + MF_{i,ind} = \Delta k_{i,int} \cdot P_i^0 + \Delta k_{i,ind} \cdot P_i^0 \tag{D. 39}$$

Formulazio horrek anomalien eraginak osagai bakoitzean era indibidualean kalkulatzea baimentzen du aldagai independente termodinamikoen arabera.

Beraz, prozedura orokor bat ezartzen da operazio akastun baldintzaren funtzio-oker intrintsekoen eta induzituen iturriak kokatzeko non ziurgabetasun ezaren iturri bakarra osagaiaren nolakotasun kurba eraikitzeko era den datu eskuragarrietatik.

D.4. BI METODOLOGIEN BERRIKUSKETA

Bi diagnostiko teknika termoekomikoek berezko informazioa eskaintzen dute:

- Funtzio-oker eta disfuntzio diagnostikoaren prozedurak Fuel-Produktu egitura produktiboa erabiltzen du osagaien sarrerak eta irteerak gainontzeko azpisistemekin lotzeko. Funtzio-oker intrintsekoen eta induzituen artean ez du bereizten, baina, i osagaiko funtzio-okerrak j-tan sortutako disfuntzioak kalkula daitezke eta baita ere kanpo produktuarekin lotutakoak. Gainera, instalazio osoaren efizientziaren aldaketa edozein osagaiaren aldakuntzarekin zelan aldatzen den ikusten da. Are gehiago, kostu kontaketarako egitura produktiboa erabiltzen denez, fluxu baten zein instalazio osoaren bai *kostu exergetikoak* bai *kostu ekonomikoak* kalkula daitezke [19], eta baita anomalien *kostu inpaktua* ere [15].
- Nolakotasun kurbek ikuspegia aldatzen dute eta osagaiak modu indibidualean ikertzen dituzte. Metodoak funtzio-oker induzituen eta intrintsekoen arteko bereizketa ahalbidetzen du aldagai termodinamiko independenteen arteko loturak (presioak, tenperaturak, emari masikoak eta osaerak) eta exergia kontsumo unitarioak aintzat hartuz.

D.4.1. Bi metodologien nahasketa

Demagun funtzio-oker intrintseko *bat baino gehiago* daudela sisteman. Jakina denez, MF eta DF diagnostikoa ez da gai bakoitzaren eragina guztizko fuel inpaktuan ezberdintzen, finean, itzulezintasun aldakuntzak fuel inpaktu ezberdina eragiten baitu osagaiaren posizioaren arabera.

Sisteman zenbait anomalia badaude, bakoitzak eragin ezberdinak sortuko ditu; hala nola, j osagai akastuan bertan $\Delta k_{j,int}$ (funtzio-oker intrintsekoa) aldatuko da eta gainontzeko i osagaietan exergia kontsumo unitarioa $\Delta k_{i,ind}$ (funtzio-oker induzitua) zein lekuko produkzioa ΔP_i (disfuntzioak) aldatuko dira. Helburua anomalia bakoitzak eragindako $\Delta k_{i,ind}$ eta ΔP_i artean ezberdintzea da kontsumo gehigarria j osagai akastuarekin lotzeko. MF eta DF diagnostikoarekin, azkeneko kontsumo gehigarria j akatsarekin erlazionatutako ΔP_i aldakuntza DF_{ij} gaiarekin ezagutarazten da baina, halere, informazio gehiago behar da gainontzeko funtzio-okerren eraginak bereizteko.

Ondorioz, diagnostikoaren informazioa nolakotasun kurben analisiarekin batzen bada, funtzio-oker intrintseko handieneko azpisistema ezagutu eta osagai askatuentzat jo daiteke. Haatik, baita une horretan ere, $\Delta k_{i,ind}$ aldakuntzak eragindako kontsumo gehigarria ezin zaio osagai bati esleitu ezta ΔP_S amaierako produktuaren aldakuntzaren zergatirik ere, analisi hori era indibidualean gauzatzen baita eta eragin induzituak osagai batek baino gehiagok sor ditzakelako.

Muga horiek egonagatik ere, nolakotasun kurben analisiarekin akats nagusiko osagaia identifikatzen da (bedi j) zein era birtualean ezabatu eta bigarren diagnostiko ikerketa burutu daitekeen. Era horretan, lehenengo kasutik ($\Delta F_T^{1\cdot}$) bigarrenerako ($\Delta F_T^{2\cdot}$) fuel inpaktuaren jaitsierak adieraziko du j anomaliaren konponketaren aurrezpena:

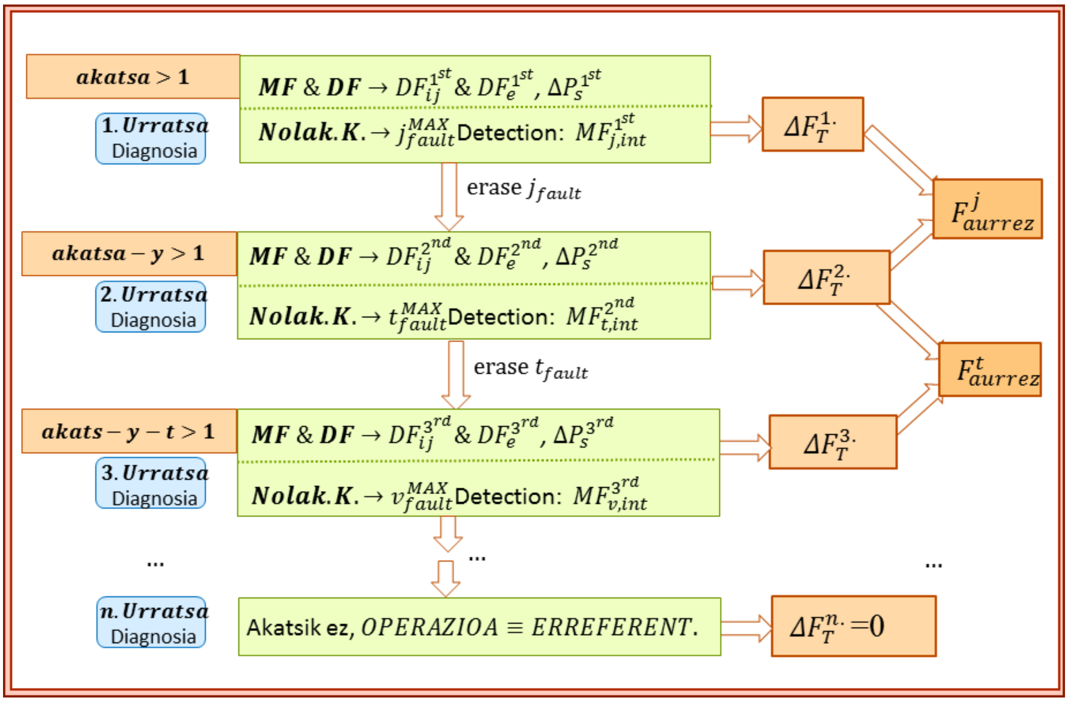
$$\Delta F_{aurrez} = \Delta F_T^{1\cdot} - \Delta F_T^{2\cdot} \tag{D. 40}$$

Era berean, ΔF_{save} horrek adieraziko ditu j funtzio-oker intrintsekoaren $\left(MF_{j,int}^{1\cdot}\right)$ eta lehenengo ikerketako eragin induzituen arteko batuketa $\left(\sum_i DF_{ij}^{1\cdot} + \sum_i MF_{ij,ind}^{1\cdot}\right)$ gehi amaierako produktuaren aldakuntza $\left(\Delta\Delta P_s^{1\cdot,2\cdot}\right)$ eta bi egoeren arteko aldaketa $\left(\Delta DF_e^{1\cdot,2\cdot}\right)$:

$$\Delta F_{aurrez} = \left[MF_{j,int}^{1\cdot} + \sum_i DF_{ij}^{1\cdot} + \sum_i MF_{ij,ind}^{1\cdot}\right] + \left[(DF_e^{1\cdot} - DF_e^{2\cdot}) + (\Delta P_s^{1\cdot} - \Delta P_s^{2\cdot})\right] \tag{D. 41}$$

$MF_{j,int}^{1\cdot}$, $\sum_i DF_{ij}^{1\cdot}$ eta $DF_e^{1\cdot,2\cdot}$, $\Delta P_s^{1\cdot,2\cdot}$ aurreko metodologiekin kalkulatzen direnez, $\sum_i MF_{ij,ind}^{1\cdot}$ kenketa erraz baten bidez kalkulatzen da.

Funtzio-oker intrintseko kopuru adinetan errepikatzen baldin bada prozedura, diagnostiko arazoa guztiz ebazten da. Irudia D. 12n metodologiaren errutina erakusten da.



Irudia D. 12 Diagnostiko metodologia MF&DF eta nokakotasun kurben nahasketarekin

D.4.2. Ikerketa kasua

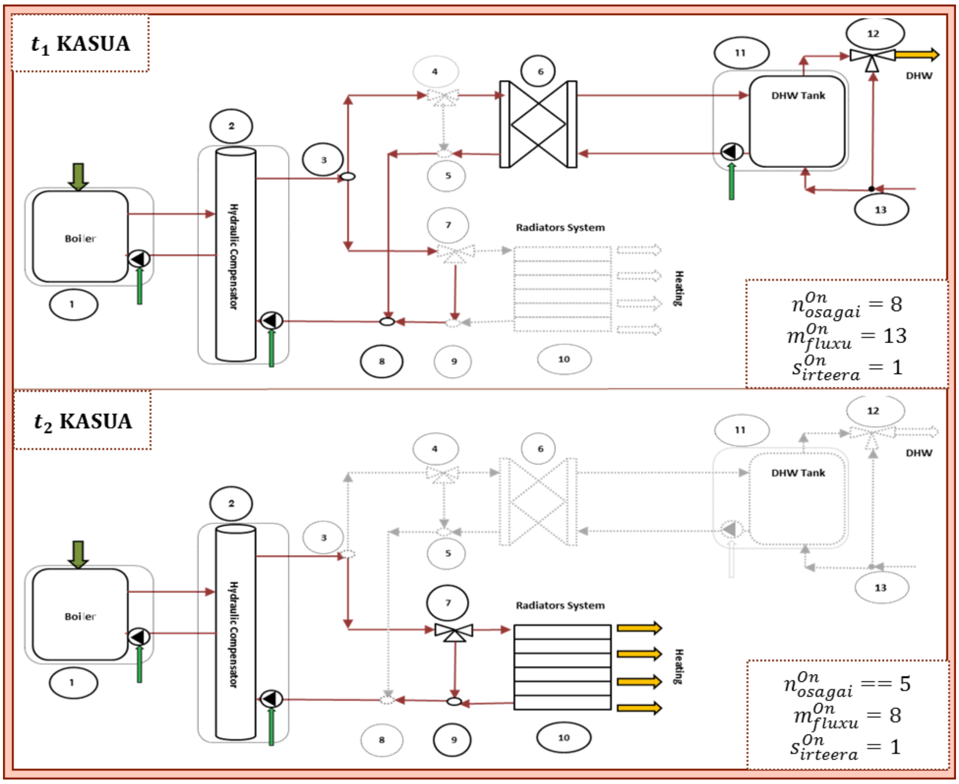
Metodologia konbinatua (fuel inpaktu formula eta nolakotasun kurben nahasketa) aurreko kasuko (vi) *Berokuntza eta EUB sistemaren ikerketa kasua*n aplikatuko da.

Alabaina, kasua erakutsi baino lehen eraikinen instalazio termikoek *azterketa dinamikoak* behar dituztela gogoratu behar da jarrera etengabean aldatzen baita, klima, erabiltzailearen eskaria eta abar medio; horrek instalazioko elementuen pizketak eta itzaltzeak eragiten baititu. Beraz, diagnostikoa bi baldintza aldakorren arteko *alderaketa*n datza eta era dinamikoan inplementatu behar da.

D.4.2.1. (vi) Berokuntza eta EUB sistemaren ikerketa kasua

Instalazio orokorra aurreko (vi) ikerketa kasukoa da (Irudia D. 4) non deskribapen osoa dagoen.

Jakina denez, lehenengo urratsa, eta analisirako sentikorrena, denbora tarte bakoitzeko egitura produktiboaren definizioa da C.3.1 Ataleko pausuak jarraituz. Esan lez, sistemaren jarrera dinamikoak osagaien modulazioa eragiten du eta, beraz, egitura produktiboa aldatuz doa osagaien pizketa eta itzaltze uneen arabera. Irudia D. 13k (Irudia C.16ren analogoa) bi kasu posible irudikatzen ditu: t_1 kasuak EUB eskaria soilik dagoeneko egoera erakusten du eta t_2 kasuak, aldiz, bakarrik berokuntza dagoenean. Argi dago biek egitura produktibo ezberdina dutena.



Irudia D. 13 Operazio egoera ezberdinak egitura produktibo ezberdinekin lotuak

C.3.2.1.2 Atalean egin antzera, guztizko modelo termoekonomiko "estatikoa" eraiki daiteke egoera dinamiko posible oro errepresentatzeko. Taula D. 8k osagai bakoitzeko F, P eta k balioak zehazten ditu Irudia D. 5ko izendapena jarraituz.

Taula D. 8 Egitura produktibo orokorra modelo termoekonomiko "estatikoan"

OSAGAIA		F	P	k
①	CB	$\dot{E}_{20}$	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_{20}/(\dot{E}_1 - \dot{E}_2)$
②	HC	$\dot{E}_1 - \dot{E}_2$	$\dot{E}_3 - \dot{E}_4$	$(\dot{E}_1 - \dot{E}_2)/(\dot{E}_3 - \dot{E}_4)$
③	D1	$\dot{E}_3$	$\dot{E}_5 + \dot{E}_6$	$\dot{E}_3/(\dot{E}_5 + \dot{E}_6)$
④	V1	$\dot{E}_5$	$\dot{E}_7 + \dot{E}_8$	$\dot{E}_5/(\dot{E}_7 + \dot{E}_8)$
⑤	M1	$\dot{E}_7 + \dot{E}_9$	$\dot{E}_{10}$	$(\dot{E}_7 + \dot{E}_9)/\dot{E}_{10}$
⑥	HX	$\dot{E}_8 - \dot{E}_9$	$\dot{E}_{15} - \dot{E}_{16}$	$(\dot{E}_8 - \dot{E}_9)/(\dot{E}_{15} - \dot{E}_{16})$
⑦	V2	$\dot{E}_6$	$\dot{E}_{12} + \dot{E}_{13}$	$\dot{E}_6/(\dot{E}_{12} + \dot{E}_{13})$
⑧	M2	$\dot{E}_{10} + \dot{E}_{11}$	$\dot{E}_8$	$(\dot{E}_{10} + \dot{E}_{11})/\dot{E}_8$
⑨	M3	$\dot{E}_{12} + \dot{E}_{14}$	$\dot{E}_{11}$	$(\dot{E}_{12} + \dot{E}_{14})/\dot{E}_8$
⑩	RS	$\dot{E}_{13} - \dot{E}_{14}$	$\dot{E}_{19}$	$(\dot{E}_{13} - \dot{E}_{14})/\dot{E}_{19}$
⑪	T	$(\dot{E}_{15} - \dot{E}_{16}) + \Delta\dot{E}_{21}$	$\dot{E}_{18} - \dot{E}_{17}$	$[(\dot{E}_{15} - \dot{E}_{16}) + \Delta\dot{E}_{21}]/(\dot{E}_{18} - \dot{E}_{17})$
⑫	V3	$\dot{E}_{18} + \dot{E}_{24}$	$\dot{E}_{23}$	$(\dot{E}_{18} + \dot{E}_{24})/\dot{E}_{23}$
⑬	D2	$\dot{E}_{22}$	$\dot{E}_{17} + \dot{E}_{24}$	$\dot{E}_{22}/(\dot{E}_{17} + \dot{E}_{24})$

D.4.2.1.1. Nolakotasun kurben diagnosia

Esan antzera, eraikinak gorabehera dinamikoekin estuki lotzen dira. Denbora tarte orotan operazio aldagai termodinamikoak ($\bar{x}$) aldatzen doazelako, osagai bakoitzaren kontsumo exergetiko unitarioa $k_i(\bar{x},t)$[5] ere aldatzen doa. Orduan, diagnostikoan moduan, CC ikasketa denbora tarte bakoitzerako errepikatu behar da elementu bakoitzean berokuntza periodoan zehar.

13 talde kontuan hartu direnez, 13 nolakotasun kurba definitu beharko dira. Helburu nagusia osagaiaren jarrera adierazteko modeloa eraikitzea da Trnsys v17-en algoritmoak jarraituz; modelo termikoaren garapena B.3.1 Atalaren antzekoa da baina, kasu honetan, urrats bat harago doa eta k_i aldagai independentea da xedea. Jomuga horretarako, Trnsys-en osagaien erreferentzia matematikoko gidaliburua jarraitzen da haren Fortran programarekin batera. Horrela, $\bar{x}$ aldagai independenteak eta osagai bakoitzaren ezaugarri fisiko zehatzak hartzen dira aintzat. Adibide gisara, bero trukagailuaren nolakotasun kurba kalkulatzen da:

Irudia D. 5ko bero trukagailuaren kontsumo exergetiko unitario kontuan hartuz:

$$k_6 = \frac{\dot{E}_8 - \dot{E}_9}{\dot{E}_{15} - \dot{E}_{16}} \qquad \text{(D. 42)}$$

Eta i ur emariaren exergia da:

$$\dot{E}_i = c_P \cdot \dot{m} \cdot T_i - T_0 - T_0 \cdot ln\left(\frac{T_i}{T_0}\right) \qquad \text{(D. 43)}$$

non c_p fluxuaren bero ahalmen espezifikoa, $\dot{m}$ emari masikoa eta T_0 giro tenperatura diren.

Aldagai independenteak $\bar{x}_6$ eta ezaugarri fisikoak dira: primarioko eta sekundarioko sarrera tenperaturak (T_8, T_{16}) (baita ere V1 eta T-ren irteerak izanik), emari masikoak $(\dot{m}_{prim}, \dot{m}_{sec})$,

[5] Lan honetan zeharreko k_i balore guztiak aldagai dependentetzat hartu behar dira; aldagai agregatuekin sortzen baita $k_i(\bar{x},t)$. Leku arrazoiak medio k_i erabiltzen da $k_i(\bar{x},t)$ beharrean.

giro tenperatura (T_0) eta bero transferentzia koefiziente totala UA. Orduan (T_9, T_{15}) irteera tenperaturak aldagai horien dependente dira.

Bero trukagailuaren irteera tenperaturak kalkulatu nahi direnez eta horren transferentzia gainazala ezaguna izateagatik, eraginkortasun metodoa -*transferentzia unitate zenbaki*aren metodoa ε- NTU erabiliko da, Trnsys-en algoritmoak egin bezala. Horretarako lehenik eta behin primarioaren eta sekundarioaren artean ahalmen termiko maximoa zehazten da:

$$C_{prim} = c_P \cdot \dot{m}_{prim} \quad \text{(D. 44)}$$

$$C_{sec} = c_P \cdot \dot{m}_{sec} \quad \text{(D. 45)}$$

$$C_{max} = \max(C_{prim}, C_{sec}) \quad \text{(D. 46)}$$

$$C_{min} = \min(C_{prim}, C_{sec}) \quad \text{(D. 47)}$$

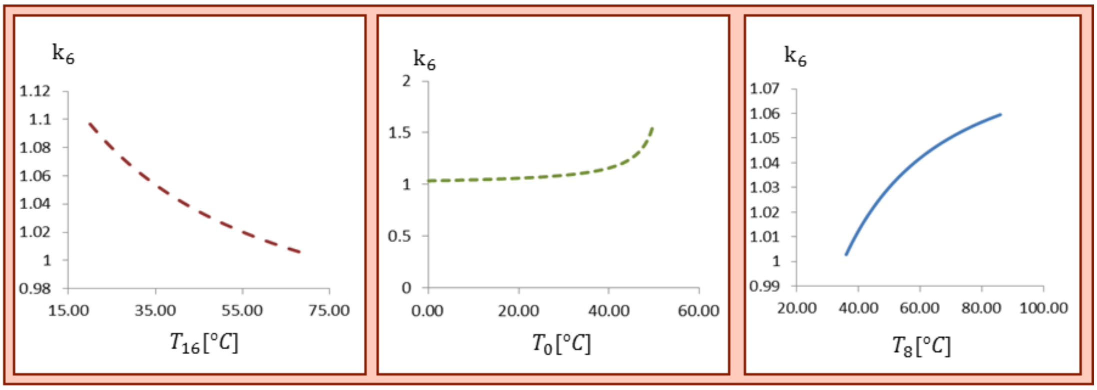
Orduan, eraginkortasuna da:

$$\varepsilon = \frac{1 - e^{\left(-\frac{UA}{C_{min}} \cdot \left(1 - \frac{C_{min}}{C_{max}}\right)\right)}}{1 - \frac{C_{min}}{C_{max}} \cdot e^{\left(-\frac{UA}{C_{min}} \cdot \left(1 - \frac{C_{min}}{C_{max}}\right)\right)}} \quad \text{(D. 48)}$$

Eraginkortasun horretatik abiatuta irteera tenperaturak zehazten dira zeintzuek, era berean, M1 eta T osagaien sarrera tenperatura aldagai independenteak diren. Horiek dira:

$$T_9 = T_8 - \varepsilon \cdot \left(\frac{C_{min}}{C_{prim}}\right) \cdot (T_8 - T_{16}) \quad \text{(D. 49)}$$

$$T_{15} = T_{16} + \varepsilon \cdot \left(\frac{C_{min}}{C_{sec}}\right) \cdot (T_8 - T_{16}) \quad \text{(D. 50)}$$



Irudia D. 14 Bero trukagailuaren exergia kontsumoaren jarrera aldagai independente batekiko

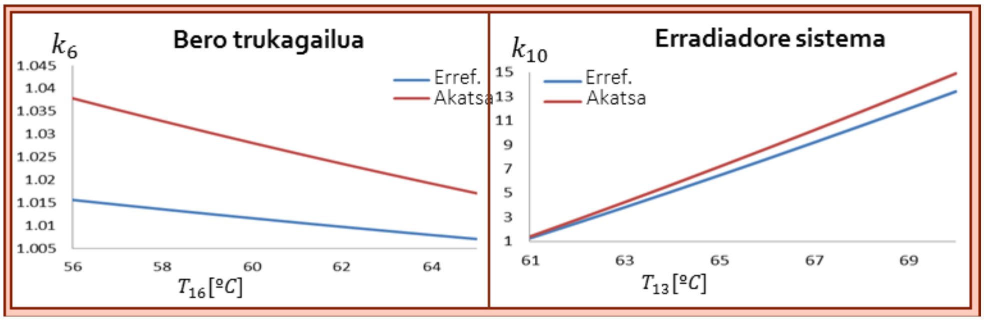
Horrela exergia kontsumo unitarioa k_6 kalkulatzen da. Irudia D. 14n, gainontzeko aldagaiak konstante mantentzean aldagai independente baten aldakuntzak kontsumoan duen eragina era grafikoan aurkezten da. $UA = 133888\, kJ/h.K$, $\dot{m}_{prim} = 1.920\, kg/h$, $\dot{m}_{sec} = 1.860\, kg/h$ balioak erabili dira eta datozen hiru tenperaturen banakako aldakuntzak neurtu $T_{16} = 35\ ºC$, $T_0 = 15\ ºC$ eta $T_8 = 75\ ^0C$ dira.

D.4.2.2. Zenbakizko adibidea

EUB eta berokuntza eskariak aurreko adibidearen berdinak dira.

D.4.2.2.1. Akats-anitzak

Esan bezala, akats bat RS erradiadore sisteman dago eta etekinaren % 10 murrizten du eta, bigarrena, HX bero trukagailuan dago eta bero transferentzia koefizientziaren % 35eko jaitsiera da. Adibidearen helburua anomalia intrintsekoen diskriminazioa da nolakotasun kurben metodoa eta MF eta DF metodoa modu paraleloan erabiliz.



Irudia D. 15 Osagai akastuen erreferentzia eta operazio baldintzen kontsumo exergetikoen kurbak

Irudia D. 15n osagai horien erreferentzia baldintzako eta operazioko nolakotasun kurbak erakusten dira horien aldagai independente baten aldakuntzarekiko (gainontzekoak konstante mantenduz).

D. 2.4.1.2. Atalaren arabera, exergia fluxuen balioak operazio baldintzetan (akats egoera erreala), baldintza askean eta erreferentzia baldintzan lortzen dira. Berokuntza periodoko balio pilatuak Taula D. 9n erakusten dira. Alabaina, baldintza askeko egoera (hori izango da erreferentziatzat hartutakoa) eta anomaliaren erreala erakusten dira soilik; finean, adibide honen jomuga akats anizdun sistema batean MF eta DF teoriaren aplikazioa baita. Nahiz eta orduz-orduko simulazioa egin exergia fluxu pilatuen balioak aurkezten dira.

Taula D. 9 Exergia pilatuen balioak erreferentzia eta baldintza askean $[GJ_{ex}]$

$[GJ]$	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}
ERREF.	122.9	100.1	372.3	351.8	192.0	180.3	153.3	38.9	29.8	182.9	169.2
ASKE	122.9	99.2	369.8	348.4	190.7	179.1	151.9	38.8	29.8	181.7	166.7

E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}	E_{19}	E_{20}	ΔE_{21}	E_{22}	E_{23}	E_{24}
57.6	122.7	111.6	37.2	28.3	0.2	6.5	2.3	149.1	0.04	0.2	5.8	0.03
57.7	121.4	109.2	36.2	27.5	0.2	6.4	2.3	155.3	0.05	0.2	5.6	0.03

D.4.2.2.2. Diagnostiko termoekonomikoa

Hasteko, funtzio-okerren eta disfuntzioen matrizea Taula D. 10on erakusten dira. Lehenengo zutabeak dagokion zenbakiarekin osagaia izendatzen du; bigarren zutabeak funtzio-okerra erakusten du (MF_i) eta jarraian disfuntzio matrize zabaldua erakusten da. Matrize horretan kanpo baliabide kontsumoen disfuntzioak ($DF_{e,i}$) eta gainontzeko taldeei dagozkion (DF_{ij})ak erakusten dira. Azkenengo zutabeak produkzio totala erakusten du.

