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# Development of a methodology for integral energy analysis of industrial processes and plants

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Ya falta menos,

Iñigo Bonilla,

# Résumé

## Resumen

La presente tesis contextualiza el consumo de energía del sector industrial cuyos procesos presentan alta variabilidad productiva y dinamismos en el perfil de consumos. Estos procesos no han sido evaluados tan extensivamente como los continuos y, sin embargo, presentan altos márgenes de eficiencia energética y potenciales de ahorro. Después de un exhaustivo análisis del estado del arte sobre modelado de procesos, se confirma una ausencia de metodologías orientadas a este tipo de procesos (normalmente con alta componente térmica). Basado en las metodologías analizadas y los estudios de mejora de la eficiencia energética de procesos, se plantea una metodología integral (multi escala -operativa, táctica y estratégica- multi nivel -dispositivo, proceso, planta, entorno-) para la identificación, cuantificación y evaluación de medidas de mejora de la eficiencia energética. La metodología propuesta analiza el proceso desde el punto de vista energético y operativo y crea modelos de simulación. Todos los fenómenos y eventos que afectan al proceso en cuestión son identificados y modelados (transcripción de ecuaciones físicas que rigen el fenómeno o parametrización). La metodología se implementa en un caso de estudio con datos reales y se procede a la validación los modelos. De este modo, varios cursos de acción son identificados y analizados en profundidad. Las medidas identificadas son modeladas y evaluadas (energética económica y ecológicamente). Como consecuencia, se obtiene ahorros energéticos de hasta el 50% con periodos de retorno de la inversión inferiores a 24 meses. Finalmente, las capacidades de la metodología, las conclusiones y sus resultados son discutidos y comparados.

## Summary

This thesis contextualises the energy consumption of the industrial sector whose processes show high production variability and dynamism in the consumption profile. These processes have not been evaluated as extensively as the continuous ones, and yet they have high margins of energy efficiency and savings potential. After an exhaustive analysis of the state of the art on process modelling, an absence of methodologies oriented to this type of processes (usually with a high thermal component) is confirmed. Based on the analysed methodologies and on the studies of improvement of the energy efficiency of processes, a comprehensive methodology (multi-scale -operational, tactical and strategic- multi level -device, process, plant, environment-) is proposed for the identification, quantification and evaluation of measures to improve energy efficiency. The proposed methodology analyses the process from the energy and operational point of view and creates simulation models. All phenomena and events which affect the process under evaluation are identified and modelled (transcription of physical equations that govern the phenomenon or parameterisation). The methodology is implemented in a case study with real data and, then, the models are validated. In this way, several courses of action are identified and in-depth analysed. The identified measures are modelled and evaluated (energy economic and ecologically). As a result, energy savings of up to 50% are obtained with PayBacks less than 24 months. Finally, the capabilities of the methodology, the conclusions and their results are discussed and compared.

# Contents

# Glossary and Acronyms

| | |
|---|---|
| **EE** | Energy Efficiency |
| **TE** | Thermal Efficiency |
| **EU** | European Union |
| **EEM** | Energy Efficiency Measure |
| **EEMs** | Energy Efficiency Measures |
| **HPHE** | Heat Pipe Heat Exchanger |
| **ISO** | International Organisation for Standardisation |
| **GHG** | GreenHouse Gas |
| **EII** | Energy Intensive Industries |
| **EnMS** | Energy Management Systems |
| **EA** | Energy Audit |
| **EU ETS** | EU Emissions Trading System |
| **ESCo** | Energy Service Company |
| **EPC** | Energy Performance Contracting |
| **BAT** | Best Available Techniques |
| **BPT** | Best Practice Techniques |
| **EEG** | Energy Efficiency Gap |
| **EIEEP** | European Industrial Energy Efficiency good Practices platform |
| **NEBs** | Non-Energy Benefits |
| **SMEs** | Small and medium enterprises |
| **BEM** | Building Energy Modelling |
| **MPS** | Manufacturing Process Simulation |
| **HVAC** | Heating, Ventilating and Air Conditioning |
| **TBS** | Technical Building Services |
| **PPC** | Production Planning and Control |
| **LCA** | Life Cycle Assessment |
| **KPI** | Key Performance Indicator |
| **LEEC** | Levelized Energy Efficiency Cost |
| **HTP** | Heat Treatment Process |
| **ATTS** | Ageing Time Temperature State |
| **STTS** | Solution Time Temperature State |
| **NCP** | Non-Continuous Process |
| **NG** | Natural Gas |
| **WHRS** | Waste Heat Recovery System |

| | |
|---|---|
| **SPP** | Simple Payback Period |
| **LEEC** | Levelized Energy Efficiency Cost |
| **ROI** | Return Of Investment |
| **CapEx** | capital expenditures |
| **OpEx** | operational expenditures |
| **Cpa** | preliminary activities expenditures |
| **TES** | Total Energy Saved |
| **HES** | Heat Exchanger System |
| **HPHE** | Heat Pipe Heat Exchanger |
| **DMP** | Decision-Making-Process |
| **SF** | Solution Furnace |
| **AF** | Ageing Furnace |
| **WHRT** | Waste Heat Recovery Technology |
| **DES** | Discrete Event Simulation |
| **CS** | Continuous Simulation |
| **FEM** | Finite Element Method |
| **GUI** | Graphical User Interface |

# 1

# Introduction and Background

**Summary**

*The aim of this chapter is to introduce the background around the energy efficiency in industry. Besides, based on the situation of the industrial energy efficiency management and the context of the manufacturing process, and after the explanation of the Energy Efficiency Potential, the motivation of this work, its research objectives and its structure are explained. The research objectives and the scope are correlated to the general motivation.*

## 1.1 The role of Energy Efficiency

The energy consumption, the environment and the quality of life are closely linked terms. Energy consumption is inherently coupled with quality of life and population growth [1]. However, this growth affects air pollution, GreenHouse Gas (GHG) emissions and energy dependence. During the last decades, Europe has successfully eliminated the most visible and immediately harmful pollutants due to their fast catastrophic effects. Nowadays, the GHGs emissions and the energy dependence still mean a risk to the European economy and style of life. In 2016, the European Union (EU) needed to import slightly over half (53.6%) of the energy it consumed. Since 2004, energy dependency in the EU has been above 50% with a highest rate recorded in 2008 (54.5%). In 2006, the energy consumption in the EU reached around 1825 Mtoe [2]. During the period of 2005-2014, final energy consumption decreased by 11% (1.3% annually).

Therefore, the EU is looking for a clean, sustainable, decarbonised and competitive energy system [3]. The European Council, in order to preserve the environment and to promote sustainable consumption and production, set three key targets for the year 2030. These targets are gathered in the 2030 Framework for Climate and Energy [4]:

- At least 40% cuts in GHG emissions (from 1990 levels)
- At least 27% share for renewable energy (in comparison with 2005 levels)
- At least 27% improvement in energy efficiency (in comparison with 2005 levels)

These targets have been tracked and adapted, and in the case of the energy efficiency improvement [4], recently incremented to 32.5%. energy efficiency is one of the most important pillars of a sustainable energy policy and a key component of climate change mitigation strategies. energy efficiency is a key factor to ensure a safe, reliable, affordable and sustainable energy system for the future as well as to boost industrial competitiveness, create jobs, reduce energy bills, help tackle energy poverty and improve air quality. The main sectors of energy consumption in the EU are: Transport, electric generation and the industrial sector, which in Europe accounts for 35% of the total energy consumption [5]. Success in this aspect will depend largely on industrial energy efficiency .

The concept of efficiency, according to the International Organisation for Standardisation (ISO) norm; ISO 17743:2015 or ISO 13273-1:2015, means *“ratio or other quantitative relationship between an output of performance, service, goods, or energy and an input of energy”* [6]. In this regard, the energy efficiency concept may be interpreted as *"using less energy to provide the same service"* , or *“increasing the production at equal consumption”.* Therefore, several methods or operational changes in many activities can achieve a reduction of energy consumption, at equal production, and/or the increasing of the production rate. Comparing to renewable energy integration, energy efficiency exhibits the best performance in terms of economic efficiency (less cost of the traded energy) and environmental sustainability (greater replacement of fossil fuels) [8]. Investing in technological EEM, such as introduction of energy-efficiency technologies, adoption of technology for intelligently control energy uses, as well as in management EEM, such as making operational improvements, can reduce energy consumption by 50% and by 10–20%, respectively [9]. Besides, energy efficiency makes energy more affordable by lowering the implicit price of energy. Subsequently, lower pricing means that a lot more population has access to energy.

The greenhouse effect and global warming, notwithstanding all of the controversy that surrounds the term, is not a scientifically controversial subject. In fact, it is one of the best, most well-established theories in the atmospheric sciences. The European governmental policies go towards providing economic advantages to industrial companies which reduce their greenhouse footprints [10, 11]. EEMs are the technical mechanism in order to reach the energy efficiency at any sector. These measures provide better economic results, according to CO2 prevention, than the decarbonisation of the electric generation [12, 13, 14]. Indeed, energy efficiency is the most cost effective way to reduce emissions, improving energy security and competitiveness, making energy consumption more affordable for consumers, as well as creating employment [15]. However, EEM still have to overcome and asses several problems [16]. Furnaces or heat equipment are usually fed by fossil combustible in the industrial sector. The comprehensive decarbonisation of the electric generation and grid, which means that the electric energy is generated free of CO2, will not reduce the GHG related to these industrial processes. The industrial sector encompasses 21% of 2010 global GHG from direct emissions[17], while electric generation for industry contributes with another 11% of 2010 global GHG from direct emissions, as depicted in Figure 1.1. Therefore, energy efficiency is essential in order to mitigate this GHG emission source.

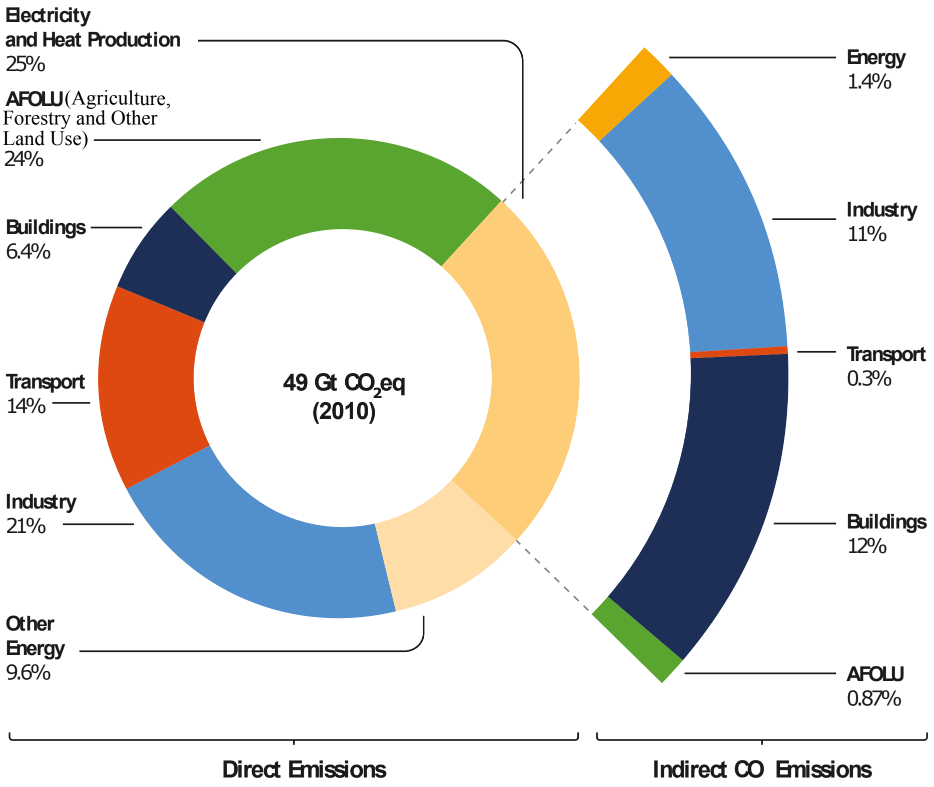


**Figure 1.1** – GHG Emissions by Economic Sectors[17].

Energy efficiency and decarbonisation go together in EU government policies, projects and programs [18]. At international level, policies such as the EU Emissions Trading System (EU ETS) are highlighted. EU ETS is a market-based mechanism which creates an incentive for Energy Intensive Industries (EII) to reduce their emission of GHG such as CO2 [19]. On the other hand, country policies, such as Voluntary Agreement (VA) or the Programme for Improving the energy efficiency in EII, in Sweden [20, 21], the Climate Change Agreements in UK [22], or the $13^{rd}$ Five-year plans in China [23] related to EII are moving the industrial production to a more carbon-neutral and competitive society. The primary aims of these policies are to be aware of energy consumption and energy efficiency level as well as to eliminate barriers. These policies will lead to improve the industrial competitiveness and to address the global climate policy framework. Currently, these policy measures show good results, however, there is margin of improvement [24]. These kind of regulatory measures have forced greater pressure and influence on corporate behavioural changes than market-based instruments, which lack of strong and economic viability from the industrial managers' perspective.

The energy dependency of external sources (such as fuel oil, natural gas, nuclear fuel), as well as the access to energy, limits and makes the industry users conditional on new investments, due to the hypothetical insecurity of the energy price or to energy supply problems [25]. Reducing the consumption of the industry sector may limit this effect. Besides, this dependency generates a high annual variability in non-householders energy prices. The price of electricity is increasing in the long term (increment about 10% in last decade) and the fuel prices presents high variability, such as the case of natural gas which shows variations up to 25% for the same period.

The EU low-carbon economy roadmap suggests that by 2050, the EU should cut GHG emissions to 80% below 1990 levels [3]. In the industrial context, it is expected that EII could cut thir emissions by more than 80%. For this end, several carbon markets have been created. The carbon emissions trading is a form of emissions trading that targets the GHG. The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing GHG emissions cost-effectively [11].

### 1.1.1 Energy consumption and cost of energy

As it was mentioned before, industrial processes are responsible for one-third of global energy demand as well as CO2 emissions [4]. In particular, over 30% of the total industrial primary energy consumption is attributed to the iron and steel, cement and refining industries. EII are those whose production costs are directly related to the energy consumption cost. Small and medium enterprises (SMEs) and large enterprises may be considered as EII. Industrial companies with high-temperature processes or with high-electric intensity level belong to this term. The industry sector in Europe reached a 35% of total final energy consumption in 2014[4], among which the EII stand out. EII represent half of the total final energy consumption in the industrial sector. Whereas the buildings sector involves a 38% of the total final energy consumption, industry sector is concentrated, in a way that a group of measures or initiatives may affect to overall energy reduction, according to energy efficiency goals, to a greater extent [26]. EII are facing challenges from both innovation and technical perspectives due to the large scale of the facilities, the character of their global markets and the potentially high reduction of production costs [27].

For that reason, the European Commission in Research & Innovation is currently focusing efforts on policy initiatives related to energy intensive processes and industries and research projects. As an example, some related European projects, such as RESLAG, EDEFU, ETEKINA, TASIO, FOUNDENERGY, H · REII, MEMAN, EU-MERCI (FP7 and H2020 European funded projects) may be highlighted. In this regard, there are associations which promote and incentive by public-private partnership the energy efficiency in industry, such as SPIRE association. The main topic in these projects is *"energy and material efficiency in production or manufacturing processes"*, focusing each one on different subjects, such as heat recovery, heat reuse, electric generation or co-generation, furnace improvements, energy efficiency measures, etc. The mission of these projects and associations is to ensure the development of enabling technologies and best practices along all the stages of large scale existing value chain productions that will contribute to an efficient process industry.

The cost of energy depends, in the industrial environment, on the kind of end-process: Electric or fuel-fired devices. The electrical cost depends on the way this energy has been obtained. There are several ways to obtain electrical energy from alternative energies, such as Solar Photo-Voltaic, Solar Thermal, Fuel Cell, Geothermal, Biomass, Wind; to conventional, such as Diesel or Natural Gas engines, Combined Cycle, Coal or Nuclear. This cost varies depending on the diverse technology involved in the process [12]. The final energy mix and the electrical market will establish the final price of electricity in each country. The thermal energy is usually obtained by the combustion of any fuel or by electricity by means of the Joule effect or the electromagnetic induction. The cost of thermal energy depends on the cost of the source (fuel or electricity) and the efficiency of the technology used to obtain this heat. Heating devices, such as boilers; natural gas furnaces; induction, resistor or radiation heaters; steam generators, coal used kilns, are common in manufacturing industry to process-manufacturing or building-heating purposes.

In addition to the intrinsic price of energy, the monetary and social cost of the GHG emissions must be taken into account. To make the Kyoto protocol and the EU GHG reduction objective effective, industries which can not get by without fossil fuels will have to implement carbon capture and storage systems in the long-term future. For these reasons, and to reach the objective, it may be expected that the "carbon cost" grows to high levels [28]. The monetary cost is assessed by the EU ETS commented before. The social cost affects the social opinion and consumers, due to the raising awareness about climate change and non environmentally harmful activities or products. Anyway, these factors must be taken into account for future economic analysis.

### 1.1.2 The Energy Efficiency Potential in Industrial Environment

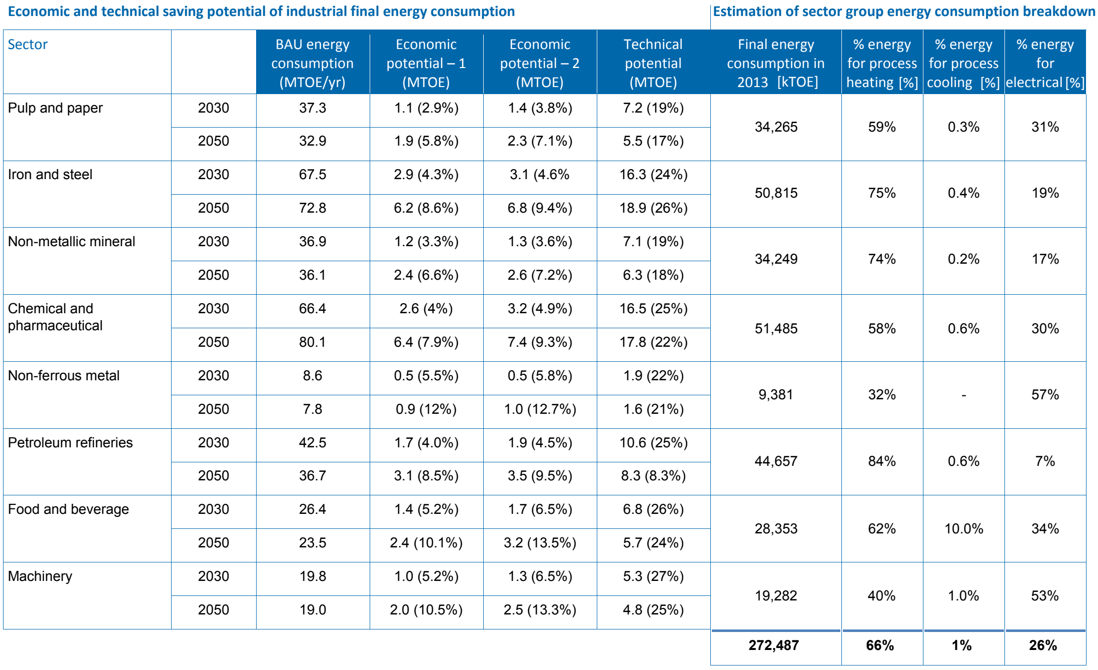
In the industry sector, and, specifically, in the manufacturing sector, energy is considered as a loss when it does not provide any contribution to the value chain. Energy losses in manufacturing processes are usually generated as thermal losses; it is the last form that energy takes before to be a waste. These losses are usually accepted as an inevitable charge. Processes which entail a state change, like fusion or boiling process, or which require high temperatures to achieve a result, such as chemistry, pulp and paper, cement, heat treatments, are used to be treated as EII. These processes require high quantities of energy and their specific energy consumption is elevated. As a consequence of these processes, high amounts of heat are generated and being irretrievable, ultimately, dropped to the environment.

The EU industry sector has a high potential for energy efficiency [29], as it is depicted in Figure 1.2. In the year 2013, the final energy consumption reached 272 Mtoe. More than the 26% of this final energy could have been saved with the 2013 existing technology. The hypothetical potential is the maximum level of energy efficiency that an industry could reach implementing all the available technological measures. The difference between technical potential frame and the first (-1) and second (-2) economic potential frames rests in the break-even point where the total investment of a measure is recovered. The first approach satisfies a 2-year Simple Payback Period, while the second satisfies a 5-year Simple Payback Period. Despite this high potential, these EEM are not being introduced in the industry. In the manufacturing industry environment, it is evidenced that an increasing level of corporate energy efficiency is directly related to an improved corporate financial performance [30].

The current trends in energy policy and in global energy consumption may result in higher energy prices and, therefore, further increase of the need for industrial energy efficiency [31]. Therefore, the energy efficiency must become a central research to reduce energy bills, decarbonisation and air pollution as well as to increase energy security and energy access. This energy efficiency potential for improving in these areas is one that every country, industry or inhabitant has in abundance and at their disposal.

The energy efficiency potential may be defined as the theoretical capacity of improvement in the energy consumption. In the manufacturing processes it is commonly represented in terms of reduction of specific energy in produced unit or in terms of energy saved. Regarding the EII, there are a good range of economically viable energy saving opportunities [29] in the different kinds of industries (as it is shown in Figure 1.2 in Section 1.1.2). Nevertheless, the economic potential and the energy efficiency application are still low. There are several barriers that difficult the transition from theory to practice. In Europe, the political frame is changing in order to overcome these barriers.

The whole industrial sector can be categorised into three different industry sorts:



Economic and technical saving potential of industrial final energy consumption

Estimation of sector group energy consumption breakdown

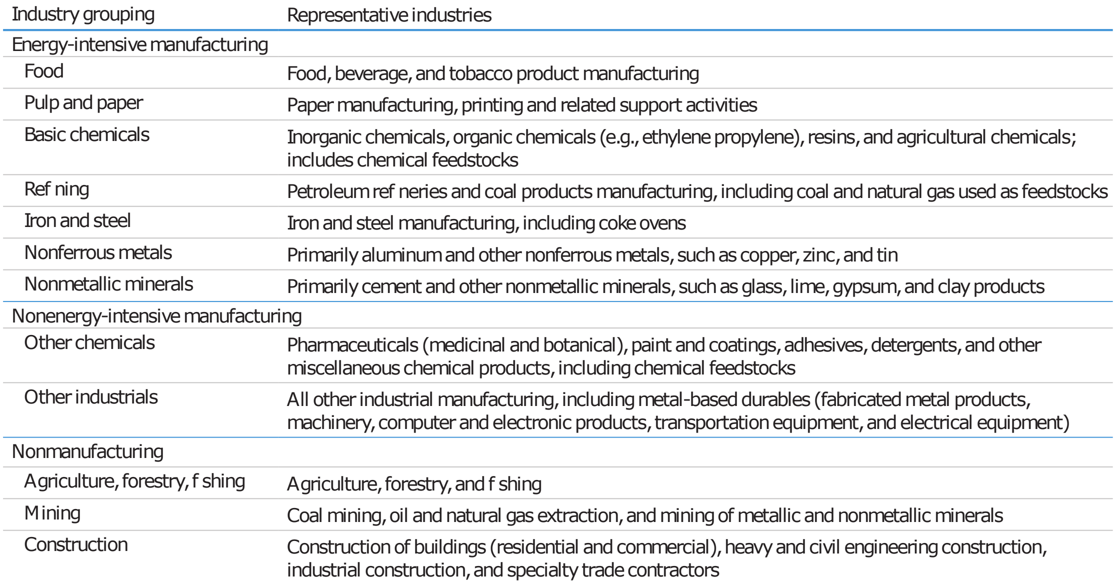
| Sector | | BAU energy consumption (MTOE/yr) | Economic potential – 1 (MTOE) | Economic potential – 2 (MTOE) | Technical potential (MTOE) | Final energy consumption in 2013 [kTOE] | % energy for process heating [%] | % energy for process cooling [%] | % energy for electrical [%] |
|---|---|---|---|---|---|---|---|---|---|
| Pulp and paper | 2030 | 37.3 | 1.1 (2.9%) | 1.4 (3.8%) | 7.2 (19%) | 34,265 | 59% | 0.3% | 31% |
| | 2050 | 32.9 | 1.9 (5.8%) | 2.3 (7.1%) | 5.5 (17%) | | | | |
| Iron and steel | 2030 | 67.5 | 2.9 (4.3%) | 3.1 (4.6% | 16.3 (24%) | 50,815 | 75% | 0.4% | 19% |
| | 2050 | 72.8 | 6.2 (8.6%) | 6.8 (9.4%) | 18.9 (26%) | | | | |
| Non-metallic mineral | 2030 | 36.9 | 1.2 (3.3%) | 1.3 (3.6%) | 7.1 (19%) | 34,249 | 74% | 0.2% | 17% |
| | 2050 | 36.1 | 2.4 (6.6%) | 2.6 (7.2%) | 6.3 (18%) | | | | |
| Chemical and pharmaceutical | 2030 | 66.4 | 2.6 (4%) | 3.2 (4.9%) | 16.5 (25%) | 51,485 | 58% | 0.6% | 30% |
| | 2050 | 80.1 | 6.4 (7.9%) | 7.4 (9.3%) | 17.8 (22%) | | | | |
| Non-ferrous metal | 2030 | 8.6 | 0.5 (5.5%) | 0.5 (5.8%) | 1.9 (22%) | 9,381 | 32% | - | 57% |
| | 2050 | 7.8 | 0.9 (12%) | 1.0 (12.7%) | 1.6 (21%) | | | | |
| Petroleum refineries | 2030 | 42.5 | 1.7 (4.0%) | 1.9 (4.5%) | 10.6 (25%) | 44,657 | 84% | 0.6% | 7% |
| | 2050 | 36.7 | 3.1 (8.5%) | 3.5 (9.5%) | 8.3 (8.3%) | | | | |
| Food and beverage | 2030 | 26.4 | 1.4 (5.2%) | 1.7 (6.5%) | 6.8 (26%) | 28,353 | 62% | 10.0% | 34% |
| | 2050 | 23.5 | 2.4 (10.1%) | 3.2 (13.5%) | 5.7 (24%) | | | | |
| Machinery | 2030 | 19.8 | 1.0 (5.2%) | 1.3 (6.5%) | 5.3 (27%) | 19,282 | 40% | 1.0% | 53% |
| | 2050 | 19.0 | 2.0 (10.5%) | 2.5 (13.3%) | 4.8 (25%) | | | | |
| | | | | | | **272,487** | **66%** | **1%** | **26%** |

**Figure 1.2 –** Saving potential and energy consumption by sector, adapted from [29].

Energy-intensive manufacturing, non-energy-intensive manufacturing, and non-manufacturing, which consume about 54% of the world's total delivered energy [32, 33]. The industry grouping and the most representative industries are represented in Figure 1.3.

The manufacturing sector comprises both non-intensive and intensive energy groups. However, the processes developed by each group or, even, by each representative industry differ significantly. The manufacturing is, by definition, "the process of converting raw material into finished useful products". In this process different types of machines, tools and devices are employed to produce the finished product. These machines, tools and devices are responsible for the energy consumption of the process. The processes or sectors where the final product cost has high dependence on the energy cost may be called energy-intensive processes. The processes within these groups are varied in many aspects, such as in raw material, kind of material, kind of energy required, way to obtain this energy, dynamic behaviour and way of production.

From the way of production point of view (or the consumption profile point of view) the different processes may be distinguished between continuous and non-continuous. The non-continuous processes (also called as batch processes) involve the processing of bulk material in batches through each stage of the desired process. Processing of subsequent batches must wait until the current batch is finished. The continuous processing involves moving one work unit at a time between each stage of the process with no breaks in time, sequence, substance or extent. In the halfway point of the previous definitions the semi-continuous processes combine continuous features with batch features.



| Industry grouping | Representative industries |
|---|---|
| Energy-intensive manufacturing | |
| Food | Food, beverage, and tobacco product manufacturing |
| Pulp and paper | Paper manufacturing, printing and related support activities |
| Basic chemicals | Inorganic chemicals, organic chemicals (e.g., ethylene propylene), resins, and agricultural chemicals; includes chemical feedstocks |
| Refining | Petroleum refineries and coal products manufacturing, including coal and natural gas used as feedstocks |
| Iron and steel | Iron and steel manufacturing, including coke ovens |
| Nonferrous metals | Primarily aluminum and other nonferrous metals, such as copper, zinc, and tin |
| Nonmetallic minerals | Primarily cement and other nonmetallic minerals, such as glass, lime, gypsum, and clay products |
| Nonenergy-intensive manufacturing | |
| Other chemicals | Pharmaceuticals (medicinal and botanical), paint and coatings, adhesives, detergents, and other miscellaneous chemical products, including chemical feedstocks |
| Other industrials | All other industrial manufacturing, including metal-based durables (fabricated metal products, machinery, computer and electronic products, transportation equipment, and electrical equipment) |
| Nonmanufacturing | |
| Agriculture, forestry, fishing | Agriculture, forestry, and fishing |
| Mining | Coal mining, oil and natural gas extraction, and mining of metallic and nonmetallic minerals |
| Construction | Construction of buildings (residential and commercial), heavy and civil engineering construction, industrial construction, and specialty trade contractors |

**Figure 1.3 –** World industrial sector: Groupings and representative industries [32].

Continuous operation seems to be the most efficient method compared to other operation conditions because the process does not have any down-time (switch-on time, transitory, switch off time, preparation, etc.). Nevertheless, the maintenance of this kind of process must be more accurate and specific failures may affect to a greater extent to the production.

#### 1.1.2.1 The Energy Efficiency Gap

The Energy Efficiency Gap (EEG), also known as Energy Gap, is often referred to the discrepancy between apparent optimal and actual implementation of the EEMs. This paradigm has been analysed for decades [34, 35]. Jaffe et al. identified three scenarios for the industrial energy efficiency: the hypothetical potential, the technologist's economic potential and the economist's economic potential.

The hypothetical potential is the maximum level of energy efficiency that an industry could reach by means of implementing the entire EEMs available with current technology (Figure 1.4: Technical Potential). The difference between hypothetical potential-frame and the technologist's economic potential-frame rests in the break-even point, where the total benefit of a measure tends towards zero. After that, hypothetical potential, economist's and technologist's potentials differ in their benefit range where a measure is accepted due to several economic factors, such as market failures or investment market risk. The technologist's economic potential is delimited by techno-economic concepts. The technologist's economic potential could be achieved by eliminating non-market failures in the hypothesis of a "perfect" energy efficiency technology market. Non-market-failure justifications of the EEG consist of, essentially, explaining why the observed behaviour is optimal from the point of view of individual energy agents [36]. A report submitted by ICF Consulting Limited [29] confirms that there is high economic and technological potential for energy efficiency, as it was shown in Figure 1.2 in Section 1.1. This study shows two perspectives for the economic potential: a 2-year simple payback period and a 5-year simple payback period.

This EEG is generated as a sum of the energy technology gap and the management practice gap [37]. The first one includes the potential for improving energy efficiency through more efficient technologies, meanwhile the management practices gap includes modifications in the working way of the entire system and, therefore, the technology related to its specific context or system (Figure 1.4 left). The authors establish that the extended energy efficiency potential, which includes energy efficiency management practices, is greater than the technical potential. However, this difference may vary widely among industrial companies.

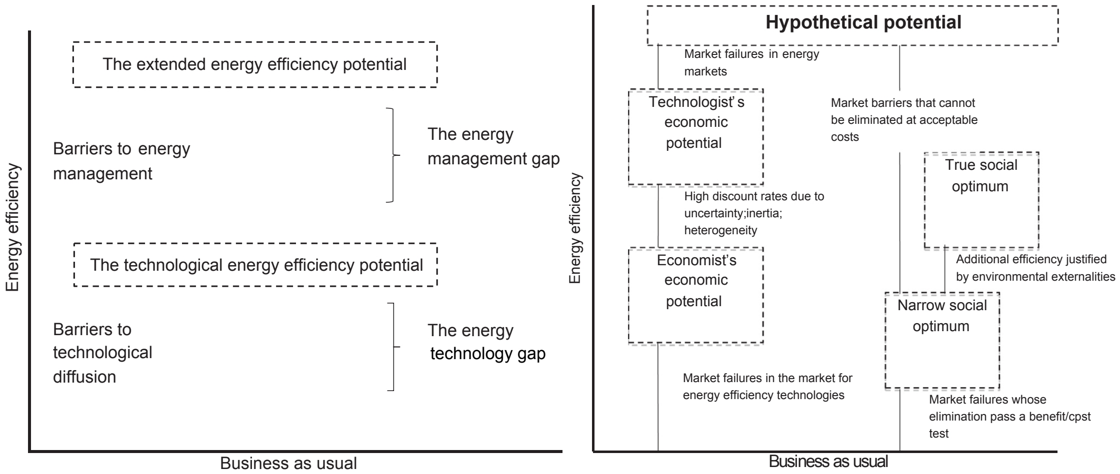


**Figure 1.4** – The extended EEG and the different potentials for energy efficiency [38].

This EEG is extensively analysed in Gerarden work [16]. The authors split the potential explanations for the EEG into three categories: Market failures, behavioural effects and macro-modelling failures. The potential market failure explanations include: Information problems, energy market failures, capital market failures and innovation market failures. The potential behavioural explanations, as it is concluded in Gerarden et al. [16], include: Inattentiveness and salience issues; myopia and short sightedness; bounded rationality and heuristic decision-making; prospect theory and reference-point phenomena as well as systematically biased beliefs. These two categories are mainly influenced by energy policies and industrial managers behaviour. The last category is oriented to the energy potential itself.

There is evidence to think that incorrect assumptions or errors in modelling extrapolation may overestimate the EEG. The potential modelling failure has fallen under the responsibility of researchers and technology suppliers. The provided solutions or the calculated gap is not as high as predicted. This section includes unobserved or understated costs of adoption; ignored product attributes; heterogeneity (across potential adopters) in benefits and costs of adoption; use of incorrect discount rates; and uncertainty, irreversibility as well as option value.

This part is biased by the high heterogeneity of the EEMs. The proposed measures for several case studies are extrapolated to the entire environment. The proposed specific EEM may not be perfectly fitted to the specific situation or scenario, generating deviations among the predicted and the post-EEM energy savings. The option value, i.e. the net benefit of delaying an investment even when the investment's net present value is positive, is a general feature of dynamic optimisation problems with uncertainty, irreversible and large investments as well as timing flexibility [16, 39]. This element is subjected to the anticipated benefit uncertainty regarding the reduction of future energy-bill prices or the savings provided by technological measures. In particular, it depends on how fast the prices of energy and efficiency technologies are changing over the time. However, in large industrial enterprises energy contracts are signed for a long time period, reducing the impact of this uncertainty.

In conclusion, while there has been significant improvement in energy efficiency in recent years, cost-effective energy efficiency options still remain. In this sense, despite the fact of theoretically being economically viable, several barriers that inhibit the implementation of the EEMs still persist.

#### 1.1.2.2 The decision-making process: Barriers and drivers

The definition of barrier proposed by Sorrel et al. [40] claims that: “A barrier is a postulated mechanism that inhibits investment in technologies that are both energy efficient and (apparently) economically efficient”. Several authors have the same concept for barrier [41, 42, 43]. The "driver" concept generates doubt or discussion, however it may be accepted as a force or mechanism to support the adoption of EEMs or to overcome a specific barrier [42]. In the end, the barriers and carriers of the EEM affect and determine the decision-making process. Therefore, the barriers and carriers taxonomy, presented at Table 1.1, compiles the different theoretical and empirical studies. These drivers and barriers affect the decision-making process of an EEM hindering the implementation and adaptation of the measure at the analysis stage.

Table 1.1 – Taxonomy of barriers and drivers proposed by Trianni et al.[18]

| Categories | Drivers |
|---|---|
| **Regulatory Internal** | - Long-term energy strategy |
| | - Willingness to compete |
| | - Green image |
| | - Voluntary agreements |
| **Regulatory External** | - Clarity of information |
| | - External energy audit/submetering |
| | - Increasing energy tariffs |
| | - Efficiency due to legal restrictions |
| | - Technological appeal |
| | - Trustworthiness of information |
| **Economic Internal** | - Cost reduction from lower energy use |
| | - Information about real costs |
| **Economic External** | - Management support |
| | - Public investment subsidies |
| | - Private financing |
| **Informative Internal** | - Management with ambitions |
| | - Staff with real ambitions |
| | - Knowledge of non-energy benefits |
| **Informative External** | - External cooperation |
| | - Availability of information |
| | - Awareness |
| **Vocational training Int.** | - Programs of education and training |
| **Vocational training Ext.** | - Technical support |

| Categories | Barriers |
|---|---|
| **Technology-related** | - Technologies not adequate |
| | - Technologies not available |
| **Information-related** | - Lack of information on costs and benefits |
| | - Information not clear by technology providers |
| | - Trustworthiness of the information source |
| **Economic** | - Information issues on energy contracts |
| | - Low capital availability |
| | - Investment costs |
| | - External risks |
| | - Intervention not sufficiently profitable |
| | - Intervention-related risks |
| **Behavioural** | - Hidden costs |
| | - Other priorities |
| | - Lack of sharing the objectives |
| | - Lack of interest in energy-efficiency interventions |
| | - Imperfect evaluation criteria |
| **Organisational** | - Inertia |
| | - Lack of time |
| | - Divergent interests |
| | - Lack of internal control |
| | - Complex decision chain |
| **Competence-related** | - Low status of energy efficiency |
| | - Implementing the interventions |
| | - Identifying the inefficiencies |
| | - Identifying the opportunities |
| **Awareness** | - Difficulty in gathering external skills |
| | - Lack of awareness |

Following the classification proposed by Trianni et al. [42, 18] the decision-making process may be divided in six steps. The six identified steps are: Awareness, needs and opportunity identification, technology identification, planning, financial and economic analysis, and installation, startup, and training. Each barrier category affects each step in a different way. The highest resistance for adopting an EEM is found in the first step. In the next steps this resistance has a progressive decrease. The economic reason has practically no repercussion in the first four steps, affecting only to sustainability analysis. The mind and management causes seem to affect the first step of the decision-making process, hampering the energy efficiency process and inhibiting the evaluation or recognition of energy efficiency solutions.