Taula D. 10 MF eta DF taulak diagnostiko pilatutik eratorria $[MJ]$

MF & DF 1.DIAGNOSTIKOA																
	$MF^{1.}$	$DF_e^{1.}$	$[DF^{1.}]$													$\Delta P_s^{1.}$
①	-1214	-1396	-	557	-24	-	-	1255	-	-486	-	6617	-34	-21	-	-
②	-450	-9	-	-	-80	-	-	-48	-	52	-	480	104	-	-	-
③	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
④	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑤	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑥	206	-12	-	-	-	-	-	-	-	-	-	-	-10	-	-	-
⑦	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑧	-136	-14	-	-	87	-	-	32	-	-23	-	-15	-25	-	-	-
⑨	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑩	1093	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑪	-40	-6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⑫	-1	-15	-	-	-	-	-	-	-	-	-	-	-	-	-	-129
⑬	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		⓪	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	

Emaitzen arabera esan ahal da:

- Anomaliako osagaiek funtzio-oker handienak dituzte (HX eta RS, $MF_6^{1\cdot} = 206\ MJ$ eta $MF_{10}^{1\cdot} = 1093\ MJ$). Halere, horiek funtzio-oker intrintsekoak eta induzituak batera dira eta, beraz, ezin da zuzenean ondoriorik atera.
- Efektu induzituen hedapena medio, beste osagaietan ere funtzio-okerrak agertzen dira ($[MF_1^{1\cdot} = -1214\ MJ]$, $[MF_2^{1\cdot} = -450\ MJ]$, $[MF_8^{1\cdot} = -136\ MJ]$, $[MF_{11}^{1\cdot} = -40\ MJ]$ eta $[MF_{12}^{1\cdot} = -1\ MJ]$) zeinek $\Delta k_i < 0$ eragiten duten.
- D.2.4.1.3 Atalean esan lez, baldintza askea inposatu denez, amaierako produkzio murrizketa dago, $\Delta P_s^{1\cdot} < 0$. Gertaera hori gainontzeko osagaien eraginkortasunean eragiten du disfuntzio negatiboaren bidez $\sum_i DF_{i,e}^{1\cdot} = -1452\ MJ$.
- Oro har, funtzio-okerrek disfuntzioak sortzen dituzte. Eragin horiek anomaliatik gorako taldeek jasaten dituzte gehien bat. Horrela, CB galdara disfuntzio handieneko taldea da $\left[DF_1^{1\cdot} = DF_{1,2}^{1\cdot} + DF_{1,3}^{1\cdot} + DF_{1,6}^{1\cdot} + DF_{1,10}^{1\cdot} + DF_{1,11}^{1\cdot} + DF_{1,12}^{1\cdot} = 6.702\ MJ\right]$.
- Bestalde, RS osagaiak disfuntzio gehien eragiten ditu $\left[DF_{1,10}^{1\cdot} + DF_{2,10}^{1\cdot} + DF_{6,10}^{1\cdot} + DF_{8,10}^{1\cdot} = 7864\ MJ\right]$.
- HX-ek ere disfuntzioak eragiten ditu $\left[\sum_i DF_{i,6}^{1\cdot} = 1239\ MJ\right]$ baina ez du horrenbesteko indarrik kate energetikoaren goialdean baitago.
- $\Delta P_{s_{DHW}}^{1\cdot} < 0$ azkenengo zutabean ikusten da.

- Halaber, osagai guztien gehiketak bi anomalien fuel inpaktua erakusten du, alegia, $\Delta F_T^{1.} = 6.296\ MJ$.

D.4.2.2.3. Nolakotasun kurben diagnostikoa

Analisi alternatiboa orduko egin zen nolakotasun kurben metodologiaren diagnostikoaren arabera eta emaitzak Taula D. 11n batu ziren. $\mathbf{MF_{int}^{1.}}$ zutabean funtzio-oker intrintsekoak daude eta $\mathbf{MF_{ind}^{1.}}$ zutabean, ordea, funtzio-oker induzituak; horiek osagaien nolakotasun kurbak lerro horizontalak ez direlako sortzen dira. Bi zutabeen gehiketak osagaien funtzio-oker totalak adierazten ditu. Azken zutabean, bestalde, disfuntzioak aurkezten dira. Datozen gogoetak egin daitezke, beraz:

Taula D. 11 MF eta DF 1. analisia nolakotasun kurbekin

		NOLAKOTASUN KURBAK		
		$\mathbf{MF_{int}^{1.}}$	$\mathbf{MF_{ind}^{1.}}$	$\mathbf{DF^{1.}}$
①	CB	-	-1214	6467
②	HC	-	-450	500
③	D1	-	-	-
④	V1	-	-	-
⑤	M1	-	-	-
⑥	HX	323	-117	-22
⑦	V2	-	-	-
⑧	M2	-	-136	42
⑨	M3	-	-	-
⑩	RS	1212	-119	-
⑪	T	-	-40	-6
⑫	V3	-	-1	-15
⑬	D2	-	-	-

- Nolakotasun kurben metodoarekin funtzio-oker intrintsekoaren eta induzituen arteko bereizketa egiten da. Horrela, taulan funtzio-oker intrintsekoen osagaiak, hain zuzen, HX eta RS $\left[MF_{6,int}^{1.} = 323\ MJ\right]$ eta $\left[MF_{10,int}^{1.} = 1212\ MJ\right]$ dira.
- Alabaina, metodologiak ez du bakoitzaren disfuntzioen jatorria ahalbidetzen, taldeen guztizko disfuntzioak soilik zenbatzen dituelako, $DF_i^{1.}$.

D.4.2.3. Bi metodoen nahasketa

Funtzio-oker intrintsekoen osagaiak identifikatu direnez, hurrengo urratsa pisu handieneko funtzio-oker intrintsekoa ezabatzea da (RS). Hori konpondu ostean eta, berriro ere, osagai oro erreferentzia baldintzetara eramanez, simulazioa burutzen da. Modu horretan lehenengo eta bigarren simulazioaren arteko fuel inpaktuaren murrizketa kalkulatzen da. Lekua aurrezteko bigarren analisiko nolakotasun kurben $\mathbf{MF}$ emaitzak batzen dira Taula D. 12n, beste diagnosiaren $\mathbf{DF}$, $\mathbf{DF_e}$ eta amaierako produktuaren aldakuntzarekin batera.

Taula D. 12 MF, DF eta ΔPs analisia 2. urratsean

		NOLAKOTASUN KURBAK		MF & DF DIAGNOSTIKOA		
		$MF_{int}^{2.}$	$MF_{ind}^{2.}$	$DF_{e}^{2.}$	$DF^{2.}$	$\Delta P_{s}^{2.}$
①	CB	-	-2048	-754	2197	-
②	HC	-	-143	1	82	-
③	D1	-	-	-	-	-
④	V1	-	-	-	-	-
⑤	M1	-	-	-	-	-
⑥	HX	317	-118	-6	-9	-
⑦	V2	-	-	-	-	-
⑧	M2	-	-45	-11	59	-
⑨	M3	-	-	-	-	-
⑩	RS	-	18	-	-	-
⑪	T	-	-33	-12	-	-
⑫	V3	-	-1	-10	-	-76
⑬	D2	-	-	-	-	-

- RS osagaiaren anomalia ezabatzean akatsa soilik HXan dago eta horregatik funtzio-okerra $MF_{6,int}^{2.} = 317\ MJ$ da. Anomalia intrintseko horiek aurreko simulazioarekiko zertxobait aldatu dira; finean, taldeen operazio baldintzak ere pixka bat aldatu direlako.
- $DF_{i,0}^{2.}$narbamena da. Izatez, HX osagaian akatsa dagoenez, EUBaren amaierako produkzioa erreferentzia baino txikiagoa da eta horrek kontsumoan du eragina $\left(\sum_i DF_{i,e}^{2.} = -792\ MJ\right)$.
- Anomalia intrintsekoen kopurua murriztu denez, guztizko produkzioaren aldakuntza $\Delta P_{s_{DHW}}^{2.}$ zerotik gertuago dago.
- Bi anomalia intrintseko egoteagatik fuel inpaktua $\Delta F_{T}^{2.} = -590\ MJ$ da.

Laburbilduz eta Ek.(D. 40)-ren arabera, RS ezabatzean lortutako aurrezpenak $\Delta F_{aurrez} = 6886\ MJ$ dira. Beraz, RSren anomaliak induzitu duen funtzio-okerra da: $\sum_{10} MF_{10j,ind}^{1^{st}} = -695\ MJ$.

Taula D. 13 Diagnostikoaren emaitza orokorrak [MJ]

	$\mathbf{RS}\,anomalia$	$\mathbf{HX'}\,anomalia$
MF_{int}	1212	317
$\sum MF_{ind}$	-695	-1270
$\sum DF$	7082	1230
$DF_e + \Delta P_s$	-714	-867
$\Delta F_{anomalia}$	6886	-590

Taula D. 13n anomalien emaitza orokorrak batzen dira. MF_{int}, $\sum MF_{ind}$ eta $\sum DF$ ilarak osagai akastunen funtzio-oker intrintsekoak zein induzituak eta osagaien disfuntzioak dira; DF_e+ΔP_s

lerroak, ordea, amaieraren produkzioaren gaineko eraginak erakusten ditu. Azkenik, $\Delta F_{anomalia}$ adierazlearekin anomalia bakoitzaren fuel inpaktua laburtzen da.

Horrela, osagai bakoitzeko anomaliaren fuel inpaktua kalkulatzen da:

- Beraz, RS osagaiak $6886\,MJ$-ko kontsumo gehigarria eragiten du eta horietako $7599\,MJ$ berezko anomaliagatik datoz eta, gainontzeko -$714\,MJ$-a amaierako produktuaren murrizketagatik.
- Bestalde, HX elementuaren anomaliak $-590\,MJ$-ko gainkontsumoa eragiten du eta $277\,MJ$ akatsarengatik eta $-867\,MJ$ EUB sorkuntzaren murrizketagatik dira.

D.4.2.4. Emaitzen eztabaida

Anomaliak kokatzeko diagnostiko metodologia berria proposatu da bi tekniken nahasketaren bitartez. Berez, ez da posiblea anomalia detektatzea eragin induzituak eta intrintsekoak matematika teknikaren bidez bereiztu gabe. Alde batetik, *nolakotasun kurben* diagnostikoak osagai bakoitzaren funtzio-oker *intrintsekoak* eta *induzituak* modu indibidualean banatzea ahalbidetzen du. Beste alde batetik, ohiko *fuel inpaktu* diagnostikoa sistema osoaren egitura produktiboa aintzat hartuz lortzen da.

Giltzarria da ez dagoela metodologia hobeagorik biak osagarriak baitira diagnostiko egokirako. Funtzio-oker eta disfuntzio metodoen bidez, funtzio-oker bakoitzaren fuel inpaktua eta amaierako produktuaren aldakuntzak eragindako disfuntzioak ikas daitezke. Halere, metodologiak ez du bereizten eragin induzituen eta intrintsekoen artean. Bestalde, nolakotasun kurben analisi indibidualak bereizten ditu. Bi teoriak nahastuz, anomalia bakoitzaren fuel inpaktua kalkula daiteke ikasketa errepikakorraren bidez.

Orduan, metodologiak osagaiak lekuko eran ikastea ahalbidetu eta eragin globala zenbakitzen du. Beraz, osagai anomaloen eraginkortasun narriaduraz gain, bakoitzaren baliabide kontsumo gehigarria kontatzen da.

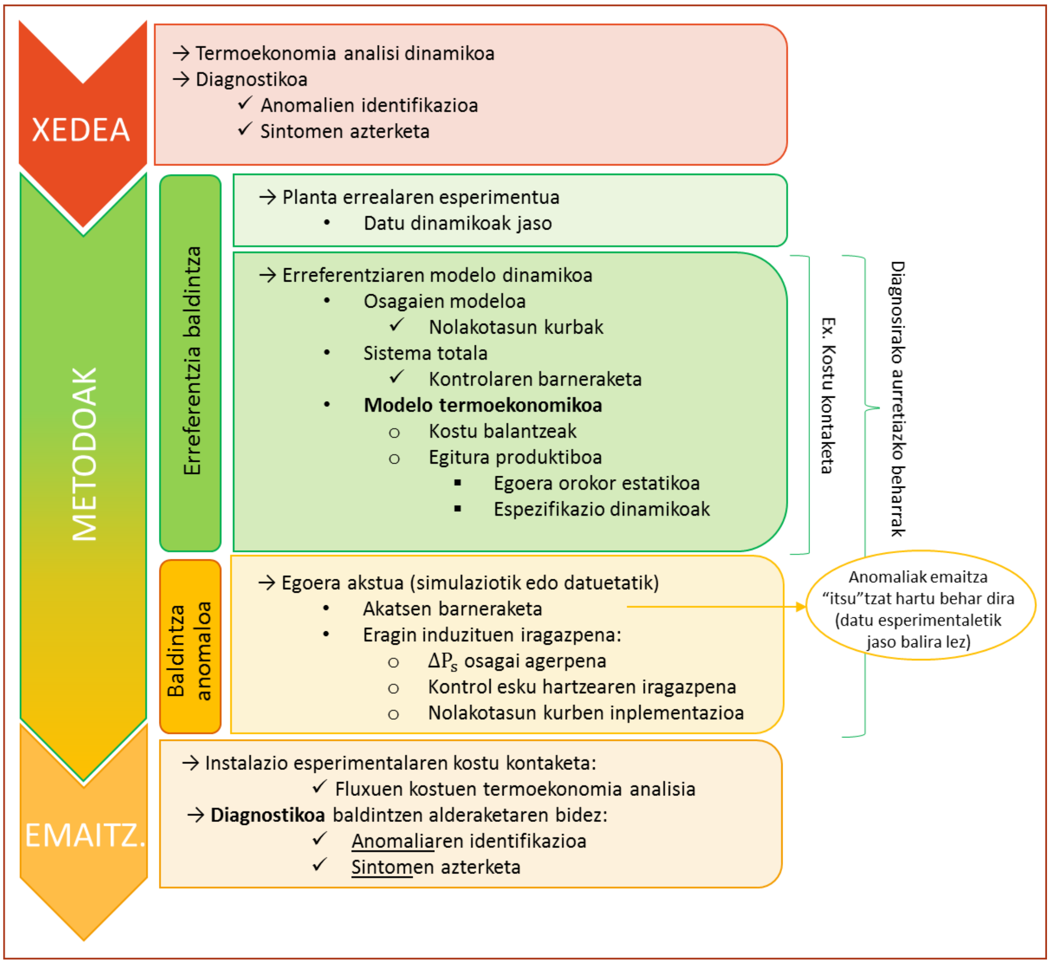
Teoria hori etxebizitza baten EUB eta berokuntza sisteman aplikatu da bi akatsekin zeinetan RSren anomalia ezaugarritu den osagai akastuen eran. Horren kontsumo gehigarria berokuntza periodoan zehar $6886\,MJ$ da, beste osagaietan induzitutako eraginengatik ($6387\,MJ$), bere gain sortutako kontsumo handitzeagatik ($1212\,MJ$) eta amaierako produktuaren aldakuntzagatik ($-714\,MJ$).

D.5. PROBLEMA ZUZENAREN EBAZPENA

Honaino, diagnostikoaren *zeharkako problema* guztiz ebatzi da, alegia, anomalia jakinen *ezagutzarekin* prozedurak horien eraginak kalkulatzen ditu fuel inpaktuaren eta funtzio-oker kostuen bitartez. Halaber, metodologia berria erakutsi da eragin induzituak eta intrintsekoak ezberdintzeko. Azken batean, akats bat badago (funtzio-oker intrintsekoa) osagai akastuen nolakotasun kurbak alteratu egiten dira eta akatsik gabeko osagaien kurbek operazio moduan baino ez dute aldaketarik jasaten lotura termodinamiko estuak medio. Helburua, hortaz, eragin intrintsekoak eta induzituak bereiztea denez, oinarria sistemaren modelo termodinamiko zuzena eraikitzean datza.

Nahiz eta diagnostiko metodologia erakargarria proposatu, aplikazioa era birtualean egin zen eta akatsen kokapenaren aurretiazko ezagutza zegoen. Gainera, nolakotasun kurbak eraikitzeko modua, kasu batzuetan, zaila eta traketsa izan daiteke ziurgabetasun iturri bihurtuz.

Gertakari horiek medio, eragin induzituak iragazteko era berritzailea eratu da diagnostikoaren *problema zuzena* anbiguotasunik gabe eta modu sistematikoan ebazteko. Gainera, metodologia hori egoera erreal batean inplementatu zenez, aplikazio errealen arazoak (esaterako, baldintza askearen lorpena) gainditu ziren.



Irudia D. 16 Metodologia zuzenaren lan katea

Irudia D. 16n diagnostiko aplikaziorako lan fluxua erakusten da: hasteko, planta erreala ikasten da, lehenengo urratsa erreferentziazko baldintzaren modelo termodinamikoa eratzea delarik (**B Kapitulua**). Modelo termoekonomikoa definitu behar da ondoren (**C Kapitulua**). Datorren urratsa akatsen detekzioan datza simulazio teknika berri baten bitartez zeinek era zuzenean zenbatzen baititu funtzio-oker intrintsekoak.

Metodologia hori ikasketa praktiko baten bidez erakutsiko da.

D.5.1. Ikerketa kasua

Ikerketa kasu hautatua **C Kapitulu**ko (v) *Eraikinean eguzki sistemaren ikerketa kasua* da. Bada, lehenengo bi urratsak (erreferentzia egoeraren modelo termikoa eta modelo termoekonomikoa) guztiz osatu dira C.3.2.1 Atalean.

Esan antzera, ideia nagusia diagnostikoaren problema zuzena HVAC&R sistemetan inplementatzeko gida egitea da.

D.5.1.1. (v) Eraikinean eguzki sistemaren ikerketa kasua

Instalazioa (v) adibidea da zeinen osagaien zerrenda Taula D. 14n dagoen. Esan lez, erreferentzia egoera guztiz modelatu da Trnsys simulazio eta Matlab softwareen bitartez datu errealekin.

Taula D. 14 Sistemaren osagaien zerrenda

		OSAGAIAK
①	B	Galdara
②	D1	B Banatzailea
③	V1	B Nahasgailua
④	HC	Orekatzaile hidraulikoa
⑤	V2	V3V banatzailea
⑥	V3	HX nahasgailua
⑦	D3	HX banatzailea
⑧	V4	H nahasgailua
⑨	D4	H banatzailea
⑩	HX	Bero trukagailua
⑪	H	Berokuntza sistema
⑫	T1	EUB tankea
⑬	T2	Eguzki tankea
⑭	V5	SC Nahasgailua
⑮	D5	SC Banatzailea
⑯	SC	Eguzki kolektorea

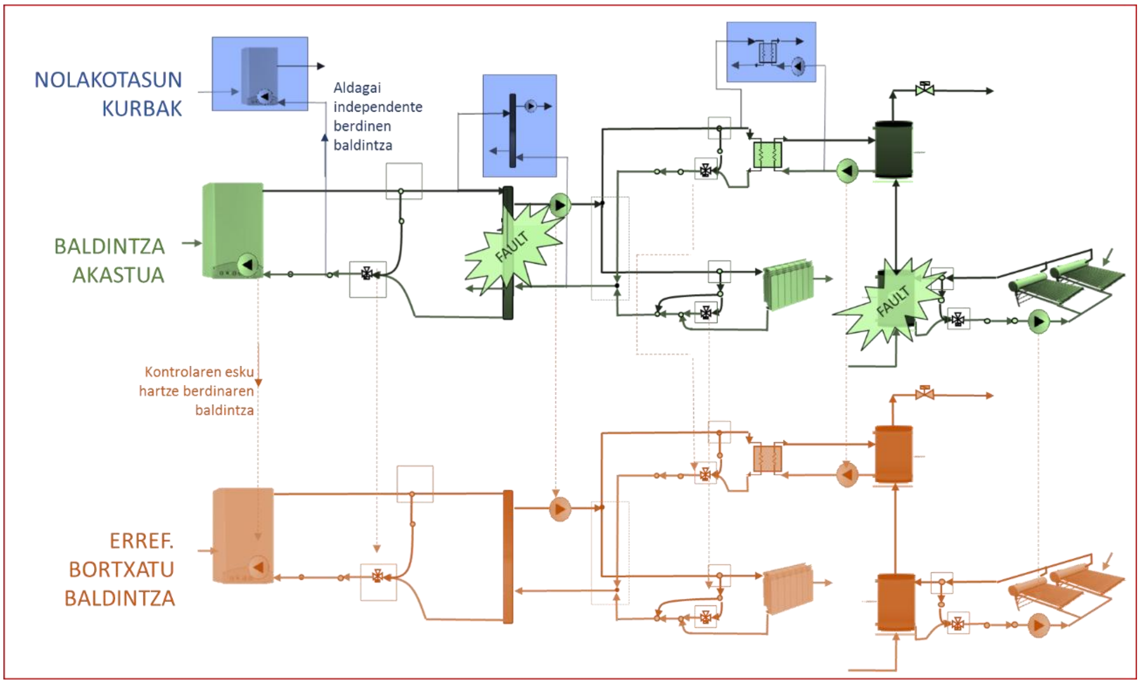
Modelo termiko horrekin, bi akats barneratu ziren osagai ezberdinetan horien parametro fisikoak aldatuz: lehenengoa *orekatzaile hidraulikoan* jarriz zen horren galera koefizientea (kJ/hm²K) 4 aldiz handituz eta bigarrena eguzki tankean parametro berdina 1,5-en handituz.

D.2.5 Atalean aurretik aipatutako (i) eta (ii) funtzio-oker induzituak saihestu ziren erreferentzia egoerako ingurugiro baldintza dinamiko eta fuel kalitate berdinak hartuz. Plantaren produkzio totala (iii), ordea, ezin izan zen baliogabetu, berokuntza eskaria [kWh] berdin mantendu arren $\Delta P_S^{heat} = 0$, EUB eskari exergetikoa [l/h] tanke tenperaturaren menpe dagoelako eta, beraz, anomaliarekin zuzenki eraginda $\Delta P_S^{DHW} \neq 0$, lehen adierazi lez. Gainontzeko funtzio-oker induzituak, berriz, Trnsys simulazio berberean saihestu ziren (hau da, hain zuzen, aplikazioaren berrikuntza bat).

Beste alde batetik, (v) eragin induzitua ekiditeko nolakotasun kurben aplikazio indibiduala egin zen: osagai bakoitzaren modelo termikoa banaka barneratu zen eta operazio baldintzen aldagai independenteen balioa aldakorrak ($\bar{x}$) hartu ziren kontutan. Banatuta egin beharrean, (D.4.2.1.1 Atalean bezala), CC aldi berean inplementatu zen akats egoerako operazio aldagaiak aintzat hartuz. Horrela, anomaliarik gabeko osagaien irteera dependenteak operazio aldagai dependenteekin bat (eragin induzituak soilik edukitzeagatik, operazio puntua bakarrik mugitu da nolakotasun kurbaren gainean); bestalde, balio horiek desberdinak dira osagai akastuetan (zeren horien CC modeloa aldatu egin baita).

Beste alde batetik, (iv) kontrol sistemaren esku hartzearen eragina *erreferentzia baldintza bortxatua*rekin iragazi egin da. Azken finean, operazio baldintza kontrol sistemaren menpe dagoenez, nolakotasun kurba gehigarria barneratzen baitu (sistemen aldagaien arteko harremana, alegia). Erreferentzia baldintza bortxatu hori aurreko *baldintza askea*ren antzekoa da baina, operazio baldintza erreferentzia kontrola aplikatu beharrean, alderantzikatu egiten da egoera eta operazio baldintzako kontrola era birtualean erreferentzian aplikatuz. Nagusiki, kontrola ponpen eta 3-bideko balbulen modulazioarekin lotzen da (edota aktibazioarekin zein itzaltzeekin). Alderantzikatzearen zergatia diagnostikoaren aplikazio errealean datza, azken batean operazio baldintza baita monitorizatutakoa eta, beraz, kontrolak zuzenean eragingo du bertan eta ez erreferentzian. Konfigurazio berriaren baldintza Trnsys simulazio berberean lortzen da D.2.2.1 Atalean esan antzera, baina operazio kontrola erreferentzian barneratuz.

Irudia D. 17n Trnsys-en akats egoera, nolakotasun kurben aplikazio indibiduala eta erreferentzia baldintza bortxatua elkarrekin zelan lortu erakusten da (leku murrizketak medio, soilik hiru osagaien nolakotasun kurbak agertzen dira).



Irudia D. 17 Datu akastuen, erreferentzia baldintza bortxatuaren eta nolakotasun kurben aldi bereko lorpena

Hori konfiguratu ondoren, diagnosi formulak denbora tarte bakoitzean aplikatzen dira; beraz, baldintza akastuaren, nolakotasun kurben eta erreferentzia baldintza bortxatuaren arteko alderaketa egiten da osagai bakoitzaren funtzio-oker intrintsekoak MF_{intr}^{i} zein induzituak MF_{indu}^{i} eta disfuntzioak DF^{i} lortzeko.

D.5.1.1.1. Zenbakizko emaitzak

Esan bezala, sistemak bi akats dauzka (bat orekatzaile hidraulikoan eta bestea eguzki biltegian). Erreferentzia baldintza bortxatua eta nolakotasun kurben irteera balioak aldi berean lortu ziren baldintza akastuarekin. Hamar segundoko ateratzen ziren datu termodinamikoak

Taula D. 15 Bi akatseko sistemarako diagnostikoaren emaitza orokorrak

			DIAGNOSTIKOA (2 akats: HC. T2)		
			ΔI		
		ΔP_s	MF		DF
			MF_{induc}	MF_{intr}	
①	B		106		605
②	D1				
③	V1				
④	HC		-2	119	4
⑤	V2		-2		-2
⑥	V3				
⑦	D3				
⑧	V4		1		-1
⑨	D4				
⑩	HX		-26		7
⑪	H				
⑫	T1	-1	-160		141
⑬	T2	-10	4	12	-25
⑭	V5				
⑮	D5				
⑯	SC		316		-309
			$F_T^0[kJ] =$		76528
			$F_T\ [kJ] =$		77305

eta diagnostikoaren ekuazioak hamar minutuko balio pilatuekin egin ziren; Taula D. 15n guztizko balioak biltzen dira.

Hortaz, akats horien ondoriozko fuel inpaktua $\Delta F_T^{2HC,T2} = 777\ kJ$ zen zeintzuetatik HCren anomaliak eragin intrintsekorik handiena duenez ($MF_{intr}^{HC} = 119\ kJ$), konpontzen lehenengoa izan beharko litzateke. Esan antzera, ezin da EUB produkzio berdina mantendu anomalia T1 tenperaturarekin zuzenki erlazionatzen baita, beraz, $\Delta P_S^{DHW} = 1\ kJ$. Funtzio-oker intrintsekoen eta induzituen arteko bereizketa ez bada nolakotasun kurbekin egiten, B galdara har daiteke (modu erratuan) osagai akastu lez (ikus haren funtzio-oker induzitu eta disfuntzio balio altuak $MF_{indu}^{B} = 106\ kJ, DF^B = 605\ kJ$).