The identified barriers that affect the industrial environment must be overcome by the different stakeholders which are involved in the energy efficiency process by promoting the drivers. The principal stakeholders that affect the drivers' attainment are the governmental bodies. Besides, other entities, among which stand out the technology suppliers or manufacturers, are responsible for promoting each category of barriers (regulatory, economic, informative and vocational training). In this sense, the authors argue that the role of stakeholders which support SMEs through providing them vocational training drivers is really crucial, as they can most effectively remove the barriers affecting the awareness and knowledge of needs and opportunities. Beyond economic and financial barriers, the supply chain of technologies, provided by technology suppliers and manufacturers, is identified as critical for the adoption of EEMs by providing both technology, information and competences for the manufacturing companies. These agents seem to be an important future element to present the benefits of the EEMs to the industrial enterprises.

However, these barriers and drivers may be interpreted from an industrial manufacturing point of view. Thiede [44] has proposed an obstacle-requirement classification with a focus on the energy efficiency for the two principal agents, industrial and scientific, involved in an EEM. Thiede's classification simplifies the Barrier-Drivers classification [42] by reducing the number of agents, and it also links the industrial demand to the industrial and technological challenges. The obstacles make reaching the excellence in energy efficiency impossible. Meanwhile, the requirements try to overcome them and ease the introduction of EEMs. Therefore, from the industrial perspective, the author identifies economic obstacles, such as small cost savings with a long amortisation period and lack of capital; organisational obstacles, such as lack of resources for EEMs, lack of responsibility in the consideration of the consumption, low transparency regarding the energy consumption; awareness and behavioural obstacles, such as hypothetical negative influence on production or lack of knowledge on energy efficiency technologies; and technology obstacles, such as the transferability of the EEM to their specific process. The main industry task, i.e. keeping on producing, is apparently confronted with the resolution of these obstacles. Against this mindset, the product and energy management oriented to energy efficiency may allow to take a leap in competitiveness in the manufacturing market.

In order to overcome these problems, and following the requirements distinguished by Thiede related to the industrial and scientific environment, the identified requirements demanded from the industrial perspective are the following:

- Considering the energy efficiency as a part of the manufacturing process.
- Breaking-down the complex energy flow to simple sub-tasks in order to control them easily.
- Easing and providing the main consumption drivers.
- Evaluating EEMs on different levels within one solution.
- Calculating realistically the key figures in the decision-making process.

The proposed requirements affect one or several obstacles.

On the other hand, the scientific or technical perspective, Thiede [44] extends and completes the list of requirements. These requirements, which guide the way of working of Thiede's procedure to reach the energy efficiency, are oriented to the comprehension of the process as well as to the modelling of the process. The main requirements demanded to the scientific perspective are the following:

- The extension of the diverse fields (economic, environmental, energy, etc.) into a holistic one for the process comprehension.
- The comprehension of the factory system as a whole.
- The dynamic treatment of relevant input and output flows.
- The evaluation of each step in the production process chain both individually and as a whole.
- The introduction of a Life-Cycle perspective.
- The inclusion of multi-objective evaluation tools for the EEMs implementation.

Therefore, the proposed requirements are targeted to provide a holistic point of view of the processes and plants, to totally comprehend of the energy and material flows as well as to understand the involved agents of the process chain. This analysis provides a technical point of view, in contrast to the policy-oriented point of view of Trianni et al. [42] classification.

#### 1.1.2.3 Non Energy Benefits

Other kind of benefits which are not always taken into account either by industrial managers, or many researcher teams, are the benefits that are not directly linked to the energy consumption and cost [45]. Industrial energy efficiency is highlighted as an important means to reach climate and energy targets. Moreover, energy efficiency has other positive side effects as well: The so-called Non-Energy Benefits (NEBs) [46]. EEMs in industry could yield a number of outcomes beyond energy and energy cost savings, for instance, productivity increase, product quality improvement, waste reduction and maintenance minimisation [47]. These outcomes do not only generate benefit in the participant of the EEMs (e.g. reduced O&M costs or safety improvement), but also generate societal benefits (e.g. health care cost savings or reduced reliance on fossil fuels) and utility benefits (e.g. energy grid saturation or peaks). Evidence suggests that NEBs are a nontrivial component of the total benefits of energy efficiency [45]. However, the uncertainty of the NEBs estimates must be addressed in order to account for the real value of energy efficiency programs and EEMs true impact.

### 1.1.3 Manufacturing process

A manufacturing process transforms raw material or previously processed objects to products by means of a process which requires labour and some equipment. In general, this process requires energy in order to provide the equipment (machines) functioning or directly to proceed to the transformation of the raw material [48]. Current trends in manufacturing aim to reduce costs and increase sustainability without negatively affecting the yield of finished products, therefore maintaining or improving profits [49]. Manufacturing processes and systems involve complex interactions between material resources, water, compressed air, heat and energy, all of which is dependent on the process and state as well as control and operation [9].

#### 1.1.3.1 Non-continuous processes

The manufacturing processes may be split into five environments (as shown in 1.5): (i) repetitive processes, in which the production lines turn out the same item; (ii) discrete, in which the production lines range from few setups and changeovers to frequent setups and changeovers; (iii) job-shop processes, in which the production lines are split into production areas; (iv) batch processes, where the products are made as specified groups or amounts, within a time frame; and (v) continuous processes, in which the production line creates a product continuously in motion. Repetitive, job-shop, discrete and batch processes may be considered Non-Continuous Processes.

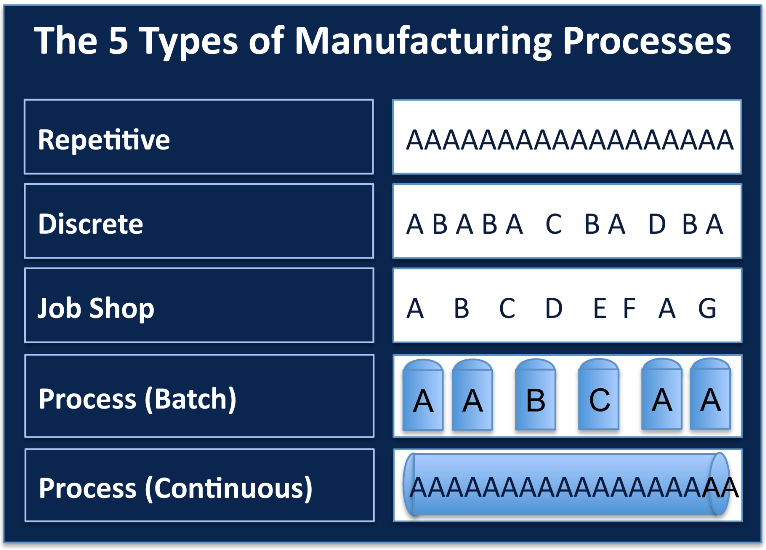


**Figure 1.5** – The 5 Types of Manufacturing Processes [50].

On the one hand, some manufacturing systems are dynamic, with states which change at discrete point in time, for instance, the non-continuous nature of the energy and material flows of the die-casting processes, the production input times and batch sizes. But on the other, some processes present an elevated continuity in the energy and material flows. Besides, hybrid configurations of manufacturing systems are present in the industrial environment (occasionally called semi-continuous).

Manufacturers most often prefer continuous type of process due to the lower cost attributed to a repetitive process, and are widely employed in the manufacture of chemical products, drugs and glass, as well as in the process of crude refining. In cases of low uncertainty and constant fixed production flow, the continuous processes present better economic-production results. However, the adaptability of the continuous processes to high variations is smaller and the initial process launch (stationary), the setup and the changeover activity are more complex. In general, continuous processes are limited to those in which the production materials are gases, liquids, powders, or slurries [50].

#### 1.1.3.2 Thermal processes

Thermal Non-Continuous Processes are defined as processes whose energy and material flows present non-constant profiles or even time-discontinuities and whose main energy resource is dedicated to increase the temperature of some raw material, product or item to obtain a certain product or objective. Within this kind of processes, those which are fed by "fluid" fuels (such as natural gas, liquid fossil fuels, biomethane or other biogas) show dynamic profiles and more complex controlling, attributed to intrinsic combustion features, comparing to the those which are not based on a flow, such as heat processes fed by an electric source (electromagnetic induction heat, resistive heat and radiation heat).

The dynamics of the flow associated to the heat generation (combustion-burning), in combination with the dynamical behaviour of the Non-Continuous Processes make the analysis of the Non-Continuous Thermal Processes heavily reliant on real process simulation. Without the capacity of this kind of modelling, the assessment of the energy efficiency and the study of new hypothesis become a non accurate procedure.

The Thermal Efficiency (TE) of the thermal processes in which the main heating equipment is fed by fuel, such as furnaces, ovens, melters and heaters, is defined as the ratio of the heat delivered to a material and the supplied energy to the heating equipment (Useful output divided by Gross fuel input in Figure 1.6). For most heating equipment, a large amount of the supplied heat is wasted in form of exhaust or flue gases, which harms this TE. These losses (the losses derived from the exhaust mass flow) depend on various factors which are associated with the design and the specific operation of the heating equipment. But also, working on non-design conditions of operation and other events that affect the correct working of these devices have a negatively impact on the TE. The TE of a fuel-fed device is limited by the temperature of the exhaust as shown in Figure 1.6- Left). In some cases, the TE is very near to the expected design efficiency. However, there may be opportunities of improvement.

The losses generated as unavoidable part of the operation of any process subordinate the efficiency. In this regard, the TE of well-operated electric-fed heating equipment presents higher TE when comparing to the fuel-fed (based on combustion). This last kind of heating devices make use of air and fuel, which are mixed and burned to generate heat. This heat is transferred to the heating device and its load. The spent combustion gases are removed (expelled) from the heating device via a flue or stack to make room for a fresh charge of combustion gases.

Therefore, the TE of a fuel-fed device is limited by the temperature of the exhaust, as shown in Figure 1.6- Right). It means that for low-temperature exhaust gases (around 240°C) the TE is limited to be below 80% for a perfect combustion and 0% of excess air, where as for very-high-temperature of the exhaust gases (around 1650°C) the TE is limited to be below 17% This heat loss, which is not present in electric-fed devices, is the greatest source of heat loss in the process. Besides, this heat loss is commonly increased by means of high excess air ratios. Other non-productive heat sinks are the heat storage, or thermal inertia, in the device structure; the ambient, by means of losses from the outside walls or envelopment; the heat transported out of the process environment by load conveyor, fixture, trays or other materials; the heat losses from openings or hot exposed parts, as well as the heat carried by cold air infiltrations into the heating device.

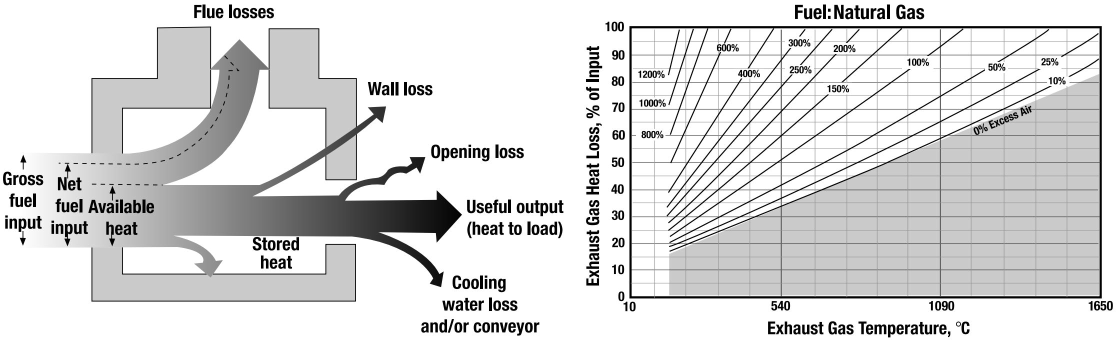


**Figure 1.6 –** Heat losses in industrial heating processes (left) and exhaust gas heat losses efficiency-limiting (right) - (adapted from [51]).

For every fuel, there is a chemically correct, or stoichiometric, amount of air required to burn it. Stoichiometric, or on-ratio combustion will produce the highest flame temperatures and thermal efficiencies. However, combustion systems can be operated at other ratios. Sometimes, this is done deliberately to obtain certain operating benefits, but often, it happens simply because the burner system is out of adjustment [51]. This theoretical ratio can go either rich or lean, generating in both cases thermal inefficiencies. Operating the burners at richer than stoichiometric combustion conditions wastes fuel by allowing it to be discarded with some of its energy unused. It also generates large amounts of carbon monoxide (CO) and unburned hydrocarbons (UHCs).

However, a lean operation produces non flammable and non toxic by-products of rich oxygen combustion (NOx, CO and UHCs), but it does waste energy. This excess air has two effects on the combustion process: it lowers the flame temperature by diluting the combustion gases and it increases the volume of gases that are expelled from the process. An accurate process-oriented air-fuel ratio is required to reduce the waste of energy and to avoid the excessive generation of harmful (for life) particles.

In conclusion, the TE of the thermal process depends on how well-built and designed the device is (and how near it is working to this operating point) and on the process temperature (or exhaust gases temperature), which acts as a limiting factor. Reducing the losses associated to these elements by the application of EEMs, which are able to make modifications to the designed device or improve the tracking of the designed operating point, brings important energy benefits in the process.

## 1.2 Energy Efficiency Management

To ease the introduction or assimilation of these policies, obligations and recommendations, several methods or procedures have been established. Energy intensive industries are being pushed to reduce their energy consumption and, thus, several measures are being carried out by industries in order to be able to meet the objectives set by the EU. Some of these measures include the installation of Energy Management Systems, Energy Audits or the implementation of certain Energy Efficiency Measures as a method to reach a well Energy Efficiency Management. However, as it will be explained in the following sections, these measures are limited and there is a need for further developments.

The main developed concept to introduce the energy management in the business is the energy efficiency management. This concept can be defined as the acquisition of knowledge, skills and experience, and the development of methods and tools to manage energy efficiently. The implementation of energy efficiency management practices makes it possible to identify the energy saving potential and to reduce the energy consumption in the industrial business [52]. In this regard, and to tackle this energy efficiency management challenge, the job-position of the "industrial energy manager" in the manufacturing sector is growing. This job has the duty to ensure the production while reducing the energy consumption. Besides, as it was introduced before, there is a high interest from government policies to increase the competitiveness of the industry by managing the energy efficiently. Energy management is widely recognised as a primary means to overcome barriers to energy efficiency. However, a high potential for improvement still remains unexploited [53, 31].

### 1.2.1 Energy Management Systems - ISO 50001

In this regard, the International Organisation for Standardisation (ISO) defines Energy Management Systems (EnMS) as a tool or procedure which helps organisations to manage better their energy use [54]. This way of working involves developing and implementing an energy policy, setting targets for energy use and designing action plans to achieve them. This modus operandi includes implementing new energy-efficient technologies, reducing energy waste or improving current processes to cut energy costs. Currently, the EnMSs are regulated by the ISO 50001 family, which includes a number of other related standards to complete ISO's energy management and energy saving portfolio. This International Standard specifies requirements to establish, implement, maintain and improve an energy management system whose purpose is to enable an organisation to follow a systematic approach to achieve continual improvement of energy performance; including energy efficiency, energy use and consumption. Therefore, the ISO 50001 creates the conditions for the integral application of methods and measures of energy management.

The EnMS, and specifically the certification ISO 50001, is focused on the continual improvement of energy performance based on Plan-Do-Check-Act cycle, represented in Figure 1.7. The process is periodically repeated in order to log improvements and to track the advance. The first step to start an EnMS is the energy audit. All data related to energy consumption and energy bills are gathered. If the previous in-plant energy monitoring system does not include the energy consumption of each individual process, step or device, some ad-hoc specific measurements will be taken. This audit returns the preliminary state of the company and indicates where the continuous meters should be located. The next part is the energy planning. In this section, the real energy consumption is metered and quantified and the final use of these consumptions are logged. This part is usually the most critical section [55]. Besides, several improvement aspects may be identified after the energy analysis. Then, the implementation and operation task starts. At this point, the identified improvements, oriented to obtain a more rational consumption, are introduced into the plant. The operators must be trained to understand their role in the EnMS.

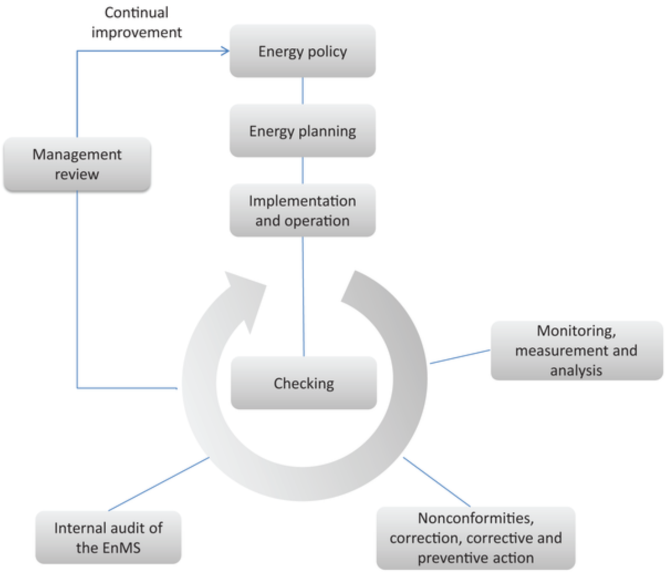


**Figure 1.7** – The cycle Plan Do Act Check of ISO 50001

The last part of the continuous cycle is the evaluation, which consists of carrying out the certification audit properly. The assessment of the implementation of the ISO 50001 standard includes an employee interview where perception and problems are compiled. At the final stage, the feedback data, such as energy information, measured way of working and selected procedures are reviewed and the implemented agreed measures are verified in advance to the ISO 50001 certificate obtaining.

The standard ISO50001 proposes a series of requirements in order to comply with the international certification. These requirements may be split into organisational and technical aspects. The organisational aspects are responsible for integrating energy efficiency aspects in the corporate policy and in the corporate culture. The technical aspects are responsible for providing the prerequisite for energy efficiency improvement (identification of consumer devices, energy data measurement, set indicators, etc.), for controlling the process and for acquiring knowledge. This standard EnMS is currently being applied to many industrial companies over the world in order to lead their organisations to a more efficient use of energy. However, the cost and time associated with the development and implementation of the EnMS are limiting the implementation of this certification [56].

On the other hand, the integration of ISO 50001 into an existing management system is apparently easy [57]. The motivations of this implementation are clear: Social, ecological and economic [58]. The company social perception improves with ISO 50001 certification advertising at the same time that the consumption or production rate improves. The ecological impact is minimised due to the reduction of the energy intensity. In contrast to these benefits, some operational and organisational difficulties have been found. The continuous measurement, the high amount of data and the lack of economic (and human) resources seem to be the principal barriers [58], setting aside the energy efficiency improvement. Beyond the international certification, the EnMS creates high interest in the research groups due to its high saving margins, its high potential and the concern of industrial business in maintaining their competitiveness. Several adaptations and modifications of the ISO 50001 EnMS have been analysed and assessed in the industrial environment in order to improve the performance of the results, or to cover standard EnMS gaps or to adapt to the specific sectors [59, 60, 61, 62]. Several research groups and industrial companies are developing specific methodologies more adapted to the different scenarios in order to take advantage of the non-reached energy efficiency potential. In this sense, many works have been developed in order to ease the introduction of these standards into the companies [63, 56, 58].

However, the certification ISO 50001 has a general and abstract description of the EnMS and leaves much room for interpretation. The certification gives only a framework and defines general requirements, but does not offer any structure or methodology to implement in companies. The introduction of EEM and the compliance of the energy reductions is the enterprise's responsibility. This often leads to disorientation and, sometimes, is the cause of failure of the entire system [52, 61].

### 1.2.2 Energy Audits and Energy Services Companies

An Energy Audit (EA) is a systematic process which discovers how a facility uses the energy. In this process some energy-efficient improvements are recommended. The process is conducted by an energy auditor (or energy auditor team) instructed to this aim. The origin of the auditor element may be internal (belonging to the business) or external (employed from a third party for this mission). The process includes inspection, survey and analysis of energy flows with the aim of reducing the energy or material input without negatively affecting the final output. Besides, the energy auditor may identify potential actions for energy or material reduction. Every large enterprise in the EU will, by law, have to undertake an EA, by following the Article 8 of the EU Energy Efficiency Directive. This audit will then have to be repeated every four years. The companies which are certificated with the ISO 50001 are exempted from these periodic audits.

The EAs are split into industrial and building audits. The industrial audit is focused on saving energy for industrial or manufacturing processes, meanwhile, the building one is oriented to Heating, Ventilating and Air Conditioning (HVAC) systems, the building insulation or the lighting system. Moreover, a common industrial EA includes the audit of the industrial plant and the offices facilities. The main objectives and results are represented in the energy audit scheme (Figure 1.8). The work of the EA ends in the orange "Energy Audit " bracket, the implementation work belongs to the audited company itself.

The EAs are the first step to improve the Energy Efficiency. However, the audit legislation presents several limitations. These audits are only informative. Enterprises may get over the formality without including any improvement. These generic proposed audits are oriented both for a bank and for a foundry, at the same level. Besides, in Spain the EA is governed by the Real Decreto 56/2016 [64], which only mandates to audit 85% of the total energy consumption. The EA must be executed by a certified energy auditor. In the pure industrial or manufacturing processes environment (non building nor office oriented), an external auditor may present a limited knowledge of the industrial process or of the operating method. On the contrary, an internal auditor may present limited knowledge of the current EEM or of the best available techniques to reduce the energy consumption and cost. Also, an industry may have problems to train an energy efficiency project manager among its staff. For these reasons a new element has appeared: The Energy Service Company (ESCo).

In the last decades many companies which offer different ways to reduce energy consumption have been created. These companies, which are seen as private-sector

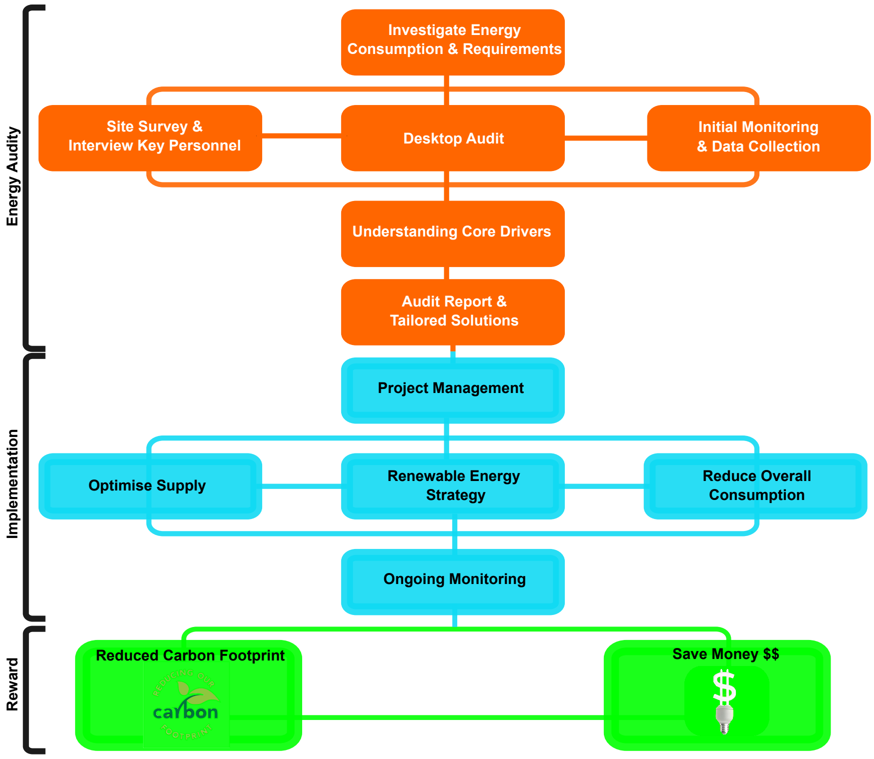


**Figure 1.8 –** Energy Audit schema

delivery mechanisms for energy efficiency [65], tend to provide resources to implement solutions as a response to the energy requirements of industrial, primary or tertiary sector. However, at least half of the ESCo projects leveraged some level of public budget. An ESCo provides both knowledge and investment funds to reduce the energy cost. As of 2014-2016, in general, the ESCo market is on a growth path, although this growth is not as widespread across countries as it was in the period 2010-2013 [66], however, after the economic crisis, the global ESCo market has experienced a growth by 8% to USD 28.6 billion in 2017 [33]. The energy services market in Spain is relatively small. Many barriers need to be overcome, from legislative to market technical barriers [65]. ESCos have the necessary know-how to provide turnkey services and solutions. These companies are achieving significant energy cost reductions by addressing various market-related barriers on the ground [18].

This scenario provides a symbiosis between ESCo and industrial companies and helps to overcome financial constraints to energy efficiency investments by assuming the initial costs. These initial costs are recovered by the ESCos through the future economic savings resulting from the reduced energy consumption. ESCos can handle projects, manage or mobilise financial resources, undertake installation and maintenance work as well as collaborate with other market players. The ESCo agent offers an opportunity to reduce customers' energy usage, while capturing business opportunities, which may, at the same time, increase revenues. Therefore, the ESCo eases the implementation bracket, allowing to reach the "reward" bracket of the energy audit scheme (Figure 1.8). Anyway, an energy efficiency-conscious industrial company may reach the same level of services by itself if interested in providing the necessary resources.

The main distinguishing characteristic of the ESCo modus operandi is the specific contract which links the ESCo and the customer business: The Energy Performance Contracting (EPC). The key characteristics of an EPC are the following: The project is a turnkey-project, savings are guaranteed, and there is no need for up-front capital. The risk is assumed by the ESCo. All the services required to design and implement a comprehensive energy saving project at the customer‘s facility, from initial energy audit to measurement and verification of savings, are provided by the ESCo. There are other kinds of contracts such as: Energy Supply Contracting, where the ESCo only supplies use energy to customers; Energy Operations Contracting, where ESCo delivers technical services to ensure the correct and efficient operation of systems and equipment; and the Third-Party Financing, where ESCo provides a distinct technical facility or system (owned by the ESCo) to correct and make the operation efficient. The value of ESCos for unlocking the energy saving potential in the market is recognised by the EU directives and initiatives in the European context, such as the Energy Efficiency Directive [4, 65].

However, the ESCo contribution presents some limitations and has margin for improvement [67]. Some innovative solutions may not be adopted by the ESCo project leader due to a lack of high-specific knowledge of the process. The implemented technologies tend to be consolidated in the industrial market. In this sense, the ESCos mostly provide crosscutting technologies, which can be applied to common processes such as motors, steam, compressed air systems, HVAC, boilers and industrial lighting [68]; instead of focusing in the manufacturing processes. In consequence, the hypothetical savings offered by an ESCo to an EII may mean a minor part of the total energy consumption. With the aim to achieve high energy savings and increase the productivity in EII, measures should be oriented to the principal manufacturing process. Nevertheless, this contribution must not be disregarded [69]. Despite the hypothetical energy efficiency increases produced by the EA or the ESCo activities, these mechanisms lower some barriers (related to behaviour, organisation and information) to future EEM implementation. Definitely, it may be concluded that in order to achieve the energy efficiency and decarbonisation targets in the EU, there is a need of stronger services such as the ones provided by the ESCo-EPC market [65].

## 1.3 Energy Efficiency Measures in Industrial Manufacturing Processes

The economic activity of a country strongly depends on three economic sectors: The industry sector, the agriculture and the service sector. Within the industry sector, the manufacturing process sector includes all kind of processes that generate a product with raw material. This sector excludes the energy and water supply, the construction activities as well as the mining and quarrying activities [70]. As it is stated before, an EEM is the technical mechanism in order to reach the energy efficiency at any sector. An important step for the adoption of the EEMs is the characterisation and classification. This step helps to gain a better understanding of the implementation process of the EEMs.

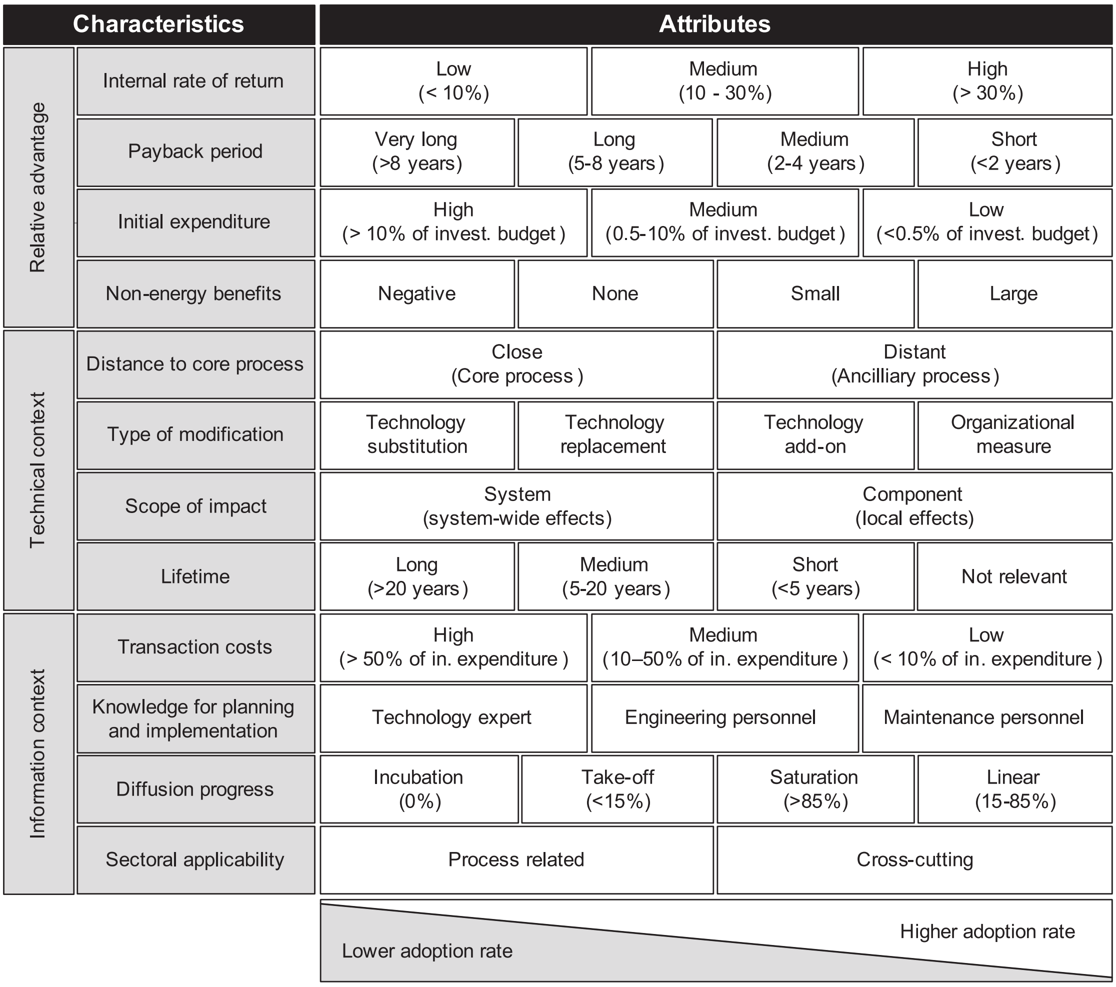
### 1.3.1 Classification and characterisation of Energy Efficiency Measures

The classification (and characterisation) scheme proposed by Fleiter et al. [71] includes results characteristics of the EEM adoption and pre-implementation features. The presented areas, categories and attributes have been developed from a methodological point of view. This classification scheme is split in three big areas: Relative advantage, technical context and information context. The main division characteristics and their attributes are depicted in Figure 1.9. They provide a classification scheme to better understanding the adoption phase of EEMs by industrial firms as well as to serve as a basis for selecting and designing suitable energy efficiency policies.

In the same way, Trianni et al. [72] propose a novel framework to characterise the diverse EEM. This characterisation, based on the selection criteria of Fleiter et al. [71], extends the basic attributes as an attribute-value system. The authors have listed and explained six independent categories: Economic, energy, environmental, production-related, implementation-related and indirect attributes. This category tries to account for the most relevant features when undertaking an investment in energy efficiency. At the same time, each category is independent of the others (to the fullest extent possible). They start from a thorough review of the previous contributions in literature and provide an innovative framework to ease decision-making and the policy-makers work.

These EEMs must be in-depth analysed in order to assure the correct working of the process. The company manager will not introduce a measure which may negatively affect the production or reduce the quality of the product. As it is well-known, the main objective of a manufacturing industry is to produce and to accomplish the customer orders. Therefore, the time-period under study for common EEMs may be elevated and reach a time frame of around two years [73]. These classifications and characterisations enhance the quality and comparability among different studies of EEMs and affect their adoption by industry managers. A well developed EEM should answer these questions to understand the situation of these specific measures, the characteristics of the measure and the expected results.

On the other way, the aforementioned kinds of procedures to obtain an energy efficiency improvement (i.e. the energy efficiency management practices and the technologi-



| Characteristics | | Attributes | | | |
|---|---|---|---|---|---|
| Relative advantage | Internal rate of return | Low<br>(< 10%) | Medium<br>(10 - 30%) | High<br>(> 30%) | |
| | Payback period | Very long<br>(>8 years) | Long<br>(5-8 years) | Medium<br>(2-4 years) | Short<br>(<2 years) |
| | Initial expenditure | High<br>(> 10% of invest. budget) | Medium<br>(0.5-10% of invest. budget) | Low<br>(<0.5% of invest. budget) | |
| | Non-energy benefits | Negative | None | Small | Large |
| Technical context | Distance to core process | Close<br>(Core process) | Distant<br>(Ancilliary process) | | |
| | Type of modification | Technology substitution | Technology replacement | Technology add-on | Organizational measure |
| | Scope of impact | System<br>(system-wide effects) | Component<br>(local effects) | | |
| | Lifetime | Long<br>(>20 years) | Medium<br>(5-20 years) | Short<br>(<5 years) | Not relevant |
| Information context | Transaction costs | High<br>(> 50% of in. expenditure) | Medium<br>(10–50% of in. expenditure) | Low<br>(< 10% of in. expenditure) | |
| | Knowledge for planning and implementation | Technology expert | Engineering personnel | Maintenance personnel | |
| | Diffusion progress | Incubation<br>(0%) | Take-off<br>(<15%) | Saturation<br>(>85%) | Linear<br>(15-85%) |
| | Sectoral applicability | Process related | Cross-cutting | | |

**Figure 1.9 –** Classification scheme for EEM by Fleiter et al. [71]

cal measures) may be classified in concordance with how the measures act in the process. This classification (shown in figure 1.10) may be arranged from "the most favoured option" to "the worst favoured option" according to the energy waste management point of view [74]. The top part of the pyramid includes prevention and minimisation categories. Theoretically, the best way to improve the energy efficiency of a process is the prevention of the consumption. Eliminating processes or devices which do not provide any value to the final product is the first step. If the process is essential the next step is to search the minimisation of its consumption. EEMs which are oriented to improve the device characteristics, by means of device substitution or improvement in the way of working are included here.

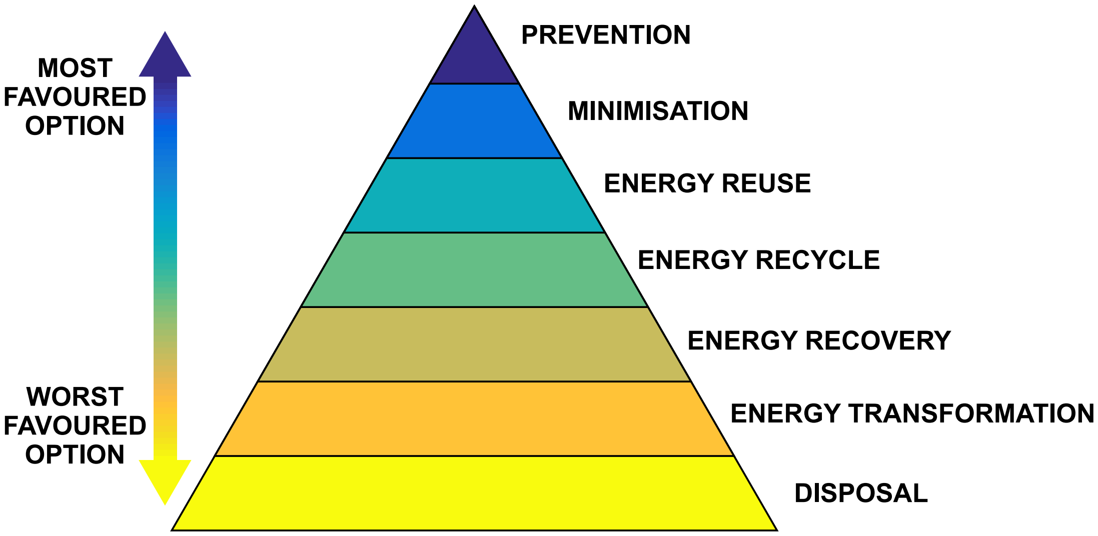


**Figure 1.10** – The Energy Efficiency hierarchy for EEM adapted from [74].

The second kind assumes that the energy consumption of the process can not be neither eliminated nor reduced. The energy in the manufacturing processes is finally transformed into heat or work. In some cases, this energy is transported by means of a tangible flow, such as stack gases or residual water (or fluid). In other ones, the energy is disposed without a clear medium without the possibility of concentrating it in a useful flow. If this energy flow can be reused in the same process by an EEM this action belongs to energy reuse category. EEMs of this category have an effect on the way of working of the process itself. The dynamic features of the process may be modified, therefore, the new behaviour should be analysed. The energy recycling consists of the straight redirection of an energy flow to another process.

The next category is the energy recovery; the energy of the flow is transferred to another useful medium-flow in order to use this energy in another process. This mechanism is used when, for example, a heat flow can not be recycled or reused due to its corrosive characteristics. In these two previous categories the dynamic behaviour of the receiving process may be changed only if the processes are connected or are interdependent.

The last kind of EEM is the transformation of the energy in other source of energy, commonly from heat to electrical energy. The energy is transformed by a heat cycle or thermoelectric phenomena. This energy efficiency hierarchy (figure 1.10) is principally guided by the exergy balance, the nearest to the pyramid base the greatest the exergy is "destroyed". The base of the pyramid is the disposal of the energy flow to the ambient. The theoretical potential of a EEM is stated by the exergy term, in application of the second law of thermodynamics.

### 1.3.2 Industrial EEMs and Best Available Techniques

Many EEMs have been introduced into the industrial environment. Any modification that reduces the specific consumption of the production process, or, ultimately, improves the manufacturing competitiveness, may be considered an EEM. The final scope, mission and result of the EEM proposed may differ among measures. The measures with the best compromise among energy and pollution results (high levels of energy and emissions reduction), low risk (guaranteed by a mature technology) and adaptability are selected as Best Available Techniques (BAT) or Best Practice Techniques (BPT). The European Commission (by the Integrated Pollution Prevention and Control organism) produces BAT and BAT reference documents or BREFs notes for each kind of industry. These documents contain the "best available techniques" for installations. A BAT may be a new technology which has just emerged, but is not yet deployed. The BPT, related to the manufacturing process, are techniques that are strongly introduced into industrial environment. These techniques are widely studied and analysed by the bibliography and proved empirically by real implementation experience. The processes towards which the BAT are oriented are common processes for different activities and common parallel technologies that are repeated in many kinds of industries.

Therefore, a large library and database, which includes "good practices", has been developed: European Industrial Energy Efficiency good Practices platform (EIEEP) [75]. The EIEEP contains aggregated data from real implementation of thousands of real energy efficiency projects in several industrial sectors. These case studies and prototypes are provided by the EU-MERCI[1] “Enablers”, i.e. partners with access to the database of the energy efficiency projects which have been implemented at national level (Austria, Italy, Poland and UK). Thanks to EIEEP the most promising and effective projects in the field of energy efficiency can be identified. Such data, together with the information coming from the BAT suggested by the BREFs at EU level and by other international

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[1] EU-MERCI stands for EU coordinated MEthods and procedures based on Real Cases for the effective implementation of policies and measures supporting energy efficiency in the Industry. European funded project H2020

platforms, are used to derive the “Good Practices”, which represent “a technique or methodology that, through experience and research, has been proven to reliably lead to a desired result in a sustainable way”.

For each “good practice” a file is available. This file includes the description of the adopted EEM and the various energy and economic indicators, which are useful to understand the opportunity to consider it for a given enterprise for each specific process. The principal industrial sectors where the “good practices” have been identified are the following: Aluminium, ammonia, cement, ceramic, coke & petroleum, copper, food & beverage, glass, iron & steel, machinery, pulp & paper.

These documents and the available EEMs, the state of the energy management in the industrial environment, the identified gap of the energy efficiency, and the role of this efficiency in the future sustainability of the world clearly lead to act for improving the energy efficiency of processes.

## 1.4 Motivation of the Thesis

The role of the energy efficiency is clear and its effects are indispensable to reach the objectives to combat the climate change and improve the competitiveness of the sectors (as Shown in Section 1.1). In addition, the existing Energy Management Systems present gaps both in the degree of specialisation (to reach the maximum level of energy efficiency) as well as in the sector of application and focus (as presented in Section 1.2). Finally, there is wide margin for energy efficiency improvement (Section 1.1.2) in the manufacturing sector. Within this sector, the energy intensive industries with non-continuous thermal processes are highlighted due to the absence of method or procedures to evaluate the energy efficiency (Section 1.1.2). Therefore the main aspects that have motivated this research work are the followings:

- The high relevance of the energy efficiency for the EU future climate goals (ecological goals) and to improve the industrial competitiveness (economic goals), as shown in Section 1.1.
- The high theoretical energy efficiency gap identified for the industrial environment (as presented in Section 1.1.2) and, in particular, for the manufacturing sector.
- The low degree of application and specialisation provided by the existing EnMS (ISO 50001) and the limited implementation of EEMs in the industrial environment in combination with the low technological deepening of the Energy Audits and the contribution of the Energy service companies (as presented in Section 1.2).
- The difficulties and challenges which the non-continuous thermal processes present

at the time of being analysed and assessed for EEMs implementation (as commented in Section 1.1.3).

- The high variety of technology and knowledge related to EEMs (as shown in Section 1.3) but which have not been implemented due to some barriers (as identified in Section 1.1.2.2).

Definitively, the presented aspects have shown the need to develop a methodology to asses both the hypothetical EEM and the process itself in order to identify, quantify and evaluate the impact on the process and the energy savings derived from these EEM implementation. For the methodology to be applicable to thermal non continuous processes, devising a way to solve the aforementioned problems was paramount. Besides, a research gap was identified in the existing literature in relation to methodologies which cover this kind of process from an integral and holistic perspective, focusing in the dynamic phenomena of the process (as shown in Chapter 2). In this context, the issues that required intensive study and that motivated this research project were:

- A deepening in the literature related to energy modelling and the selection of the features for a methodology adapted to the non-continuous thermal processes.
- The lack of decision making tools oriented to the implementation of EEMs in the manufacturing sector.
- The lack of methods and methodologies to simulate scenarios (based on EEMs implementation) in high dynamic processes.
- The lack of tools, methods and methodologies which combine energy efficiency assessment, by means of EEMs implementation, for high dynamic processes with an integral and holistic analysis.

This thesis has been launched by IKERLAN in close collaboration with the University of the Basque Country (UPV-EHU) as response to the requirements identified for the industrial sector. The need of generating a methodology to solve these problems have been arisen due to the real requirements of the manufacturing industries. The proximity to the industrial environment of IKERLAN and the UPV-EHU is a key factor. IKERLAN is a leading knowledge transfer technological centre providing competitive value to companies. Due to this proximity, the adaptation to the needs of our customers and the requirements of the industry are directly translated to research programs. In this regard, IKERLAN works as a nexus between the university and the industrial sector. IKERLAN works with several industrial manufacturing clients who demand solutions to improve their competitiveness. Besides, the aforementioned sections of the introduction (Section 1) confirm the necessities identified by IKERLAN and the UPV-EHU and establish the basis of the present research work.

Therefore, there is evidence to think that the energy efficiency in non-continuous thermal processes (manufacturing sector) can be increased. However, there are some barriers to address and the existing state of the research presents some gaps.

## 1.5 Research Objective & work structure

Against the described background, the proposed work intends to address the energy efficiency potential in the industry sector. The final aim of this work is the development of a methodology for comprehensive energy analysis of industrial processes and plants. This methodology for energy modelling of industrial processes and plants by simulation aims to ease the decision-making process [76] with reference to the most financially attractive option in energy efficiency improvement. Besides, the objectives reflect the main requirements from the scientific perspective (as explained in Section 1.1.2.2).

The main mission of this work may be split in the following three main objectives:

- To develop a methodology for integral Energy Efficiency Assessment of processes and EEMs by process simulation as well as to provide methods to optimise these EEMs and to ease the introduction in real plants (easing the decision-making process) for non-continuous thermal processes.
- To apply this methodology on the proposed case study as well as to provide an in-depth Energy Efficiency Assessment of the processes under study.
- To create a user-friendly tool to ease the evaluation of solutions and the final solution generation process.

These main objectives guide the structure of the proposed thesis, as it is shown in Figure 1.11. The first main goal is reflected in Chapter 3 -Proposed Methodology-. The second one is distributed in Chapter 4 and 5. Chapter 4 -Case Study- explains the case study and applies the proposed modelling methodology. Then, in Chapter 5: Energy Efficiency Assessment the process under study is evaluated and valuable results are obtained. Finally, the last objective is located in Chapter 5: Section 5.4 describes the user-friendly tool developed to ease the proposed Energy Efficiency Assessment introduction and to put the industry manager near to this assessment. The purpose of each chapter is summarised in Figure 1.11. The final purposes of these objectives are the following:

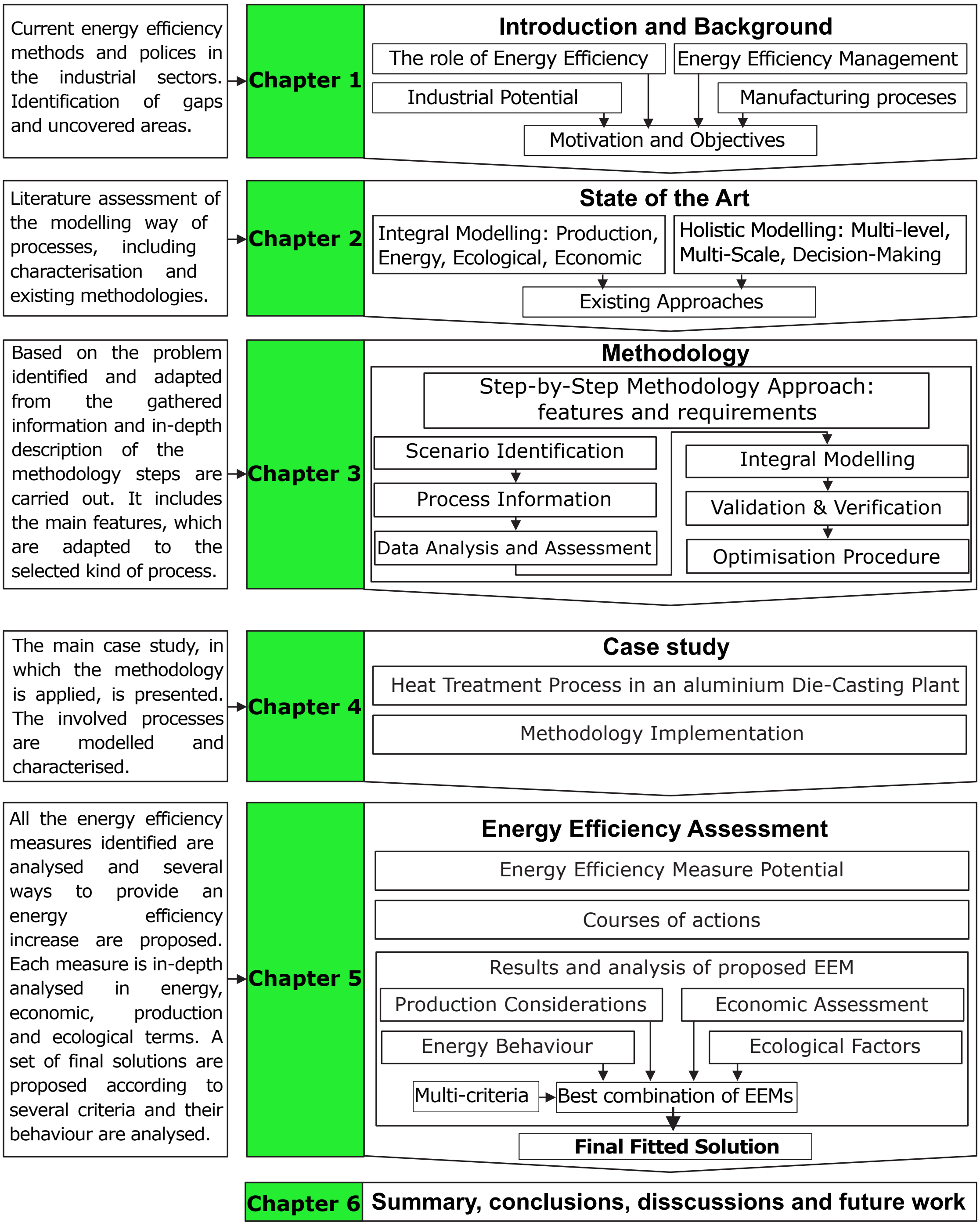
- Increase the technical energy efficiency potential of manufacturing processes due to synergies among measures [38, 37].
- Provide the identification, quantification and evaluation of EEMs in manufacturing processes.

- Obtain an energy modelling procedure oriented to high dynamical processes.
- Provide the energy savings potential and impacts on the manufacturing processes resulting from the proposed EEMs.
- Provide reliable information and support tools to reduce the decision-making process barriers.

The schema presented in Figure 1.11, shows the structure proposed for this research work in relation with the proposed chapters. After the introduction and the necessary background (reflected in Chapter 1), the state of the research on energy modelling of system is explained in Chapter 2. It includes all the context about holistic and integral methodologies. Then, and based on this context, the proposed methodology, which presents the way to address the main purposes of the present work, is widely accounted for in Chapter 3. Chapter 4 tackles the implementation of the proposed methodology in a relevant case study. The specific models of the process are generated and validated. After that, an in-depth energy efficiency assessment is carried out in Chapter 5. Besides, the proposed tool to ease the making decision process is presented. This work concludes with a summary, a set of final conclusions and a critical evaluation of the developed approach. Finally, some fields of action for further research are also identified in Chapter 6.

In addition, the main objectives are broken down in the specific objectives presented below. These specific objectives lead to achieving the aimed purposes. For that to be possible, a case study is analysed and evaluated in which some specific objectives are focused.

- To analyse and understand the current situation of the Energy Efficiency, and its potential, in the industrial sector, including the existing EEMs and the EnMS.
- To introduce the state of the art related to energy modelling of systems from an integral and holistic perspective.
- To analyse all the concerning information of the existing approaches and identify strengths, weaknesses, opportunities, and threats.
- To generate a methodology which combines the aforementioned information of modelling whereas faces the gaps identified in the existing approaches.
- To analyse, based on the proposed methodology, a relevant process and assess the energy and material flows.
- To generate models, based on the raised information, which reproduce with high accuracy the process phenomena and events.
- To identify, present and analyse hypothetical EEMs derived from the process analysis and from the EEMs research background.



Current energy efficiency methods and polices in the industrial sectors. Identification of gaps and uncovered areas.

Literature assessment of the modelling way of processes, including characterisation and existing methodologies.

Based on the problem identified and adapted from the gathered information and in-depth description of the methodology steps are carried out. It includes the main features, which are adapted to the selected kind of process.

The main case study, in which the methodology is applied, is presented. The involved processes are modelled and characterised.

All the energy efficiency measures identified are analysed and several ways to provide an energy efficiency increase are proposed. Each measure is in-depth analysed in energy, economic, production and ecological terms. A set of final solutions are proposed according to several criteria and their behaviour are analysed.

**Figure 1.11 –** Structure of the research approach.

- To propose different courses of action to evaluate several ways to tackle the energy efficiency increase in the selected process.
- To analyse the energy savings and impacts of the implementation of several EEMs (courses of action) on the specific process.
- To provide the fittest solution in relation with some diverse multi-criteria.
- To present an integral decision support tool that allows to select the best combination of solutions considering different criteria (from economic to environmental criteria).

The attainment and the degree of the aforementioned main and specific objectives will be analysed in the final conclusions (Section 6). Besides, and based on the application of a case study, the aim compliance will be assessed and quantified.

# 2

# State of the Art

**Summary**

*In this chapter the methods and classifications for assessing and modelling the energy systems are reported. Besides, based on the situation of the industrial energy efficiency management the methodological research approaches and commercial tools available are accounted for. As explained in the previous chapter one of the objectives of this thesis is to develop a methodology for integral Energy Efficiency Assessment of processes and EEMs by process simulation. Therefore, the different approaches found in literature for process modelling or simulation are summarised in the following section.*

## 2.1 Assessment by energy modelling

The energy models are approximations for the (energy) behaviour of the energy system. However, the models do not have the capacity to conclude or decide solutions by themselves, the obtained data must be processed and interpreted to assess the real implications and to generate valuable results. In general, the final aim of the energy modelling, and the ensuing analysis, may be summed up by two targets: quantifying the performance of an action plan as well as characterising the interactions between various scenarios. The general purpose of these objectives is to predict or forecast the future (predictive), to explore this future with diverse intervention scenarios (analytically) and to look back from the future to the present (backcasting) [77, 78].

### 2.1.1 Energy Models for Energy systems

The scale of the energy system assessed (world, continent, region, country, sector, zone, factory, production line, process, device) will vary the energy modelling strategy to be adopted. For large energy systems, the strategies to address this general energy modelling can be categorised into economic-based (top-down) models, engineering-based (bottom-up) models, and the hybridisation between both energy models [79].

#### 2.1.1.1 Bottom-up Models

A bottom-up energy model is an engineering approach that features a comprehensive technical database related to technology, costs, and consumption demand patterns. The bottom-up approaches ignore macroeconomic interactions by assuming exogenous energy prices, demand, and other economic theory-related inputs and, in general, are tackled by disaggregated models.

In general, the bottom-up models are rather oriented to the process or working process assessment: Optimisation, simulation, accounting, agent-based [80, 81, 82]. Optimisation models were initially designed to model the energy supply and to the subsequent extension of the modelling to the entire energy demand side (from process to facility). These models optimise the choice of technology alternatives regarding the total system costs. This energy modelling variant tries to find the lowest-cost path. Simulation models (widely analysed below) constitute a very broad and heterogeneous group, which generates difficulties to clearly define the characteristics and scope of this model type. In general, they include an introduction to technology scenarios. Large simulation models can include partial optimisation, and may consist of different modules in order to provide a comprehensive aspects coverage. Accounting models are generally characterised by exogenous definitions of many variables, and do not consider energy prices. These models are used in long-term energy approaches due to their simplicity and transparency. The agent-based models are a broader modelling class than the optimisation models, since they include the simultaneous optimisation through more agents.

#### 2.1.1.2 Top-Down Models

Top-down models, on the other hand, incorporate all the parameters within the model equations so as to minimise the number of exogenous parameters (inputs). This standpoint, based on observed market behaviour, uses aggregated data (by means of aggregated models approach) for predicting purposes. These features make the top-down approaches useful for analysing the economic impact of an energy policy.

The final specific goals of Top-Down approaches are: Tracking the destination of resources as they are processed through the energy economy; determining the economic feasibility of different energy use scenarios; predicting the economic outcomes of energy policies; finding the causes of, and solutions to, technological, market or policy failure (as introduced in Subsection 1.1.2.1). This scale is mainly oriented to system dynamics assessment or to economic assessment by means of three types of models: Econometric, input-output and economic equilibrium [80, 81]. Econometric models estimate relations between economic variables over time in order to calculate projections from the resulting model. Input-output models follow the monetary flows. The monetary effects of changes in the economy are analysed here. The economic equilibrium models are based on microeconomic and tackle prices and activities to reach an economic equilibrium. System dynamic models consist of defined behaviour rules for each model part, and are qualified to make complex non-linear simulations on this basis.

#### 2.1.1.3 Assessing of Energy models

These strategies are traditionally evaluated by Statistical Energy Analysis procedure for top-down approaches, and Process Analysis procedure for bottom-up approaches. Statistical Energy Analysis only takes account of direct energy use and is limited by the availability of statistical data. This kind of analysis provides a reasonable estimate of the energy cost of products, classifying them by kind of industry. However, the indirect energy requirements are not accounted for. Process Analysis uses more detailed data-sets to examine a defined process, manufacturing site or subsector and allows to distinguish between the different outputs from the same industry [22, 83].

For small energy systems (factory, production line, process or device) the top-down strategies become useless, although there may be exceptions here, and the general bottom-up (for general energy analysis scenarios) must be adapted. The specification of each system makes the need to adapt other less generic strategies. However, the objectives of the energy modelling remain invariable: Quantifying the performance of a process or device and characterising the interactions among proposed scenarios (introduction of EEMs). The energy modelling, and the following assessment, for the small scale is commonly addressed by individual analysis of the systems, and it is traditionally focused on the system dynamics of the process or product, the dynamical system analysis of the process or phenomena and on the thermodynamic assessment of the processes or devices. This branch of energy system analysis is more oriented towards the manufacturing system energy modelling.

"Pure" energy systems or research approaches whose characteristics only belong to one kind, without including aspects or characteristics of other groups, are not common in the real world. In fact, the combination or hybridisation of characteristics may bring better results [84].

### 2.1.2 Classification of energy modelling approaches for manufacturing systems

The industrial sector consumes about 54% of the world's total supplied energy. This sector, which uses more delivered energy than any other end-use sector (transportation, commercial and residential), can be divided into three distinct categories of industry types (Figure 1.3): Energy-intensive manufacturing, non-energy-intensive manufacturing, and non-manufacturing [32]. Manufacturing processes use one or more physical mechanisms to transform a material's form or shape [85]. Modern manufacturing includes all intermediate processes required in the production and integration of a product's components. The energy model research approaches for the manufacturing system purpose consist of reproducing the energy behaviour of these processes.

However, further than the energy and ecological impact of the manufacturing companies, the decision making process is guided by the economic interpretation. EEMs are the technical mechanism in order to reach the energy efficiency at any sector. Definitely, there are manifold kinds of energy modelling for manufacturing systems and, in consequence, they may be classified from diverse points of view.

#### 2.1.2.1 Methodological approaches for energy modelling

This classification is based on the selected methodological approach to reproduce the energy behaviour. Each approach relates the energy results to the economic, the ecological and the production variables. Several tools and methodologies have been proposed in literature in order to asses, in an accurate way, the benefits, energy parameters and cost, as well as to size the EEMs and to narrow down their limitations. These tools are based on reproducing the consumption profiles, the material flow and a continuous or ex-post analysis. Ultimately, the main four alternatives of methodological approach were analysed, evaluated and confronted with the identified obstacles by Thiede [44]. These four approaches are the following:

- Static Calculations: This approach is based on simple calculations carried out by a standard spreadsheet software from previous logged data (consumption and production). This method provides a first estimation of consumption, however, it requires a simple process with well-known patterns and routines. While the process becomes complex, the number of sub-processes grows or the uncertainty of the consumption profile increases. Therefore, the accuracy of the prediction decreases. This kind of methodology is not tend to be physics-based.

- Fuzzy Logic: The Fuzzy Logic, regarding to energy consumption, aims at predicting the consumption-profile-change by checking against a previous obtained reference. It is commonly based on "if-condition-else" rules and statements, in which range of conditions may overlap [86]. This approach is based on the modeller expertise in order to categorise energy profiles. The method has a learning period in which the different consumption profiles are compared with the production data. In this sense, the Machine Learning approach may be considered a Fuzzy Logic method [87] where the learning periods and conditions are obtained by means of pure experimental data.
- Artificial Neural Network: Artificial Neural Network is based on human neurons that are interconnected providing and receiving signals. This method is qualified to identify and learn correlated patterns between input data and outputs. This technique overcomes the disadvantages, which may be required for other methods, of describing the system analytically [88]. It is useful for application domains, where one has limited or incomplete understanding of the process.
- Simulation: Simulation is defined as the imitation of a real-world process or system over the time [48]. Simulation is employed to show the eventual real effects of alternative conditions and courses of action. Simulation is also used in many situations, such as when the real system cannot be engaged; due to its inaccessibility, riskiness or unacceptable to engage. Besides, this procedure supports the initial phases of the process development, design and construction, where other methods may present more limitations. In addition, it can be applied in processes where it is impossible or extremely costly to do experiments on the system [89].

#### 2.1.2.2 Energy modelling approaches orientation

The energy modelling may be addressed from the point of view of the manufacturing process or from the point of view of the product.

***Process-Oriented energy modelling***

The process-oriented energy modelling only takes into account the systems, subsystems and environment related to the analysed manufacturing process. This technique may be split into Building Energy Modelling (BEM) and Manufacturing Process Simulation (MPS), which commonly correspond in literature with plant and process level, respectively [90]. BEM and MPS have been used extensively to identify energy and production improvements.

BEM is traditionally employed to analyse the thermal building envelope. This method calculates the energy use from the description of assets and operations. BEM technique has a predictive task if all major inputs are certain and comparative when they are not. Besides, it complements measured data, it isolates effects and supports optimisation as well as “what if” proposals. BEM is generally used for residential and commercial building assessment. However, this kind of simulation technique is commonly oriented to the technical building services technologies (cross-cutting technologies) related to HVAC systems, lighting, compressed air, hot water, and appliances [91]. The service provided by these systems do not affect the process directly. Nevertheless, it is crucial for the plants way of working and the correct production process [44].

On the other hand, MPS is focused on modelling the energy consumption of the manufacturing process. This kind of simulation may be split in two branches: plant simulation and process simulation. From the plant perspective, the MPS branch is used to optimise a manufacturing process line by assessing parameters, such as machine utilisation and production rate [49]. This modelling technique is oriented to the value chain and affects the Production Planning and Control (PPC). The results or considerations derived from this branch are oriented to:

- Energy management, which optimises energy procurement and balance based on a given production plan.
- Process optimisation, which assesses and tackles the way of working of the process, such as working parameters or device performance.
- Process planning optimisation, which optimises production schedules.
- Strategic decision-making, which helps managers to take long-term decision on investment strategy and operational management strategy, and additionally easing the EEMs development and design stages.

The degree of depth in the modelling of the process depends on the process to simulate and the methodological approach (Section 2.1.2.1). This process-oriented approach is rather directed to the simulation methodological approach. While some process consumptions, whose energy consumption are strongly linked to identified parameters, are widely identified, other processes have high levels of uncertainty. The last kind of processes, with high variations, should be modelled by identifying the phenomena and events in order to reproduce their energy and non-energy behaviour as well as to calculate the energy flows involved. Besides, a detailed and complex software allows to control the state of the process. Simple software MPS solutions, based on deterministic assumptions, will generate fixed outputs, eventually preventing to obtain results from process modifications.

***Product-Oriented energy modelling***

In recent years the Life Cycle Assessment (LCA) has been considered a useful approach to energy modelling from the point of view of the product [92]. Brondi et. al. gather diverse LCA-related methods and tools (as shown in Figure 2.1), such as specific-LCA tools, design for environment tools, on-site assessment tools, with the subsequent intention of developing a reliable gate-to-gate LCA referred to the use of manufacturing production line, based on Discrete Event Simulation (DES) modelling of manufacturing processes.

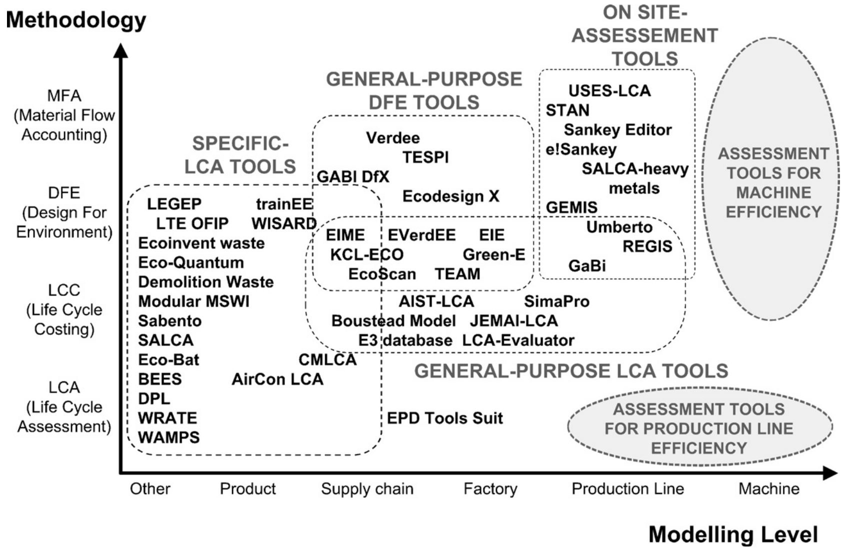


**Figure 2.1** – Different LCA tools for sustainable factory design and simulation in terms of assessment methodology and application area [92]

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LCA process includes goal and scope definition, inventory analysis, impact assessment and interpretation. The process is naturally iterative, the quality and completeness of information and its plausibility is constantly being tested. Within the LCA and the methodological approaches the analysis may be distinguished regarding the scope of the boundaries. Some terminology associated with LCA includes the following: *cradle to gate*, where impact is confined to the production stage, *cradle to grave*; where the study is extended up to disposal stage, and *cradle to cradle* which includes the recycling process [93].

### 2.1.2.3 Abstraction-degree paradigm of energy modelling approaches

This classification takes into account the way the model is time-scale reproduced.The main paradigms in energy modelling, oriented to the industrial manufacturing, are shown in Figure 2.2. This classification differs from the way of modelling, i.e. the abstraction degree and the aggregation level, and the continuous-discrete degree are indicated. The four main paradigms in energy modelling are the following: Discrete Event, Agent Based, System Dynamics and Dynamical Systems [94]. This classification is related to the mathematical approach employed for the modelling.

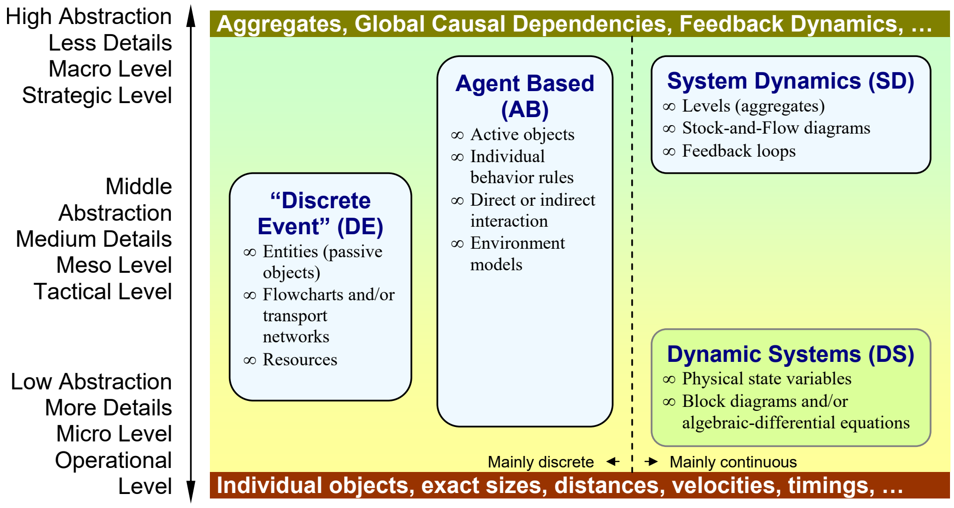


**Figure 2.2** – Time scale energy modelling paradigms [94].

- System Dynamics: System dynamics modelling addresses how a system reacts to dynamic forces and how those reactions shape its behaviour during a specific time frame by controlling the stocks [95]. This paradigm is focused on the study of information-feedback characteristics of the industrial activity to show how organisational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise. In System Dynamics, the manufacturing process is represented in terms of processes, knowledge, people-operators, money, stocks (such as material stocks), flows between these stocks, information that determines the values of the flows and the energy to develop these flow movements as well as to feed the processes.

- Dynamical Systems: This approach consists of a number of state variables and algebraic differential equations of various forms over these variables. These parameters and variables are inherently continuous and the mathematical diversity and complexity in dynamic systems domain can be much higher than in System Dynamics. In order to asses the physical relations and the process variables this approach may be supported by a thermodynamic analysis for manufacturing energy systems. This paradigm, according to manufacturing processes, may be applied to one part of the process or device disregarding other physics properties, such as pressure control analysis or thermal-energy balance assessment. In the most detailed and in-depth analysis part of the system modelling the Computational Fluid Dynamics (CFD) may be highlighted. The main method to overcome this analysis is the Finite Elements Method (FEM). Despite the fact it has its own particularities it belongs to the Dynamical System approach.

- Discrete Event: Based on the concept of entities, resources and block charts describing entity flow and resource sharing, this approach contrasts with continuous simulation in which the simulation continuously tracks the system dynamics over time. The Discrete Event modelling adopts a process-oriented approach: the dynamics of the system are represented as a sequence of operations performed over entities [96].
- Agent Based: This energy modelling draws for the modeller, which defines the behaviour at individual level (like autonomous agents) and, therefore, the global behaviour emerges as a result of these individual behaviours. It combines elements of game theory, complex systems, emergence, computational sociology, multi-agent systems, and evolutionary programming. Monte Carlo methods are used to introduce randomness. This paradigm is widely extended for the analysis of energy policies [97].

Besides, other variations of approaches may be used to complement or to structure the previous presented paradigms. Pure thermodynamic analysis may support the development of the diverse energy modelling approaches. Regarding to the thermal manufacturing processes and the fuel-based processes, the previous approaches may be fed by this thermodynamic approach, characterisation and modelling. The thermodynamic approach describes the physical behaviour of diverse processes which are involved in the manufacturing process. In addition, other specific energy modelling approaches inherently combine economic or ecological considerations. Here may be included the thermo-economic analysis of systems which addresses the exergetic analysis of the evaluated systems [98] or the Finite Element method which, for example, reproduces the heat distribution patterns in a heat exchanger, to use the obtained parameters as model inputs.

In spite of the definitions presented here, the borders are not clearly defined. As it has already mentioned for other classifications, to find a "pure" methodology or research approach that only uses one approach without including aspects or characteristics of the others may be a difficult task [96].

#### 2.1.2.4 Summary of classification

In a bottom-up modelling the indivisible individual systems are designed and modelled in detail, and, then, are related to each other to create more complex components. Finally, the whole system is represented as the sum of interactions among the detailed individual systems. This kind of modelling potentially has the ability to take into account all the elements of the systems. This advantage is transformed into a disadvantage if a crucial element is not modelled nor identified. In this case, the model may not be representative.

In a top-down approach an overview of the system is formulated, specifying, but not detailing, any first-level subsystems. Each subsystem is then refined in yet greater detail until the entire specification is reduced to base elements. This approach is often specified with the assistance of black-boxes elements, where the element phenomena and mechanism behaviour are approached but not detailed. The bottom-up energy model of manufacturing processes is commonly modelled by System Dynamics and Dynamical Systems, whereas the top-down energy model of manufacturing process uses the Discrete Event or the Agent Based approaches. However, as was previously commented, many hybridisations and specific perspectives may adapt the characteristic of the approaches to fit to a specific scenario.

In conclusion, there are many kinds of energy systems and many ways to direct the energy modelling for the energy models (as it is schemed in Figure 2.3). The system or groups of systems may be based on two kind of analysis (Top-Down & Bottom-Up), whereas the way to tackle the system modelling may differ (Energy Modelling in Figure 2.3). The scope and the system in which the model is focused guide the kind of modelling. Diverse methodological approaches may be used in order to face the proposed challenge. As the scale of the system decreases, the temporal variable and, consequently, the time dependence of the results on the transitories of the energy models become more important. The detail of the modelling depends on the energy modelling features selected for the energy model. The degree of detail of the models (and the subsequent results) depends on the scope and objectives of the energy model.

As it is exposed in the Motivation and Objectives sections (Section 1.4 and Section 1.5) an energy efficiency potential gap was identified (among other kind industries) for high energy consuming industries which processes are not continuous. That is due to the continuous processes make the analysis and optimisation of the process (energy and material) easier. Thus, several measures have already been implemented in continuous processes. Besides, the thermal processes are usually big consumers. The features of the heating equipments generate difficulties at the characterisation of the process due to its high variability. Therefore, the most adapted technique for this kind of processes (non-continuous) turn on to be the energy modelling by simulation. In this regard, many approaches for energy efficiency and process control are present in the current literature (as shown in next section: Section 2.1.3.This kind of energy modelling is selected for the work in hand and it is in-depth explained in later sections.

Definitely, energy modelling by simulation is a powerful technique to analyse and evaluate manufacturing systems, assessing the impact of system changes, and making informed decisions[49, 99, 100]. Besides, the kind of processes in mind makes this kind of energy modelling the best option. Therefore, an in-depth analysis of the features and way of working of this modelling is explained below.