Ondorio gisa, hurrengo urratsa anomalien konponketarekin bat dator. Taula D. 16ean, hasteko, HC konpondu osteko emaitzak barneratzen dira eta, geroko taulan, ordea, T2 osatzerakoan. Horien arabera, T2ak *funtzio-on* bat sortzen du erreferentzia baldintza bortxatuko kontsumoa altuagoa baita operazioarekin alderatuz gero ($\Delta F_T^{1T2} = -78\ kJ$). Kontrol sistemaren esku hartzearen iragazkiarekin zerikusia du galdararen eragin negatiboak murriztu eta EUB produktua jaisten baitu. Bestalde, HC osagaiko anomaliak eragin nabaria dauka ($\Delta F_T^{1HC} = 860\ kJ$), bereziki galdararen eraginkortasunean; are gehiago, eguzki adarra ez dago eraginda.

Taula D. 16 Akats bakarreko sistemarako diagnostikoaren emaitza orokorrak

			DIAGNOSTIKOA (1 akats: HC)		
			ΔI		
		ΔP_s	MF		DF
			MF_{induc}	MF_{intr}	
1	B		114		665
2	D1				
3	V1				
4	HC		-2	119	6
5	V2		-1		-1
6	V3				
7	D3				
8	V4		1		-1
9	D4				
10	HX		-7		-2
11	H				
12	T1	-10	-60		40
13	T2				
14	V5				
15	D5				
16	SC		-1		
			$F_T^0[kJ] =$		76522
			$F_T\ [kJ] =$		77382

			DIAGNOSTIKOA (1 akats: T2)		
			ΔI		
		ΔP_s	MF		DF
			MF_{induc}	MF_{intr}	
1	B		-8		-56
2	D1				
3	V1				
4	HC				-1
5	V2				
6	V3				
7	D3				
8	V4				
9	D4				
10	HX		-18		8
11	H				
12	T1	9	-105		105
13	T2	-10	4	12	-25
14	V5				
15	D5				
16	SC		316		-309
			$F_T^0[kJ] =$		76463
			$F_T\ [kJ] =$		76385

Erakutsi antzera, fuel inpaktu formularen gainezartzea ez da betetzen: anomalia indibidualen fuel inpaktuen gehiketa ezberdina da bi akatsak batera dauden sistemaren fuel inpaktuarekin, hots, $\Delta F_T^{1_{T2}} + \Delta F_T^{1_{HC}} > \Delta F_T^{2_{HC,T2}}$. Gainera, erreferentzia baldintza bortxatuaren fuel kontsumoa F_T^0 kasu bakoitzean ezberdina da zuzenki lotzen baita operazio baldintzekin eta, hortaz, une bakoitzeko anomalia jakinekin.

Edozein kasutan ere, anomalien osagaiak erraz identifikatzen dira (funtzio-oker intrintsekoarekin lotuz) eta horien eraginak i osagaietan ere erakusten dira (dependentzia termodinamikoengatik MF_{induc}^i eta produktu aldakuntzarengatik ΔP_i). Beraz, diagnostikoak zuzen funtzionatzen du.

D.5.1.1.2. Emaitzen eztabaida

Ikerketa kasu honen emaitzen arabera, baldintza anomaloak bi akats dauzka: bat orekatzaile hidraulikoan dago (HC) eta bestea eguzki tankean (T2). Nahiz eta anomaliak jakinaren gainean barneratu emaitza "itsu" lez hartu behar dira, monitorizazio bidez lortuko balira bezala. Horrela, diagnostikoaren problema zuzena era errazean ebazten da erreferentzia baldintzaren modelo dinamikoa izanez gero. Halaber, simulazio bakarreko metodologia bat garatu da eragin induzitu oro aldi berean ezabatzeko.

Erreferentzia baldintza bortxatua eta nolakotasun kurben irteera dependenteak akats operazio baldintzaren simulazioan bertan lortu dira; operazio kontrol berdina inposatu zaio erreferentzia baldintzari eta aldagai independente berberak ezarri zaizkio osagai indibidual bakoitzaren modeloari.

Zenbakizko balioen arabera, lehenengo diagnosiaren bitartez osagai akastuak erraz kokatzen dira horien pisua funtzio-oker intrintsekoekin adieraziz. Aurreikusi daitekeen lez, HC beti dagoenez aktibo haren eragina T2 osagaiaren akatsak baino 10 aldiz gehiago eragingo du; eragin induzituak ere azpimarratzen dira eta, emaitzak ikuskatuz, galdara oso erasanda dago. Gainera, akats bakarreko diagnostikoaren azterketak fuel inpaktu formularen zehaztapen gabezia erakusten du osagaien arteko lotura termodinamiko estuak medio.

D.6. ONDORIOAK

Kapitulu honen helburua diagnosiaren problema zuzena ebazteko anbiguotasunik gabeko prozedura eraikitzea zen. Horretarako, HVAC&R sistemen diagnosi metodoak laburbildu dira eta termoekonomia diagnostikoa era teorikoan eta praktikoan eztabaidatu da; diagnostiko termoekonomikoaren onurak eta desabantailak deskribatu dira eta horien ahultasunei irtenbidea aurkitu zaie.

Termoekonomiaren diagnostikoa lehen aldiz era *dinamikoa*n inplementatu da eraikinen energia sistemetan. Kasuan, aurretik egin ez bezala, energia horniketaren dinamismoa kontuan hartu da haren egoera uneoro aldatzen doalako berokuntza, EUB edota aireztapen eskarien aldakuntza medio. Arazoen eta ezaugarri berezien artean hurrengoak azpimarra daitezke:

- Produkzio anitzaren helburuak kontrol komandoaren etengabeko esku sartzea dakar.
- Egitura produktiboaren definizioa eztabaidagarria da dinamikoa baita. Sistemak egitura produktibo ezberdina izan ditzake osagaien pizketak eta itzaltzeak medio.
- Edozein osagaiaren eraginkortasuna estuki eraginda dago gainontzeko elementuen oreka nahiagatik.
- Amaierako produktuaren aldakuntza ezin da saihetsi eta diagnosirako kontuan hartu behar da.

Barneratutako berrikuntzen artean daude: (1) diagnostikoa bai exergia bai moneta terminoetan definitu da, (2) ΔF_T eta CC analisien konbinaketa berritzailea egin da eta (3) kontrolaren esku hartzearen eta osagaien loturen funtzio-oker eraginak iragazteko era berria garatu da simulazio bakarrarekin.

Gainera, diagnostiko termoekonomikoaren irmotze nagusia egin da: *problema zuzena*ren ebazpena. Helburua (1) akatsen kokapena eta (2) horien sintomen ezagutza du sistema berriaren eraginkortasuna erreferentziakoarekin alderatuz.

Justifikatu antzera, xedea funtzio-oker induzituen eta intrintsekoen artean ezberdintzea denez, sistemaren modelo termodinamiko zuzena funtsezkoa da. Beraz, akatsak soilik detekta daitezke aldagai termodinamikoak aztertuz eta exergia parametro agregatuak baztertuz; beste hitzetan, osagaien nolakotasun kurba eraldatuak ikuskatuz. Adierazpen hori egonagatik ere, diagnostiko termoekonomikoak osagaiak lotzen ditu eta sisteman zeharreko kostu aldakuntzak identifikatzen ahalbidetzen du. Are gehiago, egitura produktiboa aurretiaz definitu bada (esaterako, **C Kapitulu**ko exergia kostu kontaketa helburuentzako), diagnostiko termoekonomikoak ez du beharrizan konputazional handiagorik behar.

Ondorioz, funtzio-okerren detekzio soilak ez du bideratzen diagnosi problemaren ebazpena; anomalien eraginak jakinak direnean soilik erabaki daitekelako tratamendua. Hortaz, anomalien inpaktuen informazioa ematen duenez, diagnostiko termoekonomikoa tresna egokitzat har daiteke erabaki eta hautaketa prozesuetarako, besteak beste, mantenurako edota optimizazio prozesuetarako.

Termoekonomia informazioa gehitzen bada, nahiz eta akatsak topatzeko zorrozki beharrezkoa ez izan, funtzio-oker bakoitzaren garrantzia identifikatzen da. Finean, diagnostiko termoekonomikoak akatsei pisua esleitzen die eta horien eraginak zenbakitzen ditu kostu exergetikoaren igoeraren arabera.

D.7. ERREFERENTZIAK

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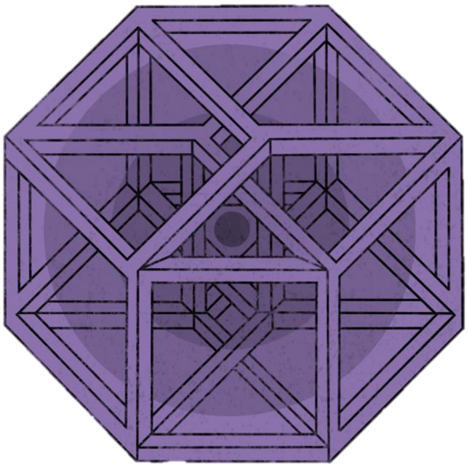


E KAPITULUA

Exergia analisi aurreratu dinamikoa eraikinetan

E KAPITULUA

SINBOLOAK

F	[kJ]	Fuela
P	[kJ]	Produktua
E_D	[kJ]	Exergia suntsiketa totala
E'_D	[kJ]	Exergia suntsiketa baldintza termodinamiko berrietan
ε	[-]	Exergia etekina
ε'	[-]	Exergia etekina baldintza termodinamiko berrietan
E_D^{AV}	[kJ]	Exergia suntsiketa saihesgarria
E_D^{UN}	[kJ]	Exergia suntsiketa saihetsezina
E_D^{EN}	[kJ]	Exergia suntsiketa endogenoa, deskonposizio metodoan oinarritua
$E_D^{EN^*}$	[kJ]	Exergia suntsiketa endogenoa, nolakotasun kurbetan oinarritua
E_D^{EX}	[kJ]	Exergia suntsiketa exogenoa
$E_{D,i\rightarrow k}^{EX}$	[kJ]	i osagaiak k-n eragindako exergia suntsiketa exogenoa
E_D^{MEX}	[kJ]	Exergia suntsiketa mexogenoa
$E_D^{AV \cdot EN}$	[kJ]	Exergia suntsiketa endogeno saihesgarria
$E_D^{AV \cdot EX}$	[kJ]	Exergia suntsiketa exogeno saihesgarria
$E_D^{UN \cdot EN}$	[kJ]	Exergia suntsiketa endogeno saihetsezina
$E_D^{UN \cdot EX}$	[kJ]	Exergia suntsiketa exogeno saihetsezina

E KAPITULUA: EXERGIA ANALISI AURRERATU DINAMIKOA ERAIKINETAN

E.0. LABURPENA

Kapitulu honetan bigarren legearen aukerako beste aplikazio bat egiten da *zeini exergia analisi dinamiko aurreratua* (DAEA) deritzon. Lehenengo aldiz baldintza dinamikoekin exergia analisi aurreratua egin da eraikinen energia horniketa sisteman.

DAEArekin exergia suntsiketa (E_D) efizientzia gabezia ezberdinetan bereizten da: osagaien kalitatea hobetuz lor daitekeen hobekuntzan (E_D saihesgarria) eta muga teknikoak medio ezinezko hobekuntzan (E_D saihestezina). Gainera, exergia suntsiketa elementu bakoitzaren berezko itzulezintasunekin (E_D endogenoa) eta gainontzeko osagaietatik eratorritakoarekin (E_D exogenoa) lotu daiteke. Informazio hori oso erabilgarria da eta ezin da beste inolako modutan lortu.

Kapituluaren ezaugarri garrantzitsua instalazioaren jarrera dinamikoarekin bat datorrenez, ebazpen eta termino berritzaileak gehitzen dira exergia suntsiketa adierazteko eta DAEA modu arrazionaletan eraikinen energia sistemetan inplementatzeko.

E.1. SARRERA

A Kapituluan adierazi lez, *ohiko exergia analisian*, etekin exergetikoa (ε) erabiltzen da osagaia eraginkortasunaren arabera ezaugarritzeko adierazle lez eta beste sistemetako osagai antzekoak alderatzeko [1]. Osagai baten helburu produktiboaren (xedea) *produktua* (P) eta hori burutzeko behar diren baliabideen arteko *fuela* (F) zatiketa bezala lortzen da [2] (biak exergia terminoetan); gainera, exergia galerarik ez bada kontuan hartzen, F eta P balioen arteko aldea osagaiaren exergia suntsiketaren berdina da (E_D) [3]. Halere, justifikatu antzera, analisi hori ezin da behar bezala egin sistemaren osagaien arteko loturak kontuan hartu gabe, horrela ezin baita benetako hobekuntza potentziala jakin [4].

Muga horiek gainditzeko, beste teorien artean, *exergia analisi aurreratua* (AEA) garatu zen. Metodologia horrekin osagai batek berez eratutako efizientzia gabeziak eta gainontzeko osagaien loturengatik sortutakoak ebaluatzen dira eta baita teknologia aurrerapenekin lor daitezkeen hobekuntzak ere [4],[5],[6]. Ondorioz, AEA baten helburu nagusia itzulezintasunen zergatiak E_D terminoetan aztertzea da ondoren etekin aldagaietan bihurtzeko [7].

Aitzinean esan antzera, osagai baten zenbait itzulezintasun ezin dira ekidin nahiz eta teknologia alternatibarik berritzaileena erabili, muga fisikoengatik, ekonomikoengatik edota teknikoengatik. Horiei exergia suntsiketa saihetsezin deritze (E_D^{UN}) [4],[8]; bestalde, gainontzeko exergia suntsiketa saihesgarria da (E_D^{AV}). Beraz, bi itzulezintasun horietan bereizketa eginik, osagai bakoitzaren potentziala ezagutzen da etekin termodinamikoaren arabera.

Are gehiago, itzulezintasunak bereizteko beste modu bat dago: osagai bateko exergia suntsiketaren zati bat beste osagaien efizientzia gabeziengatik dator. Horrela, osagai bateko E_D ez dago soilik haren etekinaren arabera, gainontzeko osagaien eraginen menpe ere baizik [9]. Beste osagaiekin bat datorren E_D-aren zati horri exergia suntsiketa exogenoa deritzo (E_D^{EX})

eta norberaren buruak eragindako itzulezintasuna, ordea, exergia suntsiketa endogenoa da (E_D^{EN}). Hortaz, bi exergia suntsiketen arteko bereizketarekin sistemen osagaien arteko loturak egokiago ulertzen dira optimizazio prozedurak aplikatzeko. Hala eta guztiz ere, E_D^{EN}eta E_D^{EX} kalkulua zailagoa da E_D^{UN} eta E_D^{AV}baino eta hori da, preseski, AEAren gakoa.

Gainera, E_D saihesgarria eta saihestezina endogenoarekin eta exogenoarekin erlaziona daiteke. Informazio hori baliagarria da hurrengorako: (1) osagaia berez hobetuz zein itzulezintasun ekidin daitekeen ikertzeko ($E_D^{EN.AV}$), (2) sistema osoaren egitura hobekuntzaren bitartez edo beste osagaien hobekuntzarekin lor daitekeen onura ikusteko ($E_D^{EX.AV}$), eta (3) zein (4) ekidin ezinezko mugak hautemateko ($E_D^{EX.UN}$eta $E_D^{EN.UN}$ balioen bitartez). Ondorioz, AEAren informazioarekin sistemaren diseinua, kontrola edo mantenua hobetu daitezke.

Kapitulu honen alderdi berria eta originaltasuna AEAren aplikazioa eraikinetan egitean datza, batez ere egoera egonkorreko baldintzak dinamikoekin ordezkatzean. Horregatik, metodologia proposamen berri honi *exergia analisi aurreratu dinamikoa* (DAEA) deitu zaio, zeinek egoera egonkorreko AEA ikerketei alde berriak gehitzen dizkion. Beraz, kapitulu honen jomuga DAEA eraikinetan zelan aplikatzeko gidaliburua egitea da.

Literaturan, AEAren zenbait aplikazio egin dira eraikinetan. Esaterako, [10] lanean AEA aire girotze sistema batean inplementatzen da batez besteko balioak erabiliz egunean zeharreko hozkuntza prozesua aztertzeko eta gaueko pilaketa ikertzeko. Erref. [11]-ean AEA eraikinen berokuntza sistema exergia-baxuetan aplikatzen da. Antzeko eran, [12] lanak berokuntza distritu sistema geotermiko bi alderatzen ditu AEAn oinarrituz. Teoria eraikinetan aplikatu bada ere, batek ere (edo bestelako beste lanek) ez du sistemaren egoera dinamikoa aintzat hartzen. Hori dela eta, DAEA aplikazioaren lehenengo lana dugu hau.

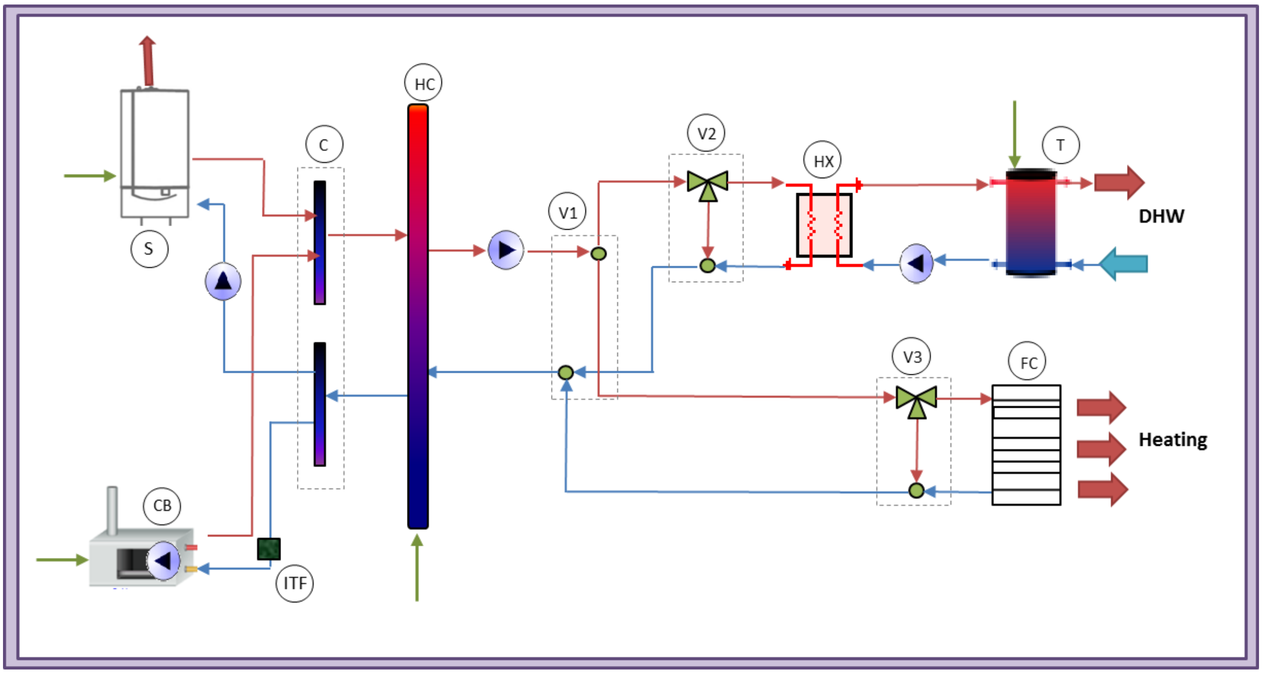
Bestalde, AEA zenbait industria mailako lanetan aplikatu da. Erref. [6] eta [13]-tan metodoa energia planta konbinatuetan aplikatzen da; [3]-k AEA analisi zehaztua egiten du xurgatze hozkuntza makinetan eta [14] lanak bero ponpa gas makina ikertzen du lehorketa sistemetarako. Kogenerazio sistemen AEA [15] lanean egiten da. Nahiz eta AEA lan anitz egon, esan lez, denak egin dira egoera egonkorrean.

DAEA aplikazioa era garbian egiteko, (vii) *Stirling eta galdara ikerketa kasua* garatuko da; beraz, alderdi teorikoa eta aplikazioa era bateratuan egingo dira.

E.2. IKERKETA KASUA

Eusko Jaurlaritzaren eraikinen kalitate kontrolerako laborategia (EKKL) erabili zen beharrezko data jasotzeko. DAEA aplikaziorako instalazioak Stirling mikro-kogenerazio motore bat eta kondentsazio galdara bat dauzka (Stirling osagaia barneratu zen eraikinen energia sistema berriztagarritzat). Evita 28c motore bat da Remeha-k sortua zeinek 1 kW elektrizitate eta 3,7-5 kW energia termiko eratzen dituen errekuntza gasen berotik, operazio tenperaturaren eta modulazioaren arabera. Halaber, galdara lagungarri baten bitartez 20 kW potentzia gehigarria sor dezake. Bestalde, BaxiRoca 24 BIOS markako eta 28 kW-ko kondentsazio galdara bat dago, katalogoaren araberako % 97 energia etekinarekin (behe bero ahalmenean oinarritua).

Osagai horiekin Vitoria/Gasteizko (Espainiako iparraldea) familia bakarreko eraikinaren berokuntza eta EUB eskariak asetzen dira. EUBaren adarrean bero trukagailu bat dago eta 1.000 litroko biltegia. Berokuntzarako bero emaria fan-coil baten disipazio bidez egiten da 3-bideko balbula batekin. Orekatzaile hidrauliko bat, zirkulazio ponpak, banaketa tutuak eta 120 sentsore daude tenperaturak, presioak eta fluxuen denboran zeharreko emariak neurtzeko, ikus Irudia E. 1.



Irudia E. 1 Ikerketa kasuko instalazioaren eskema

EUB eskari profila fluxu emari neurgailu zehatz batekin aurretiaz diskretizatu, programatu eta kontrolatu egin zen. Profilak 5 minutuko baloreak erabiltzen ditu eta instalazioko datuekin uneoro alderatu egiten ziren. Berokuntza eskaria 5RYardi HP 250 fan-coil bateria batekin eta 3-bideko balbularekin emulatu zen, eta hori ere aurretiaz Trnsys simulazio batekin definitu zen.

Kontrol estrategiaren arabera, Stirling motoreak lehentasuna dauka kondentsazio galdararekiko eta, beraz, bai bero eskaria badago bai EUB tankearen tenperatura 60 °C-tik behera badoa piztu egiten da. ET200S markako PLC Siemens IM 151-8 PN / FP CPU bat eta hedapen modulu bat dauzka eta PCra Ethernet baten bidez konektatzen da.

E.2.1. Osagaien hautaketa

Analisia hasi aurretik ikerketa funtzionala kontuan hartuz osagaiak erabaki behar dira. Batzuk beste batzuekin elkartu behar dira prozesu produktibo batekin lotzeko. Adibidez, joaneko eta itzulerako biltzaileak banaka hartuz gero, ez dute helburu produktiborik; baina, batera aztertuz gero, talde bakarrean, (C taldea) horien jomuga berokuntza eta EUBaren horniketa da. Antzekoa banatzailearekin eta nahasgailuarekin gertatzen da eta horiek ere talde bakarrean sartu dira (V1 taldea); 3-bideko balbulekin eta nahasgailuekin (V2 eta V3 taldeak) ere. Elkarrekin lotuz gero horien helburua EUBaren edota berokuntzaren banaketa da. Hortaz, talde hautatuak Taula E. 1n erakusten dira.

E.2.2. Ohiko exergia analisia

Taula E. 1 DAEA aplikatzeko osagaien zerrenda

IZENA	DESKRIPZIOA
S	Stirling mikro-kogenerazio motorra
CB	Kondentsazio galdara
ITF	CBaren sarrera tenperatura nahasgailua
C	Horniketa eta itzulera biltzatzailea
HC	Orekatzaile hidraulikoa
V1	EUB eta bero banatzailea eta nahasgailua
V2	HX banatzailea eta nahasgailua
HX	Bero trukagailua
V3	Berokuntza banatzailea eta nahasgailua
T	Biltegia
FC	Fan coila

B Kapituluko gida jarraituz, osagai indibidualen modeloak eraiki ziren eta sistema osoa bateratu zen (masa eta energia balantzeak betez), horrekin DEAEa has daiteke. Lehenengo urratsa exergia analisi ohikoa aplikatzea da osagai bakoitzaren exergia suntsiketa eta etekin exergetikoa ikertzeko. Exergia etekin dinamikoaren definizioa pausu fina da eta baliteke ikerketa osatzeko garrantzitsuenetako bat izatea. Aitzinean esan antzera, osagai baten eraginkortasuna ikuspegi termodinamikotik anbiguotasunik gabe ezaugarritzeko parametroa exergia efizientzia da, alegia P produktuaren eta F fuelaren arteko zatiketa [5]. Sistematizazio hori egonagatik ere, F eta P balioen definizioak arreta handiz aukeratu behar dira egoera dinamikoetan salbuespenak egon daitezkelako (ikus C.3 Kapituluaren azpi atala).

C.3.1 Ataleko gogoetak kontuan hartuz, exergia analisi konbentzional dinamikoa egin zen. Osagai bakoitzaren mugak giro erreferentzia dinamikoan daudela jotzen denez, ez da elementuekin exergia galerarik lotzen [16]. Orduan, exergia galerak soilik agertuko dira sistemaren osotasunean eta osagai bakoitzaren F eta P arteko aldea exergia suntsiketaren balioa E_D izango da.

E.2.3. Exergia suntsiketa saihesgarria eta saihetsezina

Aurretik aipa lez, exergia suntsiketa saihetsezinak teknologia mugak zehaztuz, osagai bakoitza era isolatuan hartuz (hots, sistematik at) eta operazio baldintza onuragarrienak aintzat hartuz kalkulatzen da. Baldintza horiekin exergia suntsiketarik murritzena lortuko da eta tenperatura alde txikiekin eta galera termiko zen mekaniko murritzekin bat dator [6],[17]; halaber, produkzio sorkuntza aldatu gabe mantenduko da. Dena den, exergia suntsiketa saihetsezinak kalkulatzeko onarpenak ingeniariaren berezko esperientzian eta helburuan oinarritzen dira eta, hortaz, hautazkoak dira hein batean.

Sistemaren k osagaiaren exergia suntsiketa sahisgarria ($E_{D,k}^{AV}$) exergia suntsiketa totalaren eta saihetzezinaren arteko aldea da:

$$E_{D,k}^{AV} = E_{D,k} - E_{D,k}^{UN} \quad \text{(E. 1)}$$

Beraz, exergia suntsiketa saihesgarriak eta saihetsezinak era indibidualean lortzen direnez, gainontzeko osagaien jarrera aldaketen eraginak ez dira aintzat hartu. Hala eta guztiz ere, aldagai independente errealak hartzen dira, edo beste era batean esanda, exergia suntsiketa saihesgarria kalkulatzean, sarrera datu errealak barneratzen zaizkio osagaiari eduki daitekeen teknologia onenaren ezaugarriak ikertzeko. Ondorioz, $E_{D,k}^{UN}$ eta $E_{D,k}^{AV}$ aldagaiek bai kalitate hobeagoko taldea ez erabiltzearen itzulezintasun kantitatea bai osagaien arteko loturak ekidin osteko itzulezintasun kantitatea barneratzen dituzte. Horregatik daude, hain zuzen, $E_{D,k}^{UN\cdot EN}$/ $E_{D,k}^{UN\cdot EX}$ eta $E_{D,k}^{AV\cdot EN}$/$E_{D,k}^{AV\cdot EX}$ konbinazioak.