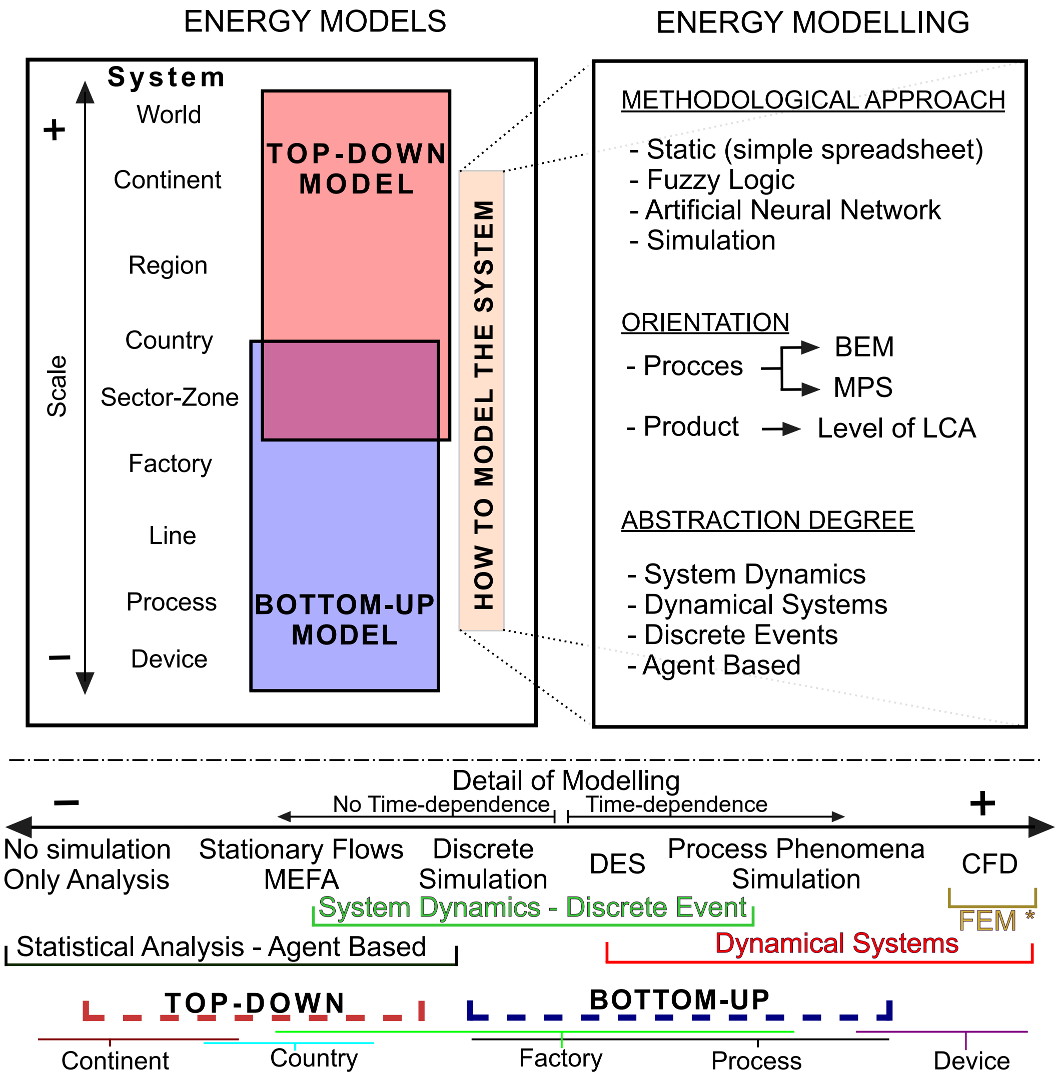


**Figure 2.3** – Classification scheme of energy models and modellings approaches.

### 2.1.3 Energy modelling by Simulation

In the "Simulation" methodological approach, the processes, sub-processes, equipment and the events are recreated to reproduce the real process virtually. After that, several hypothesis and modifications are implemented into the models to predict the results (economic, ecological, production and energy) for these new scenarios. Therefore, the variations on the characteristics of the parameters process and/or the modified features of the selected EEM are obtained, logged and evaluated. Thiede and Herrmann et al. [44, 101] conclude that the energy modelling by simulation of the process is the most adapted technique for a specific manufacturing system. Besides, the simulation approach has been highlighted as the fittest and most suitable method [102], in order to model dynamic material and energy flows in a manufacturing process environment. Therefore, the energy modelling by simulation of the process must be carried out in order to identify, evaluate and quantify the best measure to improve the energy efficiency of the process.

This kind of energy modelling allows the adaptation and adjustment of the EEM and the identification of the hidden gaps. As it is previously seen in section 1.1.2.2, the most competitive measure may vary among different scenarios. The introduction and implementation of EEM may be conducted by a series of steps of a methodology in order to automatise the measure application. However, among the proposed and analysed methodologies of energy modelling, the simulation demands the highest level of knowledge of the processes, factors and environment. Definitely, modelling by simulation is a powerful tool for energy analysis within the manufacturing industry as an effective decision-making technique in order to optimise throughput, plan and manage operations effectively, reduce bottlenecks and test various scenarios [9] as well as for the energy analysis and evaluation of hypothetical EEMs.

A well-developed model can, then, be followed by simulation, which allows for the repeated observation of the model. Therefore, the analysis of these simulated observations facilitates reaching new data and information [103]. A simulation model is referred to as static if it represents the operation of the system in a single time period; it is referred to as dynamic if the output of the current period is affected by evolution or expansion compared with previous periods. A disadvantage is that simulation models tend to be rather complex. They are often used in scenario analysis.

Within the Energy Modelling by simulation methodology two kinds of approaches can be distinguished: Continuous Simulation (CS), and Discrete Event Simulation (DES). Both of them are widely introduced into the industrial environment and the manufacturing processes [9]. DES produces a system which changes its behaviour only in response to specific events and typically models varaitions to a system resulting from a finite number of events distributed over time. DES is appropriate for systems whose state is discrete [104]. This kind of simulation approach is often employed for the production bottleneck identification, logistics of production or to optimise the production efficiency, relegating the energy consumption modelling to a second place [105, 106]. However, the neglecting of the dynamic behaviour of the energy system reduces the accuracy of simulation results [102].

CS refers to a computer model of a physical system that continuously tracks system response according to a set of equations typically involving differential equations. Continuous simulation is appropriate for systems with a continuous state that changes constantly over time. CS is often employed to reproduce the way of working of specific devices or to reproduce phenomena with a high degree of detail [107].

On the other hand, a kind of hybridisation of these opposite approaches is presented in literature. Finite Element Method (FEM) is a numerical method for solving problems of engineering and mathematical physics. This method transfers continuous features, functions, models, variables, and equations into discrete counterparts. Typical problem areas of interest are focused on specific phenomena, including structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential.

## 2.2 Economic and Ecological Modelling

The economic and ecological analysis perspective may be carried out after the energy modelling and simulation. Once the real process is represented (taking into account the energy and production variables) the economic and ecological modelling may be introduced to the assessment by means of establishing economic and ecological values to the inputs and outputs (as shown in Figure 2.4) [44]. For the economic assessment, these values are commonly obtained as the real cost of these inputs, outputs and the other cost derived from the production. The environmental impact is assessed in terms of pollutants or other emissions, such as the greenhouse gases.

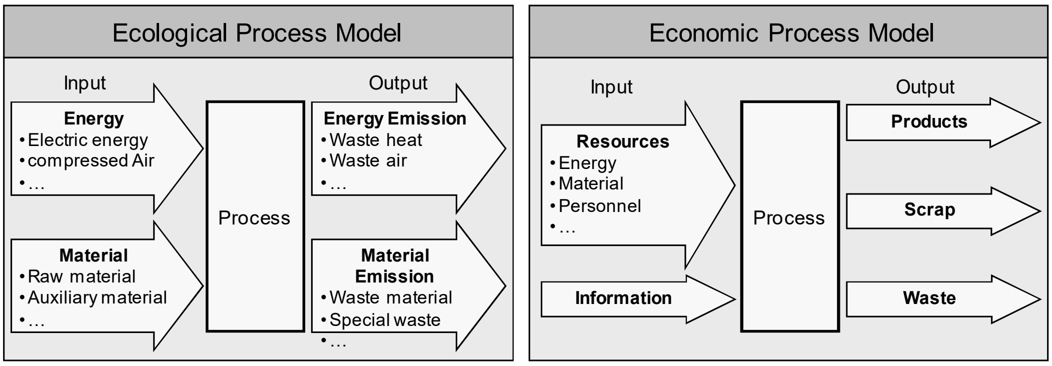


**Figure 2.4** – Ecological and Economic Modelling [44].

Despite the fact these assessment may be carried out after the energy modelling, the conceptualisation of the economic and ecological parameters should be taken into account in the energy modelling section. This previous conceptualisation (as it is shown in Figure 2.5) helps to the correct identification of the costs, ecologic parameter and to the identification of disposal or residual flows. In this regard, a holistic ecological analysis, such as the provided by Despeisse et. al. [108], may provide better identification results and a comprehensive characterisation of the wastes and residual flows.

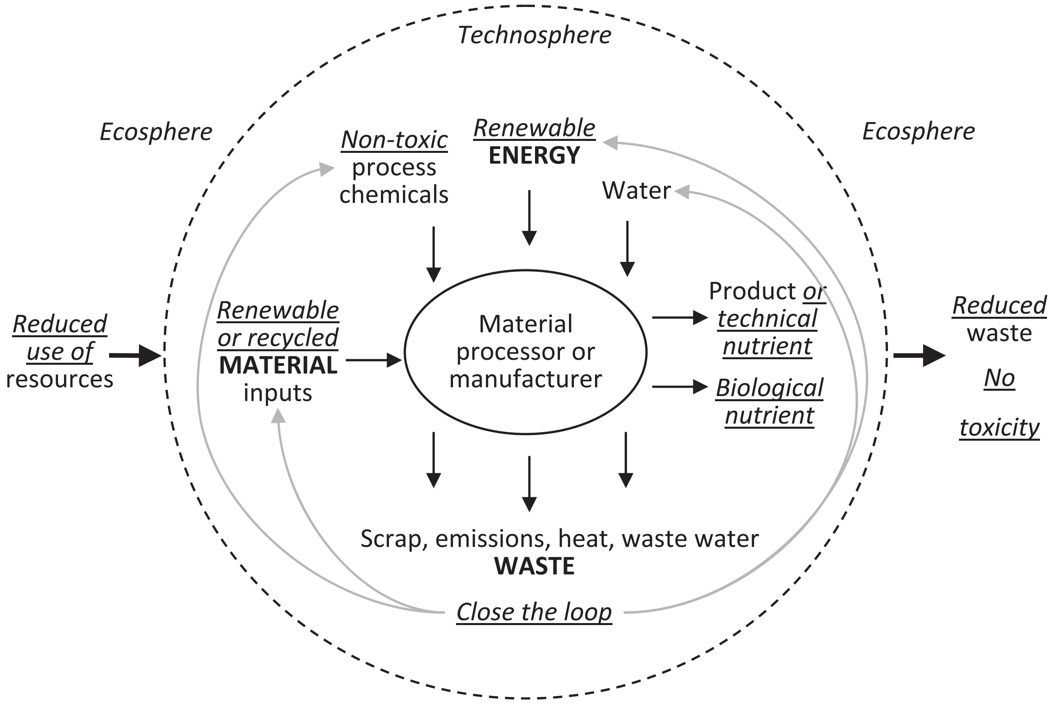


**Figure 2.5 –** Material, Energy and Waste (ecological) Modelling approach [108].

The main way to evaluate the environmental impact of a process, product, input, output or resource is by meas of a Life Cycle Assessment LCA. The LCA is a technique to assess environmental and economical impacts associated with all the stages of a product's life from initial material selection to final disposal. There are different methodological approaches or steps for the life-cycle analysis: Life-Cycle Assessment, Life Cycle Inventory, Life Cycle Impact Assessment and Life Cycle Costing [109]. This technique is based on a multi-step procedure for calculating the impact along the lifetime of a product, service or whatever under analysis. This approach is commonly carried out to obtain the carbon print of a product.

Many indicators are employed in the diverse industry sectors. These indicators may be oriented to diverse level [110]. In this regard, Ahmad et. al. classify and analyse the use of diverse industry indicators (economic, ecological and social). This classification include the diverse levels, such as product, process, plant, company or global/general, and the aspect to which they are oriented. In the case of the environmental indicators they may be oriented to aspects such as material used, energy used, water used, air emissions (pollutants, dust or greenhouse gases), wastewater and solid waste. In the same way for the economic indicators they may be oriented to aspects such as cost or profit.

Measuring energy efficiency performance of equipment, processes and factories is the first step for an effective energy management in production [55]. However, high quantities of production and energy data may not be correctly understood and may cause confusion. For that reason, the data is compressed and summarised in user-friendly indicators. A Key Performance Indicator (KPI) is a measurable value that demonstrates how effectively a company is achieving key business objectives. Organisations use KPIs to evaluate their success at reaching targets. In addition, to the production-analysis objective, energy-oriented indicators have been developed to track energy behaviour of processes or devices. These indicators allow energy managers to recognise the current situation of the device, process or plant at a glance. In the same way, for new implementation of EEMs these KPIs may provide key information to know the specific measured results. Besides, they are required to assess and track the benefits of such EEMs. These indicators may be introduced in model simulations of the manufacturing process to evaluate the effectiveness of actions over time [55].

May et al. propose a methodology to develop production-tailored and energy efficiency related KPIs [55]. One objective of these indicators is to prepare actions for EEMs implementation by identifying weaknesses and areas for energy efficiency improvements related to the energy efficiency management of production and operations. In this way, the proposed methodology for developing energy efficiency indicators highlights and represents the most representative KPIs related to energy efficiency. These indicators aim to highlight the potential areas for improving energy efficiency. The complex methodology for energy-based indicators is oriented to overcome gaps by EEMs implementation.

Schmidt et al. suggest a methodology to select KPIs for measuring the energy efficiency of manufacturing activities [111]. These indicators, which act at several levels, are able to quantify the benefits of the new EEM. The authors propose several levels of applications, from factory level to process and product level. In this work the authors provide a background of the indicators for the energy efficiency assessment. In this background, it is stated that KPIs may be adapted to each company or process and depend on the continuous measure tracking.

Chiaroni et al. present, from literature review, the most used indicators in industry for the economic evaluation of the EEM [112]. After that, they propose a novel indicator for the evaluation of investments. They propose that the entire life cycle of the EEM should be taken into account, unlike the common economic evaluation KPIs. Therefore, they propose a novel KPI called Levelized Energy Efficiency Cost (LEEC). The LEEC indicator correlates the energy savings that can be achieved through the implementation of an energy efficiency technology and the total costs incurred throughout the entire life cycle of the technology, e.g., initial investments, (O&M), disposal costs. Therefore, this KPI returns the real cost of the energy provided by this implementation.

Besides, KPIs may help to track the state of the device at maintenance decision-making process as proposed by Hoang et al. [113]. In this work, the indicators are designed (by an in-depth process analysis) to know when a device is working over nominal conditions, in a energy inefficient zone. The authors propose an energy efficiency modelling of the system for prognostic of the energy efficiency indicator to estimate the remaining energy efficiency lifetime of the system. Similar work with different orientation is proposed by Mourtzis et al. [114], providing a fast and accurate estimation of maintenance. The EEM implementation is not enough to tackle the whole potential of the energy efficiency process. The process or measure must be energy-tracked and analysed to know how it works [115]. The introduced approaches of energy indicators help this evaluation at EEM project implementation step and provide interesting information of their working behaviour. In this regard, the developed KPIs help to assess the industrial environment

In summary, the most common indicators to categorise and characterise the both modellings are represented in Table 2.1. Despite this list of indicators, there is not a common set of indicators identified for any industry. Besides, there is a lack of consistent, practically applicable and measurable indicators [110]. Notwithstanding there is not high frequencies of usage for each indicator, the assumption of several of them for any process or industry contributes to a better economic and ecological characterisation of the process.

| **Environmental Indicators** | |
|---|---|
| **Material used** | Overall materials, Raw materials, Primary packaging materials, Secondary packaging materials, Packaging related chemicals, Chemicals for cleaning and washing and Tooling materials |
| **Energy used** | Overall energy, Fuel (diesel, petrol, etc.), Natural gas, LPG, Wood/coal and Electricity |
| **Water used** | Overall water, Water in process and Water in product |
| **Air emissions** | Overall emissions, CO2, CO, SOX, NOX, N2O, H2S, H2, Volatile organic compounds, Heavy metals, Sulphur, Methane, Benzene, Ammonia, Particulate matters (suspended particles), Smoke, Dust and Heat |
| **Wastewater** | Overall wastewater, Heavy metals, COD, BOD, pH, Nitrogen compounds, Phosphorus, Arsenic, Chromium, Suspended solids, Oil, Protein and Cellulosed organic matters |
| **Solid waste** | Overall solid waste, Hazardous waste, Non-hazardous waste, Waste residue, Packaging waste, Crushed stone and sand, Waste activated charcoal, Food remains, Municipal waste, Bio-degradable waste, Sludge and methane dregs, Sand residue, Slag, Sand-down dust, Sawtrim and sawdust and Spent catalyst |
| **Economic Indicators** | |
| **Cost** | Overall materials, Raw materials, Packaging materials, Waste disposal, Operation, Investment, Fixed asset depreciation, Tax, Labour, Overhead, Maintenance, Environmental fines, Utilities (electricity, water, etc.), Injuries, Facility or equipment, Warehousing and logistics, Defective products, Research and development and Community development |
| **Profit** | Revenue, Profit, Market value, Return on investment, Payback period, Turnover (selling inventory) and Subsidy or tax relief from government |

Table 2.1 – Economic and Ecological indicators by Ahmad et.al. [110]

The aforementioned indicators are intended to explain the process operation and the other relevant process features at a glance. These indicators provide relevant information to evaluate EEMs, when comparing the existing indicators values with the expected indicators attributed to the EEM modifications on the process. This information is useful for the industrial energy managers to select the correct option to their processes.

## 2.3 Decision-Making Process

Decision-making process is the sequence of selecting choices by identifying a decision, gathering information, and assessing alternative resolutions. The energy manager, in the interest of improving the competitiveness of their factories, have to select among different options in which the resources will be employed. Figure 2.6 suggests an approach to a sequential steps procedure to take the best decision. To provide to decision-makers an instrument to address future investments or to select from different options is always an important task in the business environment. In the manufacturing process setting, according to energy efficiency investments, it is not different. The decision-making process, in consonance with the industrial manufacturing sector, is settled in the two brands of the industrial economics: policy-makers side and the industry energy manager side.

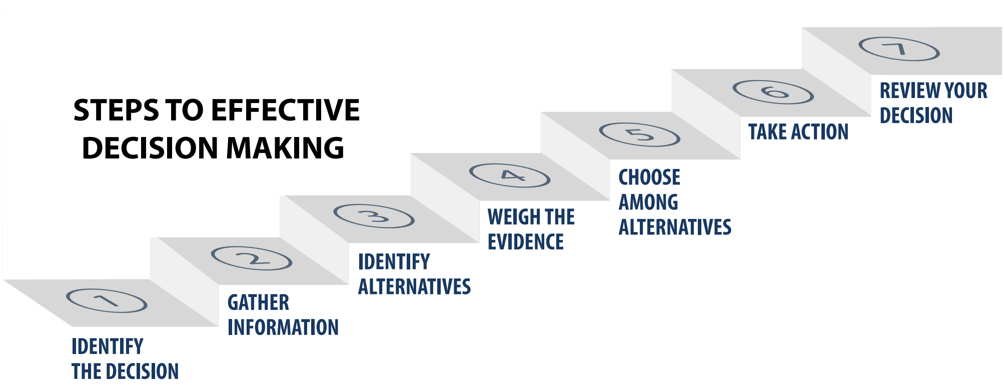


**Figure 2.6** – Steps for Decision Making Process [116]

### 2.3.1 Policy-makers and industrial perspective

The first part assesses how the policies affect the introduction of EEMs and the process improvement. The energy decision and policy-making problems include selecting among energy alternatives, evaluating energy supply technologies, determining energy policy and energy planning. There is a wide range of studies about energy decision-making problems in literature and different types of energy alternatives are considered in these studies [117].

Once the policy part is properly established the energy manager must select the best measure to improve the energy efficiency of the involved plant or processes, taking into account both the policy criteria, which regulates by means of restrictions, taxes or incentives, and the technical specifications, which derive from the technical solution. To provide and summarise the elements which intervene in the making process has become an important task [118]. Therefore, in order to supply with the best and most accurate technical information, a perfect definition and assessment of the proposed EEMs, as well as tools to ease the comprehension and the application range of these EEMs, are required.

Besides, to combine both perspectives is a difficult but necessary task. Understanding the policies in accordance with the barriers affecting different kinds of companies is necessary to better match the options to their needs and requirements, as well as to develop mechanisms and policies successfully. Lack of information combined with unfavourable reasoning in decision-making impedes the adoption of profitable EEMs [119].

### 2.3.2 Working operation, tactical and investment-process

In the end, a EEM must be introduced to provide results. If the temporal-opportunity for the EEM insertion is lost the measure would not be useful. In this sense, and within the industrial perspective, three temporal "purposes" may be clearly identified: the real-time decision making approaches, the tactical planning and the investment-step EEM decision making approaches. The first one affects the operating modes, providing decision support for the operators, who manually adapt the assets set-points. And it also conditions the automatic production set-points control through advanced process control techniques. The second purpose alludes to the load-schedule and energy forecasting issues. This part involves the optimisation of process loads based on diverse criteria, such as energy price, machine availability or the customer demand. In this sense, many actions may be tackled, such as moving consumption to off-peak hours, schedule start-ups and operating costs or providing and analysing multiple scenarios and energy types. At least, the investment-step acts at the development, design and construction phase, providing previous-to-implant information among the hypothetical EEMs for a system, process or plant.

## 2.4 Methodological research approaches and commercial tools

Although most companies try to generate productivity enhancements through EEMs, there often exists a disconnection between such improvements and the associated energy expenses/savings resulting from them [120]. Besides, energy efficiency studies underestimate both energy and the non-energy benefits of the identified EEMs [121]. In this regard, and to solve these problems, several methodologies and commercial tools have been developed to try to cover all the energy efficiency gaps and to provide support for both industrial environment as well as to guide the policy makers.

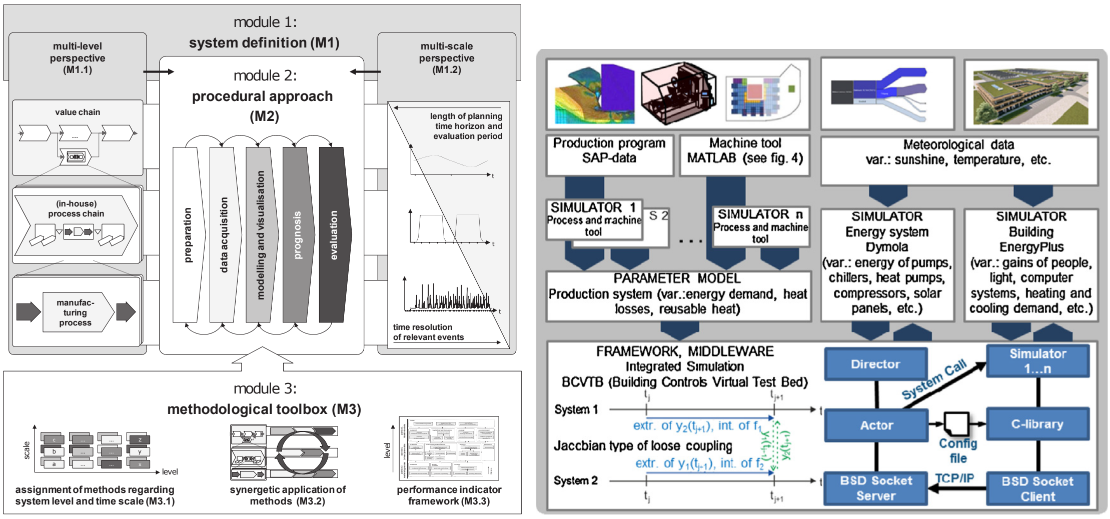
### 2.4.1 Holistic Modelling Methodologies

As it was identified, the holistic methods to improve the energy efficiency or to evaluate and assess a process take into account more characteristics of the production process and allow the identification of synergies. Therefore, most of the relevant methodologies and procedures oriented to the manufacturing process are explained here.

Energy management, digitalisation of the process and the introduction of EEM are trending topics both for industrial environment and for research teams in order to make the manufacturing process more competitive. In this sense, many methodologies are emerging to manage this digitalisation and the energy-and-material flows, with the consequent increase of energy efficiency in production [44, 52, 122, 123, 111, 124, 125, 61, 126, 127]. These advances in obtaining and processing data into useful information allow to acquire deeper knowledge of the manufacturing process. These data and information may be understood and analysed from diverse points of view.

Understanding the entire manufacturing process as a unique system seems to be the best option in order to take total control of the energy-and-material flows [44]. Not only does this point of view see the energy flow data and plant information as a whole, but also integrates production, ecological and economic considerations. This holistic view links the relation among data series (energy data, processes data, schedule data, physical process attributes (temperature or pressure level)). One branch of the proposed holistic methodologies covers from building envelope energy to energy consumption processes (according to BEM and MPS respectively), as shown in Figure 2.7b [128]. When the manufacturing process requires high amounts of energy (EII) the building envelope may be set aside. In this case, the methodologies focus on the manufacturing process, the main energy consumer. The total control and knowledge of the EII processes is indispensable to achieve objectives such as improving the energy efficiency or inserting renewable energy sources [129].

A holistic multi-level and multi-scale analysis perspective allows to select the fittest EEM for the entire system [126]. The multi-level analysis covers the value chain, the process chain, the process and the specific device, while the multi-scale covers the operating scale (seconds-minutes), the tactical scale (hours-days) and the strategic scale (months-years). Ideal approaches should integrate the different hierarchical system levels, so that all perspectives are applicable and a multi-time-scale perspective can be taken (criterion planning/evaluation perspective on production) [126]. Heinemann [126]



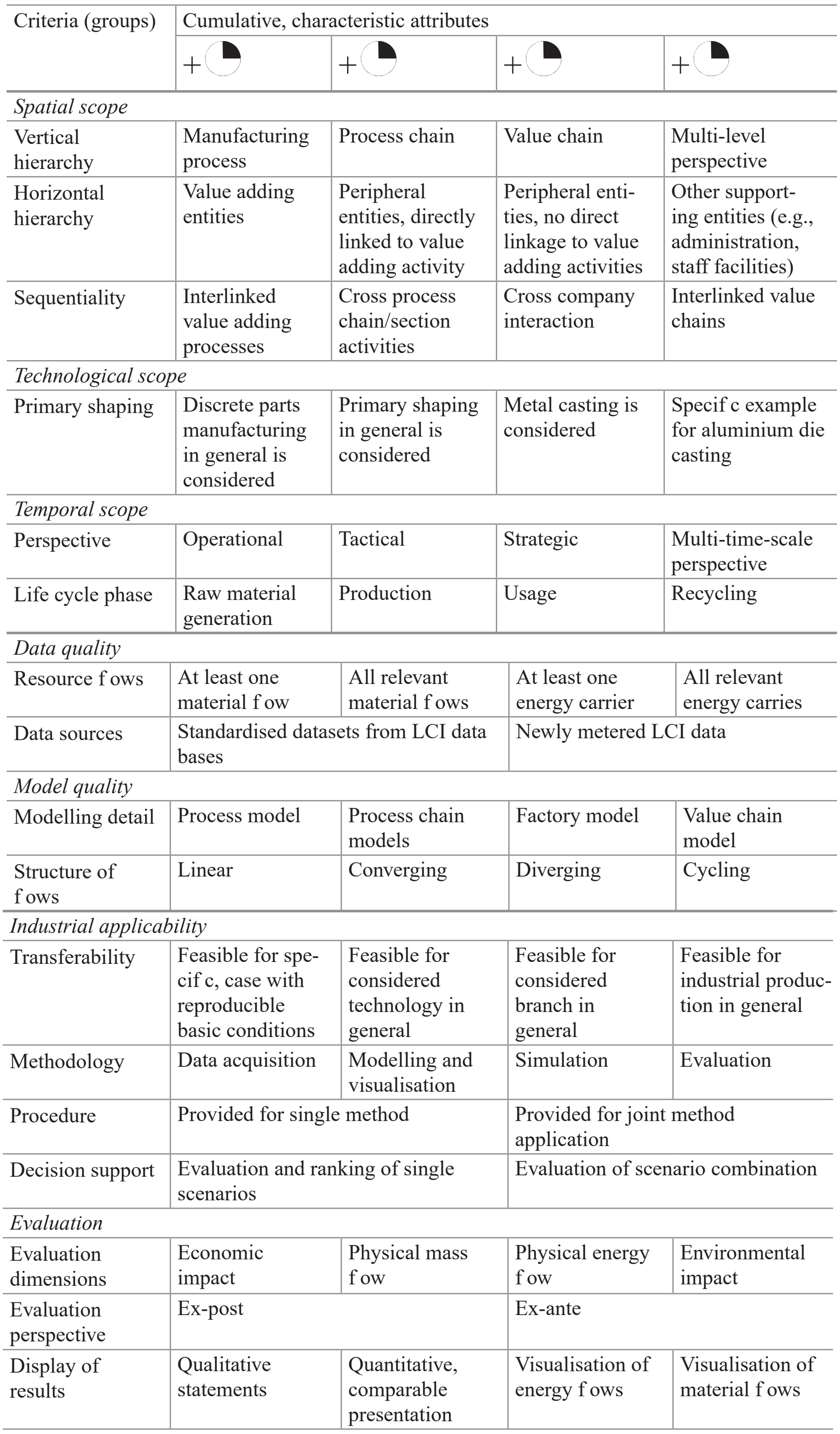
**(a)** Holistic multi-level multi-scale framework [126]. **(b)** High-complex integral methodology [128]

**Figure 2.7** – Frameworks for enhancing energy and resource efficiency in production

proposes a novel approach, which synergetically assigns methods and tools towards an energy and resource efficient, hierarchically organised industrial production. Besides, it is presented a novel method in order to evaluate the proposed approach against the state of the research (as shown in Figure 2.8. All the levels (represented in the Spatial Scope) and the scales (represented in the temporal scale) in addition to other subjects are accounted for and assessed in this evaluation criteria.

Despeisse et.al. [108] propose that data analysis should focus on the resource flows linking the system components and on how technologies are consuming and transforming the flows to create process maps of the manufacturing system. Besides, they compare the manufacturing process with an ecosystem, focusing in the fact that the overall productivity or efficiency is more important than the efficiency of individual processes or technologies. In this regard, this fact demonstrate that the modifications of the dynamics among processes may generate more relevant consequences than the modification in the process itself. This research, which is focused on resource flows to identify potential connections, proposed that the outputs of some activities could be used as the inputs, promoting recovery and reuse options. In addition, it is concluded that the manufacturers need practical approaches to improve the environmental performance in a systematic way, which evidences the need of user-friendly approaches for the industrial manager.

A representative example of the diverse range of levels and scales is shown in Figure 2.7a. The modern manufacturing process has highly dynamic energy patterns [125]. The modifications of the process, the substitution of the devices or the introduction of an EEM may affect the other processes (of the value chain) upstream and downstream. This only could be properly analysed from this holistic point of view. Compared to the isolated analysis of processes, highlighting the dependencies among the different energy



| Criteria (groups) | Cumulative, characteristic attributes | | | |
|---|---|---|---|---|
| | +◔ | +◔ | +◔ | +◔ |
| *Spatial scope* | | | | |
| Vertical hierarchy | Manufacturing process | Process chain | Value chain | Multi-level perspective |
| Horizontal hierarchy | Value adding entities | Peripheral entities, directly linked to value adding activity | Peripheral entities, no direct linkage to value adding activities | Other supporting entities (e.g., administration, staff facilities) |
| Sequentiality | Interlinked value adding processes | Cross process chain/section activities | Cross company interaction | Interlinked value chains |
| *Technological scope* | | | | |
| Primary shaping | Discrete parts manufacturing in general is considered | Primary shaping in general is considered | Metal casting is considered | Specific example for aluminium die casting |
| *Temporal scope* | | | | |
| Perspective | Operational | Tactical | Strategic | Multi-time-scale perspective |
| Life cycle phase | Raw material generation | Production | Usage | Recycling |
| *Data quality* | | | | |
| Resource flows | At least one material flow | All relevant material flows | At least one energy carrier | All relevant energy carries |
| Data sources | Standardised datasets from LCI data bases | | Newly metered LCI data | |
| *Model quality* | | | | |
| Modelling detail | Process model | Process chain models | Factory model | Value chain model |
| Structure of flows | Linear | Converging | Diverging | Cycling |
| *Industrial applicability* | | | | |
| Transferability | Feasible for specific, case with reproducible basic conditions | Feasible for considered technology in general | Feasible for considered branch in general | Feasible for industrial production in general |
| Methodology | Data acquisition | Modelling and visualisation | Simulation | Evaluation |
| Procedure | Provided for single method | | Provided for joint method application | |
| Decision support | Evaluation and ranking of single scenarios | | Evaluation of scenario combination | |
| *Evaluation* | | | | |
| Evaluation dimensions | Economic impact | Physical mass flow | Physical energy flow | Environmental impact |
| Evaluation perspective | Ex-post | | Ex-ante | |
| Display of results | Qualitative statements | Quantitative, comparable presentation | Visualisation of energy flows | Visualisation of material flows |

**Figure 2.8 –** Criteria and characteristic attributes of the main area application proposed by Heinemann [126]

systems helps to identify further saving potentials and synergies for the optimisation of the manufacturing process. Holistic methodological approaches may combine the high detailing on the process energy modelling with the plant simulation overview [49] (more oriented to the technical building services or to the production planning control).

The EEMs for the optimisation of the manufacturing process act at the different process manufacturing scales. In the lowest stage, the optimisation is achieved by modifying the device (operative-technological scale) [130, 131, 132] or modifying the manner of working of the process (operative scale). In the upper scale (tactical scale), the process is optimised by adapting the production planning and scheduling, modifying the energy source mix [125, 133] or replacing this energy source with recovered energy [134]. In the highest scale (strategic scale) actions may be considered to change the scope of the entire plant, such as the product specialisation among factories [128]. The strategic scale may affect the plant or process design stage. The plant and process design is an integral part of any product development process. The decisions taken at this stage account for the majority of the financial and environmental cost of a product [127]. Therefore, the energy efficiency potential (conditioned by the financial-economic impact) of a manufacturing process will be determined by this phase [128]. This behaviour is schemed in Figure 2.9.

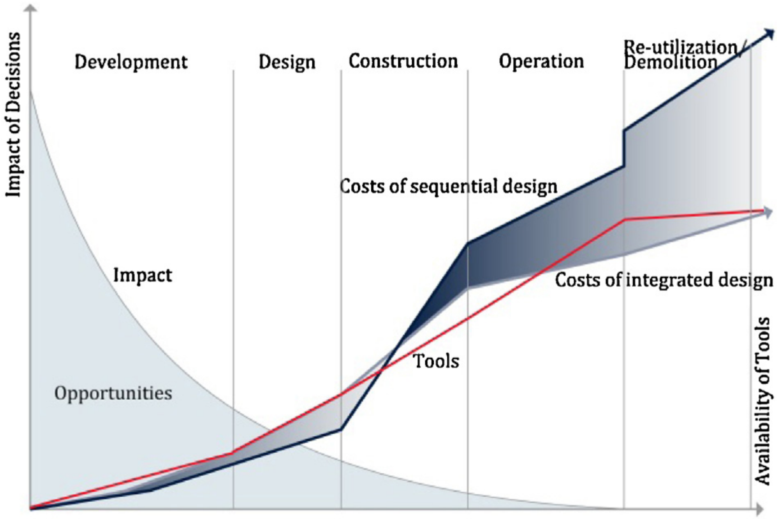


**Figure 2.9 –** Development of costs, impact and tools throughout the life-cycle phases of a production facility [128].

Many research teams propose to work in the process and device optimisation level [122, 111, 135, 87] to, then, extend the optimisation process to the whole manufacturing process [124], i.e. value chain level. Weinert et al.[124] introduce a methodology for planning and operating energy efficient production systems (Figure 2.10). The key element of this methodology is the knowledge of the power consumption profile of individual machines [136]. The power consumption profile is approximated by blocks, according to operating states, and divided in time-variables, production dependent elements and non-variable elements. The total power consumption profile is represented by the sum of the machine or device specific consumption profile, using block simplification, and the previous defined relations as well as dependencies among processes or devices. In the same way, Salonities et al.[137] focus on the process planning at tactical level. They direct their efforts to develop a decision support tool for assessing the energy efficiency of alternative process plans. The decision support combines energy auditing, life-cycle assessment and a specific mathematical method for ranking various alternative process plans which are subjected to a multi-criteria analysis.