E.2.3.1. Eraikinaren sistema termiko esperimentalean aplikazioa

Exergia suntsiketa saihetsezina talde bakoitza banaka hartuz kalkulatzen da; isolatu eta egoera onuragarrienetan lanean jartzen dira. Baldintza horiek produktu kantitate bera hornitzeko bero transmisiorako tenperatura aldakuntza txikiak eta karga galera txikiak ohi dira. Beraz, baldintza horien irizpidea zertxobait ausazkoa eta ikertzailearen esperientziaren eta helburuen araberakoak dira. Jarraian instalazioaren osagai bakoitzaren exergia suntsiketa saihetsezina definitzeko irizpideak daude:

- **C/V1/V2/V3)** Talde horien itzulezintasunak tenperatura eta presio ezberdineko emariak nahastean sortzen dira. Orduan, kontrol sistemak alde horiek ekidin egiten baditu, itzulezintasun guztiak nuluak dira; beraz, suntsiketa oro saihesgarria da.

- **ITF)** Talde honen helburua kondentsazio galdararen sarrerako emariaren tenperaturaren kontrola da. Beraz, fluxu hori jatorritik behar bezala sartzen bada itzulezintasun oro saihesgarria da.

- **FC)** Exergia suntsiketa saihesgarria merkatuko fan-coil-rik eraginkorrena hautatuz definitzen da.

- **HX)** Bero trukagailuetan entropia sorkuntza dago. Berez, exergia suntsiketa beti egongo da pinch-point bat dagoelako ΔT_P [18]. Halere, $E_{D,HX}$ balioa datozen modutan murritz daiteke: (1) antzeko bero ahalmeneko emariak batzean tenperatura profil paraleloak lortuz; (2) bero eta hotz batez besteko tenperaturen artean tenperatura ezberdintasun txikiak hautatuz; (3) bero trukagailu adiabatikoa kontuan hartuz; (4) presio galerak mesprezatuz; eta, (5) bero transferentzia koefiziente erabilgarri maximoa aukeratuz.

- **HC/T)** Osagai horien itzulezintasun zergati nagusia pilaketa barnealdeko tenperatura altuko eta baxuagoko emarien arteko nahasketa dira. Horien bilketa eraginkortasuna igotzeko, nahasketa galerak murriztu behar dira bero emaria dagokion tenperatura geruzan barneratuz, hau da, estratifikazio egoki baten bitartez bero injekzioa beharrezko maila termikoan sartuz [19]. Halaber, estratifikazio maila handitu ahala exergia pilaketa ahalmena igotzen da. Gainera, exergia ahalmena handiagoa da pilaketa tenperatura girotik gertu badago eta jaitsi egiten da giro tenperaturarik urrundu ahala. Are gehiago, sarrera tenperaturaren eta beharrezko karga mailaren arteko konpromezu bat behar da kargan tenperatura ahalik eta baxuen izateko eta ahalik eta altuen deskargan [20]. Exergia suntsiketa jaitsi egiten da bero trukagailuaren bero konduktibitatea igotzean [20]. Era berean, muga baldintza adiabatikoak jarriz gero bero galerak ekidin egiten dira, alegia, isolamendu maila hobetuz.

Hori guztia buruan izanik, HC eta T osagaietan E_D^{UN} kalkulatzeko irizpideak dira: (1) bero transferentzia fluxuen sarrera eta irteera posizioak finkoak direnez, sarrera ezin da geruza zehatzetan egin. Dena den, estratifikazio profil maximoa hautatu da; (2) RITEren legedi beharrizanak medio [21], pilaketa tenperatura 60 °C baino garaiagoa izan behar da legionalaren formakuntza ekidin ahal izateko eta arau berberak eragina dauka sarrera tenperaturan; (3) EUBaren karga eta deskarga erabiltzailearen eskariaren araberakoa da eta, hortaz, ezin dira bero jario periodoak optimizatu; (4) EKKLko planta esperimentaleko biltegian ez dago bero trukagailurik; (5) azkenik, isolamendu termikoa tankearen gainazalean jarri da adiabatiko bilakatuz.

- **S/CB)** Errekuntza sistemak, oro har, exergia suntsiketa altueneko osagaiak direnez exergia analisi banatua eta zehaztua behar dute. Errekuntza prozesuaren efizientzia gabeziaren zergati nagusiak marruskadura, nahasketa, erreakzio kimikoa eta bero transferentzia dira [22], eta horietako bakoitzak datozen ezaugarriak dauzka: (a) marruskaduraren E_D erreakzio kimikoen zein bero transferentziaren balioa baino baxuagoa da; (b) nahasketa isobarikoaren E_D, berriro ere, tenperatura eta osaera kimiko ezberdinengatik dator batik bat. Exergia suntsiketa zenbatitean ekidin daiteke baina, askotan guztiz ezinezkoa da; (c) erreakzio kimikoen E_D oreka termodinamikotik gertuko giroetan murrizten da; halere, erreakzioen exergia suntsiketak oso garaiak dira askotan; (d) bero trukeen E_D balioan eragiten dute (1) errekuntza gasen eta emari beroaren arteko batez besteko tenperatura termodinamikoen aldaketak eta (2) transferentziaren tenperatura maila. Nahiz eta E_D parametroa justifikatzeko lau arrazoi eman, prozesua aldin berean gertatzen da eta ez seriean [22].

Aurrekoak aintzat hartuz, E_D^{UN} kalkulurako hipotesiak dira: (1) errekuntza prozesuan ez dago presio jaitsierarik, (2) erreakzio kimikoen exergia suntsiketa minimizatzeko errekuntza estekiometrikoa da (λ=1) (errekuntza adiabatikoaren tenperatura eta bero transferentziaren itzulezintasunak igo arren) eta (3) bero transferentziarako ahalik eta

Taula E. 2 Osagai bakoitzean exergia suntsiketa saietsezinaren justifikazioa eta lorpen era

n	E_D-ren ZERGATIAK	E_D SAIHESGARRIAREN kalkulua
C,V1,V2,V3	Egoera ezberdinen nahasketa	Tenperatura eta presio berdinetako fluxuen nahasketa hartzen da kontuan
ITF	Beharrezko baldintzak lortzeko nahasketa	CB taldeak beharrezko sarrera baldintzekin sartzen da fluxua
FC	Galera termikoak eta presio galerak	Efizientzia altuena + presio galerarik ez
HX	ΔT pinch-point-a dago, presio zein galera termikoak	Batez besteko tenperaturen ΔT minimoa + HX adiabatikoa + ez dago presio galerik + bero transferentzia koefiziente maximoa eta konstantea
HC,T	Nahasketa, tankearen batez besteko T, karga ratioa, girorako bero galerak	Tanke mugetan isolakuntza gehiketa + presio galerarik ez
S,CB	Marruskadura, nahasketa, erreakzio kimikoa, bero trukea	Errekuntza estekiometrikoa (λ=1) + bero trukerako ΔT minimoa + presio galerarik ez

tenperatura tarte txikiena lortzea ezinezkoa da. Orduan, errekuntza gasen osaera egoera saihetsezinean ezberdina izango da kasu errealarekin konparatuz gero.

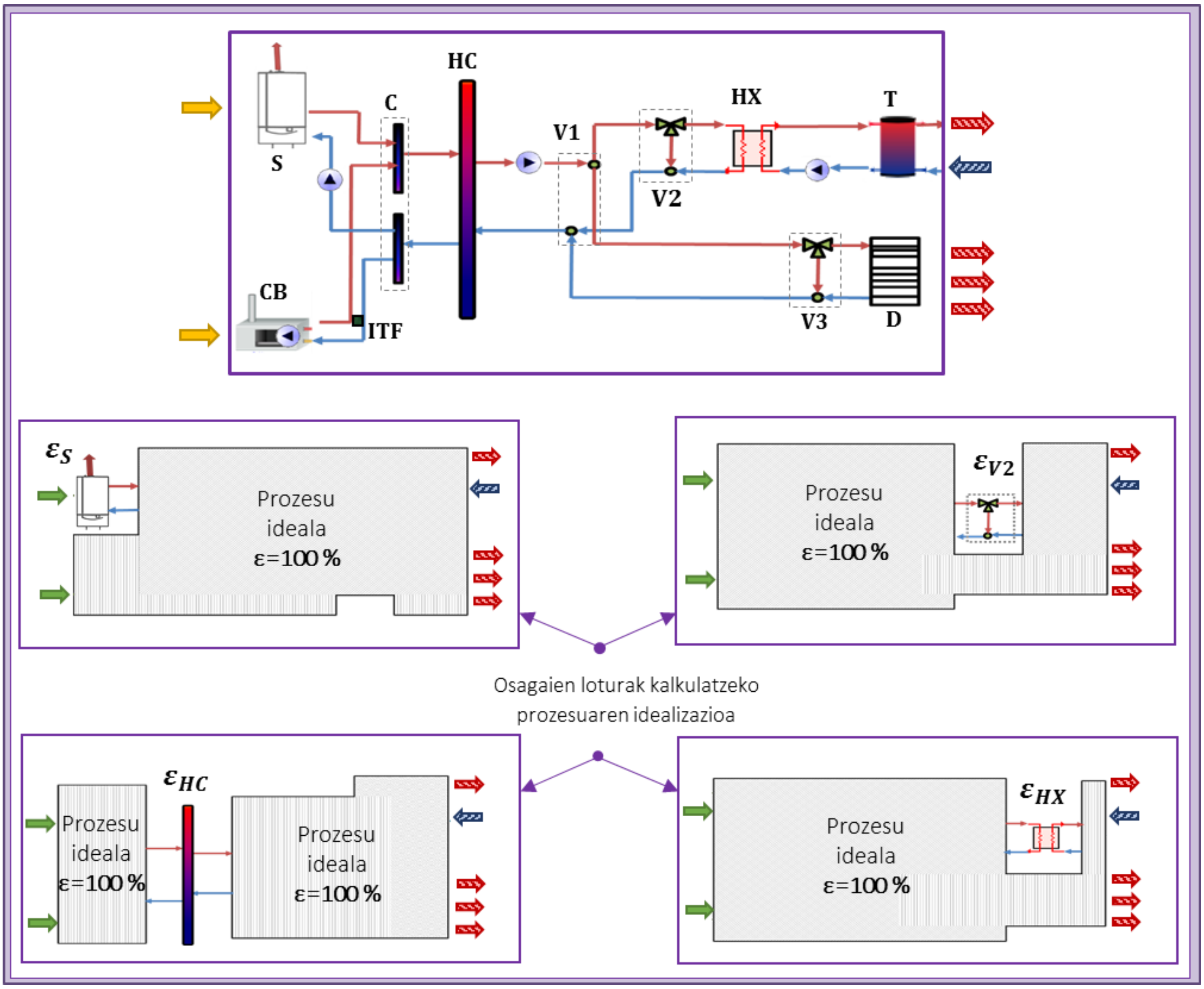
Osagai bakoitzaren ezaugarriak hautatu ostean itzulezintasunen esanahiak batzeko eta horiek zelan ekidin ikasteko Taula E. 2 bete zen; helburua E_D saihesgarriaren kalkulua baita.

Goiko irizpidez gain, osagai bakoitzaren $E_{D,k}^{UN}$ denbora tarte bakoitzean era dinamikoan kalkulatu beha da, eta orduan, unearen arabera $E_{D,k}^{UN}$ balio ezberdinak egongo dira.

E.2.4. Exergia suntsiketa endogenoa eta exogenoa

Sistemaren k osagaiaren exergia suntsiketa endogenoak ($E_{D,k}^{EN}$) E_D balio totalaren zein zati lotzen den berezko itzulezintasun intrintsekoekin adierazten du.

Erref. [23]-an garatu bezala, zenbait metodo daude exergia suntsiketa zati endogenoan eta exogenoan bereizteko. Batzuk ziklo termodinamiko teorikoetan oinarritzen dira; beraz, ezin dira ziklo teorikorik gabeko sistemetan aplikatu [24]. Beste batzuen oinarria exergiaren analisi



Irudia E. 2 E_D^{EN} kalkulurako deskonposizio metodoa, Erref. [27]-tik moldatua sentikorrean datza eta ondorengoko adierazpen grafikoetan [25]; beraz, matematika lan neketsua behar dute. Exergia balantze metodoetan edo horren baliokideetan oinarritzen dira. Beraz, eragozpen nagusia ohiko softwareekin egin ezinezko simulazio ez-estandarren beharra da [26]. Alabaina, berriki, denbora aurrezteko metodologia zuzenago bat garatu da [27] zein diseinu prozesuak eta sintesi printzipioak era sistematikoan eta orokorrean ikasten dituen. Ondorioz, metodologia hori laburbilduko eta inplementatuko da ondoren.

*Deskonposizio metodoa*ren oinarria exergia kontzeptua egitura osoarekiko independente delako gertakarian datza. Beraz, osagai bakoitzaren $E_{D,k}^{EN}$ balioak dagozkien ezaugarriekin era indibidualean iker daitezke. Horrela, instalazioa azpitalde itzulgarrietan zein itzulezinetan bana daiteke. $E_{D,k}^{EN}$ terminoa k osagaia operazioko etekin exergetikoan (ε_k) lanean jarriz lortzen da eta gainontzekoak, ordea, jarrera guztiz itzulgarri batekin, alegia % 100ko exergia etekinarekin [27]. Sinplifikazioak egonagatik ere, gainontzeko osagaien "idealizazioak" ezin du sistema osoaren egitura eta antolakuntza moldatu, osagai horren exergia suntsiketa endogenoa eta exogenoa kalkulatzeko erabiltzen baita. Gainera, guztizko produktua(k) instalazio errealaren berdinak izan behar dira. Hortaz, osagaien produkzio ekarpena eta itzulezintasunak identifikatzeko balio du.

Metodoaren adierazpen grafikoa Irudia E. 2n dago. Goiko aldean ikerketarako instalazioa dago zeinetan baliabide sarrera *erreal*ak eta amaierako produktuak marrazten diren. Beste lau irudiek exergia suntsiketa endogenoa kalkulatzeko modua erakusten dute S, V2, HC eta HX osagaietan; beraz, horien ε_k zein amaierako produktua(k) balio errealekoak dira (marra etenak).

k osagaiaren exergia suntsiketa endogenoa kalkulatu ostean exogenoa guztizko exergia suntsiketari $E_{D,k}$ kenduz lortzen da:

$$E_{D,k}^{EX} = E_{D,k} - E_{D,k}^{EN} \quad \text{(E. 2)}$$

Orduan, $E_{D,k}^{EX}$ balioak k osagaiaren exergia suntsiketa adierazten du gainontzeko osagaien itzulezintasun ezak eta sistemaren egitura elkarrekintzak medio.

E.2.4.1. Etxebizitzen instalazio termiko esperimentalean aplikazioa

Ikerketa kasuko osagai ororen $E_{D,k}^{EN}$ balioak kalkulatu baino lehen P_k definitu behar da. Horrek osagaiaren erabilpena justifikatzen baitu eta baldintza errealetan ikasi behar da (alegia, itzulezintasunekin) eta gainontzeko osagaiak operazio idealean (hipotetikoan) jarri behar dira lanean (hots, itzulezintasunik gabe). Aitzitik, etxebizitzen instalazio termikoetan DAEA aplikatzeko datozen gogoetak ezinbestekoak dira:

- EUB instalazioaren amaierako produktua da eta produkzio katearen azkeneko T biltegiak hornitzen du. Orduan, EUBaren egoera pilaketa sistemaren egoerarekin estuki lotzen da eta ez, ordea, gainontzeko elementuen pizketekin ezta amatatzeekin. Bi kasu erakutsiko dira aurreko gogoeta argi ulertzeko (C.3.1.1 Atalaren antzekoa da). Lehenengo aukeran, EUB tankearen deskargarekin guztiz hornitzen da eta bigarrenean, aldiz, ez dago EUB eskaerarik; halere, tankearen tenperaturaren araberako kontrola medio, bero sorkuntza taldeak aktibatzen dira biltegiaren set-point-a lortzeko asmoz. Orduan, EUB eskaria tankearen produktu lez hartu behar da soilik

$(P_T = P_{DHW})$; eta sistemaren gainontzeko osagaien produktua (edo produktuaren zati bat), bestalde, tankeko bero sarrera emaria da (F_T) Taula E. 3n erakutsi antzera.

Taula E. 3 Osagaien deskripzioa helburu produktiboaren arabera $\boldsymbol{E_{D,k}^{EN}}$ kalkulatzeko

k	P_k balioa $E_{D,k}^{EN}$ kalkulatzeko
S	$(F_T + P_{Heat}) \cdot \%P_S$
CB	$(F_T + P_{Heat}) \cdot \%P_{CB}$
ITF	Ez da aplikatzen
C	$F_T + P_{Heat}$
HC	$F_T + P_{Heat}$
V1	$F_T + P_{Heat}$
V2	F_T
HX	F_T
V3	P_{Heat}
T	P_{DHW}
FC	P_{Heat}

P_{Heat}	Berokuntza exergia eskaria
P_{DHW}	EUB exergia eskaria
F_T	Tankearen bero fluxu horniketaren exergia

$\%P_S$	Sren banaketa eskaria asetzeko
$\%P_{CB}$	CBaren banaketa eskaria asetzeko

- Berokuntza eskariaren produktua kontuz hautatu behar da. Pentsa daiteke berokuntza exergia fan-coil-ak emandako exergiaren balioa dela (alegia, fan-coil-aren gainazaleko tenperaturan emandako bero fluxua). Baina, gela barneko aire tenperaturarekin kalkulatu behar da (≈20 °C), instalazioaren jomuga baita barne airearen egokitze termikoa konfort baldintzak betetzeko. Beraz, bero eskariaren exergia fan-coil-ak emandakoaren balio askoz txikiagoa du eta, hortaz, osagai horren exergia suntsiketa exogenoa $(E_{D,FC}^{EN})$ oso altua da. Bestelako sistemako osagaietan exergia suntsiketa exogeno altuak dakartza horrek, eta beharrezko exergiaren eta horniketa exergiaren arteko moldaketa gabezia adierazten du; finean, sistemako gainontzeko osagaien exergia suntsiketa zati baten iturri baita.

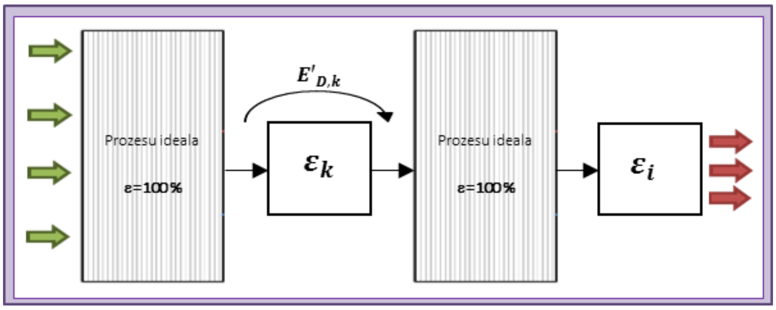
Instalazioaren zenbait elementuk, sarrera tenperatura finkatzailea (ITF) edota ponpak, esaterako, ez daukate helburu produktiborik. Horien asmoa galdararen baldintza zehatzak bermatzea edota presio galerak ekidin ahal izateko masa emariaren sorkuntza delako, preseski. Orduan, instalazioaren operazioa ahalbidetzeko baino ez daude. Horien E_D guztiz exogenoa da gainontzeko osagaien operazio baldintzek eragin baitute.

E.2.4.2. Exergia suntsiketa exogeno binarioa

Osagai bakoitzeko exergia suntsiketa exogenoa $(E_{D,k}^{EX})$ kalkulatu ondoren, zenbait ataletan bana daiteke, sistemaren osagai bakoitzari dagokion kantitatearen arabera. Hori *bi* osagaien arteko eszenatokiak eraikiz lortzen da non etekin exergetiko errealekin lan eginez ε gainontzekoak itzulezintasunik gabeko egoera idealean lan egiten dauden. Orduan, k osagaiaren exergia suntsiketak $(E'_{D,k})$ bi alde barneratzen ditu: aurretiaz kalkulatutako exergia suntsiketa endogenoa eta i osagaiaren itzulezintasunek eragindako suntsiketa ($E_{D,i\rightarrow k}^{EX}$). Azkenekoaren balioa k osagaiaren exergia suntsiketa berriari $E_{D,k}^{EN}$ balioa kenduz lortzen da:

$$E_{D,i\rightarrow k}^{EX} = E'_{D,k} - E_{D,k}^{EN} \quad \text{(E. 3)}$$

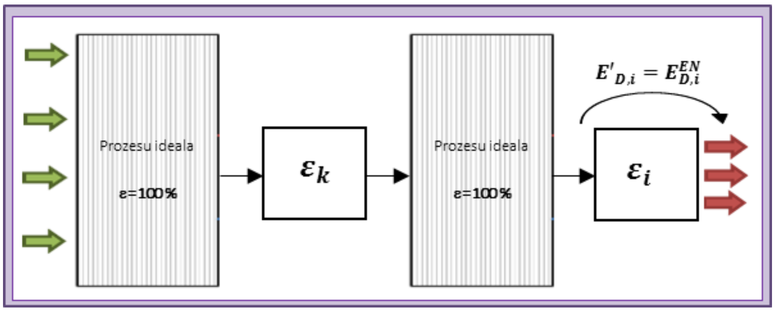
Irudia E. 3n exergia suntsiketa binarioa lortzeko metodologia erakusten da: alegia k osagaiak i elementuan eragindako itzulezintasunen kalkulua.



Irudia E. 3 $\boldsymbol{E_{D,i\rightarrow k}^{EX}}$ lortzeko azalpen grafikoa

Uretan gorako eta beherako osagaien elkarrekintza binarioen azterketaren arabera, bigarren osagaiek eraginik handiena sortzen dute uretan gorako elementuetan. Berez, ez badago sistemaren energia birzirkulaziorik, i osagaiak uretan gorako k elementuari eragindako exergia suntsiketa exogenoa ($E_{D,k\rightarrow i}^{EX}$) zero izango da eta $E'_{D,i}$ aurreko $E_{D,i}^{EN}$ balioaren berdina izango da (ikus Irudia E. 4).

E.2.5. Exergia suntsiketa mexogenoa



Irudia E. 4 $\mathbf{E'_{D,i}} = \boldsymbol{E_{D,i}^{EN}}$ berdinketaren justifikazio grafikoa uretan beherako osagaietan

Exergia suntsiketa endogenoaz eta exogenoaz gain, exergia suntsiketa gehigarria dago zein aldibereko osagaien arteko elkarrekintzekin eta sistemaren etekin errealen ondorioengatik sortzen den. Horri mexogenoa deritzo (hots, exogeno nahastua) [28] eta exergia suntsiketa totalari binarioaren batukaria kenduz lortzen da:

$$E_{D,k}^{MEX} = E_{D,k}^{EX} - \sum_{\substack{i \\ i\neq k}}^{n} E_{D,i\rightarrow k}^{EX} \quad \text{(E. 4)}$$

E.2.6. Nolakotasun kurba errealak kontuan hartuz

Deskonposizio metodoa oso erabilgarria da sistemako osagai bakoitzaren exergia suntsiketa endogenoa lortzeko, esfortzu matematiko murritza eta kalkulu errazak dituelako gainontzeko metodologiekin alderatuz gero. Alabaina, exergia aldagaiekin baino ez du lan egiten (esaterako, F_k, P_k eta ε_k) zeintzuek konstante mantentzen diren osagaien ezaugarri fisiko errealak eta operazio baldintza ezberdinak kontuan hartzean; beraz, zenbait emaitza akastu lor daitezke. Adibidez, sistemako osagai bakarra haren egoera errealetan baldin badago (ε_k egiazko balioarekin) eta gainontzekoak egoera idealean badaude ($\varepsilon = 1$), gerta daiteke hornitu beharreko produktua ezegokia izatea (P_k) (kasurako, osagaia lan tartetik at lan egitea; adibidez, CB galdarak eskari oso baxua hornitzean). Are gehiago, osagaiaren ε balioa operazio baldintzen arabera aldatuz doa.

Ondorioz, antzeko ikuspegitik hartuta, exergia etekin konstanteekin lan egin ordez, egoera termodinamiko berriaren araberako balio erreala (ε'_k) hartzen da kontuan horren nolakotasun kurbetan oinarrituz (ikus D.3.1 Atala). Exergia suntsiketa endogeno berriak ($E_{D,k}^{EN^*}$) *egiazko* E_D balioa adieraziko du dagokion P_k sortzeko.

Nolakotasun kurba errealetan oinarritutako exergia suntsiketa endogenoaren ($E_{D,k}^{EN^*}$) eta deskonposizio metodoaren balioaren ($E_{D,k}^{EN}$) kenketak termodinamika egoera berrira (ε_k) egokitzeko osagaiak sortzen dituen exergia suntsiketak adierazten ditu:

$$\Delta E_{D,k}^{EN} = E_{D,k}^{EN^*} - E_{D,k}^{EN} \qquad \text{(E. 5)}$$

E.2.7. UN/AV, EN/EX exergia suntsiketa atalen arteko nahasketa

Orain arteko DAEA garapenaren arabera, k osagai baten E_D haren zati saihesgarrian zein saihetsezinean eta endogenoan zein exogenoan banatzen da. Exergia suntsiketa gai horiek datozen balioak eratuz konbina daitezke: (1) $E_{D,k}^{AV.EN}$ parametroak k osagaiaren hobekuntzarekin ekidin daitekeen exergia suntsiketa adierazten du; (2) $E_{D,k}^{AV.EX}$ gainontzeko osagaien eraginkortasuna hobetzean murrizten den suntsiketa da; (3) $E_{D,k}^{UN.EN}$ osagai bakoitzaren mugak errepresentatzen ditu; eta (4) $E_{D,k}^{UN.EX}$ aldagaiak egituraren eta osagaien elkarrekintzen mugak adierazten ditu exergia suntsiketa terminoetan. Honela kalkulatzen dira:

$$E_{D,k}^{AV\cdot EN} = \frac{E_{D,k}^{AV} \cdot E_{D,k}^{EN}}{E_{D,k}} \qquad \text{(E. 6)}$$

$$E_{D,k}^{AV\cdot EX} = \frac{E_{D,k}^{AV} \cdot E_{D,k}^{EX}}{E_{D,k}} \qquad \text{(E. 7)}$$

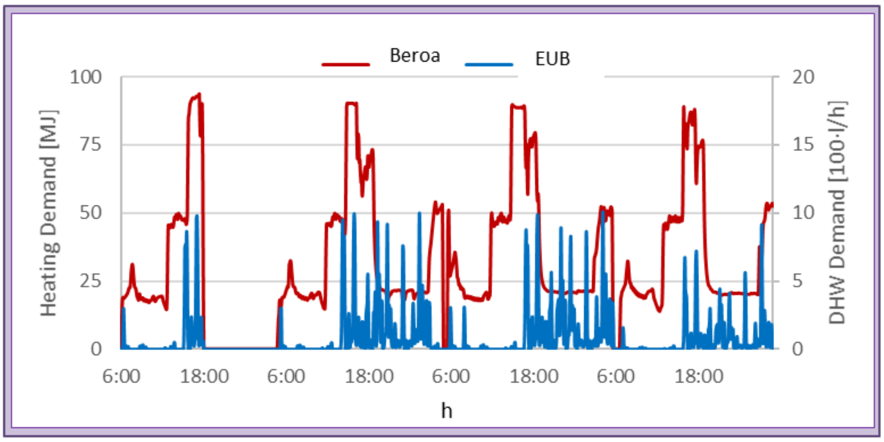
$$E_{D,k}^{UN\cdot EN} = \frac{E_{D,k}^{UN} \cdot E_{D,k}^{EN}}{E_{D,k}} \qquad \text{(E. 8)}$$

$$E_{D,k}^{UN\cdot EX} = \frac{E_{D,k}^{UN} \cdot E_{D,k}^{EX}}{E_{D,k}} \qquad \text{(E. 9)}$$

E.3. ZENBAKIZKO BALOREAK ETA EMAITZAK

Esan antzera, EKKL instalazio esperimentala erabili zen 4 eguneko azterketa egiteko. 18 Pt 100, 1/10 DIN termopare erabili ziren ($\pm$0,15°C balioko ezjakintasunarekin), 7 Siemens SITRANS FM emari neurgailu (% $\pm$ 0,1 zehaztasunarekin, 1 Itron Gallus gas neurgailua Class 1,5-ekoa fuel kontsumorako eta CVM-NRG96 Class 1-eko neurgailu elektriko 1 Striling-aren elektrizitate sorkuntzarako.