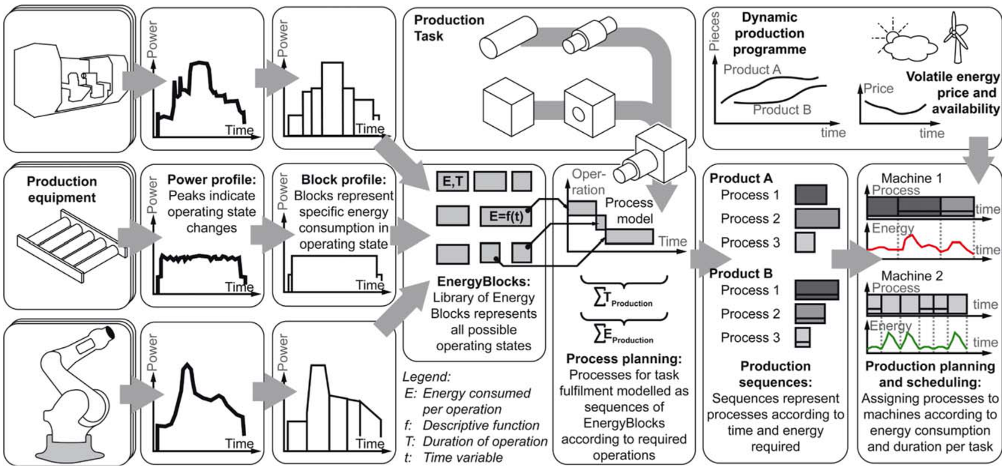


**Figure 2.10 –** Energy-profile block methodology for device-machine level consumption approach [124].

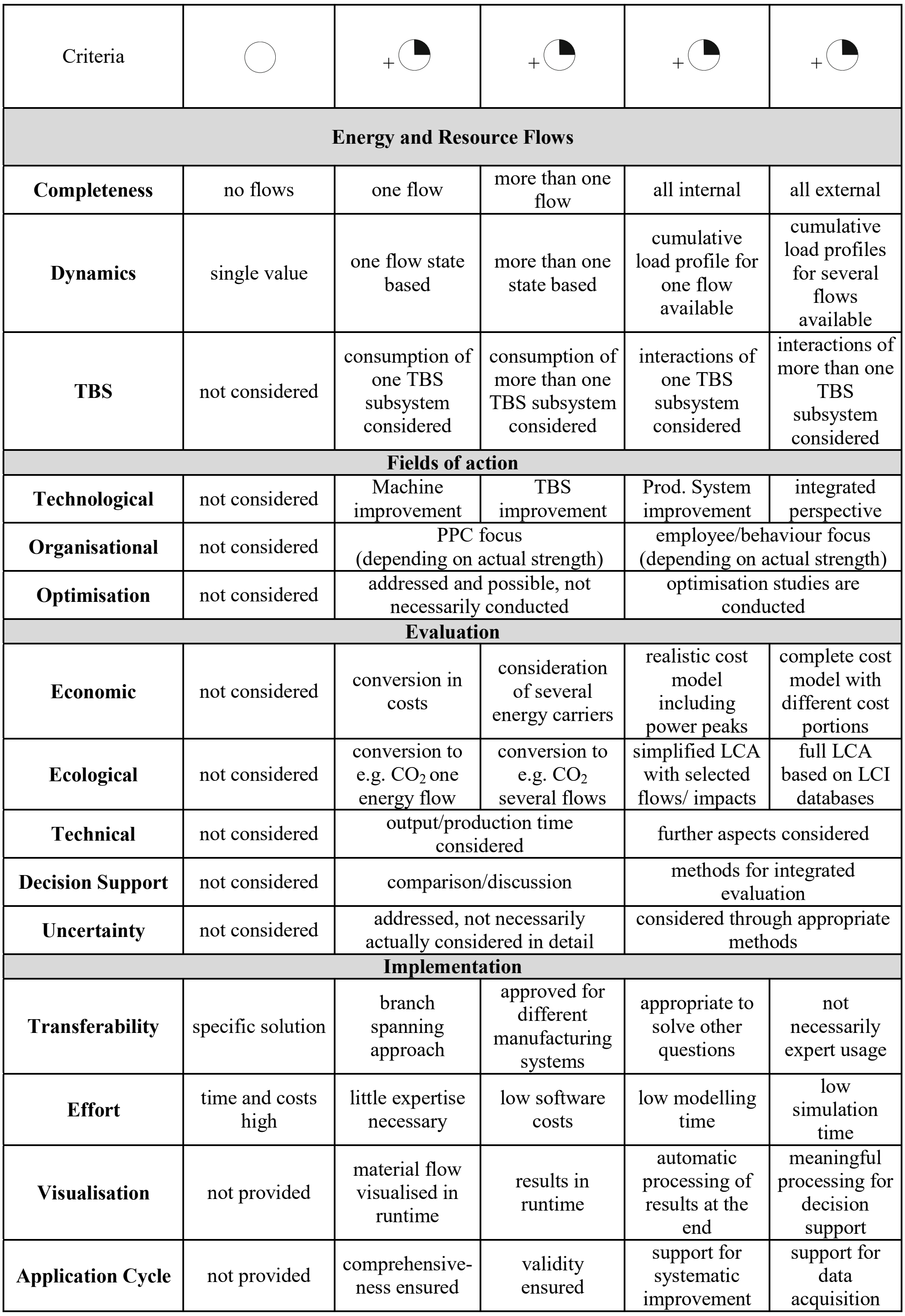
Traditionally, decisions are made based upon intuition and experience, sometimes with the support of spreadsheet tools. These approaches can be risky and are unnecessary in decision making today [76]. With the new paradigm of process digitalisation [138] a new level of data acquisition is emerging. High amounts of data may be collected and processed. These amounts of data allow the operators and managers to foresee events; providing the creation of predictive maintenance strategies [113], and proposing scheduling or operation modifications; reducing the energy consumption [139].

An indispensable part of the optimisation task is to process and understand this database. The data are used to generate models to represent the real manufacturing process in virtual environments. These models may be used to describe the energy behaviour of the system. The energy modelling is a powerful technique (for any methodological procedure: simulation, fuzzy logic, artificial neural network, static calculation or combinations) to characterise the data (for any mathematical approach: systems dynamics, dynamic systems, agent base, DES or combinations) into virtual environments to, then, analyse complex manufacturing systems allowing the evaluation of the impact of system changes [49, 99, 100].

Thiede et al. [44] identify four main alternatives of methodological approaches (statics calculations, fuzzy logic, artificial neural networks and simulation) and conclude that the energy modelling by simulation of the process is the most adapted technique for a specific manufacturing system [44, 103]. The main advantage of this methodological approach is that it may be easily adapted to the uncertainties or the high variability of the non-continuous manufacturing processes [140]. The energy modelling by simulation allows to optimise the process and to identify the energy efficiency hidden gaps during the process operation. Then they develop a generic (not related or restricted to a specific case) energy flow oriented manufacturing system simulation approach. Besides, in the same way than Heinemann, in order to evaluate their methodology, Thiede propose a criteria for evaluation of research (Table 2.11), which gives and overview of the deepening range for many aspects of the research project.

Beier presents an in-depth evaluation of existing research approaches related to electrical energy flexibility of manufacturing systems [48]. In this work, manifold methodologies and research are presented and analysed. Additionally, a novel energy flexibility planning and improvement method for real-time control of manufacturing systems is developed [129]. The proposed model, which focuses on the dynamic behaviour of renewable variable energy sources, allows the calculation of the manufacturing system evolution and, thus, the identification of relevant material and energy flows as well as the identification of related KPI under different system setups. The main schema of the proposed method is shown in Figure 2.12.

In conclusion, these approaches provided by different research teams, which combine different characteristic and requirements, are oriented to different objectives and fields of application (such as, a specific kind of industry, diverse deepening of analysis or different modelling orientations). In this regard, on the commercial perspective several software and tools, which are adapted to specific processes or objectives, have been developed.



| Criteria | ○ | +◔ | +◔ | +◔ | +◔ |
|---|---|---|---|---|---|
| **Energy and Resource Flows** | | | | | |
| **Completeness** | no flows | one flow | more than one flow | all internal | all external |
| **Dynamics** | single value | one flow state based | more than one state based | cumulative load profile for one flow available | cumulative load profiles for several flows available |
| **TBS** | not considered | consumption of one TBS subsystem considered | consumption of more than one TBS subsystem considered | interactions of one TBS subsystem considered | interactions of more than one TBS subsystem considered |
| **Fields of action** | | | | | |
| **Technological** | not considered | Machine improvement | TBS improvement | Prod. System improvement | integrated perspective |
| **Organisational** | not considered | PPC focus (depending on actual strength) | | employee/behaviour focus (depending on actual strength) | |
| **Optimisation** | not considered | addressed and possible, not necessarily conducted | | optimisation studies are conducted | |
| **Evaluation** | | | | | |
| **Economic** | not considered | conversion in costs | consideration of several energy carriers | realistic cost model including power peaks | complete cost model with different cost portions |
| **Ecological** | not considered | conversion to e.g. $CO_2$ one energy flow | conversion to e.g. $CO_2$ several flows | simplified LCA with selected flows/ impacts | full LCA based on LCI databases |
| **Technical** | not considered | output/production time considered | | further aspects considered | |
| **Decision Support** | not considered | comparison/discussion | | methods for integrated evaluation | |
| **Uncertainty** | not considered | addressed, not necessarily actually considered in detail | | considered through appropriate methods | |
| **Implementation** | | | | | |
| **Transferability** | specific solution | branch spanning approach | approved for different manufacturing systems | appropriate to solve other questions | not necessarily expert usage |
| **Effort** | time and costs high | little expertise necessary | low software costs | low modelling time | low simulation time |
| **Visualisation** | not provided | material flow visualised in runtime | results in runtime | automatic processing of results at the end | meaningful processing for decision support |
| **Application Cycle** | not provided | comprehensiveness ensured | validity ensured | support for systematic improvement | support for data acquisition |

**Figure 2.11** – Criteria for evaluation of research by Thiede [44].

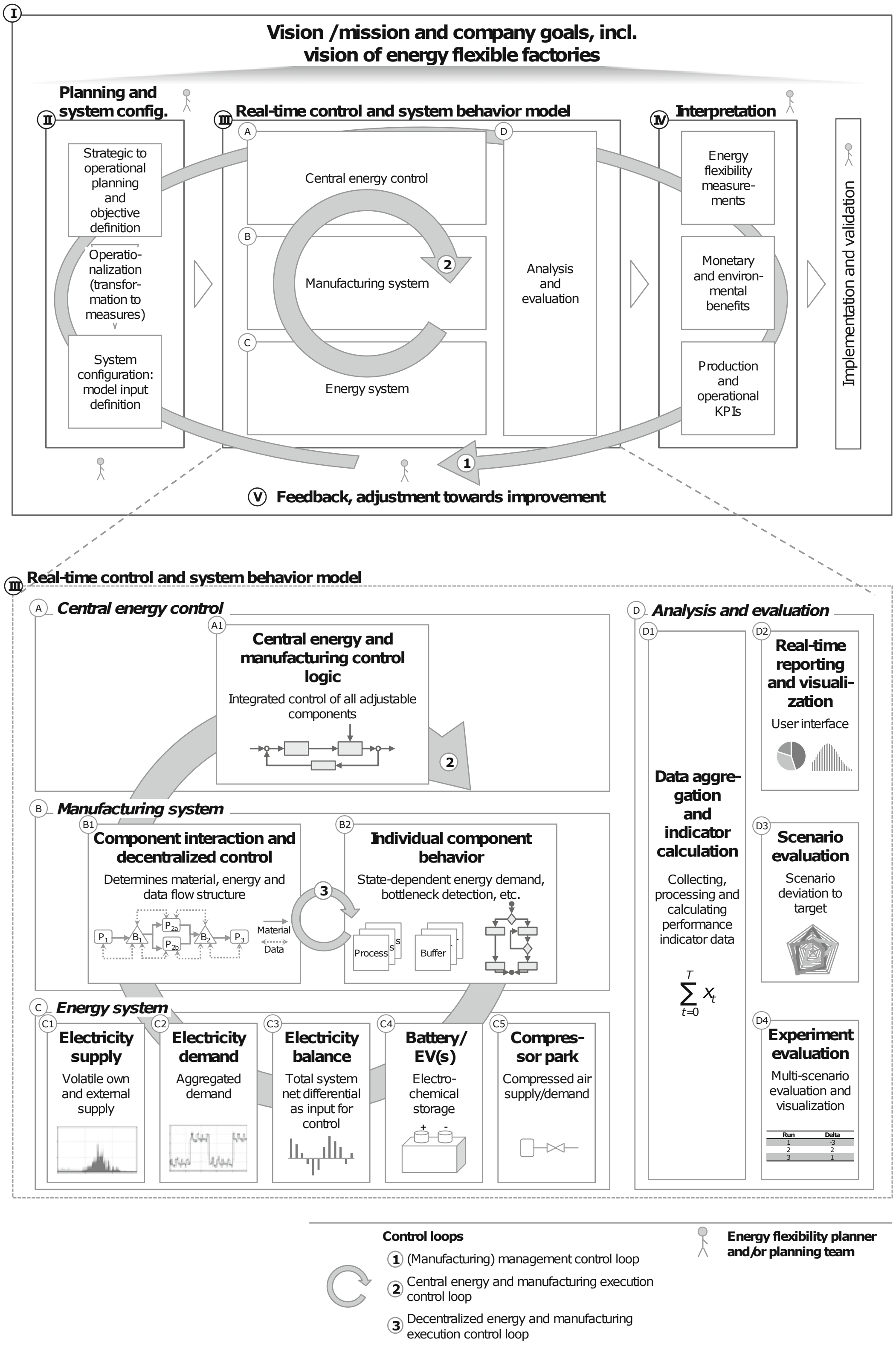


**Figure 2.12 –** Schema for energy flexibility planning and improvement by Beier [48]

### 2.4.2 Energy modelling software and commercial tools

Currently, there are many energy simulation software tools which cover different levels of complexity and response to different variables. The most complete software tools are also the most complex and, therefore, require greater expertise. Each software has its particularities and presents a diverse scope. They may be differentiated between calculation or mathematical engines, such as spreadsheet (Excel) or tools for mathematical calculus and particular specific-oriented software. These specific software may be specialised in diverse branches of the manufacturing process, while some are oriented to the building energy simulation others are directly related to the process energy profile.

Garwood et al. [49] provide a wide classification of the identified tools, based on the literature analysed by previous research work, which is oriented to energy modelling by simulation. The final aim of this work is to identify the best tool for the holistic simulation of the energy and the resource use in a factory. In this respect, the tools are classified according to the level (device-process-plant) which the tool is capable of covering, to their ability to link these levels and whether the tool is open-source or not. In summary, the author concludes that, despite the progress made to date, the generated simulation tools have been, generally, simplistic and “proof of concept” in nature, resulting in possible solutions towards a holistic energy simulation but requiring further development to obtain a comprehensive simulator [49].

| Software Tools | Machine Level | Process Level | Facility Level Energy | Facility Building | Ability to Link Layers | Open Source |
|---|---|---|---|---|---|---|
| AnyLogic | ✓ | ✓ | ✓ | ✓ | ? | ✗ |
| Arena | ✓ | ✓ | ✓ | ✗ | ? | ✗ |
| AutodeskGreenBuildingStudio | ✗ | ✗ | ✓ | ✓ | ✓ | ✗ |
| AutodeskRevit | ✗ | ✗ | ✓ | ✓ | ✓ | ✗ |
| BuildOpt-VIE | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| DELMIA | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| DesignBuilder | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| ecoinvent | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ |
| EnergyPlusSimulationEngine | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |
| ESP-r | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |
| eQUEST | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |
| FlexSim | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| HKSim | ? | ? | ✓ | ? | ✗ | ✗ |
| IBPT | ? | ✓ | ✓ | ✓ | ✓ | ✓ |
| IDA ICE | ? | ? | ✓ | ✓ | ✓ | ? |
| IES VE | ? | ✓ | ✓ | ✓ | ✓ | ✗ |
| MicrosoftExcel | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| ModelicaBuildingsLibrary | ✓ | ✓ | ✓ | ✓ | ? | ✓ |
| Plant Simulation | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| Sefaira | ✗ | ✗ | ✓ | ✓ | ✓ | ✗ |
| SIMFLEX/3D | ✓ | ✓ | ? | ? | ? | ✗ |
| Simio LLC | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| SIMUL8 | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| Simulink&MATLAB | ✓ | ✓ | ✓ | ✓ | ? | ✗ |
| TRACE 700 | ✗ | ✗ | ✓ | ? | ? | ✗ |
| TRNSYS | ? | ? | ✓ | ✓ | ✓ | ✗ |
| WITNESS | ✓ | ✓ | ? | ? | ✓ | ✗ |

Table 2.2 – Summary of modelling tools according to Garwood et al. [49]. Classification in accordance with "holistic simulation" capability.

In the field of DES, some commercial tools stand out as reported by Dias et. al [141], such as Arena, ProModel, FlexSim, Simul8, WITNESS, ExtendSim, Simio, PlanSimulation, AnyLogic, as shown in Figure 2.13. These computer simulation tools have been selected according to the intensity of usage or presence in literature or in the industrial environment [141]. However, as the author highlights, the contexts of the simulation tools, whether in the academic environment or in the industry is in constant change and, thus, the proposed study and list should be regularly updated. A considerable part of the aforementioned popular commercial tools allows to model the energy behaviour of the processes, which for the most part are deterministic modelling which does not consider dynamical changes or interactions among process consumption profiles.

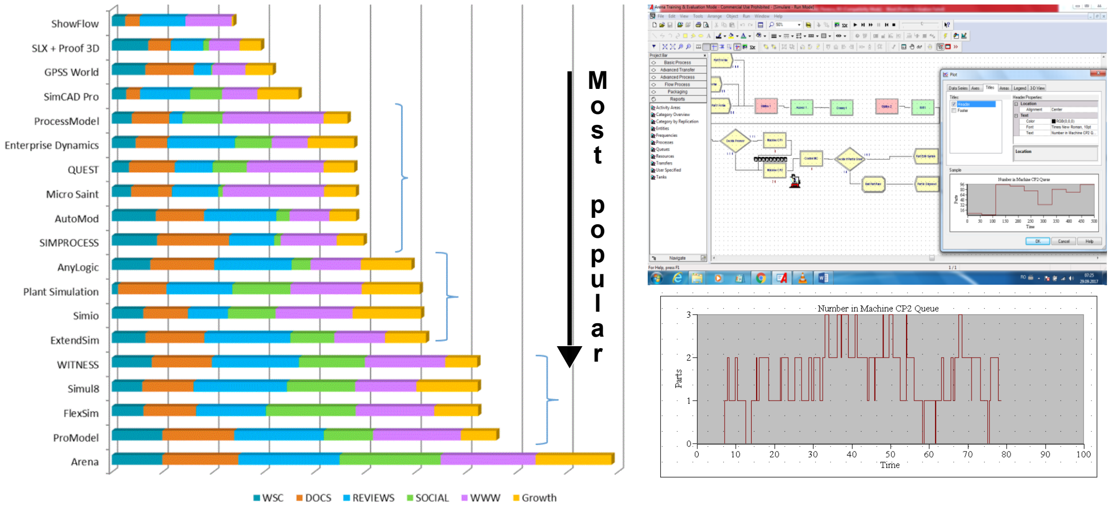


**Figure 2.13** – DES popularity list from [141] (left) and manufacturing process capture window from ARENA software [142] (rigth)

On the one hand, and related to manufacturing thermal processes or heat transfer specific calculations, other specific commercial-research software may be outlined, such as PHAST [143], Einstein [144], FurnXpert [145], HTRI Xchanger Suite [146], TechCalc 2.0 [147], etc. Each software is focused on different areas such as furnaces assessment (or heating equipment), facility thermal audits, heat exchangers, thermal insulation, or process integration. These software solutions allow to reproduce processes or phenomena with higher degree of detail than the DES software. However, the linking of processes is still not very developed. Additionally, the standardisation of the tool does not allow the in-depth degree of specification for the processes or the device specific features. The main advantage of these kinds of software is the low complexity, comparing to continuous simulation (mathematical engines), derived from the standardisation of the inputs and the easy-friendly layout and way of working.

But on the other, the software programming-based tools which are highlighted in the industrial environment and in the research literature, according to manufacturing process, allow to reproduce the process with a greater detail. These tools are characterised by a more generic orientation (to many kind of matters and objectives, than the previously addressed. These which are based on computer programming software tools, such as MATLAB, Dymola (modelica language), ANSYS and HSC Chemistry, require high level of modelling knowledge in their respective languages. Some of these commercial tools present packages or libraries which help the process programming. In this regard, a wide variety of kinds of research projects have been developed with these tools, such as [148, 149, 150, 151, 152, 153, 154], proving and evaluating the flexibility of these tools. The main advantage of these tools is that they make any modifications, variability or element introduction possible. However, the demanded complexity and the required expertise, in addition to the higher computational qualification requirements, in order to tackle the tools running move the industrial operator and the factory energy manager away. To address this problem, these tools often present applications and guide user interfaces, which, after a hidden programming development, ease the introduction to the manufacturing process.

Conforming to the real-control and electrical energy flexibility of manufacturing systems, some tools work on hourly optimisation of industrial process planning. These tools, according to forecasts of relevant market prices, consider all production constraints to advise the best operation strategy which minimises the total cost of energy. In this regard, the EnMS-tools provide visual applications for real-time monitoring an targeting, energy-load forecasting as well as its correspondent energy demand and supply optimisation according to electricity market. An updated (2017) overview of currently available modelling tools as well as their capabilities is presented by Ringkjøb et. al.[155]. The authors conclude that, despite the huge amount of tools and the working specification of these tools (such as timescales and modelling horizons and capabilities), there are still some challenges related to the representation of spatio-temporal variability and openness as well as to the demand-side perspective.

On the decision-making process perspective, practically all the tools provide information to ease the decision making process as well as to help the manager to understand all the implications related to the working operation and to the investment process. Despite this amount of available and "accessible" information for the decision-making process, the apparent lack of information on the industrial manager side still remain as a barrier. Therefore, there is a real need to develop and use optimisation techniques and tools to enhance energy and material efficiency [156] as well as to move these techniques and tools closer to the industrial environment.

## 2.5 State of the art conclusions

From the analysis of the State of the art, several conclusions may be highlighted. Based on the need of energy efficiency improvement in the industrial sector (and in the manufacturing processes in particular) identified in the first chapter (Section 1), the state of the research is focused on proposing several tools and methodologies which are oriented to reduce the energy consumption and the material required by means of the improvement and optimisation of processes and devices. However, the lack of applicability of the existing approaches and tools and the fact that no integral and holistic approaches for modelling and evaluation of production systems are available, is recurrently confirmed in literature [126, 108].

In order to cover the identified gap (shown in Section 1), it is concluded that the process must be analysed and, then, reproduced to evaluate the proposed solution. The tools and methodologies presented in this chapter provide several ways and perspectives to asses the processes. With this aim, reproducing an energy consuming process requires an energy model in order to evaluate the process interactions with the product and surroundings for the proposed EEMs. Correctly analysing a process requires adaptations to both the kind of process and the kind of analysis. For the processes under evaluation, i.e. the non-continuous thermal processes, the fittest and most promising method is the energy modelling by simulation.

An integral vision (energy, economic, production and ecological) of the process is indispensable in order to obtain the correct assessment of the process as well as the proposed EEMs. In this respect, some approaches, despite the fact of containing correct characterisations of the aforementioned elements, do not present a dynamic view of the process phenomena. These approaches are perfectly applicable for continuous process or processes with low production variability. However, the characteristics of the processes under evaluation, i.e. the non-continuous thermal processes, require the evaluation of transient phases, dynamic behaviour or variable phenomena.

The holistic perspective allows to evaluate the system by taking into account the different levels of working and production (from operative to strategical point of view) and scales (from device to plant). In this regard, the identified tools which, allow a dynamic interpretation of the events and phenomena, are commonly restricted to device evaluation.

Besides, and as it is identified, any final decision related to energy efficiency or to the implementation of a certain EEM is taken by the industrial managers. Providing the most complete and exhaustive information, as well as facilitating the interaction and the adaptation of the measures to the specific scenario is an indispensable requirement for the real implementation of EEMs. Therefore, any method which expects to be implemented and to provide applicable results should take into account the decision making process.

In this sense, the commercial tools available in literature lack of this kind of interactivity with the industrial manager. These tools are commonly oriented to a wide range of objectives, avoiding the adaptation to specific cases. On the other hand, the proposed methodologies, in spite of containing pertinent easy decision tools or procedures, and being able to assess correctly the dynamic phenomena, are focused on other kind of processes and propose other kind of analysis.

In conclusion, a method, tool or methodology which is able to provide correct evaluations of non-continuous thermal processes and of their hypothetical adapted EEMs, including an integral and holistic perspective at the same time that provides ways to ease the decision-making process, is still missing.

For this reason, and based on the state of the art analysis, a novel methodology to evaluate non-continuous thermal processes is proposed. This methodology aims to tackle both the holistic and integral modelling considerations at the same time that provides detailed and tailored information for the industrial manager.

# 3

# Proposed Methodology

**Summary**

*This chapter explains the methodological approach and the procedure to reach the final proposed methodology features. This methodology is focused on integral analysis and total assessment for EEMs implementation in non-continuous thermal processes. The novelty of this methodology consists of the adaptation of the diverse techniques, procedures and methods, which are available in literature, for the kind of processes selected.*

## 3.1 Main Methodological Features and Application

This methodology is based on energy modelling by simulation, which allows to reproduce the process and, after validation, generate scenarios and hypothesis. The proposed methodology covers the multi-level and multi-scale perspectives. It can be applied at the different stages of the manufacturing process life-cycle, such as process project development and design phases, operation phase and ex-post-installation modification phase (e.g. for new energy efficiency improvement projects). The different levels of the plant [device, sub-process, process, production line and whole plant], and the different scales of production analysis [operating (second-minutes), tactical planning (hours-days) and strategic (weeks-months-years)], are covered by the methodology. This flexible approach allows to introduce physics-based energy modelling of any energy-kind of processes (electric or thermal).

After the scientific literature evaluation and the acquisition of all the theoretical knowledge related to the main typologies of assessment (in relation to the non-continuous manufacturing thermal processes) explained in Section 2, the basis of the methodology is established. These kinds of assessment methods, which were evaluated to substantiate the proposed methodology, include methods such as dynamical systems, systems dynamics and thermodynamic principles. In this step, all the required background to understand and analyse the characteristics and the problems of the kind of processes under evaluation are considered. This methodology covers the thermal engineering knowledge of the thermal phenomena, such as an in-depth knowledge of the generic literature approaches for heat transfers or fluid dynamics, as well as the comprehension of energy modelling procedures and energy system characterisation. This part is the most academic-related part and will directly support the process characterisation and the integral modelling and will help to understand the developed physical events during the manufacturing process.

The proposed methodology is thus based on a well-founded comprehension of thermal engineering, such as heat dynamics knowledge. Besides, modelling and programming understanding is required. In this regard, the selected software to develop the modelling and simulation is MATLAB®-Simulink®, due to the dynamic working orientation and capacity. MATLAB® combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly. This methodological background comprises the statistical and mathematical approaches which are used in the others methodology blocks, such as analysis and assessment, Validation and Verification as well as the optimisation tasks. This step reflects the previous effort on searching and adapting the current state of the art to the features of the selected processes typology.

Another main feature, which determines the proposed methodology, is the kind of processes to which this methodology is oriented. The characteristics of the process-type under study, as well as the available data according to literature, guide the features of the modelling and, in general, the characteristics of the methodology [44]. The first step of the proposed methodology is oriented to the selection of the elements (production line, process chain, processes, devices or cross-cutting technologies) under study by means of a preliminary Scenario Identification. The proposed methodology encompasses the key pillars for energy saving in the industrial environment: Technical expertise, good operational data acquisition, modelling, simulation and optimisation [157]. The effort on searching, selecting and adapting the current state of the art to the features of the selected processes typology is reflected on the methodology features in order to take advantage of the identified energy efficiency gap (Section 1.1.2.1).

Ultimately, each methodology block included in the methodology is explained and detailed. These blocks are represented in Figure 3.1, in which the objectives of each methodology block are summarised. Some objectives belong to more than one methodology block due to the interactions and links among blocks. The logical step-by-step order of the Energy Efficiency Methodology is represented here. However, some iterative sequences are included, which may bring us back to a previous step. Some steps, such as the scenario selection and identification and the background acquisition to understand the other steps, which are not directly included in the methodological approach, are also introduced.

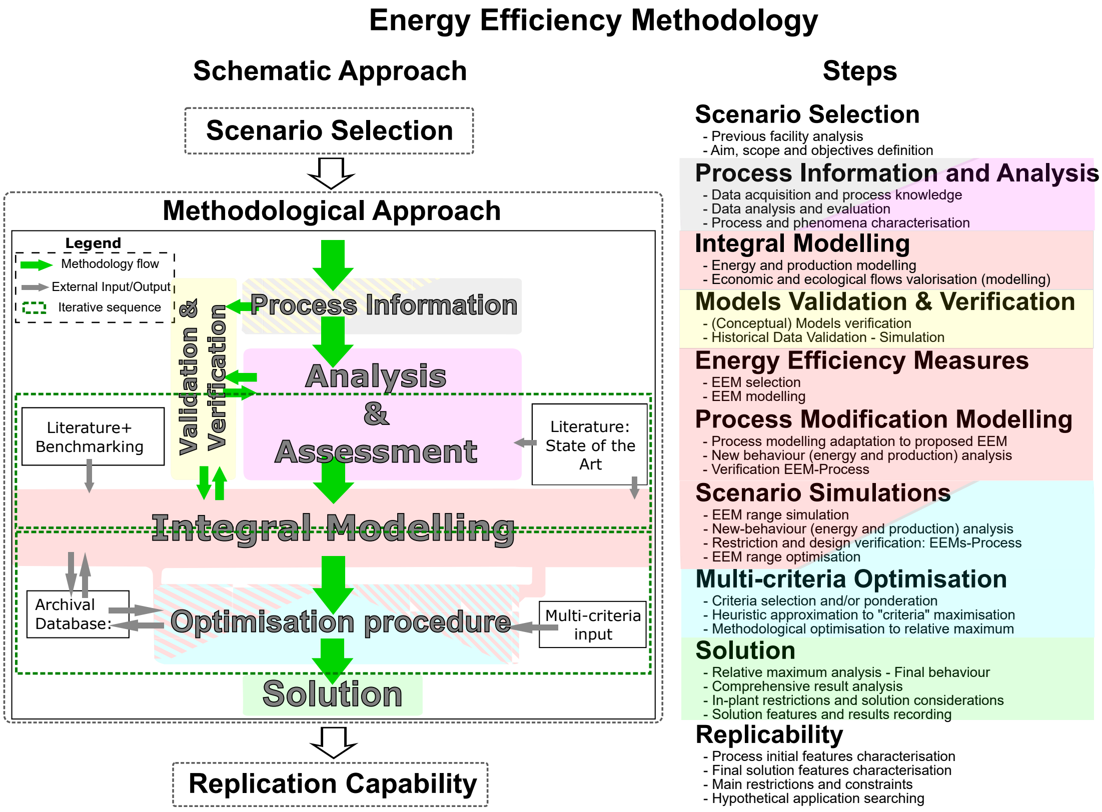


**Figure 3.1** – Energy Efficiency Methodology.

## 3.2 Methodology blocks

The blocks of the proposed methodology, such as Process Information, Data Analysis and Assessment, Validation and Verification, Energy Modelling, Optimisation and Solution, which are common to other kinds of methodologies, are thoroughly known and studied in literature. These common blocks are shown in Figure 3.2. However, this methodology fits the most adapted features (for the assessed state of the art) for each section according to the processes in mind, i.e. processes with highly dynamic energy patterns or variable production inputs. The non-continuous thermal processes of the manufacturing sector commonly present these features. The methodology follows a sequential scheme (Figure 3.2) in which several sections depend on the outputs, information or data resulting from other sections. There are two main iterative procedures in the proposed methodology: one related to the validation and energy modelling, and the other related to the EEMs proposal and modelling, in addition to the optimisation procedure. Notwithstanding, each block may present internal iterations, such as the conceptual modelling task, the data acquisition procedure or the modelling stage.

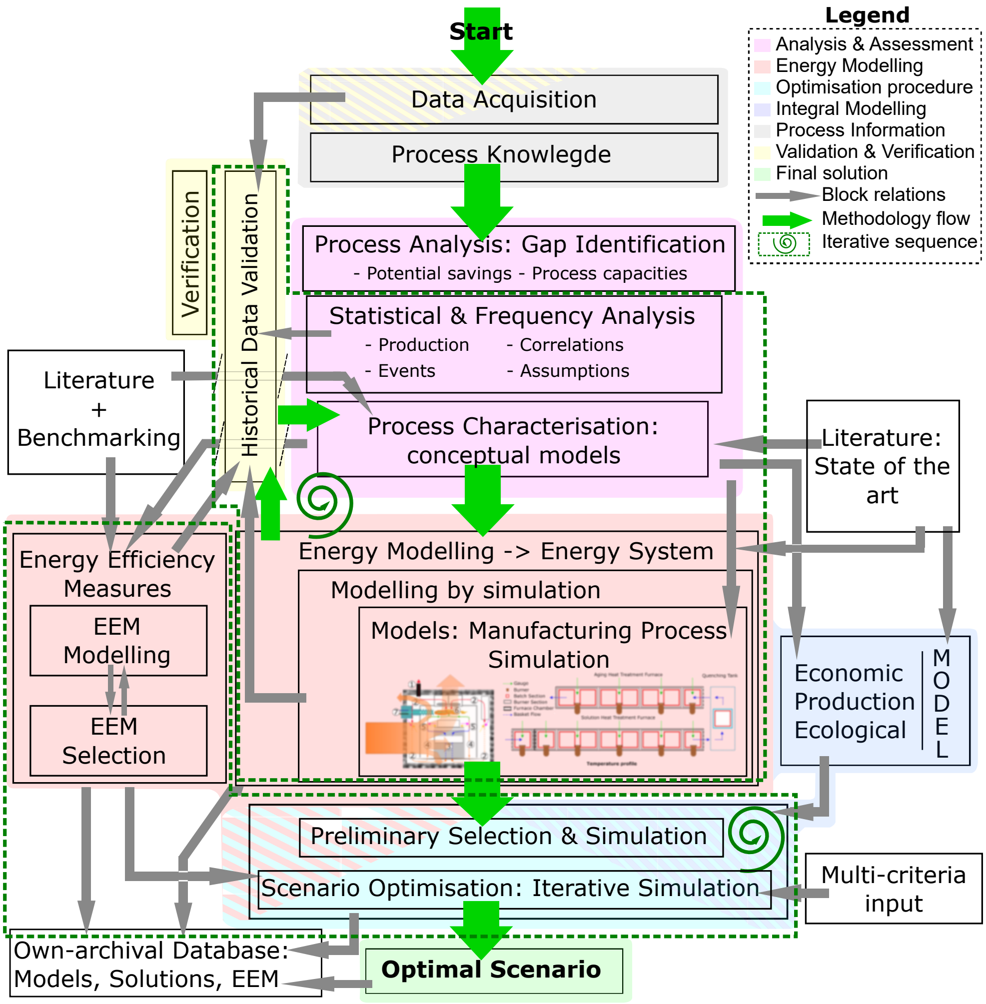


**Figure 3.2** – Methodological approach procedure.

### 3.2.1 Scenario Identification

Before entering into the technical methodological approach for the comprehensive analysis of industrial processes, a prior scenario identification, in which the methodology is applied, must be carried out. This first phase consists of knowing the client's needs. Once the capabilities of the methodological process are explained, the aim and the final scope are defined. In the same step, the requirements of the analysis and of the client are defined. These aims and scopes are heavily dependent on the process characteristics and the kind of process under evaluation. Besides, specific objectives are established in order to evaluate the process status.

In conclusion, the goal is to develop a methodology which combines energy and production data to derive an energy efficiency assessment. This assessment includes energy, production, economic and ecological impacts of the proposed EEMs. The methodology aims to be generic enough to be applied to any process and facility. However, it is clearly oriented to non-continuous thermal processes.

These manufacturing systems involve a number of interrelated elements, such as equipments' ways of working, number of product options, material handling systems, system size, process flow configuration, processing time of the operation, system and workstation capacity, space utilisation and other kind of production events. All these elements and factors generate a complex overall system. In addition to this complexity, the introduction of an EEM may affect to the overall modus operandi.

Therefore, relations among processes, a large number of modelling factors and the recreation of device phenomena, are critical for the effective development of the models for a methodology capable of improving energy efficiency and for the evaluation of EEMs. After the final development of the models, other constraints, such as unpredictable machine breakdowns, operational requirements variations, schedule modifications, and different production demands, which are not directly taken into account in the methodology, may be "manually" (by the end user) introduced, as input modifications, or by the model-maker, as a non-EEM modelling.

### 3.2.2 Process Information

The first block, after the preliminary scenario identification, consists of obtaining all the information related to the specific manufacturing process and the production modus operandi. This block consist of two main task: Process Knowledge obtainment and Data Acquisition This step is responsible for monitoring the production data and for providing the basis to characterise the process. Information can be attained in three ways: literature, monitoring and by the process information provided by the industrial operators or managers.

Both steps (Data Acquisition and Process Knowledge) may be carried out concurrently, a previous data acquisition may help to identify process events, and, in the same way, a detailed process knowledge may help to select the main variables to monitor and select the correct time step. Some features of this block, such as the monitoring interval or the selection of relevant variables to measure, may be overcome by following a "trial and error" sequence or other heuristic methods.

The lack of detailed production data and difficulties in the selection of the boundaries among operating states leads to an inaccurate simulation model generation. This scenario limits the production of detailed or precise results for the manufacturing planning [9]. Therefore, this step represents a critical point in the methodology, in which the lack of collaboration at the manufacturing facility or the lack of provided resources (devices or labour) may harm the entire energy efficiency improvement process. Several methods of data collection have been intensively used in industry and logged in literature, such as continuous automatic monitoring (including Big-Data) or specific ad-hoc monitoring (for the previous identified variables) as it is explained in the next subsection.

#### 3.2.2.1 Data Acquisition

This step gathers the data of the processes. Nowadays, huge amounts of data may be gathered by Big-Data technologies, setting up the possibility of diverse kinds of modelling. On the one hand, the proposed methodology is developed not to require high quantities of data (compared with the Big-Data technologies). The compiled data is mainly employed for the validation stage. But on the other hand, these series of data may contribute to identify events and to characterise the way of working. Therefore a bigger and more quality database will provide better energy modelling (attributed to a better conceptual model designing and a better validation process). The selected energy-modelling-method makes this “relative low” data requirement possible and acceptable due to the features of the conceptual modelling. However, ad-hoc measurements are required in order to obtain information, which is normally not directly monitored in the manufacturing processes. If a continuous permanent measurement, monitoring and tracking system, such as the one provided by the EnMSs, is not installed, several portable data-loggers and temporal devices must be implemented during a long significant interval time. But on the other hand, an in-depth understanding of the processes and of the involved phenomena is practically indispensable in order to characterise and understand the circumstances and events which happen during the manufacturing process.

Apart from the common energy and specific production data measurements, which are logged in continuous processes, in the case of non continuous thermal processes other variables and events, such as kinds of production, states of production, states of heat generators, internal characteristics of the processes as well as input and output mass flows (e.g. to obtain the infiltration flow) must be extensively measured for each type of working methods (operating state). Specific measurements reveal indispensable information of the manifold manners of working of the process (due to elements such as process interruption, load typology and ambient temperature). These reasons make the monitoring step complex, extending the analysed time period and, especially, complicating the identification of the event-to-measurement relation.

At this point, the time step of measurement must be defined by a previous ad-hoc analysis. If the dynamic of the process presents high variations in short time periods, the time step must be adapted, and, definitely, it will allow to correctly characterise the shortest critical event. Different time-steps should be analysed for the processes in order to achieve a compromise among data-weight and information quality. The duration or period of the developed events in the sub-processes will determine this value. Nowadays, with the current technology of data transfer or the novel monitoring devices a high amount of data and logs would not suppose a problem. The non-continuous thermal processes are commonly commanded, guided or subordinated by mechanical devices with high mass inertia (such as process doors, roller conveyors or special forklift transports). Therefore, the mechanisms, whose movements are determined by an operator or conditioned by the high device weight, allowing to select a reasonable time step in the range of several seconds. The time step must be selected after an in-depth knowledge acquisition process in order to identify and characterise the involved production and operational events which affect the main variable profile or the process modus operandi.

#### 3.2.2.2 Process Knowledge

The selected energy modelling typology allows low amount of data for the modelling, but requires an in-depth understanding of the manufacturing process and of the involved phenomena in order to characterise and understand the phenomena and events happening during the manufacturing process. The proposed methodology, which is focused on the highly dynamic patterns of production, events and consumption, emphasises this step to understand the phenomena and events, as well as to identify potentials, EEMs, synergies and incompatibilities in a preventive way. As it was introduced before, an in-depth knowledge acquisition process in order to identify and characterise the involved production and operational events is required to select the time step.

This step is crucial to avoid redundant actions, such as re-modelling, re-selection of the measure time-step or to avoid the misidentification of events or phenomena in other sections. The way to proceed at this step may vary considerably from one process to another. Three ways have been identified: the device data-sheets and process technical files evaluation, the main variable profile observation in historical data and the managers' and operators' report assessment. The complilation of high quantities of data without understanding how the processes and devices work could generate wrong conclusions. This fact is amplified in processes with high variability and many operating states, such as the processes under study, i.e. noncontinuous thermal processes.

The **technical specification** files (or modus operandi documents) and the device **data sheets** are the main way to obtain information of the way of working of the manufacturing process and the working way of the devices. The way the manufacturing process is developed is registered in technical specification files, in which each part of the process is explained and the specific production requirements or the process characteristics are logged. These files are commonly used to instruct employees/operators. These documents may add features or characteristics of the involved devices. However, the real design characteristics or way of working of each machine and device is widely explained in the data-sheets, in which the design working conditions and the response (outputs) to diverse inputs are illustrated.

On the other hand, some anomalies and other working characteristics may be obtained by **analysing the main variables recorded** and comparing these variables with the theoretical expected behaviour under an expertise-based criteria. In this regard, this comparison procedure allows to identify both malfunctions and non-designed ways of working. Nevertheless, the search and identification of the different events and phenomena is not an easy task "on paper". For complex-industrial-plants, the context-extraction from the available historical data requires a significant amount of time, effort and experience [125]. The energy variables depend on many phenomena and the distinction among different phenomenon behaviour may suppose an unfeasible task. This way of obtaining process knowledge is useful to confirm events and to link them with outputs.

The last step is the information provided by the **manager and operators**. A good information flow with the process work-team allows to identify non-described events or anomalies. This information flow is based on the acquired experience provided by years of working experience. Several small variations, which may have been taken into account by the operators, may not be registered in any document.

Several criteria may be used in order to recognise if the data and information acquired is sufficient, both for validation and conceptual model design. These criteria include verifications such as the total identification and correlation of operating states of the device with the phenomena observed, as well as the verification of the coherence of the yearly consumption (compulsory for any industry to register) with the extrapolation of the measured period. This process should be prolonged until new operating states are not identified as new data is arriving. In this regard, if the production input is variable along the time (seasonally for example), the modelling will only ensure accuracy on this period. At last, if the extrapolation of the consumption (as well as the production) is coherent with a longer logged period , it will mean that the data acquisition is sufficient. In this context, the industrial operator or manager's expertise may provide useful information of the particularities of the period under analysis. This step is subjected to a certain degree of subjectivity, and, as it was commented before, may present several differences among manufacturing processes.

Definitely, all the information that can be compiled before characterisation will reduce the iterative process of modelling-validation. Avoiding, to a greater extent, this point will generate future modelling problems and will delay the validation and verification step. In order to make use of this data and to obtain reliable information for the modelling stage, this data and information must be analysed and the hypothesis must be tested. This task is carried out in the following section.

### 3.2.3 Data Analysis and Assessment

Once the compiled data is considered sufficient to cover the validation step and the process characterisation, the next step consists of processing and arranging this amount of data as valuable and treatable information. The whole process or processes under evaluation are analysed in overall terms in order to identify apparent gaps or potential events for the energy efficiency improvement. This step consists of comparing the overall indicators of production (such as specific consumption) with those of other facilities or with the BAT or BPT for the process. Then the most representative variables are subjected to statistic and sensitivity analysis to identify correlations, to exclude non-related events and to quantify how variations in events or inputs affect the linked variables. In the end, with the raised conclusions, the conceptual models are planned according to the process or device features.

The main particularity of this section is that the uncertainty of the events and the high variability of the profiles makes the search of correlations between events and variables (thermal or production) very complex. Correlating the gathered data to events and phenomena requires an in-depth analysis of the involved phenomena of the process. Obtaining reliable and verifiable conclusions from the analysis implies a high advantage at the modelling and validation steps. Some assumptions should be adopted for the non-measurable or unknown features which can endanger the correct characterisation.

#### 3.2.3.1 Process Analysis: Gap identification

The first step after the data acquisition is to carry out a comprehensive characterisation of the energy flows in order to identify energy gaps, future energy efficiency actions or EEMs. The energy distribution of the entire system is assessed by means of an energy analysis. Besides, an exergy analysis for the different energy flows is carried out in order to provide a quantitative analysis of the quality of these flows.

Energy, is a property of objects, systems or flows which can be transferred to others or converted into different forms. The total energy amount of a flowing medium takes into account both latent and sensible heat, as well as the “mechanical” energy content reflected in its pressure [158]. Enthalpy ($H$), as shown in Equation 3.1, which is defined as the variation of internal energy ($U$) and pressure ($p$) times the volume ($V$) [159], is commonly employed to define the energy content of a medium. Nevertheless, both mechanical and pressure are negligible for non-pressurised processes and, consequently, enthalpy is assumed in consonance with the thermal internal energy. In the manufacturing process environment, thermal energy may be represented by the heat created from a chemical oxidation or electric source or by dissipation. The main three heat-transfer methods are radiation conduction and convection. Besides, the heat storage in moving (solid and/or fluid) systems, which may be considered as an advection method of heat transfer, is common in existing manufacturing processes. Advection is the transport mechanism of a fluid from one location to another. In this regard, this method is analysed as a simple bulk movement of heat in form of thermal energy stored.

$$H = U + p \cdot V \tag{3.1}$$

The energy flows of the industrial process must be identified in order to assess the primary energy inputs required for a process [160]. An energy analysis is the first way to evaluate the different systems [161, 22, 162]. The power content ($P$), or heat flow ($\dot{Q}$), of a fluid stream (such as stack gases or recirculating flow) is mainly obtained according to the medium temperature ($T_i$) and the mass flow ($\dot{m}$). This thermal power content ($\dot{Q}$), may be defined by the enthalpy (in consonance with the temperature) or by the specific heat ($Cp$ $[J/kg/K]$), as shown in Equation 3.2.

$$\dot{Q} = \dot{m} \cdot (H_1 - H_2) \rightarrow \dot{Q} = \dot{m} \cdot \int_{T_1}^{T_2} Cp \cdot \delta T \approx \dot{m} \cdot Cp \cdot (T_1 - T_2) \qquad [W] \tag{3.2}$$

The power transferred of a heat transfer through radiation ($\dot{Q}_{rad}$) is obtained conforming to Planck's law and the black body approach (according to Equation 3.3). Where $\sigma$ is the Stefan–Boltzmann constant $[W/m^2/K^4]$; $Area$, in $[m^2]$, is the radiation surface of the emitting body; $T_1$ and $T_2$ the absolute temperature $[K]$ of the confronting elements and $\epsilon$ is the emissivity ($[-]$), which means the ratio of a surface's ability to emit radiant energy compared with the ability of a perfect black body of the same area at the same temperature.

$$\dot{Q}_{rad} = \sigma \cdot Area \cdot \epsilon \cdot ({T_1}^4 - {T_2}^4) \qquad [W] \tag{3.3}$$

The power transferred in a heat transfer through convection ($\dot{Q}_{conv}$ $[W]$) is approached by means of the heat transfer coefficient conforming to Newton's law of cooling approach (according to Equation 3.4). Where $h$ is the heat transfer coefficient $[W/m^2/K]$, $Area$, in $[m^2]$, is the convection surface of the system, $T_f$ and $T$ represent the absolute temperature $[K]$ of the surface and of the environment, respectively. The basic relationship for heat transfer by convection is:

$$\dot{Q}_{conv} = h \cdot A \cdot (T_f - T) \qquad [W] \tag{3.4}$$

The power transferred of a heat transfer through conduction ($\dot{Q}_{cond}$ $[W]$) is approached by means of the Fourier's law of thermal conduction approach (according to Equation 3.5 for 1-D approach). Where $k$ is the material's conductivity $[W/m/K]$; $Area$, in $[m^2]$, is the cross-sectional surface area of the system; $e$, in $[m]$, corresponds to the thickness of the system under evaluation; $T_1$ and $T_2$, which create the temperature gradient, represent the absolute temperature $[K]$ at the beginning and after the thickness, respectively. The basic relationship for heat transfer by conduction is:

$$\dot{Q}_{cond} = -k \cdot A \cdot (T_1 - T_2)/e \qquad [W] \quad (3.5)$$

In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, reaching maximum entropy [163]. To obtain this maximum useful work the process must be reversible. Exergy is a property which combines a system and its environment and depends on the state of both elements. The exergy of a system in equilibrium with the environment is zero. Exergy analysis is an innovative instrument for thermodynamic analysis [22, 98, 164] and, in special, to evaluate the waste heat opportunities [165]. The main characteristic of the exergy, in comparison with the energy, is that the exergy may be destroyed. As it is shown in Figure 3.3, which links the exergies of the two flows in a heat exchanger, there is an exergy lost.

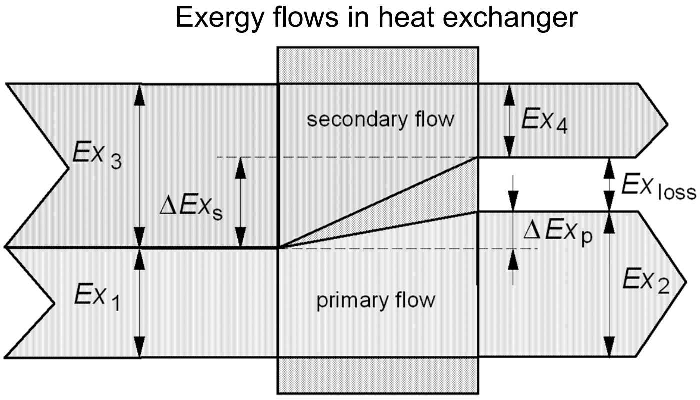


**Figure 3.3 –** Exergy flows and exergy efficiency in a generic heat exchanger.

Neglecting the potential and kinetic variation effects, the exergy associated to a stream of matter depends on its physical structure and chemical components [166]. For common fuels, the Lower Heating Value only differs from the real exergy around 5% [167]. In this regard, the total exergy of the fuels is the sum of the exergy of the flow and the chemical exergy, nevertheless, chemical exergy is significantly higher with respect to exergy of the flow. For other streams (hot mass flows) the exergy is approached as thermal exergy. In this regard, the power exergy content of a heat flow is approached to the thermal exergy content of the flowing stream, as shown in Equation 3.6.

$$\int \delta Ex_{\dot{Q}} = \int (1 - \frac{T_0}{T}) \cdot \delta Q \rightarrow Ex_{\dot{Q}} = (1 - \frac{T_0}{T}) \cdot \dot{Q} \qquad [W] \quad (3.6)$$

Where $Ex_{\dot{Q}}$ is the exergy associated to the heat flow, $T_0$ and $T$ are the ambient and bulk flow temperature $[K]$, and $\dot{Q}$ is the correspondent power content of the flow. In order to distinguish this term at the unit representation, some authors use the *exergy* "surname" in the units, i.e. exergy joules as $J_{ex}$ or exergy watt as $W_{ex}$.

These thermodynamic properties (Energy, exergy, temperature and mass flow rate) define integrally the thermodynamic characteristics of the flows. The energy, temperature and mass flow rate are the main indicators for the thermal manufacturing processes. The concept of exergy lets the analyst look for process-improvement opportunities offered by limiting the destruction of exergy [168]. In this regard, other non-energy related parameters must be assessed to proceed to the correct characterisation of the flow, including chemical considerations, such as corrosivity or chemical incompatibilities, and other kind of physical and thermal characteristics such as density or heat capacity.

In conclusion, the energy flows are evaluated and quantified by these proposed mechanisms. The energy flows whose properties and characteristics make any kind of action possible, from prevention to energy transformation (as shown in Section 1.3.1 in Figure 1.10), are identified. The sub-processes, machine or device efficiencies are calculated and compared to the theoretically expected outcomes, such as those provided by data sheets or modus operandi documents or technical files (as explained in Section 3.2.2.2) or to the BAT (as introduced in Section 1.3.2). Therefore, the potential margins of improving and the overall way of working, according to the energy efficiency, are settled.

#### 3.2.3.2 Statistical and Frequency Analysis

In this subsection the monitored data is confronted with some hypothesis in order to confirm or refuse the initial hypothesis. For that to be possible, several statistical mechanisms are employed. In statistics, Pearson coefficient is a measure of the linear correlation between two variables. In the same way, Spearman's analysis assesses how well the relationship between two variables can be described using a monotonic function. However, it must be always present that correlation among variables does not (necessarily) imply causation. Both of them are proposed to prove or refuse a correlation among variables due to their simplicity and to the fact their their results suppose a good compromise. These methods, which are useful to characterise and quantify relations in production, are widely employed to evaluate the defective production. Nevertheless, there are manifold statistical probes to determine the relations among factors [169].

The Pearson coefficient result is a correlation coefficient $\rho$ with the value range [-1; 1] in which the sign describes the type of dependency. The value stands for the degree of the correlation: 0 for no correlation and 1 for a perfect linear correlation [169]. Spearman's coefficients record the monotony and allow to identify non-linear correlations. The p-value, which is determined by the observed correlation and the sample size, studies the probability that, when the null hypothesis is true, the set of observations will be greater than or equal to the actual observed results. It is commonly accepted that p-values lower than 0.05 indicate that the hypothesis analysed is statistically significant [170].

In order to achieve significant results the number of "experiments" must be large enough to be able to affirm or refuse the null hypothesis. The number of identified anomalies should not surpass certain levels. The variables under study to set a correlation analysis should be isolated from other process changes. The data from processes with many operating states, such as transitory and turn down, or recurring anomalies should be previously treated and classified in order to obtain a clear variable analysis correlation.

The factors to correlate may be quantitative, measurable and physics related property, or qualitative, based on a distinctive criterion. The qualitative variables may be categorical or dichotomous. The aforementioned methods are focused on quantitative variables. However, a qualitative factor may be related to a quantitative variable (e.g. specific energy consumption with an operating state) with several modifications. The Pearson and Spearman analyses are implemented in MATLAB® as functions in the general library. In this regard, other statistical and correlation analyses are developed and available in MATLAB® library.

Despite the fact that this kind of processes present high dynamic behaviour and production input, repetitive sub-processes or routines are employed for the production processes. In order to assess and quantify these repetitive routines (if any), and to correlate events with energy consumption behaviour or production inputs, first, these recurrent events must be isolated and evaluated with frequency analysis of the profiles. This analysis may be visually represented as frequency-weighted histogram pictures (as it is exemplified on the right in Figure 3.4).

This frequency analysis helps to group the events, to identify phenomena as well as to arrange the data for statistical analysis. Then, diverse variables can be confronted across the temporal spectrum for each desired stage time (time differential or time interval). In Figure 3.4 hundreds of time intervals (in green) are represented for a certain variable of the process. The average values of this variable may be compared (correlated) to the average values of other variables for the entire interval time or broken down by smaller gap times.

Based on the identified hypothesis of Section 3.2.2, this part allows to detach the real

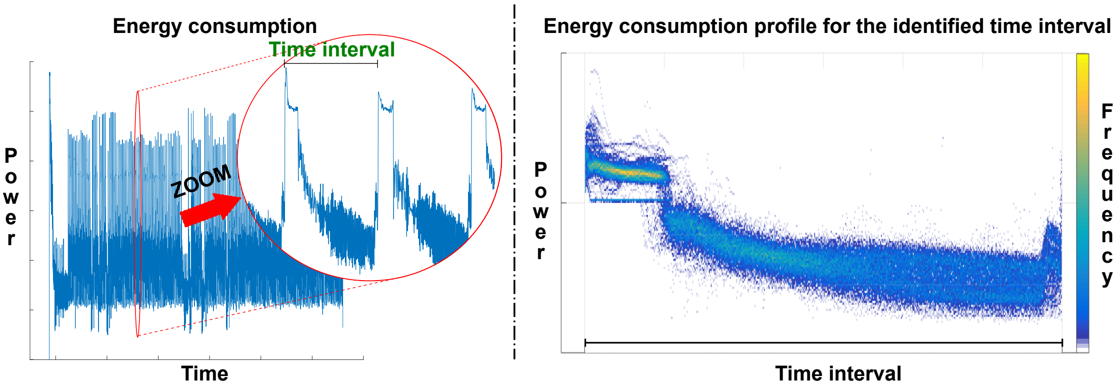


**Figure 3.4 –** Behaviour profile for an identified repetitive time-interval.

and relevant hypothesis from the others. Besides, this combination of analyses helps to identify and to quantify the relation among variables that, eventually, will be modelled.

### 3.2.3.3 Process Characterisation: Conceptual Models

Conceptual models, according to the energy modelling of a process, may be defined as a kind of high-level information and knowledge acquired by the previous characterisation and data acquisition of the process [100]. Once the raw data and information is filtered, the conceptual model can summarise this information in tangible relations, equations, premises and assumptions. The main characteristic of a conceptual model, in comparison to the computer models, is that it is not specific to the software in which it is developed. Then, these models, which have abstract characteristics, are translated to computer models by model designing, as it is represented in Figure 3.5 by Robinson et al. [171].

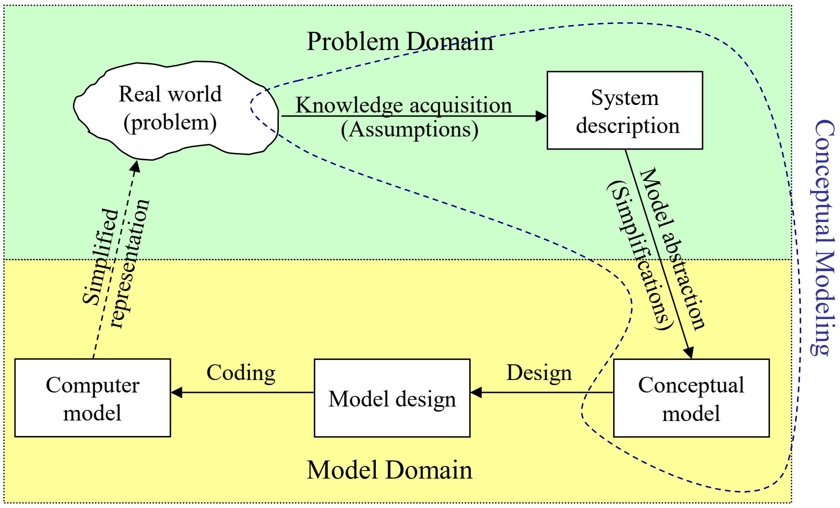


**Figure 3.5 –** The artefacts of conceptual modelling from [171]

Furian et. al. [172] identify, after an in-depth discussion of the existing framework, some potential improvements to the current conceptual model representations. In this regard, they propose a new hierarchical structure for Discrete Event Simulation (DES) purpose, as shown in Figure 3.6. However, the identified steps and the described phases can be used for many kinds of modelling. Definitively, the proposed procedure facilitates the modelling of more complicated systems where multiple entities interact throughout various activities [172].

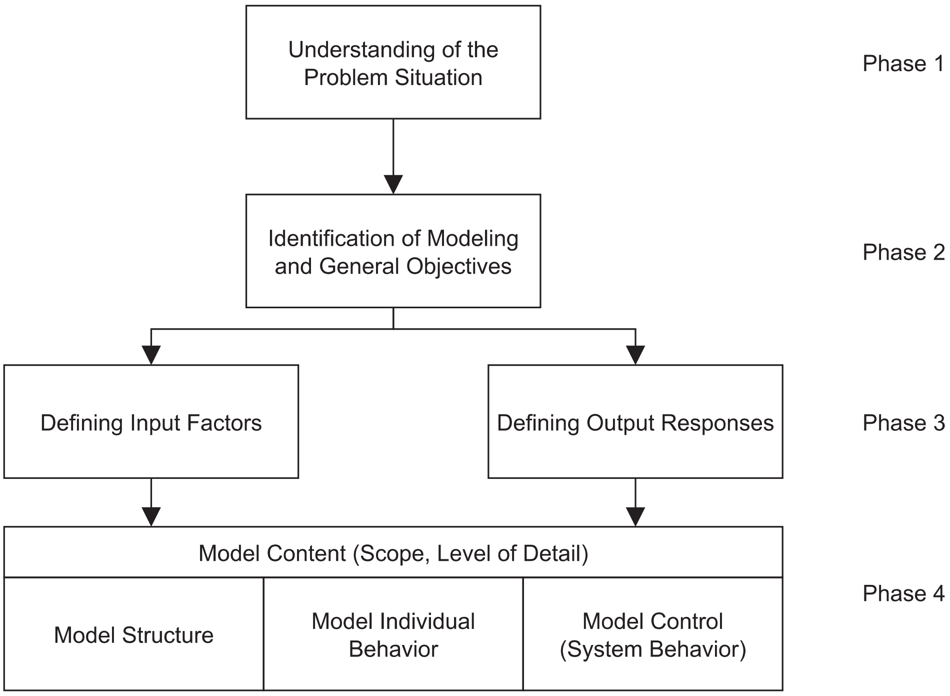


**Figure 3.6 –** Structure of the Hierarchical Control Conceptual Modelling framework proposed by [172].

Other important characteristic of the conceptual models, and of computer modelling in general, is that the level of complexity of the conceptual models may ultimately harm the model results (as it it shown in Figure 3.7). This harm comes from the modelling translations and from the higher sensitivity of the computer models to non-relevant inputs [171]. To find the correct degree of complexity according to the process characteristics, the expected results and the available data information is the real task of this analysis.

In conclusion, the conceptual modelling is the abstraction of a simulation model from a real world system and describes how the real process is conceived. The conceptual model does not describe the real system. This conception may be subjected to measurement errors, failed assumptions or to incorrect relations. The final objectives of the computer model will determine the conceptual models. The phases (shown in Figure 3.6) proposed by Furian et. al. [172] help to guide the conceptual model generation at the same time that support the scope definition.

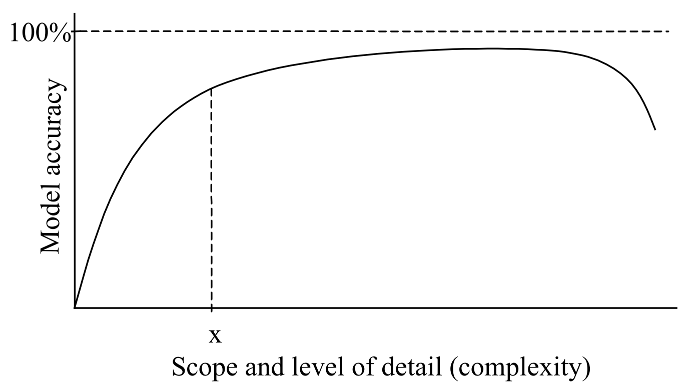


**Figure 3.7 –** How simulation model accuracy changes with the complexity of the model from [171].

The conceptual models assumed for the proposed methodology are mainly based on physics laws or on derived assumptions widely employed and verified in the scientific field, such as the heat transfer coefficient $h$ $[-]$. This fact eases the verification of the models due to the strong foundations provided by the mechanism utilised. However, the confirmation or testing of the correct selection and adaptation of these selected mechanisms should be evaluated under the verification task (explained in Section 3.2.5.1).

The observation of the registered data and a heuristic approach are utilised to develop the non-physics based simplifications and the relations between parameters.

### 3.2.4 Integral Modelling

The models are approximations of the behaviour of the system. In this regard, the model is designed in order to enable the introduction of the proposed EEMs, which intend to cover the energy efficiency gap. This modelling aims to acquire a good compromise between complexity and replicability. An appropriate degree of simplification allows wider use of modelling and simulation [157]. These blocks include the energy and production modelling features. The proposed process models are widely varied in complexity, according to their relative relevance (to energy consumption), the required degree of deepening, or the correct phenomena reproduction.

#### 3.2.4.1 Energy Modelling: Manufacturing Process Simulation

The energetic modelling of the process is the crucial point of the methodology, ensuring results as accurately as the models and model inputs allow to. This is the main stage of evaluation and quantification. Here, the way the energy of the process is transferred (by means of energy flows) between processes or sub-processes is defined. In each manufacturing process, the consumed energy is required to change the original state of raw materials. Final products require a series of processes and sub-processes in order to reach the final product characteristics. These processes are detailed and accounted at *Process characterisation: Conceptual models* in Section 3.2.3 and translated to virtual models in this stage. Emphasis is given to the energetic modelling and its particularities due to the relative significance of this part.

In this section, the conceptual models, which were approached or adapted to the process-specific phenomenon development by means of the obtained parametrical assumption (In Section 3.2.3.3), are translated to the computer models. As it is commented before, these assumptions may be directly obtained by measurement analysis or by the virtual reproduction of the involved process phenomena by means of a parallel simulation-environment. Here, the main generic elements of the manufacturing process are described and characterised.

**3.2.4.1.1 Energy Modelling Elements.** The energy models must be detailed enough to consider the dynamic of the different stages in the process with the aim of minimising errors in the obtained process performance. The energy model is split into internal and external mass and energy balances in order to cover the main two parts of any non-continuous thermal process (as shown in Figure 3.8).

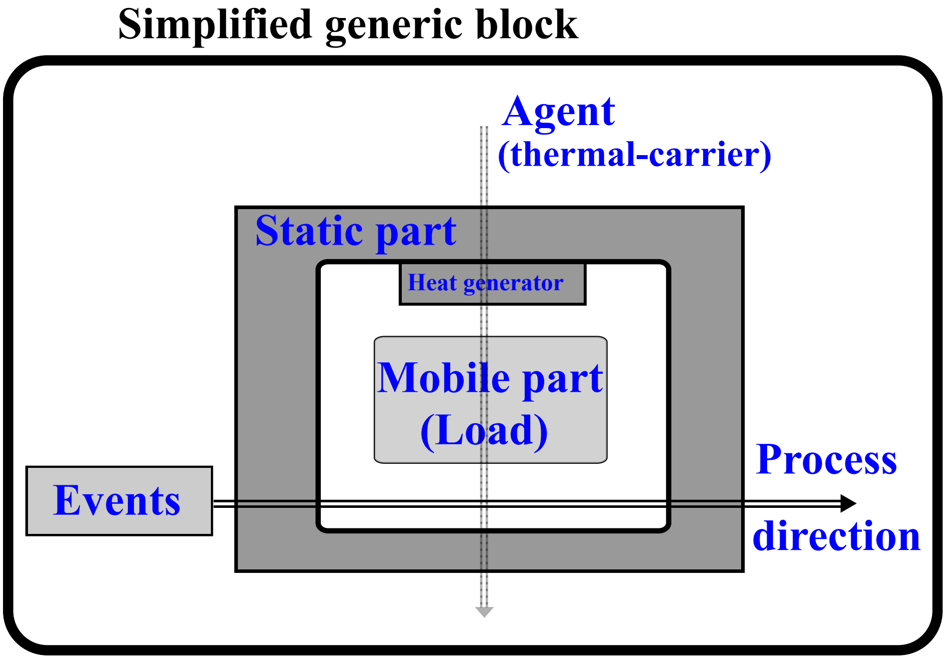


**Figure 3.8** – Simplified generic design block for energy modelling.

The first main part is the **load** (also referred to as Mobile part or solid flow). The load is the object of the manufacturing process. The most restrictive requirements of the way of working of the process have their origin in this element. The entire process and other elements are created and designed to comply with these requirements. The load performance is commanded by the sub-block events, which are determined by the production input (Time Line signal). The load properties [such as thermal properties (conductivity, heat capacity, emissivity, etc.) or geometric, composition and weight features] are also previously determined by the production input (Main Production).

The second main part of the modelling is the **static part**. This part encompasses all the environment of the process: all the devices and instruments within the process, the envelope of the process (such as the construction walls or the basement) and the environment characteristics (humidity, temperature, pressure, etc). This part explains the critical elements or devices, such as the thermal inertia, the heat generators, monitoring and controlling device.

Both parts are designed and modelled independently and then are linked through the **thermal carrier**. The thermal-carrier or agent leads the way that the static part links or connects with the mobile part. For common non-continuous thermal processes, this agent is commonly represented by a fluid governed by heat transfer laws, such as combustion air. However, other kinds of agents can be considered, such as radiation heat transfer, induction heat transfer or electric-contact heating. The main heat transfer phenomena discussed in this work are involved in this step. This agent is responsible for providing the thermal requirements to the load by transferring the energy used in the heat generators. For common fuel-fired heat generator systems (burners), this agent is combustion air and the heat transfer mechanism is the forced convection in which fluid motion is generated by an external source (like a pump, fan, suction device, etc.). A process can comprise more than one kind of thermal carrier which can work at the same time or in different time steps. A radiation heat transfer agent and a forced-convection heat transfer agent may coexist at the same time. Alongside natural convection, thermal radiation and thermal conduction, the forced-convection mechanism is the main method of heat transfer and allows significant amounts of heat energy to be transported very efficiently.

**3.2.4.1.2 Energy sources and heat generators.** The main energy sources identified for this kind of processes to produce heat are the fuel combustion and the electricity. The heat produced by means of a resistive/inductive system is accounted for as the total energy consumption employed by the heat generator. The heat produced by combusting a fuel may be explained according to the lower or higher heating value.

The Lower Heating Value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which implies that the latent heat of water vaporisation in the reaction products is not recovered. The higher heating value (also known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C. This value takes into account the latent heat of vaporisation of water in the combustion products.

The modelling of these sources mainly affects the thermal-carrier. A fuel-fired based heat generator requires a tangible flow (combustion air flow commonly). However, the heat generators based on electricity may use thermal radiation, the load itself (in inductive or contact-resistive systems) or also a tangible flow as a thermal carrier. In fact, combinations of methods may be utilised, such as radiation heat transfer based on fuel combustion, conforming to special requirements of the load.

**3.2.4.1.3 Thermal inertia.** The thermal inertia of the different devices (or of the load itself) plays an important role to achieve an exhaustive evaluation and comprehension of the thermal manufacturing process. The process thermal inertia represents the energy capacity content of the system environment. This environment consists of the diverse structures or materials that form the process devices. The thermal inertia term takes into account all the heat storing capacity in the process envelopes, insulation and refractories. Besides, it includes any device whose temperature can be increased, i.e. all the equipment which lays in the "heat-chamber", from conveyors to monitoring devices.

In order to determine the overall values of the thermal inertia, some measurement variables (Section 3.2.2) must be monitored during start-ups (and/or switch offs) of the process in order to determine the energy consumption required to reach a stationary situation in the process manufacturing. The main values of a generic thermal inertia are: total capacity and heat transfer rate. The total capacity of the inertia represents the maximum amount of energy [kWh or equivalent] which the static solid components are able to absorb once the maximum temperature is reached (stationary). The heat transfer rate represents the speed at which this energy is absorbed [kW]. Thus, the energy balance (energy consumption, lateral heat loses, stack energy, energy absorbed by load) corresponding to the start-up period provides the total capacity value of the thermal inertia. The heat transfer rate may be calculated by external surface temperatures or directly measured by a heat flux sensor - thermal cameras[1] and it is directly related to the lateral heat losses of the system. This heat transfer "speed" may vary according to the internal temperature and the thermal isolations of the system.

In this regard, the energy inertia related to the static part is responsible for the lateral heat losses. The lateral heat losses of a system come from the different levels of temperature of the system in comparison with the environment. These losses mainly correspond to the heat conduction phenomenon from the system "solid base" to the ground, the natural convection forces that appear on the process envelope and the radiation mechanisms of all surfaces of the system.

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[1] https://www.fluke.com/en-us/products/thermal-cameras

In order to be able to reproduce this system's behaviour, the static inertia (or the envelope inertia) is modelled as a group of layers which are able to accumulate energy (as shown in Figure 3.9. These layers transfer energy between them and ultimately among the two boundaries. The "internal" boundaries are the thermal agents involved in the process, which transfer energy in consonance with their levels of energy (temperature based). Therefore, this block absorbs heat from the internal surface, then this heat goes through the Static Part, at the same time the static part (Thermal Inertia block) stores energy (as shown Figure 3.8), and transfers the heat to the surroundings (external environment) by following the defined heat transfer rate.

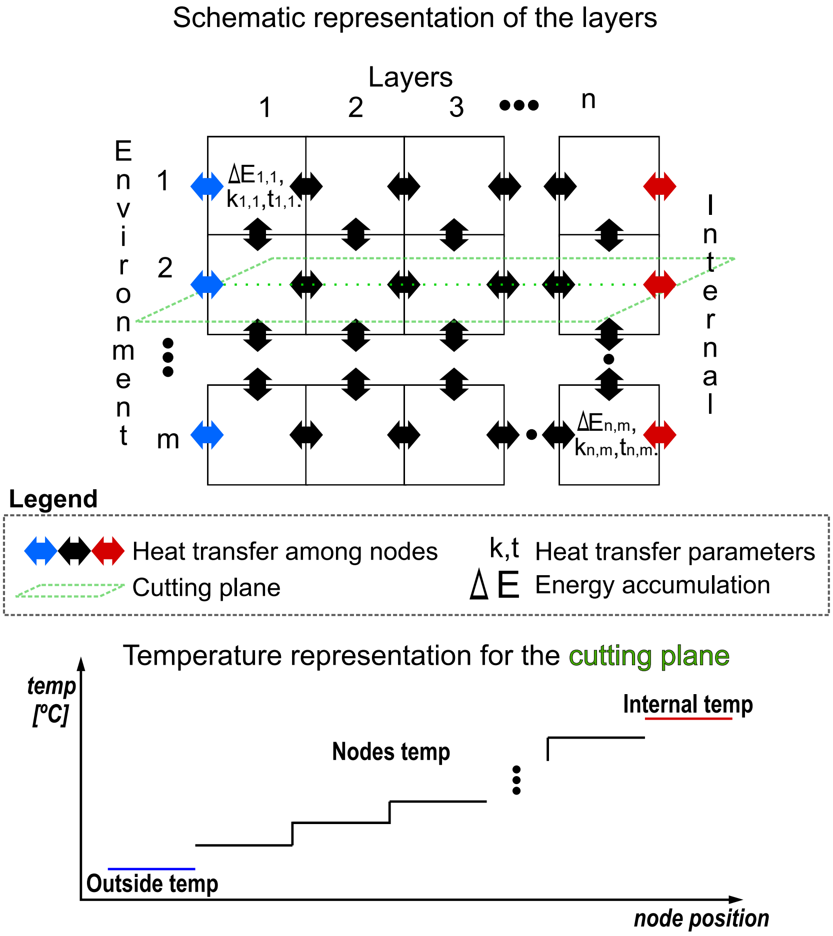

**Figure 3.9** – Simplification of the Inertia energy modelling.

This heat transfer rate is modelled as a set of virtual thicknesses "$t$" and thermal conductivities "$k$", as it is shown in Figure 3.9, in order to reproduce the obtained heat transfer rate features. Then, the heat is transferred to the adjacent layers by simple imitation of the conduction mechanism. The sum of the energy absorbed by each node (**ΔE** in Figure 3.9) represents the thermal inertia energy (at the moment of evaluation). Due to the fact that it has no sense to simulate neither thickness nor conduction parameters, the transfer parameter is selected to reproduce the real time and temperature behaviour of the inertia. Consequently, these layers simulate the time-delay of the inertia. This inertia modelling is developed, as exposed before, due to the impossibility of knowing the thickness, layers, and material conductivities of already built processes. However, if these factors are known, the virtual layers may be replaced by the real ones.