EUB eta berokuntza eskariak Trnsys v17-aren bidez kalkulatu ziren eta zegokion kontrol sistema aplikatu zen. Eskariak Irudia E. 5n daude. Nahiz eta datuak 10 segundoko jaso, modelo matematikoak 5 minutuko denbora tarteekin eraiki ziren, horrekin nahikoa baita era zehatzean osagaien pizketa eta itzaltze eremu trantsitorioak adierazteko.



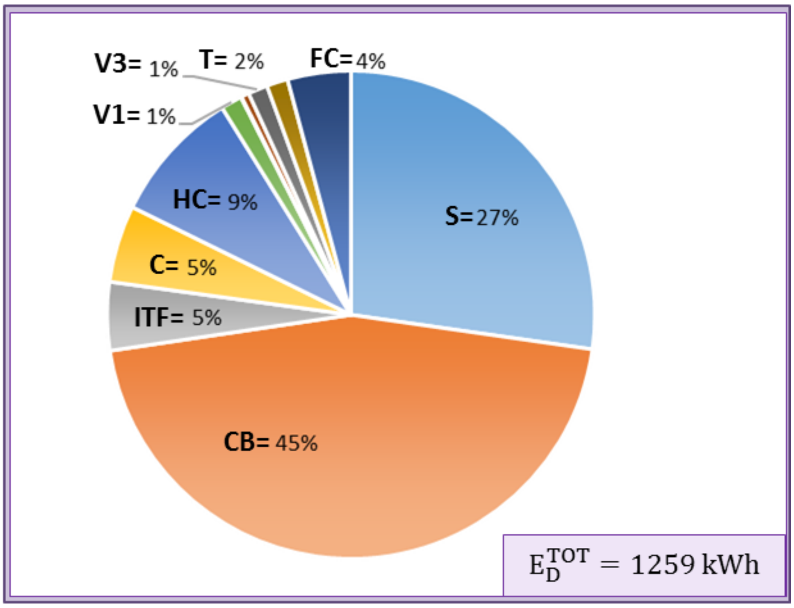
Irudia E. 5 Berokuntza eta EUB eskariak instalazioak asetzeko

B.3.1. Atalean eztabaidatu gisa, osagai bakoitzaren ezaugarritze matematikoa lortu zen Trnsys eta Matlab konbinazioaren bitartez. Datu esperimentalen eta simulazio emaitzen arteko errore erlatiboa osagai indibidual bakoitzerako %$\pm$3 baino txikiagoa zen. Baina, azpisistema oro lotu ostean, instalazioaren errore maximoa %$\pm$9 baliotik behera dago. Errore hori osagai indibidualen errorea baino altuagoa da osagaiak aldi berean modelatzean ziurgabetasuna igotzen baita.

E.3.1. Ohiko exergia analisia

Ohiko exergia analisiarekin osagai bakoitzaren denbora tarteko exergia suntsiketa ($E_{D,k}$) kalkulatzen da. Haatik, osagai bakoitzean eta sistemaren osotasunean exergia balantzea aplikatzean berdina lortzen da.

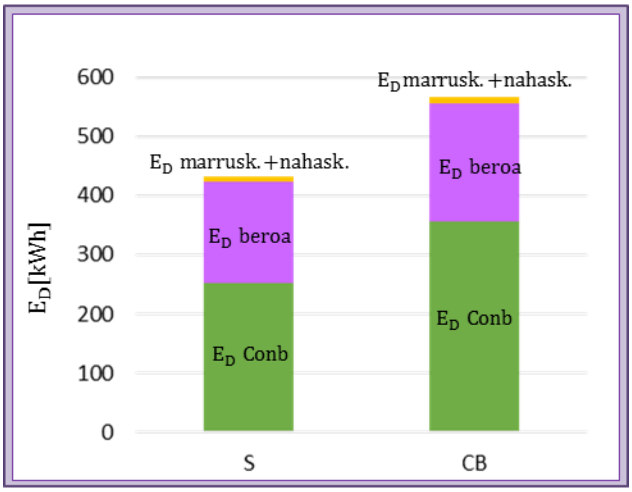
Irudia E. 6n 4 eguneko exergia suntsiketa totala ($E_D^{TOT} = 1259\ kWh$) eta osagai bakoitzaren ehunekoa marrazten da. $E_{D,k}$ sorkuntzaren zergatiak E.2.3.1 Atalean era banaduan justifikatu dira eta **¡Error! No se encuentra el origen de la referencia.**n batu.



Irudia E. 6 Osagai bakoitzaren $\boldsymbol{E_{D,k}}$ aldagaiaren batez besteko ekarpena guztizkoaren arabera

Pentsa bezala, errekuntza osagaiek exergia suntsiketa garaiak dauzkate. Kontrol estrategia medio, CB galdara laguntzailea da eta S taldea baino denbora gutxiagoan hartzen du parte. Halere, guztizko exergia suntsiketaren % 46 burutzen da CBn eta Sn, aldiz, % 27. $E_{D,S}$ balioa $E_{D,CB}$ kantitatea baino baxuagoa da Sk beroa eta elektrizitatea era berean sortzen dituelako eta, berez, exergia etekin ε_{CB} altuagoa duelako. Gainera, CBaren ahalmen nominala Sa baino askoz altuagoa da.

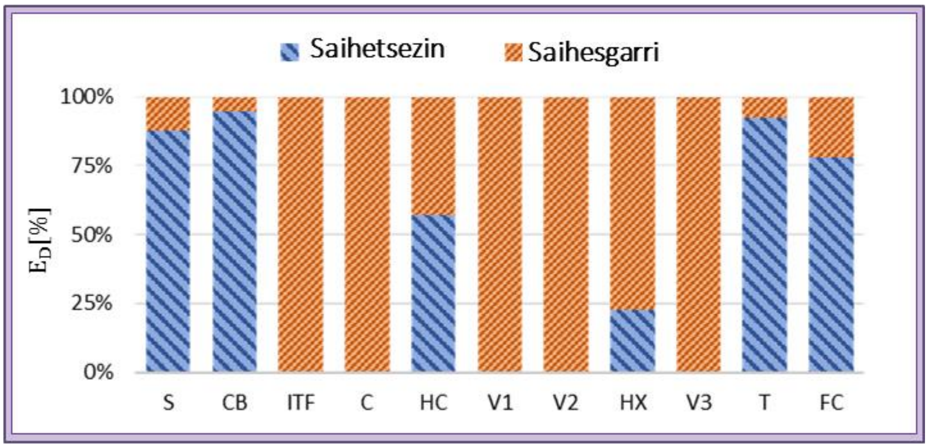
E.2.3.1 Atalaren (S/CB) zatiko instrukzioak jarraituz, suntsiketak datozen taldeetan bana daitezke: (1) marruskadura, (b) nahasketa, (c) erreakzio kimikoak eta (d) bero transferentzian. Emaitzen arabera, suntsiketa gehiena azkeneko bi zatietan gauzatzen da, Sn eta CBn, % 59,7 eta % 64,3 errekuntza erreakzioengatik dator eta % 40,2 eta % 35,6 bero transferentzietatik, hain zuzen (ikus Irudia E. 7).



Irudia E. 7 Exergia suntsiketaren banaketa errekuntza osagaietan, Erref. [22]-an oinarrituz

E.3.2. E_D saihesgarria eta saihetsezina

Osagai bakoitzaren E_D saihetsezin eta saihesgarria aurreko urratsak era dinamikoan jarraituz lortu ziren eta batez besteko ehunekoen balioak datorren Irudia E. 8n jasotzen dira.



Irudia E. 8 Osagai bakoitzaren ehuneko exergia suntsiketa saihetsezina eta saihesgarria

Ikus antzera, osagaien E_D^{UN} balioak saihesgarriak (E_D^{AV}) baino altuagoak dira. Esaterako, S eta CB elementuetan ia exergia suntsiketaren % 88 saihetsezina da; izatez, erreakzio kimikoen itzulezintasunak murrizterakoan bero transferentziaren itzulezintasunak igotzen baitira errekuntza tenperatura igoz.

Ohiko exergia analisiaren emaitzak zein DAEAaren balioak Taula E. 4n batzen dira.

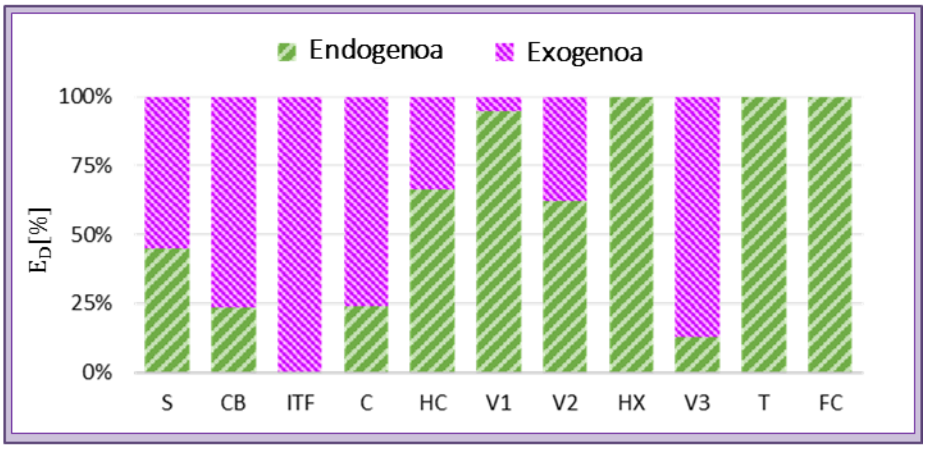
Taula E. 4 DAEAren eta ohiko analisiaren batez besteko balioak

Osagaia k	F_k [kWh]	P_k [kWh]	ε_k [%]	$E_{D,k}$ [kWh]	$E_{D,k}^{UN}$ [kWh]	$E_{D,k}^{AV}$ [kWh]
S	456.01	111.77	25%	344.24	302.67	41.56
CB	665.36	91.44	14%	573.92	542.62	31.30
ITF	116.75	59.31	51%	57.44	0.00	57.44
C	180.30	115.29	64%	65.01	0.00	65.01
HC	146.93	35.01	24%	111.92	63.99	47.93
V1	94.39	76.61	81%	17.78	0.00	17.78
V2	234.41	233.74	100%	0.68	0.00	0.68
HX	29.24	22.78	78%	6.46	1.47	4.99
V3	84.80	68.50	81%	16.30	0.00	16.30
T	32.77	14.97	46%	17.80	16.49	1.31
FC	65.33	12.34	19%	53.00	41.32	11.68

Instalazioaren modelo fisikoaren ondorioz, E_D balioak HC igaro ondoren nabari jaisten dira, hau da, itzulezintasunak murriztu egiten dira energia HC osagaia zeharkatu ondoren. Azken batean, unitate hori eta gero, EUB eta berokuntza adarretan banatzen baita bero transferentzia eta, orduan, energia (eta exergia) fluxu kantitate gutxiago daramate eta, hortaz, exergia suntsiketa gutxiago dago.

E.3.3. E_D endogenoa/exogenoa

Lau egunetako entseguan osagai bakoitzaren exergia suntsiketa exogenoa eta endogenoa Irudia E. 9n dago.

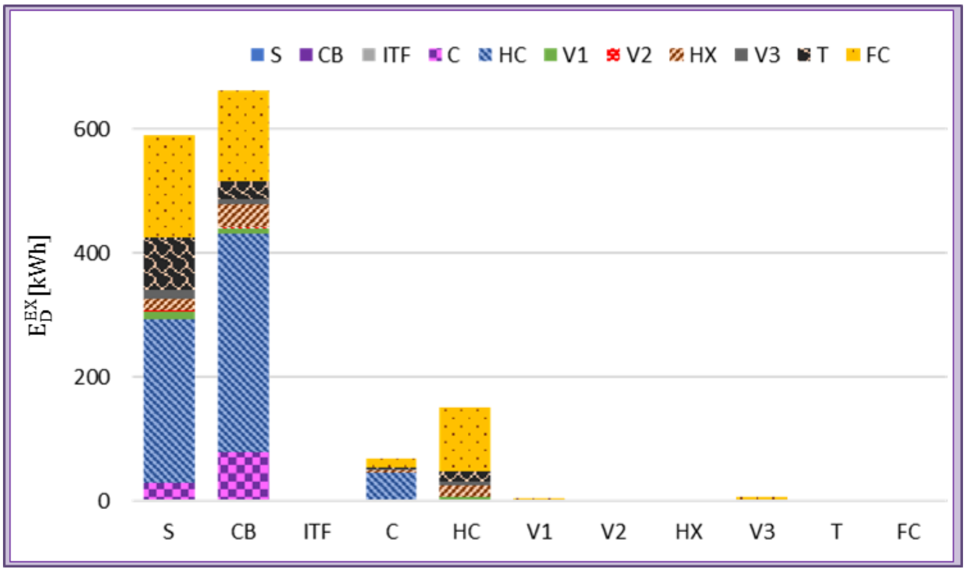


Irudia E. 9 Osagai bakoitzaren exergia suntsiketa endogenoaren eta exogenoaren banaketa

Esan lez, zenbat eta osagaiak amaierako produktura gehiago hurbildu orduan eta exergia suntsiketa exogeno gutxiago daukate. Beste hitz batzuetan, sistemaren amaierako produktua konstante mantentzen bada $(E_{P,TOT} = P_{DHW} + P_{Heat})$ eta uretan beherako osagaiek exergia suntsiketa gehigarria badute, uretan gorako elementuek produktu kantitate gehiago sortu beharko dute itzulezintasun horiei aurre egiteko; ondorioz, uretan gorako elementuekE_D handiagoa dute. Horrela azaltzen dira sorkuntza motoreen E_D^{EX} balio altuak.

Helburu produktiborik ez edukitzeagatik, ITF osagaiaren exergia suntsiketa guztiz exogeneoa da. Bestalde, bero trukagailuaren (HX), pilaketa tankearen (T) eta fan-coil-aren (FC) suntsiketak guztiz endogenoak dira energia banaketa katearen amaieran baitaude eta sistemaren bukaerako produkzioarekin zuzenean lotzen direlako.

Osagaiaren exergia suntsiketa exogenoa gainontzeko elementuen eraginak aztertzeko bana daiteke elkarrekintza binarioen bitartez. Irudia E. 10n elkarrekintza binario horiek exergia suntsiketa terminoetan marrazten dira eta osagai bakoitzaren jatorriaren araberako kolore bat daukate.

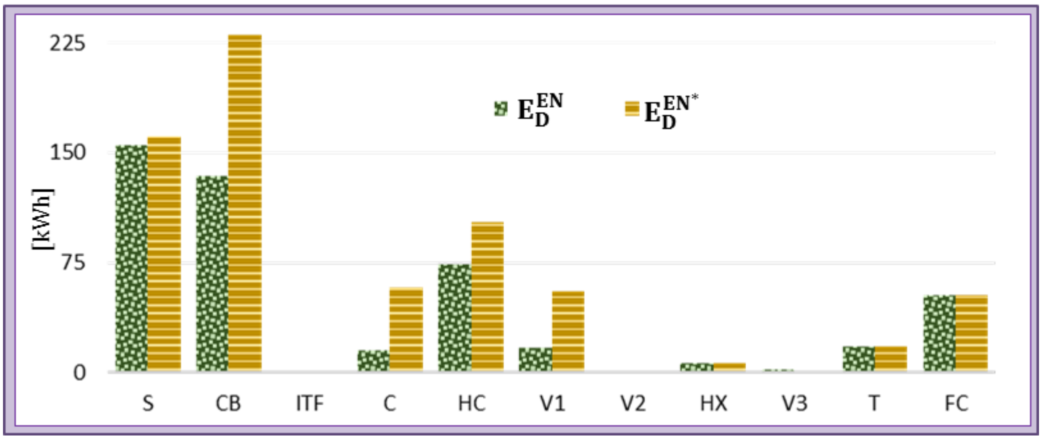


Irudia E. 10 Exergia suntsiketa exogeno binarioaren batez besteko balioak osagaietan

Normala denez, FC osagaiak E_D exogeno gehien eragiten du, berokuntza adarreko amaierako elementua izateaz gain, exergia suntsiketa endogeno altua duelako.

E.3.4. Nolakotasun kurba errealak kontuan hartuz

DAEA aplikazioan aurrerapauso bat egin daiteke osagai bakoitzaren exergia suntsiketa endogenoa exergia etekinaren kurba errealarekin (ε'_k) egiten bada, balio konstante bat erabili beharrean, sistemaren egoera denbora tarte bakoitzean aldatu ahala. Metodo honekin lortutako exergia suntsiketa endogenoaren eta deskonposiziotik lortutakoaren aldea ($\Delta E_{D,k}^{EN}$) aztertuz esan daiteke, kasu batzuetan ε konstantearen sinplifikazioak $E_{D,k}^{EN}$ kalkulatzeko emaitza eztabaidagarriak ekar ditzakela.



Irudia E. 11 Osagaien exergia suntsiketa endogenoa deskonposizio metodoaren ($E_{D,k}^{EN}$) eta nolakotasun kurben ($E_{D,k}^{EN^*}$) arabera

Irudia E. 11n sistemako osagai bakoitzaren $E_{D,k}^{EN}$ eta $E_{D,k}^{EN^*}$ balioak konparatzen dira.

Alderik nagusiena kondentsazio galdaran dago efizientzia exergetikoaren kurba (ε'_{CB}) laua ez baita eta nabarmen jaisten baita eskaria jaistean. $\Delta E_{D,k}^{EN}$ handiko beste osagaiak horniketa eta itzulera biltzailea (C) eta orekatzaile hidraulikoa (HC) dira, horien exergia suntsiketa endogenoa tenperatura ezberdineko emariak batzean sortzen baita eta horrek sistemaren egoerarekiko menpekotasun handia dauka. Gainontzeko osagaien exergia suntsiketa endogenoa bi metodoetan oso antzekoa da.

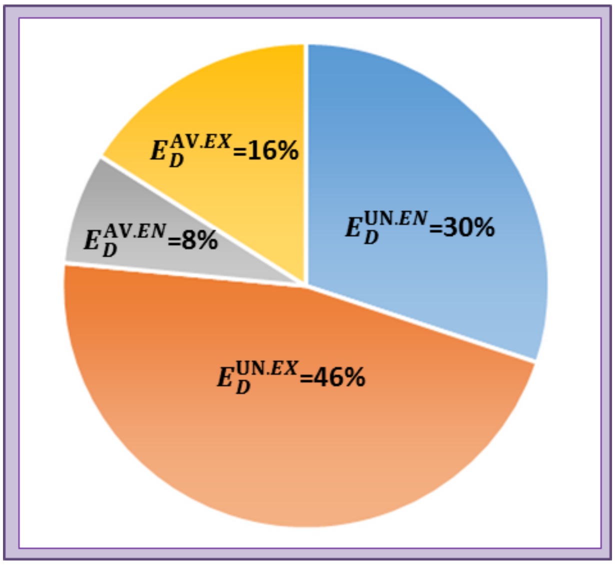
E.3.5. UN/AV, EN/EX exergia suntsiketa zatien konbinazioa

Amaitzeko, osagaien exergia suntsiketa saihesgarria eta saihetsezina nahastean exergia suntsiketa exogenoarekin eta endogenoarekin gertakari berriak identifikatzen dira. DAEA aplikazioaren emaitzak 4 eguneko periodoko etxebizitza instalazio baten aplikazioan Taula E. 5n daude; osagaiaren hobekuntza potentziala modu horretan ikuskatzen da.

Taula E. 5 DAEAtik emaitza agregatu zehaztuak

Osag. k	E_D [kWh]	Saihetsezina		Saihesgarria	
		$E_D^{UN,EN}$ [kWh]	$E_D^{UN,EX}$ [kWh]	$E_D^{AV,EN}$ [kWh]	$E_D^{AV,EX}$ [kWh]
S	302.67	149.25	153.43	5.67	35.96
CB	542.62	125.39	417.23	8.41	22.28
ITF	0.00	0.00	0.00	0.00	57.16
C	0.00	0.00	0.00	15.36	49.13
HC	63.99	48.41	15.58	25.58	22.29
V1	0.00	0.00	0.00	16.87	0.91
V2	0.00	0.00	0.00	0.40	0.25
HX	1.47	1.49	0.00	4.97	0.00
V3	0.00	0.00	0.00	2.11	14.21
T	16.49	16.13	0.00	1.67	0.00
FC	41.32	39.55	0.00	13.44	0.00

Antzeko eran, Irudia E. 12n sistema osoaren lau konbinazioak irudikatzen dira.



Irudia E. 12 $E_D^{UN.EN}$, $E_D^{UN.EX}$, $E_D^{AV.EN}$, $E_D^{AV.EX}$ ekarpenak sistemaren guztizko exergia suntsiketarekiko

Beraz, exergia suntsiketa totalaren zati gehiena saihetsezina da zeinen % 39 osagaien barne mugetatik datorren eta gainontzeko % 61 elementuen arteko elkarrekintzengatik eta egitura mugetatik.

Exergia suntsiketa saihesgarriari dagokionez, guztizko $E_D$aren % 8 baino ezin da murriztu merkatuko teknologiarik onenak hautatzean eta % 15, aldiz, sistemaren osagaien arteko elkarrekintzak hobetuz, adibidez, kontrol sisteman eraginez.

Laburbilduz, DAEA azterketaren emaitzen arabera, sistemaren hobekuntza potentziala oso baxua da eta mugatuta dago. Era berean, $E_D^{AV.EX}$ balioa $E_D^{AV.EN}$ emaitza baino altuagoa izateak sistemaren arteko elkarrekintzak oso gogorrak direla adierazten du eta, beraz, kontrol estrategiaren hobekuntza izan behar dela aldatzen lehen gauza. Alabaina, $E_D^{AV.EX}$ terminoak osagaien arteko loturen perfekzio gabeziak eta banakako itzulezintasunak aintzat hartzen ditu, merkatuko ekipamendurik onena ez erabiltzeagatik.

Informazio hori guztia kontrol estrategiaren optimizaziorako erabil daiteke edota akatsen detekziorako zein diseinurako.

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E.4. ONDORIOAK

Exergia analisi aurreratu dinamikoa (DAEA) lehen aldiz aplikatu da eraikin bateko energia termikoaren hornikuntza sisteman. Eraikinek lehen mailako energia eskariaren ekarpen nagusia izateagatik horien hobekuntza potentzialaren jakintza oso garrantzitsua da energia eskaria murrizteko eta CO_2 igorpenak jaisteko. DAEA aplikazioaren bitartez egin daiteke kapitulu honetan zehar erakutsi antzera.

DAEAk mugapen teknikoen suntsiketaren zati ekidingarria antzeman egiten du exergia suntsiketa alderdi saihesgarriarekin eta saihetsezinarekin. Gainera, DAEAk osagaiak berak eragindako itzulezintasunak identifikatzeaz gain, gainontzeko osagaien efizientzia ezen atzeraezintasunak neurtzen ditu exergia suntsiketa endogenoaren eta exogenoaren terminoak erabiliz. Ondorioz, exergia analisi ohikoarekin lortu ezinezko emaitzak ematen ditu.

Alabaina, nahiz eta analisia oso erakargarria izan, zenbait oztopo zerrendatu behar dira. Hasteko, exergia suntsiketa saihetsezinak ingeniariaren ikuspegiaren eta irizpidearen araberakoak dira; horregatik, kapituluan zehar irizpide hautatuak zehaztasunez garatu dira.

Gainera, E_D endogenoaren zein exogenoaren kalkuluan, zenbait informazio gal daiteke kantitate termodinamiko errealak erabiltzen ez badira, esaterako, exergia etekinaren aldakuntza. Baina, arazo hori osagaien nolakotasun kurben barneraketarekin gainditzen da.

Amaitzeko, E_D balioaren banaketa zehaztua egiteaz gain, DAEAren aplikazioaren abantaila da ez dela inolako erreferentzia baldintzarik definitu behar sistemaren eraginkortasuna hautemateko. Beraz, metodo orokorra da zein kontrolerako, diagnostikorako edota diseinu helburuetarako erabil daitekeen. Are gehiago, oinarri parametroa exergia suntsiketa izateagatik, sistemaren osotasunarekiko osagai bakoitzaren ekarpen erreala erakusten da. Hori exergia etekinaren (ε) bezalako parametro adimentsionalak erabilita ez da ikusten, nahiz eta uretan gorako efizientzia etekinak uretan behekoak baino handiagoak izan, exergia suntsiketa handiagoak dakartelako exergia kantitate handiagoarekin lan egiten baitute. Adibidez, horniketa eta itzulera biltzailearen (C) eta fan-coil-aren (FC) arteko kasua. Emaitza gisa, zenbait informazioa gaizki interpreta daiteke E_D balio globala erabiltzen ez bada.

Bestalde, kapituluan dinamismoaren alderdi berritzailea gehitu zaio DAEAri, orain arte, eraikinen instalazio termikoak egoera egonkorrean ikasi baitira beti.