In conclusion, both the energy storage behaviour of the inertia and the inertia damping effect (shock absorption of temperature variations and time delay characteristic) are represented by the inertia modelling. The approach of heat transfer at the boundaries (blue and red arrows in Figure 3.9) is commanded by real heat transfer mechanisms, such as natural or forced convection, radiation or conduction.

**3.2.4.1.4 Energy Balance.** The concept of energy conservation as expressed by an energy balance equation is central to any engineering calculations. A balance on energy is crucial to solving many problems. In order to avoid ignoring elements or phenomena involved in the process, several energy (and mass) balances must be carried out. The energy modelling proposed in this work is based on the modelling of several subsystems linked to each other. Each subsystem (process or sub-process) is modelled from the proposed generic blocks (as shown in Figure 3.8). The mobile and static parts are designed to comply with their respective balances, bearing in mind their thermal inertias or materials stocks (load). It means that each element (both static and mobile parts) is modelled, and works, as an independent system, which is, then, connected to other systems (energy and production (if any) connections).

The first main group of balance (mass and energy) concerns the load. The load takes energy from the static part through the thermal carrier. The energy accepted by the load is the same as that given by the thermal carrier. This thermal carrier may have its own balances if it is a fluid-based medium, and lack them (acting as a driver) in the specific case of a non tangible thermal carrier (such as only radiation, induction or electric-contact heat transfer). These balances act according to the overall energy balance (similar to the internal blue boxes in the right side of Figure 3.10). However, the block analysis is carried out as a "white box" (as shown in Figure 3.11)), in which each box is modelled in detail.

Black box models (as the approach presented in Figure 3.11) are simply the functional relationships between system inputs and system outputs. By implication, black box models are lumped together with parameter models [175]. The parameters of these functions do not have any physical significance in terms of equivalence to process parameters. This is the disadvantage of black box models compared to mechanistic models[175], represented as white boxes in Figure 3.11 . For the selected kind of processes for the work in hand, i.e. non-continuous thermal processes, these black boxes are not able to reproduce the real behaviour of the system due to the high variability that each block

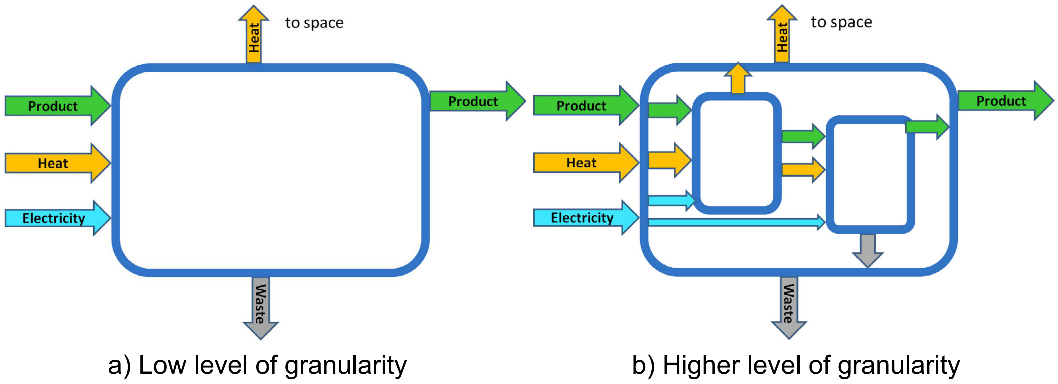

**Figure 3.10** – Disaggregation balance levels for energy modelling according to Wright et al. [173].

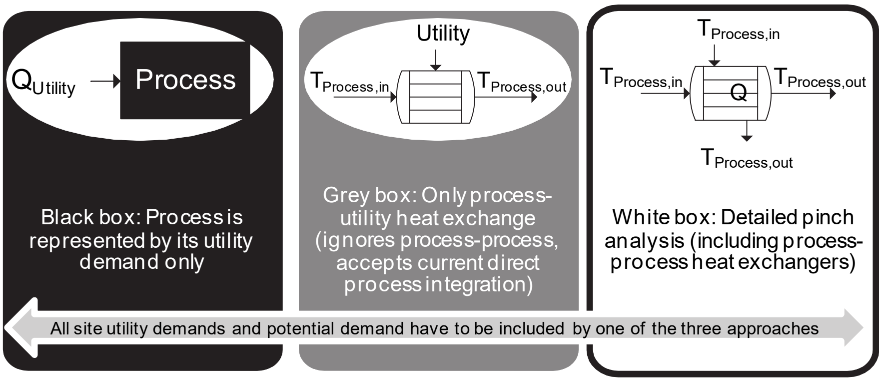

**Figure 3.11** – Black-White Box analysis for energy modelling according to Hackl et al. [174].

may present. Notwithstanding, box modelling and the connection among boxes is similar to the black box assessment approach.

The second main group encompasses the static part and the process environments. This overall balance takes into account the energy introduced (by means of fuel, gaseous mass flows, solid mass flow (load), lateral heat losses, stack energy, energy absorbed by load). This general energy balance is represented by the coloured arrows in the blue boxes of the Figure 3.10).

Both groups are tackled and connected by means of a "black box" assessment method. This means that both the static part and the mobile part work independently from each other. In the context of process modelling, individual process units work without concerning other system working. The input and output streams are instead analysed by applying constraints imposed by nature, namely conservation of mass and conservation of energy. The inner workings (specif phenomena of minor devices, such as real movement of the rollers -spin- or real detailed working of the fans) of the tangible apparatus are not relevant for the analysis.

In this regard, each system (or block) presents an energy accumulation attributed to the increase of temperature. This is modelled for each block according to the first law of thermodynamics. This stored energy is due to the solid system inertia (load or envelope-device systems) or the thermal carrier inertia (if it is tangible-flow based). Besides, these blocks are connected to one another by means of production commands. These production commands are varied in kind and role, such as the load movement, the state of working, the operating state or other special conditions.

#### 3.2.4.2 Production Modelling

The process production of any process is guided by the overall planning of production and the unexpected events. On the "overall planning" side, perspectives on the dynamics of the manufacturing production and of business decisions can be operational, tactical and strategic [126]. Therefore, production and organisational control involves the usage of a strategy, tactical action plans, and operational supervision to monitor and improve the company processes [176]. The proposed multi-scale methodology covers the three main levels: Operational, Tactical and Strategic.

- Operational level: This level of production planning considers the process modus operandi at real time. Operational control regulates the day-to-day output related to expected schedules. Comparing real-time data with simulated data may help to determine current non-determinant failures or to predict failures [113].
- Tactical level: This level is intended to fulfil a specific objective in the context of an overall plan [125]. The tactical planning covers the plant resources distri-

bution as well as, related to the energy performance in the manufacturing sector, the characteristics of the manufacturing process and products, fuel mix, energy prices, physical capabilities of the equipment, the environmental conditions and the user (control room team operating equipment). The tactical level is linked to the economic and production part of the integral modelling and, to a lesser extent, to the integral aggregation of the scenario models (relations among models and models capabilities).

- Strategic level: This level is responsible for allocating overall resources for each business part. The strategic decisions guide the business along the years [128]. This level may cover diverse levels of aggregations, focusing on one plant (independent of the others) or encompassing the highest level of aggregation, such as national or international inter-company process chains. This highest level comprises different companies or plants which work together to manufacture the product.

Each of these hierarchical levels is quite different regarding the necessary knowledge, methods and tools for planning, design, modelling and controlling. Each level also involves several possibilities to influence the energy and resource efficiency, which are, again, very different regarding their individual effects [177]. The tactical level is linked to the economic and production part of the proposal modelling and, to a lesser extent, to the integral modelling of the scenario, where the operational level is primarily responsible. Current operative-effectiveness indicators of devices are time-based.

**3.2.4.2.1 Process way of working and Model input.** The proposed methodology involves several different time scales concerning this complex process. In addition, factory operation depends heavily on customer demands. The operation of each factory would be very different with different throughputs. In this regard, the models and methodology work at tactical and operational levels (as it is schemed in Figure 3.12), relegating the strategic level as a specific set of tactical and operational characteristics extended during a long period of time.

The operational level is directly determined by the models. Each operational condition, working requirement or restriction (in essence, the way of working of each device) must be previously defined and introduced to the specific model blocks. If a device modification is carried out (or identified-discovered) or a new device is introduced into the real system, the models (at script level) should suitably be modified to the new characteristic or adapted to the change, and accordingly, restart the iterative methodology procedure from modelling to validation (if possible). Therefore, implicated process phenomenon modifications or new state-designs are not allowed once a simulation is launched. The aspects related to the operational level are fixed and can be only modified at the design phase. Hence, if new operating status or conditions are identified, the internal script of the model should also be modified. Each designed and modelled operating status may

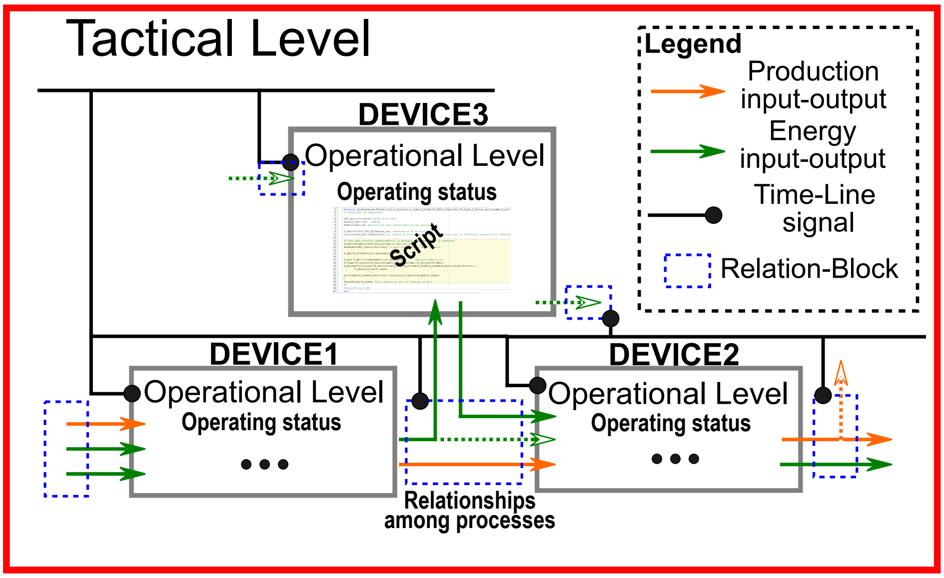

**Figure 3.12** – Tactical and Operational Level Representation.

be accessed, once it is introduced in the scripts through an external command without modifying the script. Each modelled operating status should be verified and validated to the possible extent or, at least, it should be endorsed that this working status is "near" to some validated working status. The energy modelling by simulation (by reproducing of phenomena) allows to introduce little variation, which may not be validated, provided that these variations do not drastically modify the way of working.

In Figure 3.12 a generic process is schemed. Each "Device" represents a process or device of the selected manufacturing line. These "devices" include all the identified operating status and conditions modelled as scripts. The operating states are commanded by the Time-Line signal (black line in Figure 3.12). This Time-Line signal, also controls all the modifications or characteristics related to the relationships among processes and the main production input. The "devices" are also connected to each other by means of solid coloured lines (current flow state of working) and dashed coloured lines (existing or available flow states of working). These lines represent the connections among processes. In the current set of operating status of Figure 3.12 "Device1" has an energy connection with "Device2". However, an hypothetical energy connection with "Device3" is modelled and may be activated as "imposition" of Time-Line signal or as a consequence of the internal operating status script.

The **operating status** (as shown in Figure 3.12) is defined by a series of parameters which determine the way of working for each designed scenario. Each device is modelled to work according to the value of this group of signals. These signals will dictate the way of working (among the diverse identified and modelled states) of the devices themselves. These signals (such as device limitations or geometric parameters) may be constant during the entire period, or time variable special clauses, which can be attributed to an unusual event, such as sub-device malfunction or transitory parameter. In short, this set of inputs determine the individual way of working of each specific device. At device level, if the operating status and the load input are determined, the response (outputs) is determined.

On the other hand, the modification of the logical connections among processes may be modified at upper level (without in-script code modifications) by Time-Line command or by the activation of a specific condition in the Operating status internal code. This kind of modification involves the changing of the energy and production output-inputs direction of the device model as well as the operating states. In summary, this agent commands the working of the process by interventions at the operating states and at the relationship among processes. At this point, the operating characteristics (at operational level) could be modified on the condition that this event had been previously identified and modelled at operational level - MATLAB® script. These changes do not suppose nor require the re-validation and verification step provided as long as these changes do not involve out of range working parameters. This fact is possible due to the theoretical robustness provided by the energy modelling by simulation.

These **relationships among processes** (as shown in Figure 3.12) are represented by means of actuator-signals. The holistic models react, change the status, or, definitely, modify the previous relationship according to a working signal. This main signal, which is previously identified at the data analysis and assessment section in conjunction with the process knowledge section, is characterised and introduced to the models as a set of status-direction (as it is shown in the dashed blue squares in Figure 3.12- [Relation-Block]) variables which command the entire model of working. These Relation-Block flows may be modified in the holistic window (developed in Simulink software environment), which includes all the modelled processes, if the "device" has the specific kind of input. For example, in Figure 3.12, "Device3" has a non-employed energy input and "Device2" has a non-connected energy output; if the connection of the flows has technical and physical sense, a minor change in production line window could connect these flows (energy output of Device2 with energy input of Device1). Then, any change may be included in order to forecast the future workings. In short, this set of inputs determines the relation among the modelled devices. At tactical level, for the same specific signals for each device, the overall response may be different according to the relationships among processes.

As a consequence, the **relationships among manufacturing processes** or steps as well as the hypothetical **operating states** are dictated by means of the aforementioned ways of acting (Time-Line signal, process window, block response and internal script). These model drivers are synthesised in the **Time-Line signal** (as shown in Figure 3.12). In this regard, the Time-Line generated is expected to guide the process during the analysed period as it was previously established and, in the same way, to be modified by the responses of the devices. Once a hypothesis (operating status or relationship among processes) is modelled and implemented, it may be accessed by the Time-Line input.

The **main production**, or **load**, completes the information required to set a correct simulation. For the same Time-Line, which defines the operating status and the logical connections among blocks during a period, a different load will produce different outputs and results. Although the "instructions" to the process and devices may be the same, the outputs depend, ultimately, on the material production (solid flow). The energy models, which reproduce the process workings according to this production input, are responsible for tracking the load requirements and for complying the process restrictions. These load restrictions may be implemented as imposed limitations at device level or as working sets at tactical level. This production input is defined as a quantity of material (with specific properties according to the specific main scenario of the manufacturing process) and as a time value in which these batches are introduced to the first step of the first sub-process. This production input is introduced to the model as an array of material which works as a queue. In the same way, the introduction times (for each batch material input) may be defined as a fixed array or as a response of the process way of working [when the previous batch reaches a specific condition (or groups of conditions), the next load is able to be introduced]. For simulation, these arrays may be generated randomly (within some margins) or using real production weeks with real production conditions and clauses.

Besides, some production conditions must be determined in order to launch the simulation according to the specific observed modus operandi parameters (by default unless a work modification was observed, such as burner nominal power anomalies, burner disconnections, ambient temperature or pressure controller damper state).

In summary, this production modelling allows a flexible modification of the working parameter as it is explained before. The connections and influences among elements are summarised in Table 3.1, in which the re-validation presumption is explained. This validation depends on the kind of modification. If the modification only affects in low quantitative terms (within the expected values ranges), this validation may be avoided. However, other strong quantitative or qualitative modifications should be validated with real measured data through parallel simulation tests, or, at least, they should be strongly verified (based on logical reasons and physics phenomena).

**3.2.4.2.2 Process control: Operative-effectiveness indicators.** L¡ The control of the process is managed from two perspectives: Overall manufacturing process indicators and device modus operandi indicators.

The first branch evaluates the process for the analysed period as a whole, taking into account the overall rates of main inputs and output results. In this regard, common

| | **Influenced or changed by modification on:** | | | | |
|---|---|---|---|---|---|
| Element | Time-Line | Process window (Simulink) | Block Response | Internal Script | Required validation |
| "Operating Status" | ✓ | ✓ | ✓ | ✓ | Only Internal Script changes[1] |
| "Relationships among processes" | ✓ | ✓ | ✗ | ✗ | No[2] |
| "Main production" | ✓ | ✗ | ✗ | ✗ | No |

[1] Unless the modifications are minors.

[2] Unless the new relationship is far away from the designed input-output ranges.

Table 3.1 – Changes-behaviour and validation requirements of the proposed production modelling elements.

indicators, which are very recurrent in the scientific literature and in the industrial environment, have been developed in the existing literature to assess the process in a simple way. They are useful to compare similar processes or other production facilities. In general, these key performance indicators do not provide the reasons under these values, but allow to evaluate at a glance the overall working of the manufacturing process. The most common and used indicators employ and combine terms such as total production, material input, consumed energy, production time, idle time, total time, etc. Each kind of manufacturing system should carry out several modifications to each specific process or directly design its own adapted KPIs [55]. On this matter, the KPIs, which combine an element according to another element, are considered "specific". The specific indicators allow to make better comparison at operational level, due to the fact they are capable of avoiding the gross value and making possible the comparison among different scales. These disaggregated indicators have been developed for many sectors and are used to track energy efficiency progress over time and also to calculate the technical potential for energy reductions in each sector [178].

Definitely, the indicators, in the same way as the objectives, should be SMART: specific, measurable, achievable, relevant and timely. The indicator, described without ambiguities, should clearly and directly relate to the outcome. The indicator should have the capacity to be counted, observed, analysed, tested, or challenged. The indicator is achievable if the performance target accurately specifies the amount or level of what is to be measured in order to meet the result/outcome. A relevant indicator should be a valid measure of the result based on research and professional expertise. Finally, a indicator should be well time-bound defined in order to be capable to identify events, trends or specific situations.

As it is shown in Figure 3.13, the indicators must be designed according to the specific aim and following some criteria in order to facilitate the utilisation and the subsequent management. In conclusion, these KPIs will provide the overall working of the whole manufacturing process analysed.

Several manufacturing common KPIs have been proposed to analyse in a simple way

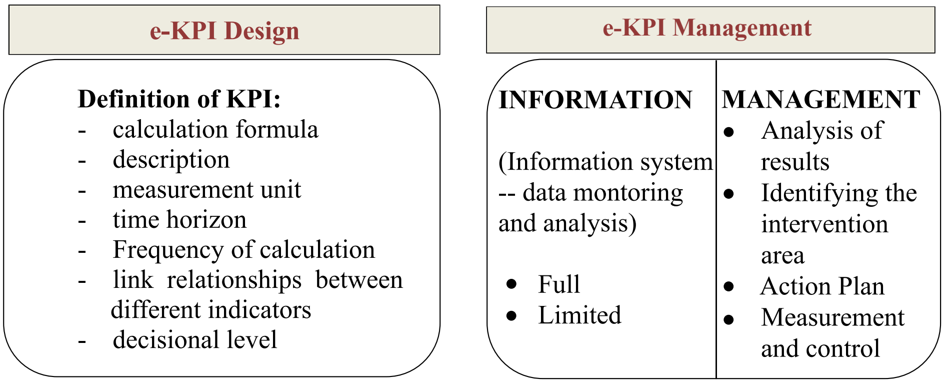

**Figure 3.13 –** Design and management of KPIs according to May et al. [55].

the process and to allow overall comparison among devices, processes, manufacturing lines or facilities. The best representation of each specific manufacturing process can be achieved with different sets of indicators. However, the most representative KPIs, such as Specific Production $SP$, Specific Time Consumption $STC$, Specific Load Consumption $SLC$, Defective Production $DP$, Energy Efficiency $EE$ and Overall Equipment Effectiveness $OEE$, are introduced according to the following equations:

$$SP = \frac{Production}{Time} \tag{3.7}$$

$$STC = \frac{Consumption}{Time} \tag{3.8}$$

$$SLC = \frac{Consumption}{Production} \tag{3.9}$$

$$DP = \frac{Production}{Input} \tag{3.10}$$

$$EE = \frac{EnergyRequired}{Consumption} \tag{3.11}$$

$$OEE = \frac{WorkingTime}{Time} \tag{3.12}$$

Where $Production$ represents the amount of produced output $[kg-units]$, $Input$ represents the amount of load introduced $[kg-units]$, $Time$ represents the period evaluated $[hours-day]$, $WorkingTime$ represents the time that the process or device is actually working $[hours]$, $Consumption$ represents the total amount of spent energy $[kW]$ and $EnergyRequired$ represents the theoretical minimum energy to reach the desired features of the production $[kW]$. Following the guideline proposed by Mat et al.[55], the frequency of calculation should be defined for the time horizon selected, and it should also evaluate at which level the indicator (within the time selected time horizon) provides more or better information.

Other more-specific indicators such as the load-restriction compliance or the specific device parameters or operating procedures should be ad hoc defined for the selected scenario.

The second branch, i.e. thed evice modus operandi indicators, are responsible for evaluating the operative of the devices from a load-time perspective. However, the time-based view alone is not sufficient [55] for these equipments due to the different working loads which they are subjected to. Even when a device may be working the entire stage-time, it may be working at partial load. For these reasons, the next family of indicators (Equations 3.13-3.14-3.15) have been selected to represent the real modus operandi of the devices: Nominal Load (NL), Mean Load (ML) and Specific Load (xL):

$$ML = \int^{iT} \frac{load}{iT} \delta t \tag{3.13}$$

$$NL = \int^{iT} \frac{time\_load^{100\%}}{iT} \delta t \tag{3.14}$$

$$xL_x^y = \int^{iT} \frac{time\_load_{x\%}^{y\%}}{iT} \delta t \tag{3.15}$$

where $iT$ [time] represents the interval time which is analysed. The *load* term represents the working way of the device for the selected "measurable" characteristic (it may vary among upper and lower range).These ranges may be defined for a specific characteristic or a property, and then, weighed to a percentage in which 0% means “off” or "minimum" and 100% means “full load” or "maximum". The *time_load* term represents the time when the device is working at full load (or maximum), for $NL$ indicator, or among “x” and “y” load, in $xL$ indicator. While $ML$ integrates all the states of working, $xL$ considers an interval of load, from load “y” to the selected specific load “x”. $NL$ is the representative state of working when the load is the nominal load. The *time_load* term is measured in time units. The term *load* may make reference to any kind of load, such as weight working load, power working load, temperature, level of energy, etc.

In conclusion, this production modelling, in combination with the proposed energy modelling, makes the following actions possible:

- The introduction of production conditions.
- The insertion of processes or device limitations.
- Giving a complete freedom when introducing production input (such as changes in kind of production).

- New device implementation in the process.
- EEMs implementation in the process.
- The modification of the manner of working.

In the same way, the analysis and assessment of the production parameters are tracked by the simulation results and summarised in the proposed indicators.

### 3.2.4.3 Economic Modelling

The economic modelling provides the economic evaluation of the hypothetical modifications introduced in the system. This modelling connects the savings with the expenditures and investments. The economic analysis is carried out as a comparison of the baseline (current operational, tactical and strategic manner of working) with the proposed EEM introduction for the evaluated manufacturing process. The explicit economic savings are obtained according to the energy savings and ecological savings valorisation. The implicit economic savings are accounted for as a reduction of the expenditures, which are introduced in the expenditure section.

The economic assessment gives a monetary value to all the previous outputs provided by the energy and production modelling by simulation and, it also, provides an approach to the investment cost, the operation&maintenance cost and the implementation cost. The Energy Efficiency increase of the processlays on three factors: energy, time and production. A specific set of tactical and operating conditions (established at the production modelling input) EEM may modify the final energy consumption, the total duration of the process or the total production. These three factors may be linked by means of the production specific consumption indicator (in terms of energy for quantity of production e.g. [kWh/ton$_{\text{produced}}$]). The economic valorisation of the energy savings is directly translated into an economic value by means of the cost[2] of the energy used. The ecological valorisation is made according to the cost of the $CO_2$ European emissions allowance[3]. Both principal savings are represented as $S_{NG}$ [€] and $S_{CO_2}$[€].

In contrast with the savings, the operational expenditures (OpEx), the capital expenditures (CapEx) and the preliminary activities expenditures (Cpa) derived from the EEM are proposed (also in €). The OpEx is divided into: parasitic load (due to any power consumption as a part of the proposed EEM or the process modification), the operating and maintenance cost (O&M) and the personnel cost. If any operating saving is incurred, it will be accounted for in the OpEx term as a negative cost. The CapEx

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[2] Energy price per gigajoule [€/GJ]: https://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=ten00118&language=en

[3] Carbon price per ton from [€/ton]: https://markets.businessinsider.com/commodities/co2-emissionsrechte

correspond to the technological investment (perishable and device) and to the installation, and the Cpa correspond to previous researching works. The Cpa may be saved if the same measure is proposed for another production line, process or factory.

As a final conclusion of this assessment, three economic indicators are approached: LEEC, Simple Payback Period (SPP) and the Return Of Investment (ROI) for each measure. The LEEC indicator proposed by Chiaroni et al. [112], correlates the energy savings that can be achieved through the implementation of an energy efficiency technology and the total costs incurred throughout the entire life cycle of the technology, e.g., initial investments, (O&M), disposal costs. Therefore, this indicator returns the real cost of the energy provided by this implementation. The SPP accounts for the time required to recover the cost of an investment, with zero interest rate, while the ROI measures the gain or loss generated by an investment in relation to the amount of money invested (for a specific period).

$$SPP = \sum_{t=0}^{SPP} CF_t \geq 0 \tag{3.16}$$

$$LEEC_T = \frac{\sum_{t=0}^{T}(C_{pa} + CapEx_t + OpEx_t)}{\sum_{t=0}^{T} TES_t} \tag{3.17}$$

$$ROI_t = \frac{CF_t}{(C_{pa} + CapEx_t + OpEx_t)x100} \tag{3.18}$$

and:

$$CF = (S_{NG} + S_{CO_2}) - (C_{pa} + CapEx + OpEx) \tag{3.19}$$

where CF [€] considers net cash inflows during the period ***t*** [years]. The term TES represents the Total Energy Savings generated by the EEM to keep the same levels of production.

The cost of the EEMs may increase non-linearly in adaptation to the real behaviour of the engineering costs. It means that introducing a measure with a low degree of implementation (for instance: a reduction around 10% of the infiltration area) has a fixed cost and a limited variable cost, whereas introducing a measure with a medium degree of implementation would maintain practically the same fixed cost while the variable would increase proportionally, as shown in the schematic Figure 3.14. On the other hand, the total implementation of the EEM (reduction of the entire area of infiltration) would be a hard task, in which the variable cost would grow up exponentially, as shown in Figure 3.14. The costs assumed for the EEMs under research are accounted for in Section 5.

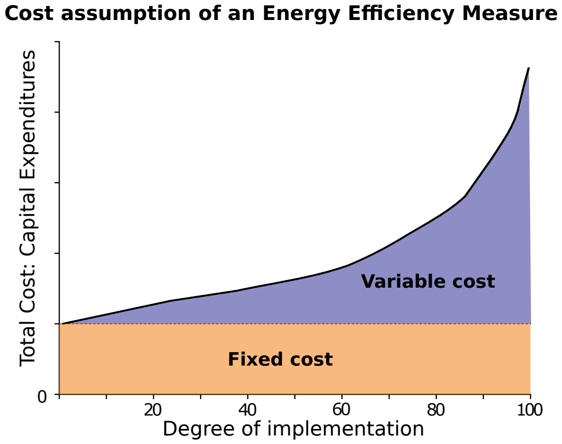

**Figure 3.14** – Simplification schema for fixed and variable cost assumption for a generic EEM.

#### 3.2.4.4 Ecological Modelling

Two ways of evaluating the ecological impact have been assessed according to the two sources of energy of the non-continuous processes: electric consumption and fuel consumption.

For the electric consumption, the employed approach accounts for the ecological impact of the generation and distribution of this energy. It mainly depends on the source or method to obtain this energy. The electric consumption, directly obtained from the national grid, presents the average characteristics of the country's way of generating this electricity. The carbon intensity and pollutants of grid electricity are determined by the fuel mix used in the process of generating it. Concerning this point, there are stated reports for each pollutant for the electric grid [179, 180]. If the electric energy is produced ad hoc for the process by means of any power plant, co-generation system, renewable source or energy transformation (previous recovery), the associated ecological impact will be assessed according to this source and method.

The ecological assessment for fuel consumption takes into account the carbon dioxide ($CO_2$) and nitrogen oxide ($NO_x$) generation. These are produced during fuel burning at the heat generators (and reproduced by the models with the help of the data sheet information). The analysis of the generated $CO_2$ accounts for the the fuel generation, transmission, combustion and distribution [181] of this combustible. The $NO_x$ generation is approached by the performance graphs of the heat generators included in the worksheets, according to the instantaneous power. The $NO_x$ emission data is given for specific nominal conditions (such as percentage of $O_2$ or the temperature of the firing chamber) and adapted later to the process conditions (such as real $O_2\%$ or real combustion temperature).

#### 3.2.4.5 EEMs modelling

The energy and production modelling procedures to reproduce the EEMs are the same as the proposed above. The EEM may be designed as a production-model modification, as a different set of connections among processes, as an internal-device modification, as a new device introduction or as a combination of the aforementioned options. The model is designed in order to enable the introduction of the proposed EEMs, which cover the energy efficiency gap. The EEMs are introduced as model parameters or blocks in the simulation window environment (squares in Figure 3.15). These blocks include the energy and production modelling features. The proposed EEMs are widely varied in complexity and process-orientation, such as working load variation, device parameter modifications, introduction of a new device (new block or "Devise" in Figure 3.12), device modus operandi modification or tactical/schedule changes.

Therefore, two kinds of EEM modelling are proposed. The first one is related to the process parameter modification, which is referred as $\text{EEM}_{para.}$ (as shown in the green word and square in Figure 3.15) and is modelled as a simple working parameter modification. However, in order to make this modification effective some minor changes on the already generated models may be required. In general, these parameters are already introduced in the existing models as a non-adjustable element. With an $\text{EEM}_{para.}$, the parameter under study is established as a "variable" block input. In this regard, if the parameter is modified from its previous ranges, a new "operating status" is created. This kind of EEM modelling requires low modelling work, due to the easy access to model parameters. In general this kind of EEM is focused on process management measures (such as pressure controlling, infiltration area or process time regulation).

The second kind of EEM proposed is related to the introduction of new devices, which modifies any flow (in direction and quantity) of the processes. This kind of measure modelling, referred to as $\text{EEM}_{block}$ includes a new model generation. This model, is then included in the process window and the relation among processes is restructured, as it is shown (purple word and square) in Figure 3.15. These new blocks may affect the main production output or only modify a non-production input. For example, a heat recovery system introduced to increase the temperature of the heat generator combustion air only affects the heat generation behaviour and may go unnoticed by the main production input, whereas a new preheating chamber located before a main process changes drastically the conditions of the production previous to the main process. This modelling, in general, presents more challenges both in terms of modelling and at the validation step. This kind of measure is usually oriented to technological measures.

In many cases, the managers and operators fix conditions of production or requirements in order to be able to track the weekly or monthly production schedule. In some cases, they face unexpected events, which may complicate the attainment of the production objectives. Well-known is the fact that the industry's main objective is to track

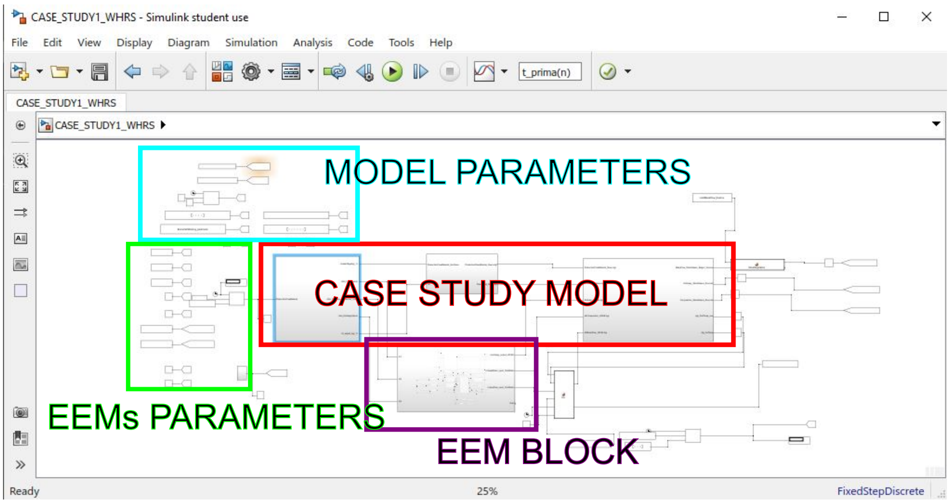

**Figure 3.15** – Lay-out of the model environment.

the production schedule, at the expense of other criteria, such as the energy efficiency of the processes. In other cases, the restrictions are very conservative in order to ensure the required levels of quality or to avoid any reprocessing afterwards. However, these restrictions may be overestimated, but it is not possible to "try" new restriction hypothesis due to the expenses of this trial (lost of raw material or production time lost). Therefore, a simulation scenario in which these loosen-up restrictions are introduced, may be economically assessed as a kind of EEM. In this regard, knowing the real limitations of these margins and the consequences of moving through (or beyond) the established restriction ranges, as well as being able to make adjustments, means a production advantage to track the production objectives in a more efficient way. Besides, decisions made under an incomplete understanding may provide non-economical results in the long term. Some of the hypothetical EEMs may affect these restrictions and will allow to acquire knowledge for future operating and tactical decisions.

#### 3.2.4.6 Modelling conclusions

In conclusion, the integral modelling allows to reproduce, to a large extent the energy and production behaviour of the process in manifold scenarios. In this regard, the models allow input modification (within margins) by the users and adaptations by the programmer for new hypothesis and scenarios. The diverse modelling (production, energy, economic and ecological) and the results are related as it is shown in Figure 3.16. The information flow during the simulation to obtain the final results is represented as the red line, whereas the black line represents the external inputs. The blue squares and the black squares represent the modelling and the assessing sections, respectively. There is not a specific criterion for where to start the sequence of modelling.

The modelling methodology and the way of reproducing the models is flexible enough

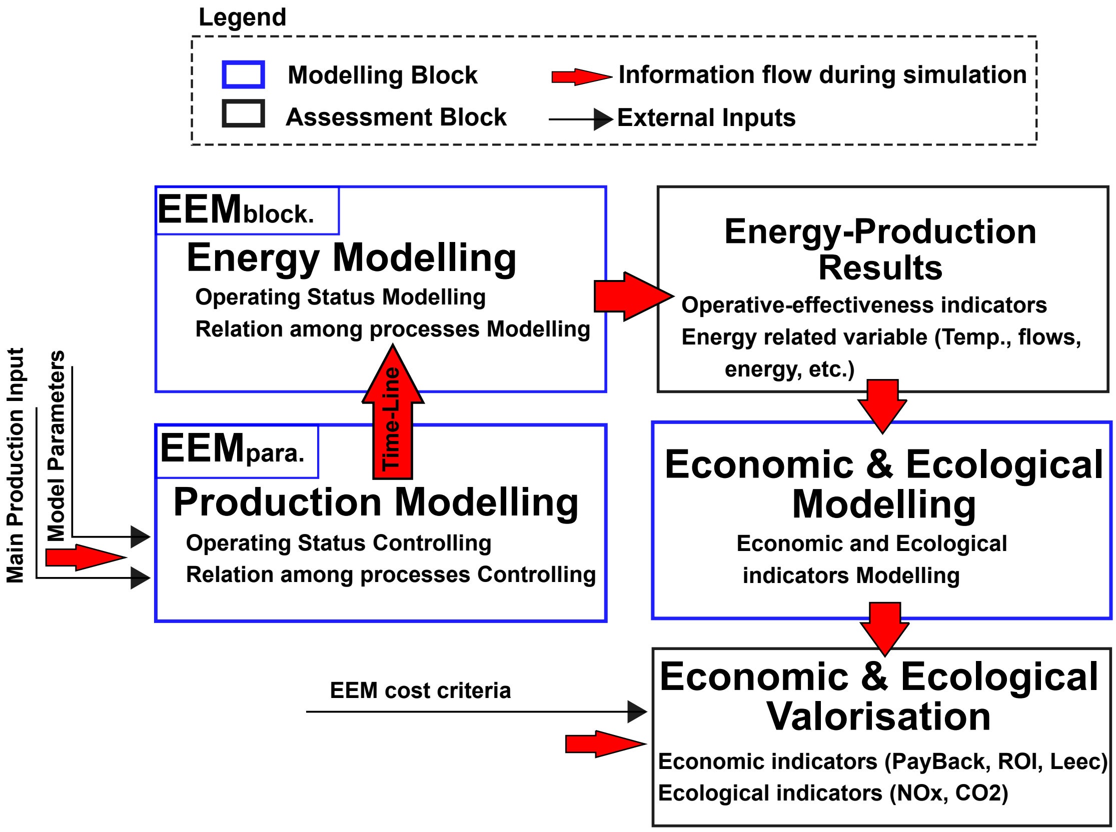

**Figure 3.16** – Interrelations among models and modelling and simulation sequences.

to introduce other kinds of events, such as device degradation, punctual malfunctions or unpredictable machine breakdowns, which is not the main methodology objective, as a non-EEM hypothesis. These events should be assessed and input-format adapted to the models in a previous stage. However, this point is not assessed in this work.