Bukatzeko, DAEAk osagaien arabera era landuan ebazten du sistema baten itzulezintasunen kokapena, barne atzeraezintasunak zein loturen efizientzia gabeziak aintzat hartuz. Jarrera dinamikoa medio, eraikinen sistemen aplikazioa egoera egonkorreko sistemen hori baino zailagoa da; halere, DAEA era berdintsuan aplika daiteke zenbait onarpen kontuan hartuz. Beraz, energiaren erabilpenaren murrizketa analisi honen informazioarekin erraz lor daiteke.

Etorkizuneko urratsa izango da emaitzak ekonomia zein ingurugiro inpaktu terminoetan ematea, edo beste era batean esanda, exergia unitatetatik unitate monetarioetara edo CO_2 igorpen terminoetara igarotzea. Hori **C Kapitulu**ko exergoekonomia eta exergoingurugiro analisiekin lortzen da, Gainera, DAEA diagnostikoan ere inplementa daiteke.

E.5. ERREFERENTZIAK

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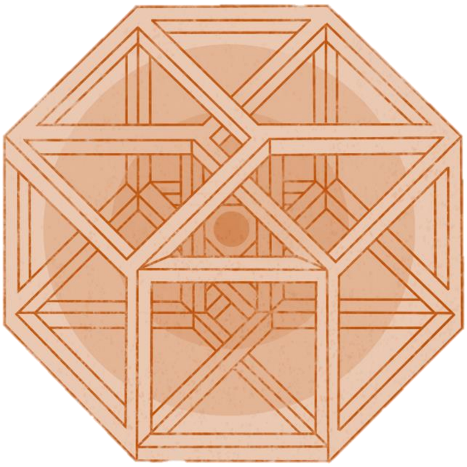


ONDORIOAK

Ekarpenak • Etorkizun lerroak

eman ta zabal zazu

UPV EHU

ONDORIOAK • EKARPENAK • ETORKIZUN LERROAK

Tesi honen berebiziko erronka eraikinen energia sistemetan termoekonomia analisi dinamikoak aplikatzea da. Horretarako, edozein teoriaren inplementazioa irizpide kritikoz aztertu behar denez, oinarrizko baldintzetatik moldaketa zehatzetara igarotzen da.

Egun, eraikinen arloa bigarren legearen analisiak aplikatzeko inguru ezin hobea eskaintzen du batez ere ikerketa dinamiko berritzaileentzako. Azken batean, eraikinen energia aurrezpena mundu mailako behar agintaria baita eta exergia aplikazioak horretarako erabiltzen baitira.

Gogoeta horien arabera, **A Kapitulu**an *exergia*ren erabilera justifikatzen da ondorioztatuz exergia etekinek baliabideen erabilpena hobeto erakusten dutela eta baita energien arteko loturak ere, sistemen sintesirako eta optimizaziorako funtsezko giltza izanik. Gainera, energia ikasketek emaitza eztabaidagarriak edo zalantzazkoak ekar ditzakete, exergia azterketek, ordea, osagaien eta sistemaren arteko alderaketa ahalbidetzen dute. Tamalez, kapitulu horretan azaldu gisa, oso gutxitan aplikatu da exergia eraikinetan, finean, inplementazioan arazoak daudelako, zeintzuek, preseski, tesi honetan ebazten diren.

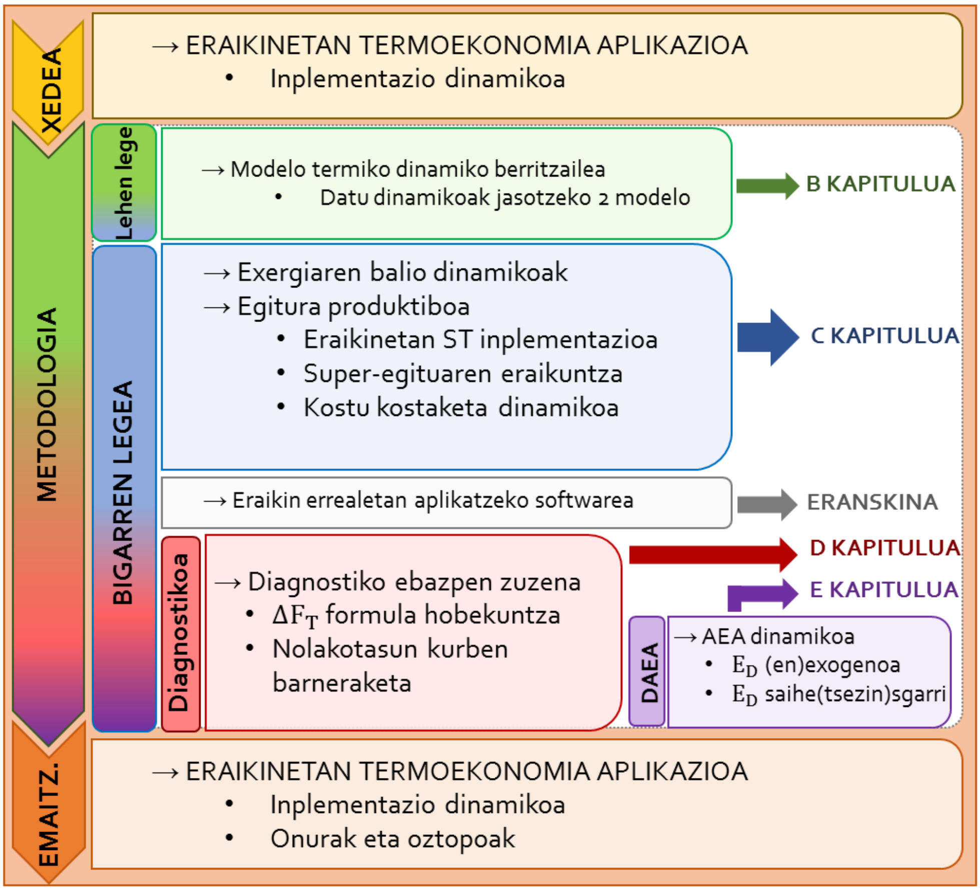
Ondorioz, eraikinen arloari dagokionez, dinamismoa oinarrizko egoera denez ikasketa egonkorrek ez dute zentzurik eta azterketa aldakorrak, aldiz, analisiaren bizkarrezurra dira (nahiz eta bibliografia hedatuak beharrizan hori eskas erabili). Orduan, termoekonomia analisiak egoera zehatzetara egokitu behar dira eta inplementazioaren urrats bakoitza kontu handiz aplikatu behar da teoriaren erabilpen egokirako eta emaitzen interpretazio zuzenerako. **¡Error! No se encuentra el origen de la referencia.**ek tesian zeharreko helburu nagusiak j asotzen ditu.

Hortaz, **B Kapitulu**ak *modelo termiko dinamiko*en erabilera justifikatu eta bi metodologia berri proposatzen ditu: lehenengoak ez dauden sistemak konfiguratzeko eta, bigarrena, instalazio monitorizatuak simulatzeko. Erakutsi lez, lehenengo legearen modelaketa funtsezko pausua da bigarren legearen datozen aplikazioetarako.

Exergiaren oinarrizko erabilpenak kontsumoaren garapena eta kostuak kokatu ez arren, ekonomiaren ikuspegiarekin konbinatuz kostu formakuntzaren irudia lortzen da. Are gehiago, *termoekonomia sinbolikoa*k (ST) analisia exergia sistema osoaren kontsumoarekiko itzulezintasun bakoitzaren pisu faktoretzat hartuz ahalbidetzen du. Aurrerapen lez, **C Kapitulu**ak eraikinetan ST zelan aplikatu erakusten du, ahalik eta sakonen, onurak zein desabantailak analistaren helburuaren eta irizpideen arabera deskribatuz. Jomuga lortzeko, super-egitura proposamen bat dago zein denbora tarte bakoitzean instalazioaren konfigurazio zehatzetara egokitzen den.

Hala eta guztiz ere, egitura produktibo dinamikoaren definizioa anbiguoa izan daiteke eta hori da, hain zuzen, termoekonomia aplikazioaren muga nagusia. Gainera, *exergia kostua*ren murrizketa xedetzat hartu behar da baina benetako bidea diseinu parametro elementalen eraldaketan datza.

Helburu praktikoa **Eranskin**ean garatzen da termoekonomian oinarritutako eraikinen instalazio termikoentzako software dinamiko baten bitartez. Alabaina, oztopo handia da emaitzen zehaztasuna zuzenki lotzen dela sentsoreen kopuruarekin.



Irudia F. 1 Tesiaren helburuen lan katea

Tesiaren beste helburu bat eraikinen aplikazioetan bigarren legearen diagnostikoa inplementatzea da. Finean, termoekonomia informazioa gehituz gero, nahiz eta akatsak identifikatzeko guztiz beharrezkoa ez izan, anomalien garrantziaren informazioa eskaintzen baitu. Hasteko, fuel inpaktuaren ohiko formula begi kritikoz analizatu eta hobetu egiten da nolakotasun kurben gehikuntzarekin.

Orduan, **D Kapitulu**an *diagnostiko termoekonomikoa*ren problema zuzena sistema errealetan lehen aldiz ebazten da (alegia, sintomen arabera anomaliaren determinazioa); zeren, tesi hau baino lehenagoko diagnostiko termoekonomikoak akatsa ezagun izanik horien efektuen kuantifikazioan oinarritzen baitira. Kasu horretan ere, teoriaren onurak eta oztopoak azaltzen dira eta teoria berria ikerketa kasuekin egiaztatzen da. Ondorioz, iradokitako diagnosi metodologiak funtzio-okerrak detektatzeaz gain, eraginak ere zenbatzen ditu egin daitekeen tratamendua erabakitzeko.

Bigarren legean oinarritutako beste aukera bat exergia analisi aurreratua (DAEA) da zeinek osagaiaren beraren itzulezintasunak eta besteen efizientzia ezen atzeraezintasunak zenbatzen dituen exergia suntsiketa saihesgarria/saihetsezina zein endogenoa/exogenoa terminoen bitartez. Gainera, **E Kapitulu**aren ezaugarri berritzailea DAEAren azterketa dinamikoaren barneraketa da. Berriro ere, horren abantailak eta desabantailak laburtzen dira.

Ekarpen teorikoez gain, zazpi etxebizitzen energia termiko sistemen ikerketa kasuak erabiltzen dira tesiaren helburuak betetzeko:

- (i) iEKG eraikinaren ikerketa kasua
- (ii) Eraikin birgaitzearen ikerketa kasua
- (iii) Eskola baten ATU ikerketa kasua
- (iv) DHW instalazio sinplea
- (v) Eraikinean eguzki sistemaren ikerketa kasua
- (vi) Berokuntza eta EUB sistemaren ikerketa kasua
- (vii) Stirling eta galdara ikerketa kasua

Era berdintsuan, justifikatu antzera, bigarren legeko edozein aplikaziorako beharrazko datuak ohiko energia ikerketarako datuen berdinak dira (tenperaturak, masa emariak, kontzentrazioak, etab.) baina exergia aldagai agregatuak erabiltzen dira. Beraz, bigarren mailako analisia izanagatik ere, informazio gehigarri erabilgarria eskaintzen du energia sistemen ulermena handituz.

Hortaz, ikerketa hau eszeptizismo osasuntsuz eraiki da, alegia, bigarren legearen analisien teoria eta ideia inposatuak zuhurtzia handiz aplikatuz. Emaitza orokorra da, nahiz eta azterketa zailagoa izan, termoekonomia aplikazioak merezi duena eta erabakiak hartzeko tresna egokia dena. Horri esker, energia aurrezpenaren eta ingurugiro zainketaren xedeak pixkanaka lor daitezke.

IKERKETAREN EGUNGO EKARPENAK

Datozen Taula F. 1 eta Taula F. 2etan PhD-aren ekarpenak jasotzen dira (argitarapenei eta kongresuei esker) zeintzuek tesiaren edukiari zurruntasuna ematen dioten. Bakoitza dagokion kapituluaren gaiarekin lotzen da.

Taula F. 1 Tesiaren ekarpena argitarapen eta liburuen bitartez

ARGITALPENAK eta DOKUMENTU TEKNIKO-ZIENTIFIKOAK		
HARREMANA	INFO.	EDUKIA
A Kapitulua **C Kapitulua**	**Izenburua:**	A Symbolic Exergoeconomic study of a retrofitted heating and DHW facility
	Autoreak:	Picallo-Perez A., Sala-Lizarraga J. M., Iriba-Solabarrieta E., Hidalgo-Betanzos Juan M.
	Aldizkaria:	*Sustainable Energy Technologies and Assessments, 27, 119-133. (2018)*
A Kapitulua **C Kapitulua**	**Izenburua:**	New Exergetic Methodology to Promote Improvements in nZEB
	Autoreak:	Picallo-Perez A., Hidalgo-Betanzos Juan M., Sala-Lizarraga J. M.
	Libura:	*Application of Exergy*, 978-1-78923-267-7
D Kapitulua	**Izenburua:**	A comparative analysis of two thermoeconomic diagnosis methodologies in a building heating and DHW facility
	Autoreak:	Picallo-Perez A., Sala-Lizarraga, J. M., Escudero-Revilla C.
	Aldizkaria:	*Energy and Buildings 146 160–171 (2017)*
D Kapitulua	**Izenburua:**	Application of the malfunction thermoeconomic diagnosis to a dynamic heating and DHW facility for fault detection
	Autoreak:	Picallo-Perez, A., Sala-Lizarraga, J. M., Iribar-Solabarrieta, E., Odriozola-Maritorena, M., & Portillo-Valdés, L.
	Aldizkaria:	*Energy and Buildings*, Vol *135*, Pages 385-397 (2017)
D Kapitulua	**Izenburua:**	Thermoeconomic Approach to the Diagnosis of A DHW Microcogeneration Plant
	Autoreak:	Picallo-Perez, A., Iribar-Solabarrieta, E., Apaolaza A. & Sala-Lizarraga, J. M.
	Aldizkaria:	*Modern Environmental Science and Engineering, Vol 2 Number 8, Pages 507-514 (2016)*
C Kapitulua	**Izenburua:**	Symbolic Thermoeconomics in building energy supply systems
	Autoreak:	Picallo, A., Escudero, C., Flores, I., & Sala, J. M.
	Aldizkaria:	*Energy and Buildings. Vol 127, Pages 561-570 (2016)*

Taula F. 2 Tesiaren ekarpena kongresuen bitartez

KONGRESU ZIENTIFIKOETAN EKARPENAK		
HARREMANA	INFO.	EDUKIA
Eranskina	**Izenburua:**	Software for the supervision of heating and DHW facilities through Exergoeconomics application
	Autoreak:	Picallo-Perez A., Renilla R., Heredia M., Sala Lizarraga J.M
	Kongresua:	*VIIII European Conference on Energy Efficiency and Sustainability in Architecture a Planning + II Advanced Construction Congress (2018, Bilbao, Spain)*
	SARIA:	**BEST PAPER AWARD**
B Kapitulua C Kapitulua	**Izenburua:**	Thermoeconomic analysis under dynamic operating conditions for space heating and cooling systems in an educational building
	Autoreak:	Picallo-Perez A., Catrini P., Piacentino A., Sala Lizarraga J.M
	Kongresua:	*The 13th Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES (Palermo, Italy)*
C Kapitulua	**Izenburua:**	Application of Thermoeconomy for an intelligent management of air conditioning systems
	Autoreak:	Picallo-Perez A., Sala Lizarraga J.M, Pérez-González D., Gomez-Elvira I
	Kongresua:	*VIII European Conference on Energy Efficiency and Sustainability in Architecture a Planning + I Advanced Construction Congress (2017, San Sebastian, Spain)*
A Kapitulua	**Izenburua:**	Nueva metodología para fomentar mejoras en EECN *New methodology to promote improvements in nZEB*
	Autoreak:	Picallo-Perez A., Hidalgo-Betanzos J.M, Sala Lizarraga J.M
	Kongresua:	IV Congreso Edificios Energía Casi Nula 2017 *(2017, Madrid, Spain)*
C Kapitulua	**Izenburua:**	Symbolic thermoeconomic analysis in a nZEB cogeneration facility for heating and DHW supply
	Autoreak:	Picallo-Perez A, Perez D, Ruiz de Laramendi X, Sala Lizarraga J.M.
	Kongresua:	*10CNIT. 10º Congreso Nacional de Ingeniería Termodinámica (2017, Lleida, Spain)*
C Kapitulua	**Izenburua:**	Análisis exergético y cálculo de costes en una instalación geotérmica para calefacción y ACS del Pais Vasco *Exergetic analysis and costs assessment in a geothermal facility for heating and DHW in the Basque Country*
	Autoreak:	Perez D, Picallo-Perez A, Ruiz de Laramendi X, Sala Lizarraga J.M.
	Kongresua:	*V Congreso de Energía Geotérmica en la Edificación y la Industria (2017, Madrid, Spain)*
C Kapitulua	**Izenburua:**	Thermoeconomics, a tool for improving sustainability in buildings
	Autoreak:	Picallo A., Iribar E., Martin A., Hernandez A., Sala J.M.
	Kongresua:	*VII European Conference on Energy Efficiency and Sustainability in Architecture a Planning (2016, San Sebastian, Spain)*
D Kapitulua	**Izenburua:**	Thermoeconomic approach to the diagnosis of a DHW Microcogeneration plant
	Autoreak:	Picallo A., Perez-Iribarren E., Sala J.M., Apaolaza A.
	Kongresua:	*12th REHVA World Congress CLIMA 2016 (2016, Aalborg, Denmark)*
B Kapitulua	**Izenburua:**	Testing and analysis of the results of a condensing boiler and solar collectors hybrid installation for heating and DHW
	Autoreak:	Picallo A., Perez-Iribarren E., González-Pino I, Heras J., Sala J.M.
	Kongresua:	*VI European Conference on Energy Efficiency and Sustainability in Architecture a Planning (2015 San Sebastian, Spain)*
B Kapitulua	**Izenburua:**	Planta experimental para ensayos de instalaciones térmicas híbridas *Experimental Plant for testing thermal hybrid facilities*
	Autoreak:	Picallo A., Perez-Iribarren E., González-Pino I, Heras J., Sala J.M.
	Kongresua:	*Climatización 2015 (2015, Madrid, Spain)*

Are gehiago, "*EXERGY ANALYSIS AND THERMOECONOMIC OF BUILDINGS – design and analysis for sustainable energy systems*" izenburuko liburu bat idatzi da Pr. José María Sala-Lizarraga-rekin batera zein onartua eta edizio prozesuan dagoen ELSEVIER INC. konpainia ospetsuarekin.

Beste bi argitarapen prestatu dira **D Kapitulua**rekin eta **E Kapitulu**arekin erlazionatuta nazioarteko aldizkarietan argitatzeko asmoz, izenburuak dira:

"DYNAMIC ADVANCED EXERGY ANALYSIS IN BUILDING HEATING SYSTEMS –Dynamic Modelling, Avoidable/Unavoidable, Endogenous/Exogenous and Mexogenous Exergy Destruction Assessment" Picallo-Perez Ana, Sala Jose Mª, Tsatsaronis George, Sayadi Saeed.

"OVERVIEW AND IMPLEMENTATION OF DYNAMIC THERMOECONOMIC & DIAGNOSIS ANALYSIS IN HVAC&R SYSTEMS" Picallo-Perez Ana, Lazzaretto Andrea, Sala Jose Mª.

ETORKIZUNEKO IKERKETA LERROAK

Tesi hau hemen bukatu arren, hainbat etorkizunerako ikerketa lerro zabaltzen ditu eraikinen energia aurrezpen hobeak lortzeko:

Ikerketaren aplikazio praktikoari dagokionez, proposatutako termoekonomia softwarea anitz hobetu daiteke: kosturik gabeko aplikazio bat eraikitzea hobe da lizentzia beharrezkoa duten Matlab eta Excel programen ordez. Gainera, kalkulu abiadura, programazioa, prozedura, etab., asko hobetu daitezke erabiltzen erraza eta kostuen kontaketarako erabilera askoko tresna sortzeko.

Gainera, termoekonomia diagnostikoa software berberean barnera daiteke. Azken batean, erreferentzia sistema definituta badago, termoekonomia diagnostikoak ez du datu gehigarririk behar aurreko kostu kontaketaren ikerketarekin alderatuta. Programa hori giltzarria bilaka daiteke eraikinen instalazio termikoen kudeaketarako, mantenurako eta optimizaziorako, sistemaren jarrera anomaloak kokatu eta nahi ez diren etenaldiak edota kostuen penalizazioak ekidin egiten dituelako.

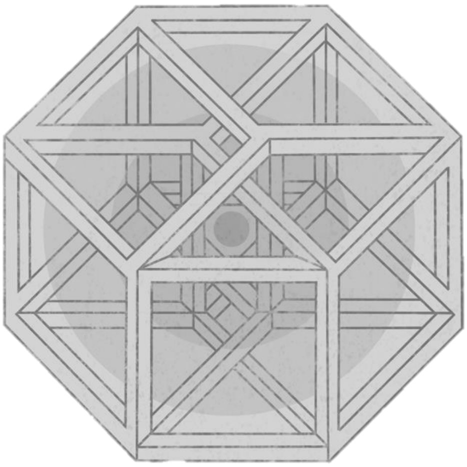
Nahiz eta software hori eraikinen sistema energetikoak optimizatzeko zein mantentzeko oso eragingarria izan, oztoporik nagusiena sentsoreen muga da zeinek denbora errealeko monitorizazioan eta emaitza erreakzioan eragiten duen. Orduan, eraikinen energia sistemetan neurketarako elementu gehiago lekukotu beharko dira kudeaketa egokia eta optimoa bideratzeko.

Beste ikuspegi bat diagnostikoaren problema zuzenaren hobekuntzarekin bat dator, teknika berritzaile bat izanik, hondakinak ez baitira ikerketan zehar kontuan hartu. Beraz, datorren urratsa disipazio osagaien barneraketa izan daiteke eraikin sistemen aukera oro kontuan hartzeko.

Aireztapen sistemak, esaterako, funtsean disipazio instalazioak dira eta egoitza arloko barne airearen kalitate beharrizanak medio hirugarren sektorean gero eta gehiago hedatu dira. Tamalez, oso sistema konplexuak direnez, horien jarrera termoekonomikoa era lausoan aztertu da. Izatez, oinarrizko ideia kanpo baliabideak kontsumitzea da barneko aire prozesatua kanporatzeko (ondorioz, aire horrek kostua dauka) eta kanpoko aire batekin ordezkatzeko (aurretiaz tratatu behar da konfort baldintzak lortzeko). Beraz, aireztapenaren helburua exergia suntsitzeko ordaintzea/kontsumitzea da; orduan, aireztapen sistemaren anomaliak exergia suntsiketa gutxiago eragingo du, hain zuzen, kontraesankorra dirudien gertakaria eta, beraz, sakonki ikertu beharreko kontua.

Horretaz aparte, lan honetan zehar exergoingurugiro aplikazioaren aipu laburra egin da. Horren arabera, ingurugiro inpaktuaren kuantifikazioa ikerketaren emaitza gehigarria da sistemaren irudi energetiko, ekonomiko eta ingurugiro argazki orokorra lortzeko. Esan lez, haren inplementazioa azaldutakoaren analogoa da baina hemen, ordea, bizitza ziklo analisiaren datuak behar dira. Horrela, analisia *sehaskatik hilerrira* egiten da.

Amaitzeko eta garatutako arrazoiak kontuan hartu, EBaren Direktibak zein nazioko gobernu probintzialek exergia analisien barneraketa kontsideratu beharko lukete informazio gehigarri erabilgarria eta helburuak era azkar batean lortzeko. Azken batean, tesiaren ondorioak bigarren lege analisiak babesten eta sendotzen dituzte mundu mailako beharrizanak argitzeko eta hobetzeko.



ERANSKINA

Termoekonomia kalkulu dinamikorako softwarea

eman ta zabal zazu

UPV EHU

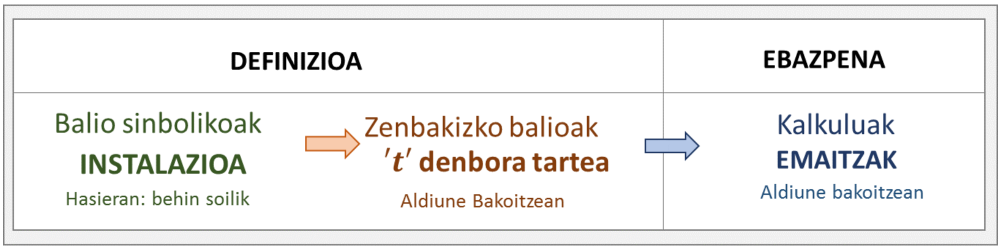
ERANSKINA: TERMOEKONOMIA KALKULU DINAMIKORAKO SOFTWAREA

ERANSK.0. HELBURUAK

Eranskin honen helburua eraikinen energia instalazioentzako kostu kontaketa eta ikuspenerako software orokor baten eraikuntza da **C Kapitulu**ko teoria eta urratsak jarraituz. Produktuen kostu termoekonomikoak (berokuntza, hozkuntza, EUB, etab.) eta barne fluxuen kostuak denbora tarte bakoitzeko zenbatzen dira dagokion kontrol estrategiaren arabera. Beraz, osagai bakoitzaren egiazko galerak zein eraginkortasunak zehazten dira.

Orain artera, programa Matlab-en eta Excel-en konbinazioaz egiten da; lehenengo programan kalkuluak egiten dira eta, bigarrenean, ordea, datuak erregistratu eta erakusten dira. Hiru azpiataletan banatzen da programa Irudia Eransk. 1n erakutsi antzera:

1. Sistemaren parametro orokorren definizio sinbolikoa (soilik behin, hasieran).
2. Balio numerikoak (denbora tarte bakoitzean).
3. Kalkuluak eta emaitzen lorpena (denbora tarte bakoitzean).



Irudia Eransk. 1 Programaren hiru fase nagusiak

Irudia Eransk. 1n adierazi lez, lehenengo bi faseak (sinbolikoa eta zenbakien zehaztapena) instalazioaren definizioari dagozkio; hirugarren fasearen oinarria matrizeen ebazpenean datza.

Lehenengo urratsa Excel-en egiten da sistemaren definizio sinbolikoa bideratuz, beste hitz batzuetan, sistemaren *egitura estatiko orokorra* zehazten da. Gero, zenbakizko data barneratzen da eta denbora tarte bakoitzean kalkuluak burutzen dira Matlab-en laguntzaz. Horren ostean, egitura produktibo dinamikoa deribatzen da; dagozkion emaitzak Excel-en batzen dira.

ERANSK.1. BALORE SINBOLIKOAK

Hautaketa bakarrik behin egiten da Excel-en interfazean eta instalazioaren *egitura estatikoa*ren determinazioari dagokio. C.3 Atalean garatu lez, egitura horrek sistemaren konfigurazio oro barneratzen ditu eta nahikoa da parte hartu gabeko fluxuei zero balioa esleitzea denbora tarte bakoitzeko *egitura dinamiko* aktiboa lortzeko.

Eransk.1.1. Instalazioaren zehaztapena

Sistemaren konfiguraziorako lehen urratsa datuak idaztea da, ikus Taula Eransk. 1. Ondorioz, sistemaren fluxuak 1 zenbakitik i-ra izendatzen dira.

Taula Eransk. 1 Sistema osoaren konfigurazio orokorra

Osagai produktiboak	n	Fluxu totalak	i	Kanpo sarrerak	e
Disipazio osagaiak	d	Hondar irteerak	r	Irteerako produktu erabilgarriak	s

Era berdinean, i zenbakien arabera sarrerak (e) zein irteerak (s eta r) definitzen dira. Gainera, horien 'TYPE'arekin eta 'Ext.Val' (kanpo ebaluaketa) ezaugarriarekin lotutako balioak gehitzen dira.

- 'TYPE' atalak baliabide izaera adierazten du (ikus Taula Eransk. 2 (b)).
- 'Ext. Val' zatia kanpo balorazioarekin lotzen da, hots, ez badago kanpo ebaluaketarik '1' jartzen da eta, bestalde, dagokion balorea.

Datorren urratsa n azpisistema identifikatzean datza instalazioaren egitura fisikoa eta produktiboa aintzat hartuz, ikus Taula Eransk. 3.

Taula Eransk. 2(a) Kanpo sarreren eta irteeren identifikazioa (b) Baliabide mota (c) Kanpo ebaluaketa

(a)

	KANPO BALIABIDEAK				
	F_e	TYPE	Ext.Val.	P_s	
1	e_1			s_1	1
...	...			...	...
e	e_e			s_e	s

(b)

TYPE	
0	-
1	ELEK.
2	EUG
3	GN
4	GASOLEO
5	BIOMASA
6	BESTEAK

(c)

Ext.Val.	
1	EZ
Balioa	BAI

- *Egitura fisikoa* determinatzeko, sarrera fluxuei dagozkio*n* i fluxu izendapena jartzen da lehenengo zutabean eta bigarrenean, aldiz, irteera fluxuaren zenbakia.
- Ondoren, osagai bakoitza kutxa beltzat hartzen da *egitura produktiboa*ren identifikaziorako zeinen sarrera F eta irteera P (edota R) diren; horiek sarrera eta irteera fluxuen bitartez eratzen dira. Lehenengo osagai produktiboak adierazten dira eta ondoren disipazio osagaiak. Hortaz, F, P eta R ezberdinak kortxeteen bidez '[ ]' banatzen dira dagozkien fluxu zenbakiaren arabera. Alegia, kortxeteen barnean baliabide edo produktua mugatzeko fluxu multzoaren konbinazioa dago.

Taula Eransk. 3 Determination of static physical and productive structure

	EGITURA FISIKOA		EGITURA PRODUKTIBOA		
	SARRERAK	IRTEERAK	FUELA	PRODUKTUA	
1	$\sum i_{in_1}$	$\sum i_{out_1}$	$[i^1_{F_1}] + [i^2_{F_1}] + \cdots$	$[i^1_{P_1}] + [i^2_{P_1}] + \cdots$	1
...	...	...	...	...	...
n	$\sum i_{in_n}$	$\sum i_{out_n}$	$[i^1_{F_n}] + [i^2_{F_n}] + \cdots$	$[i^1_{P_n}] + [i^2_{P_n}] + \cdots$	n

Halaber, definizio sinboliko energetikoa eta exergetikoa (F, F^{En} eta P, P^{En}) ezberdinak badira (**C Kapitulu**ko (iii) *Eskola baten ATU ikerketa kasuan* bezala) Taula Eransk. 4ren analogo bat bete behar da energia terminoetan.

Taula Eransk. 4 Egitura fisiko eta produktibo estatikoa energia unitateetan

Egitura EXERGETIKOA eta ENERGETIKOA ezberdina? (YES = 1 / NO = 0)	1

	EN. EGITURA FISIKOA		EN. EGITURA PRODUKTIBOA		
	SARRERAK	IRTEERAK	FUELA	PRODUKTU SARRERAK	
1	$\sum i_{in_1}$	$\sum i_{out_1}$	$[i^1_{F_1^{en}}] + [i^2_{F_1^{en}}] + \cdots$	$[i^1_{P_1^{en}}] + [i^2_{P_1^{en}}] + \cdots$	1
...	...	...	...	...	...
n	$\sum i_{in_n}$	$\sum i_{out_n}$	$[i^1_{F_n^{en}}] + [i^2_{F_n^{en}}] + \cdots$	$[i^1_{P_n^{en}}] + [i^2_{P_n^{en}}] + \cdots$	n

Eransk.1.2. Kanpo informazioaren zehaztapena

Taula Eransk. 5 Kanpo baliabideen eta osagaien kostuak eta datu ekonomikoak

BALIABIDEAK	[c€/kWh eNergia]	Kalitate faktorea
Elektrizitatea	21,81	1
Sareko ura [€/m3]	0,52	-
Gas naturala	5,27	1,04
Gasoleoa	9,43	1,04
Biomasa	4,10	1,03
Besteak	0	1

DATU EKONOMIKOAK	
i = urteko interes efektiboa	0.05
n = sistemaren bizitza erabilgarria	20
Kapitalaren berreskuratze faktorea	0.08

	EROSKETA KOSTUA[€]
1	
...	...
n	

Kostu exergoekonomikoen kalkuluak kanpo informazioa behar du. Beraz, e kanpo baliabideen kostu ekonomiko unitarioak [€/kWh] (fuela, elektrizitatea, ur hotza, etab.) behar dira eta baita n osagaien erosketa, operazio eta mantenu kostuen bektorea [€] ere.

Bestelako datu ekonomikoak behar dira, esaterako, interes efektiboa eta osagai bakoitzaren bizitza erabilgarria; informazio hori guztia Taula Eransk. 5n dago. Denbora tarte bakoitzean baliabideen kostuak aldatuz badoaz, taula horiek eguneratu beharko dira.

ERANSK.2. ZENBAKIZKO BALOREAK ETA KALKULUAK

Egitura produktibo estatikoa definitu ostean, denbora tarte bakoitzean zenbakizko datuak jaso eta beharrezko emaitzak lortzen dira. Fase horiek lau urrats nagusitan banatzen dira Irudia Eransk. 2n erakutsi lez:

Irudia Eransk. 2 Programa orokorraren desagregazioa

1. Simulazio datuen edo datu monitorizatuen transferentzia eta egiaztapena.
2. Datuetatik abiatuz fluxuen exergia kalkulua (Excel-en).
3. Egitura dinamikoaren hautaketa, kalkulu matrizialak eta emaitzen lorpena (Matlab-en bidez).
4. Analisiaren emaitzen erregistroa eta grafikoak.

Lehen pausua datuak sentsoreetatik edota simulaziotik jasotzea da. Gainera, zaraten iragazpena eta egiaztapena egiten da. Sentsore denen balioak Excel-en jaso ondoren, dagozkien exergia fluxuak kalkulatzen dira horien formula sinbolikoan oinarrituz (zenbait fluxuk zero balioa izan ditzakete).

Gero, denbora tarte zehatzerako operazio modu aktibatua identifikatzen da, alegia, une hartako osagai piztuak detektatzen dira. Horrela, instalazioaren egitura *fisikoa* eta *produktibo dinamikoa* memento horretarako definitzen dira. Jakina denez, elementuen pizketa/itzaltzea ponpen zein 3-bideko balbulen posizioen araberako da (hots, fluxu deuseztatuen menpekoa).

Matlab-en barne programak azpitalde aktiboak identifikatzen ditu n_i^{ON}, d_i^{ON}, i_i^{ON}, r_i^{ON}, e_i^{ON}, s_i^{ON} (aktibatu gabeko taldeek produktu eta fuel nuluak izango baitituzte $F_{OFF} = 0$ edota $P_{OFF} = 0$) eta, beraz, lortutako matrizeak eta bektoreak dagokion termoekonomia ikasketarekin lortuko dira.

Azkenengo urratsa emaitzen kalkuluarekin eta analisiarekin bat dator.

Eransk.2.1. Sentsorearen arabera exergia kalkulua

Oro har, sentsoreen datuak dira:

- Tenperaturak (T_i)
- Entalpiak ($m_i \cdot \Delta T_i$)
- Balbulen irekiera eta itxiera proportzioak (v_i)
- Fuel kontsumoa (gasolioa, gas naturala, elektrizitatea, etab.) (F_i)
- Ponpen aktibazioa, itzaltzea eta modulazioa (on-off $Bi_{0/1}$, ehunekoak $Bi_{\%}$)

Aldagai horietatik, eta fluxu motaren arabera, E_i exergia fluxua kalkulatzeko formula programatzen da, esaterako:

- Bero fluxua: $E_{heat} = Q_{heat} \cdot \left(1 - \frac{T_0}{T_i}\right)$
- Elektrizitate fluxua: $E_{elec} = W_{elec}$
- Masa fluxua: $E_{mass} = m_{mass} \cdot c_{P_{mass}} \cdot \left[(T_i - T_0) - T_0 \cdot ln\left(\frac{T_i}{T_0}\right)\right]$
- Fuel fluxua: $E_{fuel} = m_{fuel} \cdot f_i \cdot BBA$

non $\left(1 - \frac{T_0}{T}\right)$ Carnot-en faktorea den; T_0 eta T_i ingurugiro eta i fluxuaren tenperaturak dira K unitateetan; c_P masa fluxu espezifikoa da; BBA behe bero ahalmena da eta f_i fuel motaren araberako koefiziente taulatuak (adibidez, gas oliorako 1,04 da).

Taula Eransk. 6 Fluxuen balio exergetikoa

Fluxuen exergia balioa [kW]		
E_1	…	E_n
	⋮	⋮

Sistemaren i fluxuak, preseski osagaien zein inguruaren arteko loturak, sentsore kopuruaren eta datuen arabera definitzen dira Excel-en ikus Taula Eransk. 6. Horrela, bestalde, osagaiak determinatzen dira (zeintzuek "kutxa beltzat" jotzen diren). Hortaz, ikasketaren zehaztasunak sentsoreen datu kopuruarekin lotura zuzena dauka.

Eransk.7.1. Emaitzen lorpena eta analisia

Excel-en 'RESULTS' orrian, datozen taulak betetzen dira eta memento horretako osagai aktiboak azpimarratzen dira eta itzaliak, ordea, ezkutatu:

- Exergia kontsumo unitarioen taula (k_i [-]) eta osagaien energia zein exergia etekinak (ε_i, η_i [%]) eta horien F_i zein P_i.
- Fuelen ($k^*_{F_i}$[-]) , produktuen ($k^{e,*}_{P_i}$[-]) eta hondakinen ($k^{r,*}_{P_i}$[-]) kostu exergetiko unitarioen taula.
- Kanpo baliabide kontsumoaren kostu exergoekonomiko unitarioaren eta kostu totalaren taulak exergia unitateetan (c_{F_i}, C_{F_i} eta $c^e_{P_i}$, $c^r_{P_i}$, $C^e_{P_i}$, $C^r_{P_i}$ [c€/kW$_{ex}$]) zein energia unitateetan (c_{F_i}, C_{F_i} eta $c^e_{P_i}$, $c^r_{P_i}$, $C^e_{P_i}$, $C^r_{P_i}$ [c€/kW$_{en}$]).
- Bai fuel kontsumoarekiko bai osagaien erosketa, operazio eta mantenu kostuekiko kostu exergoekonomiko unitarioak eta totalak exergia zein energia unitateetan ($c^e_{P_i}$, $c^r_{P_i}$,$c^z_{P_i}$ $C^e_{P_i}$, $C^r_{P_i}$, $C^z_{P_i}$ [c€/kW$_{ex}$] eta [c€/kW$_{en}$]).

Zerrenda hori eginagatik, ikerketaren helburuaren arabera erakutsi nahi diren emaitzak aukera daitezke. Beraz, zenbait taula eralda edota ezaba daitezke eta taula berriak zein grafiko erakargarriak barneratu.

Eransk.2.2. Matlab-en barne programa

Jarraian Matlab-en programa (Excel-ekin lotua) erakusten da:

ERANSK.3. ALGORITMOA

AAAProgramaTOT

```
for mes=1:1
% me situo en el MES
Localiz='C:\Users\apicallo001\LCCE\1.Beca_Doctorado\15.Estancia\2018\2.PADOVAlazzaretto\4.Research\2.EstudioSolar\3.Diagnosis\';
MesNum=int2str(mes);
d='V3V_3.xlsx';

filename=strcat(Localiz,d);
AAAProductStruc

strcat('Los calculos EXERGETICOS UNITARIOS están copiados en el excel MES:_',int2str(mes))

clear all
end
```

1. AAAProductStruc

```
aLeerDatos
%define estructura generica con todo ON
aEstructura
%Define estructura activa instantanea
aEstructuraDin

% Para los n componentes y m flujos
F=Af*B;
P=Ap*B;
Ps=Ap*Bs;

Aux_e=Af/[Ap;alfa_e;alfa_x];
FP=[Aux_e(:,1:(n))];


PF =diag(P)*FP'*inv(diag(F));

%compruebo que salga bien
kd =F./P;
kd =diag(kd);
KP =PF *kd;
Ft_F =ones(1,(n))*(eye((n))-PF);
Pt_P =ones(1,(n))*(eye((n))-FP);

ValoracionExt

ke =Ft_F *kd;
KP_ampliada =[ke;KP];
Bcomprob=[Af-kd*Ap;alfa_e;alfa_x]\Je;
Bcomprob=Bcomprob';
Bcoste=[Af-Ap;alfa_e;alfa_x]\Je;


%calculo costes

kp_e=(inv(eye((n))-KP))'*(ke)';

aMatrizKR

kp=(inv(eye((n))-KP-KR))'*(ke)';
kp_r=kp-kp_e;

kf =Ft_F'+PF'*kp;


B_kp =kp.*P;
B_kp_e=kp_e.*P;
B_kp_r=kp_r.*P;
B_kf =kf.*F;

FtEco=(ones(1,(n))*(eye((n))-PF)).*Ce';
FtEcoCO2=(ones(1,(n))*(eye((n))-PF)).*CO2e';

keEco=(ke).*FtEco;
keEcoCO2=(ke).*FtEcoCO2;

%calculos costes Termoeconomicos
cp_eEco=(inv(eye((n))-KP))'*keEco';
cp_rEco=(inv(eye(n)-KR*inv(eye(n)-KP))-eye(n))'*cp_eEco;
```

```
cp_Eco=cp_eEco+cp_rEco;

cp_eEcoCO2=(inv(eye((n))-KP))'*keEcoCO2';
cp_rEcoCO2=(inv(eye(n)-KR*inv(eye(n)-KP))-
eye(n))'*cp_eEcoCO2;
cp_EcoCO2=cp_eEcoCO2+cp_rEcoCO2;

cp_zEco=(inv(eye(n)-KP))'*(Z(1:(n),:)./P);


%Considerando solo Coste Fueles
cfEco2=PF'*cp_Eco+FtEco';
CfCost2=(cfEco2).*F;

cfEco2_CO2=PF'*cp_EcoCO2+FtEcoCO2';
CfCost2_CO2=(cfEco2_CO2).*F;

Cp_eCost_CO2=cp_eEcoCO2.*P;
Cp_rCost_CO2=cp_rEcoCO2.*P;
Cp_Cost_CO2=cp_EcoCO2.*P;

%Considerando Costes Totales
cpEco_f=cp_Eco+cp_zEco;
cfEco=PF'*cpEco_f+FtEco';

Cp_Cost=cp_Eco.*P;
Cp_eCost=cp_eEco.*P;
Cp_rCost=cp_rEco.*P;
Cp_zCost=cp_zEco.*P;
CfCost=(cfEco).*F;
```

BCostesEnergeticos
BoRehacerEstructura
B2CopiarExcel

2. aLeerDatos

aaaCrearVectorExcel

```
nmse=xlsread(filename,'LecturaDatos','C1:G2');
nP=nmse(1,1);
nD=nmse(2,1);
n=nD+nP;
m=nmse(1,3);
sR=nmse(2,3);
mP=m-sR;
e=nmse(1,5);
sP=nmse(2,5);
s=sP+sR;
```

aPosicion

```
B=xlsread(filename,'LecturaDatos',posB);
E=xlsread(filename,'LecturaDatos',posE);
Z=xlsread(filename,'LecturaDatos',posZ);
Cost_entr=xlsread(filename,'LecturaDatos',pos_ent)
;
C_entr=Cost_entr(:,1);
CO2_entr=Cost_entr(:,2);

[Prueba,txt,todoF]=xlsread(filename,'Estructura',po
sEstructuraF);
[Prueba,txt,todoP]=xlsread(filename,'Estructura',po
sEstructuraP);

OnOff_E_B=xlsread(filename,'Estructura',posEstruc
F_E_B);

if OnOff_E_B==1

[Prueba,txt,todoF_E]=xlsread(filename,'Estructura',
posEstructuraF_E);

[Prueba,txt,todoP_E]=xlsread(filename,'Estructura',
posEstructuraP_E);
end

EntrSal=xlsread(filename,'Estructura',posEntrSal);

%Defino flujos Entrada y Salida
entry=EntrSal(1:e,1);
entrType=EntrSal(1:e,2);
entryValor=EntrSal(1:e,3);
SalidaExt=EntrSal(1:s,4);

B=B';
E=E';
```

3. aEstructura

```
%Creo Matrices vacias
Ap(n,m)=0;
Af(n,m)=0;
Entra(n,m)=0;
Sale(n,m)=0;

%Generar matriz de incidencia ESTRUCTURA
FISICA (entra / sale)
```

aIncidenciaExergia
aIncidenciaEnergia

```
%Creo matrix alfa_e + VECTOR ENTRADA + SALIDA
```

aMatricesEntradasSalidas

```
Je=[zeros(n,1);Bentr;zeros(m-n-e,1)];


%llamo a subprogramas para el cálculo de las
Bifurcaciones:
% aplico TEORÍA DE COSTES
```

```
cFiguales
cPiguales

%Creo matriz de Bifurcaciones

if size(alfa_xF,1)==0
if size(alfa_xP,2)<m
alfa_xP(size(alfa_xP,1),m)=0;
end
alfa_x=[alfa_xP];

elseif size(alfa_xP,1)==0
if size(alfa_xF,2)<m
alfa_xF(size(alfa_xF,1),m)=0;
end
alfa_x=[alfa_xF];
else
if size(alfa_xP,2)<m
alfa_xP(size(alfa_xP,1),m)=0;
end
if size(alfa_xF,2)<m
alfa_xF(size(alfa_xF,1),m)=0;
end
alfa_x=[alfa_xP;alfa_xF];
end
```

4. aEstructuraDin

```
F=Af*B;
P=Ap*B;

contNOm=0;
contNOn=0;
contNOnP=0;
contNOnD=0;
contNOe=0;
contNOs=0;
contNObP=0;
contNObF=0;
for i=1:m
if B(i,1)==0
contNOm=contNOm+1;
numNOm(contNOm,1)=i;
end
end
for i=1:n
if F(i,1)==0 && P(i,1)==0
contNOn=contNOn+1;
numNOn(contNOn,1)=i;
end
end
for i=1:nP
if F(i,1)==0 && P(i,1)==0
contNOnP=contNOnP+1;
numNOnP(contNOnP,1)=i;
end
end
for i=1:nD
if F(i+nP,1)==0 && P(i+nP,1)==0
contNOnD=contNOnD+1;
numNOnD(contNOnD,1)=nP+i;
end
end
for i=1:e
if Bentr(i,1)==0
contNOe=contNOe+1;
numNOe(contNOe,1)=entry(i,1);
numNOentr(contNOe,1)=i;
end
end
for i=1:s
if B(SalidaExt(i,1))==0
contNOs=contNOs+1;
numNOs(contNOs,1)=SalidaExt(i,1);
end
end
for i=1:length(x_bifurP)
if x_bifurP(i,1)==0
contNObP=contNObP+1;
numNObP(contNObP,1)=i;
end
end
for i=1:length(x_bifurF)
if x_bifurF(i,1)==0
contNObF=contNObF+1;
numNObF(contNObF,1)=i;
end
end

%Elimino Columnas y filas de 0 de las Ap y Af / Entra y Sale; y columnas de alfa_e y
%alfa_xP y alfa_xF
Ap2=Ap;
Af2=Af;
Entra2=Entra;
Sale2=Sale;
alfa_e2=alfa_e;
alfa_xP2=alfa_xP;
alfa_xF2=alfa_xF;

if OnOff_E_B==1
Ap2_E=Ap_E;
Af2_E=Af_E;
else
Ap2_E=Ap;
Af2_E=Af;
end


for i=1:contNOm
Ap(:,numNOm(contNOm+1-i))=[];
Af(:,numNOm(contNOm+1-i))=[];
Entra(:,numNOm(contNOm+1-i))=[];
Sale(:,numNOm(contNOm+1-i))=[];
alfa_e(:,numNOm(contNOm+1-i))=[];
end
for i=1:contNOn
Ap(numNOn(contNOn+1-i),:)=[];
```

```
Af(numNOn(contNOn+1-i),:)=[];
Entra(numNOn(contNOn+1-i),:)=[];
Sale(numNOn(contNOn+1-i),:)=[];
end

if OnOff_E_B==1
for i=1:contNOm
Ap_E(:,numNOm(contNOm+1-i))=[];
Af_E(:,numNOm(contNOm+1-i))=[];
Entra_E(:,numNOm(contNOm+1-i))=[];
Sale_E(:,numNOm(contNOm+1-i))=[];
end
for i=1:contNOn
Ap_E(numNOn(contNOn+1-i),:)=[];
Af_E(numNOn(contNOn+1-i),:)=[];
Entra_E(numNOn(contNOn+1-i),:)=[];
Sale_E(numNOn(contNOn+1-i),:)=[];
end
else
Ap_E=Ap;
Af_E=Af;
end


if size(alfa_xF,1)==0
else
for i=1:contNOm
alfa_xF(:,numNOm(contNOm+1-i))=[];
end
end

if size(alfa_xP,1)==0
else
for i=1:contNOm
alfa_xP(:,numNOm(contNOm+1-i))=[];
end
end


%Elimino filas de 0 de alfa_xP y alfa_xF
if contNObP==0
else
for i=1:contNObP
alfa_xP(numNObP(contNObP+1-i),:)=[];
end
end
if contNObF==0
else
for i=1:contNObF
alfa_xF(numNObF(contNObF+1-i),:)=[];
end
end
%Redimensiono la matriz
if size(alfa_xF,1)==0
alfa_x=[alfa_xP];
elseif size(alfa_xP,1)==0
alfa_x=[alfa_xF];
else
alfa_x=[alfa_xP;alfa_xF];
end

%Elimino filas de 0 de alfa_e y Bentr
Bentr2=Bentr;
entry2=entry;
entryValor2=entryValor;
for i=1:contNOe
Bentr(numNOentr(contNOe+1-i),:)=[];
alfa_e(numNOentr(contNOe+1-i),:)=[];
entry(numNOentr(contNOe+1-i),:)=[];
entryValor(numNOentr(contNOe+1-i),:)=[];
end

%Elimino los flujos 0 de las B, Be, Bs y E
Be2=Be;
Bs2=Bs;
B2=B;
E2=E;
for i=1:contNOm
Be(numNOm(contNOm+1-i),:)=[];
Bs(numNOm(contNOm+1-i),:)=[];
B(numNOm(contNOm+1-i),:)=[];
E(numNOm(contNOm+1-i),:)=[];
end

%Elimino los equipos 0 de las CO2e Ce

Ce2=Ce;
CO2e2=CO2e;
Z2=Z;
for i=1:contNOn
Ce(numNOn(contNOn+1-i),:)=[];
CO2e(numNOn(contNOn+1-i),:)=[];
Z(numNOn(contNOn+1-i),:)=[];
end

nP2=nP;
nD2=nD;
n2=n;
m2=m;
sR=sR;
mP2=mP;
e2=e;
sP2=sP;
s2=s;

n=n-contNOn;
nP=nP-contNOnP;
nD=nD-contNOnD;
m=m-contNOm;
e=e-contNOe;
s=s-contNOs;

%los datos genericos estás guardados con la
nomenclatura 2
Je=[zeros(n,1);Bentr;zeros(m-n-e,1)];
```

5. ValoracionExt

```
contENTRY2=0;
for i=1:m
if Be(i,1)==0
else
contENTRY2=contENTRY2+1;
entryNuev(contENTRY2,1)=i;
end
end


Ft_F2=ones(1,(n))*(eye((n))-PF);
for comp=1:n
kePond=0;
keDiv=0;
for entr=1:e
if Entra(comp,entryNuev(entr))~=0

kePond=kePond+Be(entryNuev(entr))*entryValor(e
ntr);
keDiv=keDiv+Be(entryNuev(entr));

Ft_F2(1,comp)=Ft_F2(1,comp)*(kePond/keDiv);
end
end
end
 Ft_F=Ft_F2;


compEntraNuev(1,n)=0;
for comp=1:n
for entr=1:e
if Entra(comp,entryNuev(entr))~=0
compEntraNuev(1,comp)=comp;
end
end
end
for comp=1:n
if compEntraNuev(1,comp)==0
Ft_F(1,comp)=0;
end
end
```

6. aMatrizKR

```
%matrices KR
if n==0
KR=[];
else
KR(n,n)=0;
end

for res=1:nD
for prod=1:nP

KR(res+nP,prod)=kp_e(prod)*KP(prod,res+nP)/(kp_
e(res+nP)-ke(res+nP))*P(res+nP)/P(prod);
end
end
```

```
Rs=KR*inv(eye(n)-KP)*Ps;
Ps_p=Ps-Rs;
```

7. BCostesEnergeticos

```
F_E=Af_E*E;
P_E=Ap_E*E;
rmto_E=P_E./F_E;



%calculos costes Termoeconomicos en BASE
ENERGETICA
facF=F./F_E;
facP=P./P_E;

cp_eEco_E=cp_eEco.*facP;
cp_rEco_E=cp_rEco.*facP;
cp_Eco_E=cp_Eco.*facP;

cp_eEcoCO2_E=cp_eEcoCO2.*facP;
cp_rEcoCO2_E=cp_rEcoCO2.*facP;
cp_EcoCO2_E=cp_EcoCO2.*facP;

cp_zEco_E=cp_zEco.*facP;

%Considerando solo Coste Fueles
cfEco2_E=cfEco2.*facF;
cfEco2_CO2_E=cfEco2_CO2.*facF;

%Considerando Costes Totales
cpEco_f_E=cpEco_f.*facF;
cfEco_E=cfEco.*facF;
```

8. BoRehacerEstructura

```
%Rehacer cosas para Copiar
%Bcomprob AMPLIADA

contZeros=0;
Bcomprob2=ones(1,m2);

for i=1:m2
for j=1:contNOm
if numNOm(j,1)==i
Bcomprob2(1,i)=0;
end
end

end
for i=1:m2
```

```
if Bcomprob2(1,i)==0
else
contZeros=contZeros+1;
Bcomprob2(1,i)= Bcomprob(1,contZeros);
end
end

%[F P diag(kd)]AMPLIADA
F2=Af2*B2;
P2=Ap2*B2;
for i=1:n2
if P2(i,1)==0
kd2(i,1)=0;

else
kd2(i,1)=F2(i,1)/P2(i,1);

end
end

 %[F_E P_E rmto_E]AMPLIADA
F_E2=Af2_E*E2;
P_E2=Ap2_E*E2;
for i=1:n2
if F_E2(i,1)==0
rmto_E2(i,1)=0;
else
rmto_E2(i,1)=P_E2(i,1)/F_E2(i,1);
end
end

%[kf kp_e kp_r] AMPLIADA


contZeros=0;
kf2=ones(n2,1);
kp_e2=ones(n2,1);
kp_r2=ones(n2,1);

%[cfEco2  CfCost2]
cfEco22=cfEco2;
CfCost22=CfCost2;

%[cfEco (cp_eEco+cp_rEco) cp_zEco CfCost
(Cp_eCost+Cp_rCost+Cp_zCost) Z]
cfEco_2=cfEco;
cp_eEco2=cp_eEco;
cp_rEco2=cp_rEco;
cp_zEco2=cp_zEco;
CfCost_2=CfCost;
Cp_eCost2=Cp_eCost;
Cp_rCost2=Cp_rCost;
Cp_zCost2=Cp_zCost;
Z2=Z;

%[cfEco2_CO2 cp_eEcoCO2 cp_rEcoCO2
CfCost2_CO2 Cp_eCost_CO2 Cp_rCost_CO2]
cfEco2_CO2_2=cfEco2_CO2;
cp_eEcoCO22=cp_eEcoCO2;
cp_rEcoCO22=cp_rEcoCO2;
CfCost2_CO2_2=CfCost2_CO2;
Cp_eCost_CO22=Cp_eCost_CO2;
Cp_rCost_CO22=Cp_rCost_CO2;

%[cfEco2_E cp_eEco_E cp_rEco_E]
cfEco2_E2=cfEco2_E;
cp_eEco_E2=cp_eEco_E;
cp_rEco_E2=cp_rEco_E;

%[cfEco_E cp_zEco_E ]
cfEco_E2=cfEco_E;
cp_zEco_E2=cp_zEco_E;

%[cfEco2_CO2_E cp_eEcoCO2_E cp_rEcoCO2_E]
cfEco2_CO2_E2=cfEco2_CO2_E;
cp_eEcoCO2_E2=cp_eEcoCO2_E;
cp_rEcoCO2_E2=cp_rEcoCO2_E;

for i=1:n2
for j=1:contNOn
if numNOn(j,1)==i
kf2(i,1)=0;
kp_e2(i,1)=0;
kp_r2(i,1)=0;

cfEco22(i,1)=0;
CfCost22(i,1)=0;

cfEco_2(i,1)=0;
cp_eEco2(i,1)=0;
cp_rEco2(i,1)=0;
cp_zEco2(i,1)=0;
CfCost_2(i,1)=0;
Cp_eCost2(i,1)=0;
Cp_rCost2(i,1)=0;
Cp_zCost2(i,1)=0;
Z2(i,1)=0;

cfEco2_CO2_2(i,1)=0;
cp_eEcoCO22(i,1)=0;
cp_rEcoCO22(i,1)=0;
CfCost2_CO2_2(i,1)=0;
Cp_eCost_CO22(i,1)=0;
Cp_rCost_CO22(i,1)=0;

cfEco2_E2(i,1)=0;
cp_eEco_E2(i,1)=0;
cp_rEco_E2(i,1)=0;
cp_zEco_E2(i,1)=0;
cfEco_E2(i,1)=0;
cp_zEco_E2(i,1)=0;
cfEco2_CO2_E2(i,1)=0;
cp_eEcoCO2_E2(i,1)=0;
cp_rEcoCO2_E2(i,1)=0;

end
end

end
for i=1:n2
```

```
if kf2(i,1)==0
else
contZeros=contZeros+1;
kf2(i,1)=kf(contZeros,1);
kp_e2(i,1)=kp_e(contZeros,1);
kp_r2(i,1)=kp_r(contZeros,1);

cfEco22(i,1)=cfEco2(contZeros,1);
CfCost22(i,1)=CfCost2(contZeros,1);

cfEco_2(i,1)=cfEco(contZeros,1);
cp_eEco2(i,1)=cp_eEco(contZeros,1);
cp_rEco2(i,1)=cp_rEco(contZeros,1);
cp_zEco2(i,1)=cp_zEco(contZeros,1);
CfCost_2(i,1)=CfCost(contZeros,1);
Cp_eCost2(i,1)=Cp_eCost(contZeros,1);
Cp_rCost2(i,1)=Cp_rCost(contZeros,1);
Cp_zCost2(i,1)=Cp_zCost(contZeros,1);
Z2(i,1)=Z(contZeros,1);


cfEco2_CO2_2(i,1)=cfEco2_CO2(contZeros,1);
cp_eEcoCO22(i,1)=cp_eEcoCO2(contZeros,1);
cp_rEcoCO22(i,1)=cp_rEcoCO2(contZeros,1);
CfCost2_CO2_2(i,1)=CfCost2_CO2(contZeros,1);
Cp_eCost_CO22(i,1)=Cp_eCost_CO2(contZeros,1);
Cp_rCost_CO22(i,1)=Cp_rCost_CO2(contZeros,1);


cfEco2_E2(i,1)=cfEco2_E(contZeros,1);
cp_eEco_E2(i,1)=cp_eEco_E(contZeros,1);
cp_rEco_E2(i,1)=cp_rEco_E(contZeros,1);
cp_zEco_E2(i,1)=cp_zEco_E(contZeros,1);
cfEco_E2(i,1)=cfEco_E(contZeros,1);
cfEco2_CO2_E2(i,1)=cfEco2_CO2_E(contZeros,1);
cp_eEcoCO2_E2(i,1)=cp_eEcoCO2_E(contZeros,1);
cp_rEcoCO2_E2(i,1)=cp_rEcoCO2_E(contZeros,1);

end
end


PF2=zeros(n2,n);
FP2=zeros(n2,n);
Ft_F2=zeros(1,n);
Pt_P2=zeros(1,n);

%[FPdiag(kd)]AMPLIADA
%[FPding(kd)]AMPLIADA
j=0;
for i=1:n2
if P2(i,1)==0
FP2(i,:)=zeros(1,n);
PF2(i,:)=zeros(1,n);
Ft_F2(1,i)=0;
Pt_P2(1,i)=0;
else
j=j+1;
FP2(i,:)=FP(j,:);
PF2(i,:)=PF(j,:);
Ft_F2(1,i)=Ft_F(1,j);
Pt_P2(1,i)=Pt_P(1,j);
end
end

FP3=zeros(n2,n2);
PF3=zeros(n2,n2);

j=0;
%[FPdiag(kd)]
for i=1:n2
if P2(i,1)==0
FP3(:,i)=zeros(n2,1);
PF3(:,i)=zeros(n2,1);
else
j=j+1;
FP3(:,i)=FP2(:,j);
PF3(:,i)=PF2(:,j);
end
end

%KR&KP
KP2=zeros(n2,n);
KR2=zeros(n2,n);
ke2=zeros(1,n);


j=0;
for i=1:n2
if P2(i,1)==0
KR2(i,:)=zeros(1,n);
KP2(i,:)=zeros(1,n);
ke2(1,i)=0;
else
j=j+1;
KR2(i,:)=KR(j,:);
KP2(i,:)=KP(j,:);
ke2(1,i)=ke(1,j);
end
end

KR3=zeros(n2,n2);
KP3=zeros(n2,n2);

j=0;

for i=1:n2
if P2(i,1)==0
KR3(:,i)=zeros(n2,1);
KP3(:,i)=zeros(n2,1);
else
j=j+1;
KR3(:,i)=KR2(:,j);
KP3(:,i)=KP2(:,j);
end
end
```

9. B2CopiarExcel

```
xlswrite(filename,Bcomprob2,'LecturaDatos',posBc
omprob);

% Resultados
xlswrite(filename,[F2P2kd2],'Resultados',posF_P);
xlswrite(filename,[F_E2P_E2rmto_E2],'Resultados',
pos_FP_E);


xlswrite(filename,[kf2kp_e2kp_r2],'Resultados',posk
f_kp);

xlswrite(filename,[cfEco22*100cp_eEco2*100cp_rE
co2*100CfCost22Cp_eCost2Cp_rCost2],'Resultados'
,pos_cSoloFuel);
xlswrite(filename,[cfEco_2*100(cp_eEco2*100+cp_r
Eco2*100)cp_zEco2*100CfCost_2(Cp_eCost2+Cp_r
Cost2+Cp_zCost2)Z2],'Resultados',pos_cTodoCost);
xlswrite(filename,[cfEco2_CO2_2cp_eEcoCO22cp_r
EcoCO22CfCost2_CO2_2/1000Cp_eCost_CO22/100
0Cp_rCost_CO22/1000],'Resultados',pos_cSoloFuel
_CO2);

xlswrite(filename,[cfEco2_E2*100cp_eEco_E2*100c
p_rEco_E2*100],'Resultados',pos_cSoloFuel_E);
xlswrite(filename,[cfEco_E2*100(cp_eEco_E2*100+
cp_rEco_E2*100)cp_zEco_E2*100],'Resultados',pos
_cTodoCost_E);
xlswrite(filename,[cfEco2_CO2_E2cp_eEcoCO2_E2
cp_rEcoCO2_E2],'Resultados',pos_cSoloFuel_CO2_
E);

% tengoqueampliarmatricesydefinirposiciones
xlswrite(filename,Ft_F2,'PF','B3');
xlswrite(filename,PF3,'PF','B4');
xlswrite(filename,Pt_P2,'PF',posPtPcop);
xlswrite(filename,FP3,'PF',posFPcop);

xlswrite(filename,ke2,'PF',poske_cop);
xlswrite(filename,KP3,'PF',posKPcop);
% xlswrite(filename,ke_r2,'PF',poske_rcop);
xlswrite(filename,KR3,'PF',posKRcop);
```

- ## aaaCrearVectorExcel

```
% crearvectorconlassiglasdelExcel:
for n=1:26
primera=double('A');
siguiente=primera+1*(n-1);
alf1(n,:)=strcat(siguiente);
end
for n=1:26
primera=double('A');
siguiente=primera+1*(n-1);
alf2(n,:)=strcat('A',siguiente);
end
for n=1:26
primera=double('B');
siguiente=primera+1*(n-2);
alf3(n,:)=strcat('B',siguiente);
end
for n=1:26
primera=double('C');
siguiente=primera+1*(n-3);
alf4(n,:)=strcat('C',siguiente);
end
for n=1:26
primera=double('D');
siguiente=primera+1*(n-4);
alf5(n,:)=strcat('D',siguiente);
end
v_excel=char(alf1,alf2,alf3,alf4,alf5);
```

- ## aPosicion

```
% leerexcel
if 2+m<27
posB=[v_excel(2),'5:',v_excel((2+(m-1))),'5'];
else
posB=[v_excel(2),'5:',v_excel((2+(m-1)),:),'5'];
end

if 2+(m-1)<27
posE=[v_excel(2),'10:',v_excel((2+(m-1))),'10'];
else
posE=[v_excel(2),'10:',v_excel((2+(m-1)),:),'10'];
end

posZ=['J15:J',int2str(15+(n-1))];
pos_ent=['C36:D41'];

posEstructuraF=['C4:D',int2str(4+(n-1))];
posEstructuraP=['F4:G',int2str(4+(n-1))];

posEstrucF_E_B=['G',int2str(6+(n-1))];
posEstructuraF_E=['C',int2str(11+(n-
1)),':D',int2str(9+2*n)];
posEstructuraP_E=['F',int2str(11+(n-
1)),':G',int2str(9+2*n)];

if e>s
posEntrSal=['L4:O',int2str(4+(e-1))];
else
posEntrSal=['L4:O',int2str(4+(s-1))];
end


% escribirexcel

if 2+(m-1)<27
```

```
posBcomprob=[v_excel(2),'6:',v_excel((2+(m-
1))),'6'];
else
posBcomprob=[v_excel(2),'6:',v_excel((2+(m-
1)),:),'6'];
end


posF_P=['B3:D',int2str(3+(n-1))];
poskf_kp=['G3:I',int2str(3+(n-1))];
pos_cSoloFuel=['L3:Q',int2str(3+(n-1))];
pos_cTodoCost=['U3:Z',int2str(3+(n-1))];
pos_cSoloFuel_CO2=['AD3:AI',int2str(3+(n-1))];


pos_FP_E=['B',int2str(7+n),':D',int2str(6+2*n)];
pos_cSoloFuel_E=['L',int2str(7+n),':N',int2str(6
+2*n)];
pos_cTodoCost_E=['U',int2str(7+n),':W',int2str(
6+2*n)];
pos_cSoloFuel_CO2_E=['AD',int2str(7+n),':AF',i
nt2str(6+2*n)];

posPtPcop=['B',int2str(6+n)];
posFPcop=['B',int2str(7+n)];

if 4+n<27
poske_cop=[v_excel(4+n),'3'];
posKPcop=[v_excel(4+n),'4'];
poske_rcop=[v_excel(4+n),int2str(6+n)];
posKRcop=[v_excel(4+n),int2str(7+n)];
else
poske_cop=[v_excel(4+n,:),'3'];
posKPcop=[v_excel(4+n,:),'4'];
poske_rcop=[v_excel(4+n,:),int2str(6+n)];
posKRcop=[v_excel(4+n,:),int2str(7+n)];
end
```

○ <u>aIncidenciaExergia</u>

```
% DefinirEntradas+
for j=1:n
c=todoF(j,1);
if iscellstr(c)==0
c=[c{:}];
Entra(j,c)=1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Entra(j,str2double(C))=1;
end
end
end
% DefinirSalidas-
for j=1:n
c=todoF(j,2);
if iscellstr(c)==0
c=[c{:}];
Sale(j,c)=-1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Sale(j,str2double(C))=-1;
end
end
end



%
GenerarmatrizdeESTRUCTURAPRODUCTIVA(
AfyAp)

% FUELES(Ponerlesigno+/-alosFueles)

for j=1:n
c=todoP(j,1);
if iscellstr(c)==0
c=[c{:}];
Af(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE==1
Af(j,str2double(C))=-1;
else
Af(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
```

```
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end


% PRODUCTOS(Ponerlesigno+/-
alosProductos)

for j=1:n
c=todoP(j,2);
if iscellstr(c)==0
c=[c{:}];
Ap(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE==1
Ap(j,str2double(C))=-1;
else
Ap(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end
```

○ aIncidenciaEnergia

```
Ap_E(n,m)=0;
Af_E(n,m)=0;
Entra_E(n,m)=0;
Sale_E(n,m)=0;

if OnOff_E_B==1
%
GenerarmatrizdeincidenciaESTRUCTURAFISIC
A(Entra_E/Sale_E)
% DefinirEntradas+
for j=1:n
c=todoF_E(j,1);
if iscellstr(c)==0
c=[c{:}];
Entra_E(j,c)=1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Entra_E(j,str2double(C))=1;
end
end
end
% DefinirSalidas-
for j=1:n
c=todoF_E(j,2);
if iscellstr(c)==0
c=[c{:}];
Sale_E(j,c)=-1;
else
numB=strfind(c,'+');
remain=c;
for i=1:(length(numB{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,'+');
end
Sale_E(j,str2double(C))=-1;
end
end
end


%
GenerarmatrizdeESTRUCTURAPRODUCTIVA(
Af_EyAp_E)

% FUELES(Ponerlesigno+/-alosFueles)

for j=1:n
c=todoP_E(j,1);
if iscellstr(c)==0
c=[c{:}];
```

```
Af_E(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE==1
Af_E(j,str2double(C))=-1;
else
Af_E(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end


% PRODUCTOS(Ponerlesigno+/-
alosProductos)

for j=1:n
c=todoP_E(j,2);
if iscellstr(c)==0
c=[c{:}];
Ap_E(j,c)=1;
else
numBP=strfind(c,'+');
numBN=strfind(c,'-');
remain=c;
SE=0;

for
i=1:(length(numBN{1})+length(numBP{1})+1)
if length(remain{1})>0
[C,remain]=strtok(remain,['+','-']);
[C,parentes]=strtok(C,['[',']']);
if SE==1
Ap_E(j,str2double(C))=-1;
else
Ap_E(j,str2double(C))=1;
end
signal=length(c{1})-length(remain{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end
end
end
end
end

end
```

- **aMatricesEntradasSalidas**

```
% ordenolasentradas
[EntO,orden]=sort(entry(:,1));
EntO=[entry(orden)entrType(orden)];


% Creovectoresnulos
alfa_e(e,m)=0;
Bentr(e,1)=0;
% creomatrizalfa_e+vectorBentr
for i=1:e
alfa_e(i,entry(i))=1;
% Aquíledoyvaloresnumericos
Bentr(i,1)=B(entry(i));
end

% creomatrizdecostesCeyCO2e
Ce(m,1)=0;
CO2e(m,1)=0;
Be(m,1)=0;
for i=1:m
for e2=1:e
if i==EntO(e2,1)
% Aquíledoyvaloresnumericos
Be(i,1)=B(EntO(e2,1));
Ce(i,1)=EntO(e2,2);
CO2e(i,1)=EntO(e2,2);
end
end
end
```

```
% ¡OJO!SEMULTIPLICAPORENTRA
Fe=Entra*Be;
calcCentra

[SalidaExt,orden]=sort(SalidaExt(:,1));
Bs(m,1)=0;
for i=1:m
for s2=1:s
if i==SalidaExt(s2,1)
% Aquíledoyvaloresnumericos
Bs(i,1)=B(SalidaExt(s2,1));
end
end
end
```

○ cFiguales

```
% detectosilasalidafor mapartedelFuel
x_bifurF=[];
alfa_xF=[];
for equip=1:n
for flujos=1:m
if -Sale(equip,flujos)==1
if -
Sale(equip,flujos)==Af(equip,flujos)|Sale(equip,
flujos)==Af(equip,flujos)
% strcat('E',num2str(flujos))

% aquíheidentif
icadolasalidaquecorrespondeaFuelFnumSal
FnumSal=flujos;
c=todoP(equip,1);
numP=strfind(c,'[');
parentes=c;
i=1;

FuelNum=[];

% Aquíidentif icolossubgruposdefueles[F1],[F2]
whilei<(length(numP{1})+1)

[C,parentes]=strtok(parentes,['[',']']);
cruz=strfind(C,'+');

if length(C{1})==1&cruz{1}>0
i=i-1;
else
Fuel(i,1)=C;
prod=C;
% Aquisacolosfuelos(Bi-Bj)
SE=0;
resto=prod;
numBP=strfind(C,'+');
numBN=strfind(C,'-');

if length(numBP{1})>0|length(numBN{1})>0
%
AquícreomimatrizFuelNum=[P1P2]porcadaco
mponente
for
pos=1:(length(numBP{1})+length(numBN{1})+1
)
if length(resto{1})>0
[prod,resto]=strtok(resto,['+','-']);
if SE==1
fuelnum=str2double(strcat('-',prod));
else
fuelnum=str2double(prod);
end
signal=length(C{1})-length(resto{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end


end
FuelNum(pos,i)=fuelnum;
end
else
fuelnum=str2double(prod);
FuelNum(1,i)=fuelnum;
end
% Aquiterminodesacarlosfuelos(Bi-Bj)
end
i=i+1;
end
% FnumSal
x2_bifur=[];
alfa2_x=[];
for i2=1:size(FuelNum,2)
for j2=1:size(FuelNum,1)
if FuelNum(j2,i2)==FnumSal|FuelNum(j2,i2)==-
FnumSal
% identif
icodóndeestáelFueldesalidaehagoP(x)/Q(x).
% Seránsolo2flujos:entrada(+)ysalida(-)
for j3=1:size(FuelNum,1)
if FuelNum(j3,i2)>0
% Aquíledoyvaloresnumericos
P_x=B(FuelNum(j3,i2));
else
Q_x=B(-FuelNum(j3,i2));
```

```
end
end


if P_x==0||Q_x==0
x2_bifur=0;
else
x2_bifur=P_x/Q_x;
end

for j3=1:size(FuelNum,1)
if FuelNum(j3,i2)>0
alfa2_x(1,FuelNum(j3,i2))=1;
else
alfa2_x(1,-FuelNum(j3,i2))=-x2_bifur;
end
end
end
end
end

if size(alfa2_x,2)<size(alfa_xF,2)
alfa2_x(size(alfa2_x,1),size(alfa_xF,2))=0;
elseif
size(alfa_xF,2)<size(alfa2_x,2)&&size(alfa_xF,2
)~=0
alfa_xF(1,size(alfa2_x,2))=0;
end

x_bifurF=[x_bifurF;x2_bifur];
alfa_xF=[alfa_xF;alfa2_x];

end
end
end
end
```

- ## cPiguales

```
% detectocuantosproductoshayparahacer-
>Cp1=Cp2
alfa_xP=[];
x_bifurP=[];

for equip=1:n
c=todoP(equip,2);
numP=strfind(c,'[');
parentes=c;
i=1;

ProductNum=[];

% Aquíidentif
icolossubgruposdeproductos[P1],[P2]
whilei<(length(numP{1})+1)

[C,parentes]=strtok(parentes,['[',']']);
cruz=strfind(C,'+');

if length(C{1})==1&cruz{1}>0
i=i-1;
else
Product(i,1)=C;
prod=C;
% Aquisacolosproductos(Bi-Bj)
SE=0;
resto=prod;
numBP=strfind(C,'+');
numBN=strfind(C,'-');

if length(numBP{1})>0|length(numBN{1})>0
%
AquícreomimatrizProductNum=[P1P2]porcada
componente
for
pos=1:(length(numBP{1})+length(numBN{1})+1
)
if length(resto{1})>0
[prod,resto]=strtok(resto,['+','-']);
if SE==1
% strcat('-E',prod)
productnum=str2double(strcat('-',prod));
else
% strcat('E',prod)
productnum=str2double(prod);
end
signal=length(C{1})-length(resto{1})+1;
for N=1:length(numBN{1});
if signal==(numBN{1}(1,N))
SE=1;
end
end
for N=1:length(numBP{1})
if signal==(numBP{1}(1,N))
SE=0;
end
end

end
ProductNum(pos,i)=productnum;
end
else
% strcat('E',prod)
productnum=str2double(prod);
ProductNum(1,i)=productnum;
end
% Aquiterminodesacarlosproductos(Bi-Bj)
```

```
end
i=i+1;
end
%
SehacreadolamatrizProductNumparaelcompo
nenteequip

%
conseguirelvalordelabifurcacioncp1=cp2b=P(x)
/Q(x)
if i-1>1
% elvalordeP(x)
x2_bifur=0;
alfa2_x=0;

for j2=1:i-1
Pmultip=0;
Pmult=0;

for i2=1:size(ProductNum,1)
% Aquíledoyvaloresnuméricos
if ProductNum(i2,j2)~=0
if ProductNum(i2,j2)>0
Pmult=B(ProductNum(i2,j2));
alfa2_x(j2,ProductNum(i2,j2))=1;
else
Pmult=-B(-ProductNum(i2,1));
alfa2_x(j2,-ProductNum(i2,j2))=-1;
end
Pmultip=Pmultip+Pmult;
end
end
% aquíobtengolaxdelabifurcacion

% ¿EXISTENESOSFLUJOS?

x2_bifur(j2,1)=Pmultip;

end

Pdivide=0;
cPmas=1;
whilePdivide==0
if x2_bifur(cPmas,1)==0
cPmas=cPmas+1;
else
Pdivide=x2_bifur(cPmas,1);
end
if cPmas==(length(x2_bifur)+1)
Pdivide=1;
cPmas=cPmas-1;
end
end
for div=1:length(x2_bifur)
x2_bifur(div,1)=x2_bifur(div,1)/Pdivide;
end

% copiarlasxenlamatrizalfa_xP
for j2=2:i-1
for i2=1:size(ProductNum,1)
if ProductNum(i2,cPmas)~=0
if ProductNum(i2,cPmas)>0
alfa2_x(j2,ProductNum(i2,cPmas))=-
x2_bifur(j2,1);
else
alfa2_x(j2,-
ProductNum(i2,cPmas))=x2_bifur(j2,1);
end
end
end
end
alfa2_x(cPmas,:)=[];
x2_bifur(cPmas,:)=[];

if size(alfa2_x,2)<size(alfa_xP,2)
alfa2_x(size(alfa2_x,1),size(alfa_xP,2))=0;
elseif
size(alfa_xP,2)<size(alfa2_x,2)&&size(alfa_xP,2
)~=0
alfa_xP(1,size(alfa2_x,2))=0;
end

else

x2_bifur=[];
alfa2_x=[];

end

%
Sehacreadolamatrizalfa2_xparaelcomponente
equip

x_bifurP=[x_bifurP;x2_bifur];
alfa_xP=[alfa_xP;alfa2_x];
end
% x_bifurP
% alfa_xP
```

ERANSK.4. ONDORIOAK

Eranskin hau **C Kapitulu**aren aplikazio praktikoa da: termoekonomia oinarrizko software bat garatu da etxebizitzen energia instalazioak ikuskatzeko.

Programaren erabilerak ohiko energia azterketen datu termodinamiko berberak behar ditu (tenperaturak, masa emariak, kontzentrazioak, etab.). Ondorioz, oso tresna erabilgarria da zeinek ez duen datu gehigarririk eskatzen eta, haatik, kostu formakuntza prozesua ulertzeko informazio ezin egokiagoa eskaintzen duen.

Datuekin osagai bakoitzaren eta sistemako fluxuen kostuen kalkulu dinamikoa era sistematikoan egiten da. Orduan hobekuntzarako punturik ahulenak eta kontrolaren optimizaziorako giltzarriak identifika daitezke.

Orain artean, programa Excel-en eta Matlab-en konbinaketa lez dago baina helburura lizentzia beharrik gabeko tresna bat eraikitzea da termoekonomiaren aplikaziorako. Datorren urratsa termoekonomia diagnostikoaren inplementazioarekin bat dator (**D Kapitulua**) zeinek, operazio baldintzaren eta erreferentziaren arteko alderaketaren bitartez, sistemaren jarrera anomaloak identifikatzen dituen, gerta daitezkeen etenaldiak ekidin egiteko eta kostuen penalizazioak saihesteko.

2018

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eman ta zabal zazu

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