### 3.2.5 Validation & verification

The validation and verification are essentially comparative or testing processes to determine if the product (the conceptual model and the final models in this case) is consistent with its specifications or satisfies the requirements [182]. The model's representation of the problem entity, the model's structure, the logic of the model's processes, as well as the mathematical and causal relationships should be "reasonably" selected for the intended purpose of the model. This step must ensure that a model behaves in its desired way and adequately reflects the modelled (real) system [48]. In the same way, the simplifications assumed must be then corroborated by parallel analysis or studies. This last point is required to be covered by parametrisation complex physics phenomena which the model does not include.

#### 3.2.5.1 Verification

The verification process ensures that the model was built correctly [100]. The proposed methodology is based on energy modelling by computerised simulation. The process phenomena are recreated following the physics laws that are involved in the specific process. The conceptual model verification is accomplished due to the fact that the theories and assumptions underlying the conceptual model are physics-approach based phenomena, such as convection coefficients, heat conduction, advection or lumped-capacitance [183]. Therefore, the verification step is partially inherent to the procedure of modelling [100]. Thus, if the translation to the MATLAB®-Simulink® environment of the statements is correct the verification is successful. The verification of a specific modelled phenomena can be done by testing its behaviour with a set of different input parameters and comparing obtained results with known results.

However, many suppositions and simplifications have been assumed. Therefore, it must be ensured that for the range of parameters used for modelling the assumptions remain correct. For that to be possible, analytic and statistical assessment (as introduced in Section 3.2.3) has been developed, both for the general modelling and for the validation step.

#### 3.2.5.2 Historical Data Validation

Validation is the process of determining the degree to which the model is an accurate representation of the real scenario. For this methodology, the simulation results are endorsed by means of the "historical data validation" method. This method is used to compare the obtained results with historical data in diverse conditions, which presents an acceptable theoretical medium-low degree of subjectivity [184]. This historical data consists of relevant sets of compiled data which correctly characterise all the operating states, events and manner of working of the process under study. The validation criteria depends on the available information from the manufacturing process, which is based on the quality of the measured data (error), and on the previously defined scope of the Energy Efficiency Assessment. These historical data sets employed for endorsing the modelling must not be the same utilised for obtaining the conceptual models.

In order to sustain the validation, the difference between the measured real data and the data provided by the models must be compared. This comparison, based on historical data confrontation, provides the error of the simulation for the evaluated variables. The error is calculated using the direct difference between the values of the real measured variables and the values resulted from simulation for a representative time interval. The production input, the initial parameters, the operating states and other non-predictable inputs should be introduced as input. For a representative time sample (e.g. a unit batch time) both the overall behaviour and the trends should be tracked. However, for the representative period, the specific error occasionally may increase by reducing the time sample, due to non-identified input variations or non-perfect phenomena modelling.

The validations are considered accomplished when the results are a faithful representation of the measurements. The quantity of the absolute or relative error must be small enough to overcome the validation criteria. In general, this criterion is established as the maximum theoretical measurement error. More relevant than the value of these errors is the capacity of the model to track the trends and to predict events. Greater uncertainty in the data monitoring stage will provide higher indeterminacy at this stage. Strong modifications in the process will require a new validation process preceded by a new monitoring stage.

### 3.2.6 Optimisation Procedure

The variability of the manufacturing industry, mainly attributed to customer-s demand, determines the final manner of working of the manufacturing process. The factory operation differs with different throughputs. Therefore, the production criteria or the instructions may focus on different points. For these reasons, an absolute static optimum may not exist. This optimum must be adapted to the real conditions of the production for each specific moment and requirements or be adapted to the process manager criteria. In any case, to reduce the energy consumption of the manufacturing process (by maintaining the existing production conditions and rate) is a key objective for improving the efficiency. Apart from the energy efficiency (reduction of the specific consumption), each industry may show different interests or objectives, such as increasing the annual production or reducing the polluting emissions.

Notwithstanding, these interests or objectives will finally depend on the economic capacities of the industry. The projects, which modify the existing way of working or introduce a new device to improve any result, involve different expenditures and savings. For an equal value of Simple Payback Period (SPP), the capital expenditures may vary considerably, which may make one option unaffordable for a specific business. For these reasons, a multi-criteria optimisation process is required in order to avoid non-interesting projects. Therefore, the proposed optimisation procedure reaches an optimum solution by introducing the manager restrictions or requirements. In this regard, "optimal" solutions may vary significantly in relation to the criteria introduced. However, the ultimate criteria selected, once some other criteria have been applied, is the reduction of the SPP. This proposed procedure suggests as the final solution (among those which comply the previous criteria and restrictions) the one with the lowest SPP, due to the real industrial criterion identified in Chapter 1.

#### 3.2.6.1 Dynamic response and EEM range sensitivity analysis

The dynamism of the production, the capacity range of the device and the diverse ways of working make different optimisations with different objectives possible. For instance, altering the energy supply of a manufacturing process may change the overall requirements of the system. From the heat-transfer point of view, a “small” mass flow at high temperature (energy from burners) and a “big” flow at lower temperature (recovered energy) are not the same, even at equal power. This analysis has been made possible due to the energy modelling by simulation approach, in addition to the previous in-depth analysis to characterise all the events and variables.

However, this dynamic behaviour implies an additional challenge when preparing the optimisation of the process. Each condition, criteria, modification may affect the overall process behaviour directly or indirectly at any time-stage of the manufacturing process (such as, turn-on, start-up period, transitory period, stationary period and turn-off). For this reason, each hypothesis must be analysed during the entire representative period in order to have the complete available information for decision-making process. Nevertheless, to make a *caeteris paribus*[4] analysis, simulation and evaluation with a substantial amount of EEMs may require a huge amount of time and computational power.

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[4] All other things/parameters/conditions being equal

A sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions [185]. With this in mind, and in order to ease the optimisation procedure, a previous sensitivity analysis, for each EEM is suggested. For a specific case study and a representative period analysis, a unique EEM is implemented to, then, carry out minor modifications in the degree of implementation. The range analysed must cover the entire proposed range, and the selected variation interval should be representative enough to assess the trends at the results. This process is repeated for each proposed EEM. Consequently, the trends of each EEM for each relevant indicator are obtained. These trends and results will be the base of the subsequent heuristic approach to the optimal solution (for the established specific criteria). Synergies or effects-overlapping are not identified at this point.

#### 3.2.6.2 Multi-criteria making decision

An optimisation criteria (such as energy reduction, production rate increase, time reduction, etc.) must be first selected in order to guide the EEM selection. Some criteria depend on the specific scenario, such as the kind of manufacturing process, the involved devices, the production restrictions or the hypothetical ways of working, while others may remain practically invariable in case studies. In the second group, the main identified criteria are the following: overall energy consumption, overall energy efficiency, total production, total production time, savings per month, etc. Definitely, every indicator considered as relevant at the economic modelling process or identified at previous steps may be selected as an optimisation or restriction criterion.

These criteria may be split among "optimisation capable" or as a "restriction". The restriction criteria will ensure that the solution complies with this indicator value (or remains between the range limits) while the optimisation capable criterion tries to optimise this indicator. The weighted optimisation criteria is adjusted as a relation among the relative improvements of each specific criterion. In a scenario of several criteria optimisation, the improvement (increase or decrease according to the criteria features) of each criteria impacts, in a weighted way, on an overall fictitious indicator.

Due to the dynamical behaviour of the processes under study (and non-linear results of the EEMs) each increment of EEM improvement affects the system on a different way and generates diverse economic situations. The diverse economic conditions are explained in Section 3.2.4.3, in which the non-linearity of the cost is exposed. Besides, some phenomena are connected with a variable by means of a non-linear relation (such as the furnace chamber pressure and the infiltrations), or, directly, related to a experimental result (such as the NOx produced by a specific (fuel-fired) heat generator and the power provided by this heat generator). Slight modifications on the working conditions, provided by an EEM range variation, may move the system to a new operating status in which one or more devices modify each behaviour. Therefore, each measure must be analysed individually for each range. In this regard, the final solution results (combination of EEMs) will not probably be the sum of the individual results.

#### 3.2.6.3 Final solution optimisation

In this section the two steps to accomplish the most efficient solution are presented. At the first stage, an out-of-simulation heuristic approach is carried out. Here, the main EEMs, as well as their ranges, are bounded and the most adapted combination or combinations are delimited. Then, this combination of EEMs is simulated in order to verify that the dynamism and the interactions among EEMs do not negatively influence the other criteria or process restrictions. However, the expected optimum, reached by this range and EEMs selection, may not be the relative optimum. Therefore, an iterative optimisation procedure is carried out (as it is shown in Figure 3.17).

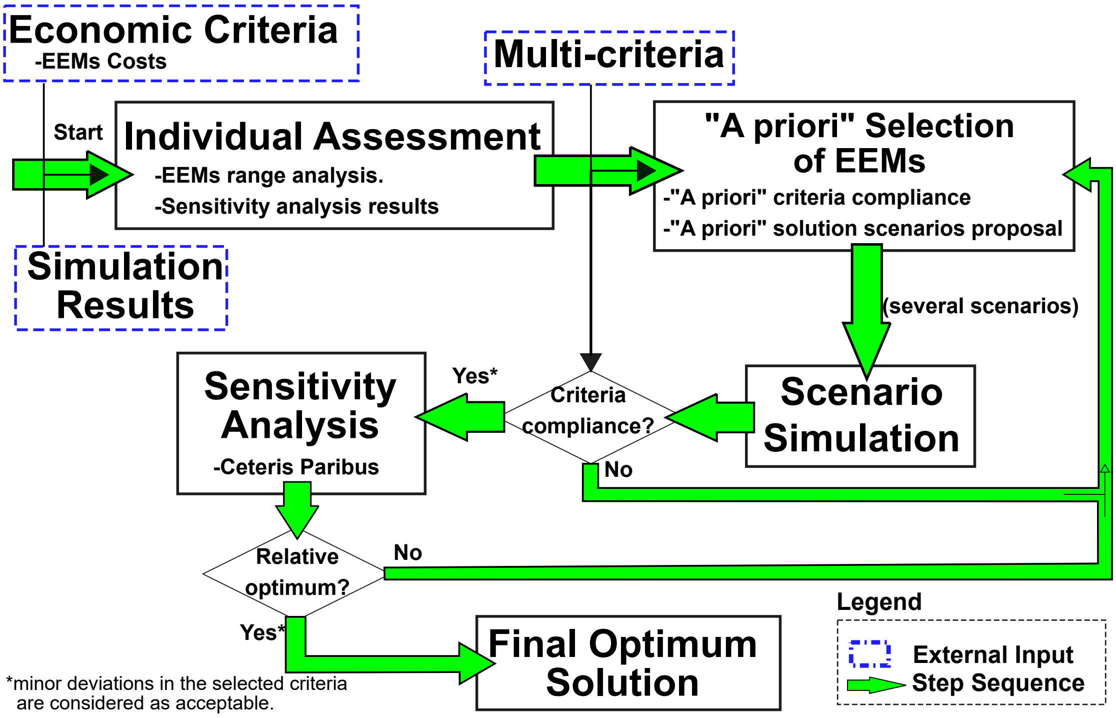

**Figure 3.17 –** Process optimisation scheme.

The three main inputs required for the optimisation criteria (once the models are generated, the EEMs identified and modelled and many scenarios simulated) are: Economic Criteria, the Multi-Criteria and the Simulation Results (as shown Figure 3.17). The Economic Criteria accounts for the cost of the proposed EEMs, whereas the Multi-Criteria input introduces the selected criteria of optimisation. The Simulation Results compile all the previous sensitivity results for each individual measures, which are then subjected to the Economic Criteria (EEMs costs) in order to obtain the economic indicators. The conditional blocks "$CriteriaCompliance$?" and "$RelativeOptimum$?" evaluate if the optimisation restrictions and criteria are accomplished and if the relative optimum is reached, respectively. These blocks provide information about whether any modification in the EEMs range worsens or not the indicators that are to be optimised. As shown in Figure 3.17, minor deviations in the selected criteria are considered acceptable in order to reduce the required time for the first iteration (i.e. ”*CriteriaCompliance*?”), bearing in mind the expected margin of error of the simulation models. This fact provides a fast convergence towards the solution.

For this final solution procedure, a fixed criterion is previously established: the energy efficiency of the manufacturing process. This criterion is directly linked to the specific energy consumption. In the absence of any other criterion, the optimisation procedure will prioritise this optimisation. If any other criterion is imposed, the procedure will comply (if possible) with this criterion or set of criteria and, then, the procedure will try to optimise the scenario to reach the maximum energy efficiency.

**3.2.6.3.1 Heuristic approximation to "criteria" maximisation.** The obtaining of an optimum for the selected criteria is not a direct task, due to the dynamic way of working of the devices and the interrelated processes. A preliminary approximation to the final solution, based on the simulated scenarios for the diverse EEM ranges (if applicable), is carried out (as shown in Figure 3.17 - ”*Apriori*”*selectionofEEMs* block). The production, economic, energy and ecological indicators of the evaluated scenarios are analysed in order to obtain a compromise among a specific combination of EEMs, the selected final criteria as well as the impact on indicators (for the EEMs combination selected) of the individual results (indicators variation) of each EEM.

**3.2.6.3.2 Optimisation to relative maximum.** Once the combination of selected measures and ranges, which is expected to approach the maximum energy efficiency point (within the restrictions, constrains and selected criteria), is obtained, this scenario is simulated. Then, EEM range variations are suggested to test if this combination is actually the one that optimises the criteria. An iterative simulation procedure is considered in order to evaluate how slight modifications on the measure ranges affect the indicators (as shown in Figure 3.17 - *SensitiveAnalysis* block). After that, by comparing the set of simulation which complies with the criteria and restrictions, and/or optimises the efficiency, the final solution is chosen. Consequently, synergies or effects-overlapping are identified at this point. If as a result of the interactions among EEMs the first scenario is far away from the expected point, a new combination (with other EEMs) is proposed and analysed.

In this regard, this optimisation procedure reaches a relative optimum for the selected criteria. The absolute optimum for the selected conditions may remain hidden or be not achievable. In the same way that some measures can generate synergies, other sets of measures may soften the combined impact. This cushion effect is common for EEMs which affect to the same phenomenon. This is clearly shown at the infiltration flow in heated chambers, where infiltration flow depends on the area of infiltration and on the chamber pressure. However, a combination of EEMs which affect to this phenomenon may make sense due to the Pareto principle [5] according to the trends of engineering expenditure cost. Anyway, each range of combinations has to be analysed individually in order to find the optimum.

In conclusion, this approach provides a multi-criteria optimisation tool for EEMs implementation assessment. The models reproduce the trends of the system and of the modifications (EEM) in order to, then, provide a valorisation of the results. After that, by means of this optimisation procedure both the criteria of optimisation and the EEMs valorisation are introduced and combined to obtain a final optimum solution.

## 3.3 Main methodology conclusions

The main conclusions derived from this step-by-step development of the methodology are synthesised in this section. As it is stated before, the methodological steps do not suppose much novelty due to the fact that they are common for this kind of approaches (the ones mentioned in Section 2.4.1). The real innovation of this methodology are the contents of each section.

In this regard, a flexible approach for energy modelling of non-continuous thermal processes, based on dynamic simulation of processes, which combines energy, production, economic and ecological assessment of processes and hypothetical EEMs is proposed. In order to cover the energy efficiency gap identified in Chapter 1 for non-continuous thermal processes by adapting and improving the procedures and methodologies for integral and holistic modelling found in literature (Chapter 2).

The main features of the proposed methodology are: the **flexibility** of the modelling, the **way of modelling** (based on energy modelling by simulation), the **dynamic assessment** capacity of the processes (interrelations up and downstream), the **kind of data** characteristics which is commonly available for this kind of processes as well as the **interactive multi-criteria** introductions.

This flexible approach allows to introduce physics-based energy modellings of any energy-kind of processes (electric or thermal). The methodology is oriented to thermal processes because the fact that the electric energy models may be more easily reproduced with other kind of energy modelling. Nevertheless, this approach may present advantages for the energy modelling of hybrid (electric-thermal) processes, in which the disadvantage

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[5] The Pareto principle, related to the EEMs-ranged costs, states that, for many events, roughly 80% of the range improvements come from 20% of the investment. This is motivated by the exponential cost trend of common engineering constructions.

is an increase of the modelling working time (attributed to the electric-energy models). This aforementioned approach balances out the better understanding of the process due to the physics based thermal-energy models.

The proposed energy modelling by simulation, which reproduces the "real world" and shows the eventual real effects of alternative conditions and courses of action, allows to evaluate the energy behaviour of the systems and to introduce production events at the same time that these events modify the processes. This kind of modelling is based on real phenomena reproduction (if possible). On the other hand, the manner the energy modelling by simulation is modelled (blocks, connection window and time-line event introduction) allows to easily modify the models to introduce new modifications. Subsequently, in the proposed block by block modelling, each block is able to work independently of each other, providing that each input is among the expected range. This fact generates robust results for the dynamic event. Besides, it allows for analysing the sensitivity of a parameter for any range of variation. In this regard, the proposed energy modelling by simulation requires high knowledge and time to create the models, but, once they are created, modifications are easily implemented.

The dynamic assessment proposed in this methodology allows to connect processes and relate phenomena, events and operating status of each device. Therefore, any modification which may affect another process, device or condition is taken into account. The reliability of the results of the dynamic events and relations is guaranteed due to the kind of modelling.

With this methodology, a manufacturing process line can be comprehensively assessed and evaluated. This analysis allows to identify the existing energy efficiency gaps of the involved processes and to propose EEMs. The data required for this evaluation (and validation) are not based on big-data technologies. However, this evaluation requires an exhaustive compilation of information about any implicated device and the theoretical way of working of the process. This information is compared with measured data and the exceptional features and conditions which could have affected the process.

As a result, the optimum solution (EEM) or combination of solutions, obtained following the proposed optimisation procedure, is determined in order to reach the highest level of energy efficiency in the process, based on the criteria introduced. Once some simulation results are obtained (production, ecological and energy), the economic cost criterion introduced can be interactively modified to be adapted to the cost fluctuations or recalculations.

The main challenges and problems identified in the state of the art are addressed. The decision-making problem, which prevents a correct selection of EEMs, is addressed by means of the introduction of a multi-criteria procedure. This methodology covers all the required fields (energy, production, economic and ecological impacts) to provide an integral and complete analysis and solution. Additionally, it is designed to assess diverse levels of production (from operating to strategic) and to tackle diverse scales of a factory from a holistic perspective (from plant, and even surroundings, to devices), putting a special focus on the production line (set of interrelated processes). This methodology is not developed only as an abstract mental task, but it is also implemented in a real process. This process, which brings the main features (such as dynamic phenomena, variable production input, devices and process interrelations) for which the methodology has been designed, allows the methodology to be widely implemented.

# 4

# Case Study

**Summary**

*This chapter explains the main case in which the methodology is applied. This case corresponds with a non-continuous thermal process, which presents highly-variable dynamic behaviour (natural gas consumption, production input and residual streams), from manufacturing industry. The first part of the methodology, which comprises the data acquisition, the process characterisation, the process modelling and the validation, is implemented. As a consequence, an in-depth analysis of the involved processes has been developed.*

## 4.1 Case study: Heat Treatment Process in Aluminium Die-Casting

According to the methodological approach, the first step consists of the identification of the scenario. In this case, an Aluminium Die Casting industry, which produces low weight metal parts with high mechanical properties by means of the process shown in Figure 4.1. The aluminium alloy is generated and melted in a furnace, has been selected. After that, the liquid aluminium alloy is degassed and transported to the die-casting section. The liquid alloy is introduced into the die-casting device, where parts are formed and cooled. Then, the solid parts are placed in baskets and subjected to a thermal Heat Treatment Process (Heat Treatment Process (HTP)), at different levels of temperatures and times (bottom section of Figure 4.2) in order to improve the mechanical characteristics of the parts. Finally, the parts are mechanised and, then, they are subjected to several quality controls. The HTP (represented in the top section of Figure 4.2) is the second major consumer of thermal energy (of Natural Gas (NG)) of the plant, following closely by the melting furnace. Besides, both processes present high exergy residual heat flows.

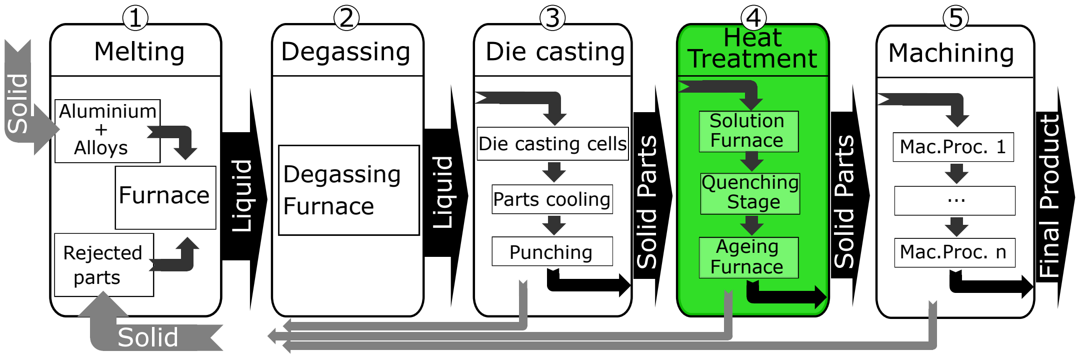


**Figure 4.1** – Aluminium Die-Casting process schema.

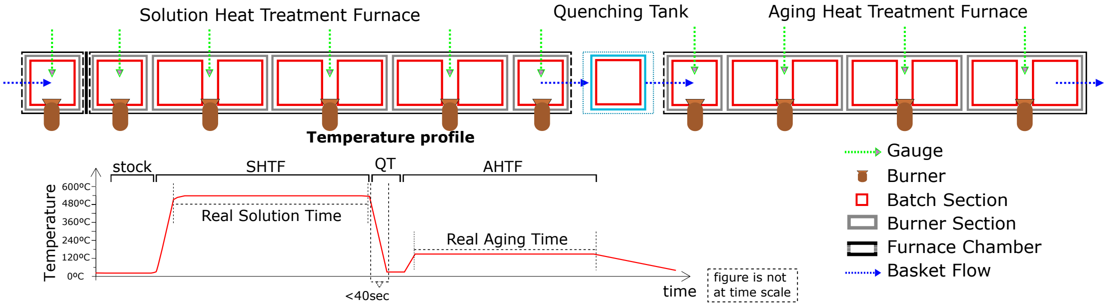


**Figure 4.2** – HTP and time-temperature required profile

The main disposal flow of the melting furnace presents a high exergy value. The furnace heats and melts the load by means of two natural gas burners. The disposal flow, i.e. the stack gases flow, leaves the system after an internal regenerator [51]. A regenerator (or regenerating device) is an insulated container that can absorb and store thermal energy. During the operating cycle, the gases exhausted by the process flow through the regenerator, heating the storage medium. When the medium becomes fully heated (charged), the exhaust flow is shut off and the cold combustion air enters the unit. As it passes through, the air extracts heat from the storage medium, increasing its temperature before it enters the burners. Eventually, the heat stored in the medium is drawn down to the point where the regenerator requires recharging. At that point, the combustion air flow is shut off and the exhaust gases return to the unit.

The furnaces of the degassing and transporting system scarcely represent a minor part of the energy consumption, and the sources are split in many flows which complicate the hypothetical recovery/recycle/reuse. These furnaces are rail guided mobile devices, which complicates the implementation of EEMs. Then, these furnaces inject the molten alloy into the Die-Casting machines which, after the cooling stage (carried out by water or compressed air), create the solid parts. These devices have two main consumptions, the electrical consumption, which provides the forces to introduce the molten metal and to punch the parts, and the compressed air consumption, which cools the parts. High values of exergy destruction have been identified at this point. A new mechanism to cool the part is currently being developed. However, this is the most critical process in the plant (bottleneck), so modifications or interference are not allowed.

Once the solid parts have been generated, they go to the HTP. The furnaces which form this process are natural gas-fed. In an intermediate step the batches are cooled with high exergy destruction. The parts are cooled at ambient temperature after the last heat treatment, which also supposes a high, but lower, exergy destruction due to the lower temperature. Both furnaces dispose of the exhaust gases to the environment by means of individual tangible flows. These flows present high values of exergy and not compromising corrosivity ranges. The last part of the manufacturing process is the machining of the parts. Only electrical and compressed air consumption is required for the machining devices. Besides, the energy efficiency indicators show acceptable levels and consequently, low potential for improvement.

As a result of this previous facility analysis, the HTP has been selected (consideration with the industrial manager suggestions) as the production line in which the Energy Efficiency Assessment will be carried out. This kind of processes represents 37% of the total natural gas consumption of the entire plant. The melting process accounts for half of the consumption, whereas the crucible furnaces for maintaining and degassing are responsible for 12%. The remaining natural gas consumption belongs to the heating of the plant. Within the HTP, the solution process entails around 85% and, thus, the ageing process involves the remaining 15%. HTP is a group of industrial and metalworking processes used to alter the physical, and sometimes chemical, properties of a material, such as hardening or softening a material. Metallic materials consist of a microstructure of small crystals called "grains". The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behaviour of the metal. A HTP modifies these structures.

## 4.2 Summary description

The HTP of a real low-pressure aluminium die-casting consists of three main sub-processes: The Solution Furnace (Solution Furnace (SF)), the quenching stage and the Ageing Furnace (Ageing Furnace (AF)), as shown in Figure 4.2. Both furnaces are constituted by a different number of stages. Each furnace has its respective conditions of time and temperature, which correspond to the T6 HTP for aluminium alloys [186]. The most crucial point is the solution sub-process because the time and temperature conditions must be accurately tracked to ensure the correct grain transformation. The ageing sub-process is also essential for the final product, but it allows variations in the time-temperature conditions. These durations, in which the parts must remain at specific temperatures, are referred to as Solution Time Temperature State (Solution Time Temperature State (STTS)) and Ageing Time Temperature State (ATTS). In order to preserve the confidential parameters of production for the produced part the current time values of STTS and ATTS are considered 100%. These values are measured in hours/minutes and represent the time that the parts remain at process conditions. For example, if the total time since a batch enters the furnace until it leaves is 10 hours, but during the first hour and a half it has not reached the temperature of the process, this indicator (STTS or ATTS) will be 8.5 hours.

The main characteristics of the HTP are outlined below. The input of this Non-Continuous Process is variable in batch format, while it stops at weekends. In the first step, the parts are introduced in batches (packs of steel baskets) into the SF.The baskets are then quenched and, after this quenching process, they are subjected to the ageing process. There is an internal door between the first and second stage of the SF. This process is manually commanded to start the introduction of batches in the SF, it then works automatically. Both solution and ageing HTPs are fed by NG fired burners. The furnace chambers are below ambient pressure to avoid hot air leaks.

The proposed energy efficiency assessment, which is carried out by the implementation of the presented methodology, allows to identify, quantify and evaluate the energy savings and the impact on the behaviour of the HTP under evaluation. After the monitoring and process information acquisition, the process is analysed in order to identify energy gaps, future energy efficiency actions or EEMs. The solution exhaust gases have been identified as a useful high exergy flow. In this regard, the ageing stack gases present non-negligible levels of energy and exergy. Several inefficiencies with high margins of improvement have been identified, such as the reduction of the infiltration area, the regulation or reduction of the internal pressure, the reduction of the basket weight and the internal door re-activation.

The main course of action is the implementation of a Waste Heat Recovery System (WHRS) based on Heat Pipe Heat Exchanger (Heat Pipe Heat Exchanger (HPHE)) technology with the aim of recovering the energy of the solution gases, as shown in Figure 4.3. Besides, the recirculation of the ageing stack gases is proposed, which allows to increase the exergy and energy of the WHRS flow. Afterwards, some other EEMs have been simulated and analysed in combination with the proposed WHRS. Other combinatorial hypotheses, which combine several EEMs, are proposed in the following

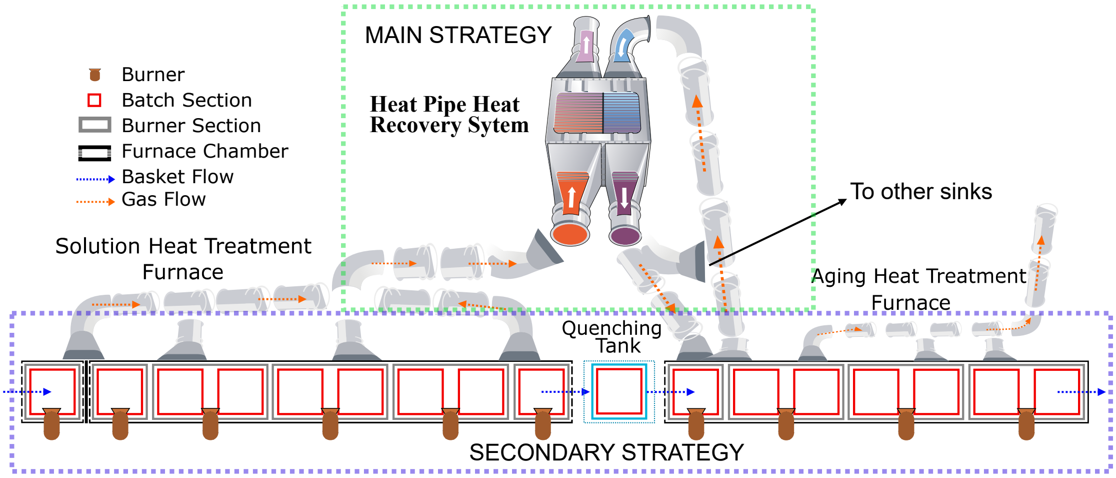


**Figure 4.3** – HTP and WHRS. Strategic course of action.

pages in order to evaluate synergies and relationships among energy flows and among processes or sub-processes.

Finally, all these proposals are analysed by the models and evaluated under diverse criteria. For this analysis some working conditions, some economic assumptions and a wide variety of measures were selected in order to obtain some specific optimums. This case study is oriented to the analysis of the main measure, the WHRS measure, and how other changes in the process, other modus operandi and the tactical decisions affect the HPHE design, the process energy behaviour and the production plan. The results show that there are high margins of improvement in manifold ways. The potential may reach up to 50% of the current energy consumption.

## 4.3 Process Information

All the information related to this specific process is compiled in this section, as following the first part of the Methodology (Section 3.2.2). The production characteristics, the device features and the consequent restrictions and limitations derived from these aspects are accounted for. In the first step, the physical mechanisms which are involved is this process are identified, introduced and explained. Then, the main characteristics of the production process and devices are detailed. Finally, the restrictions or limitations of the processes are exposed.

### 4.3.1 T6 Heat Treatment technical considerations

The procedure of the thermal process of this HTP corresponds to the T6 heat treatment process [186]. T6 Heat Treatment is a two-phase process which is applied to aluminium, copper, or silicon alloys to increase the strength of the alloy by as much as 30%. A standard heat treatment consists of solution, quenching , and ageing. These process are explained as follows [187]:

- Solution (or solutioning): which comprises holding of the alloy in temperature levels below the temperature of the eutectic reaction in order to dissolve the precipitations of other compounds ($Mg_2Si$ typically), homogenise the chemical elements concentration and the change in the silicon precipitations morphology.
- Quenching: which is the rapid cooling of a workpiece in water, oil or air to maintain certain material properties by reducing the window of time during which these undesired reactions are both thermodynamically favourable, and kinetically accessible.
- Ageing: which consist of the soaking of the supersaturated alloy to separate strengthening phases from the supersaturated solid solution.

The nominal process temperature is 540°C and 160°C for SF and AF, respectively, as it is schemed in Figure 4.2. These temperatures correspond to the temperature below the temperature of the eutectic point of the alloy and to the temperature selected for covering the ageing requirements, respectively. The duration the parts are kept in those conditions are not provided here due to confidentiality issues. The time durations were selected to comply a variety of mechanical characteristics, such as tensile strength, elongation and impact strength. Notwithstanding, these time durations and temperatures may be slightly modified while keeping the aforementioned properties in the same value range (as shown in Figure 4.4 for the tensile strength).

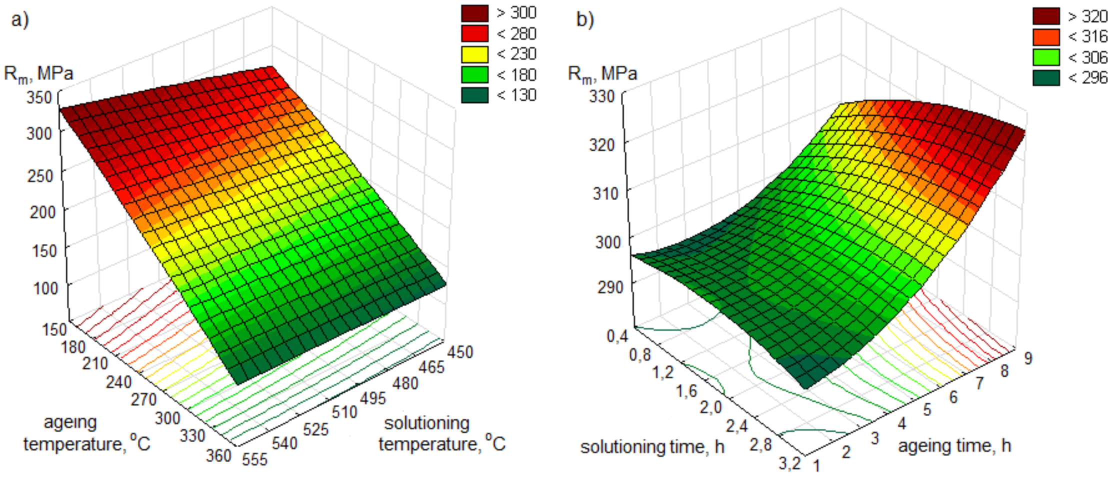


**Figure 4.4** – Effect of parameters of the solution and ageing operations on the tensile strength [186].

Besides, the time-parameters depend on the thickness of the treated element and of the kind of casting. On the basis of the results discussed by Pedza et al.[186], considerable discrepancies have been identified concerning the ranges of the temperature and duration of the solution and ageing operations. However, the shortening of these durations seem to be possible without any considerable effect on obtained mechanical properties.

The last technical consideration of this process concerns the moment when the load (or, specifically, each part) reaches the temperature. From the previous assessment, slight variations on the time, or even on the nominal temperature, would not generate appreciable modifications to the properties. On one hand, the external parts (the parts located on the boundaries of the fixture) reach the expected temperature before the internal ones due to the heat transfer mechanisms. But on the other, these parts are more exposed to temperature peaks. The parts are introduced to both furnaces at ambient temperature (around 25°C). The process is managed to reach the required level of temperature as soon as possible. The time that the load (on average) takes to reach the temperature is taken into account to establish these durations.

### 4.3.2 Production characteristics

The HTP production depends on the previous processes, and specifically on the die-casting machines, which commonly cause the bottleneck in this kind of factories. In this regard, the die-casting machines are preceded by the degassing and holdings furnaces, which in turn are fed with melted alloy by the melting furnace. Both volumes of work, i.e.the melting and the heat treatment process, rely on this die-casting process. A batch-stock based strategy is employed in order to control this HTP production. A reasonable quantity of batches is stocked previous to the HTP in order to avoid discontinuities and non-production stops, as well as to reduce the dependency on the previous process production. Thus, the production should be practically continuous. Nevertheless, these perfect conditions are subjected to the real way of working of the factory. Several non-perfect working conditions have been identified in the analysed weeks. When the first furnace is ready, the first input goes into the furnace and, after a specific batch duration (to comply with the parts requirements), the process works automatically as a pull strategy. If there is not a batch in the stock, an empty batch is introduced into the furnace.

The HTP works following a weekly timetable, that is, the factory produces during the working-week (Monday to Friday) and stops during the weekend (Saturday to Sunday). The specific HTP production load is demarcated by the basket dimensions, each kind of part will be arranged to allow the highest number of parts inside. Besides, some production modifications may modify this production rate, such as the variation of total load among weeks [due to the different shape of the parts (engine-blocks, vehicle suspensions, steering knuckle, etc.) or to the customer's demand for this week] or the working calendar. The furnaces have a theoretical mass limitation. However, it is far away from furnace nominal working conditions. Initially, there is no load at the turn-on stage. Notwithstanding, exceptional load-input introductions have been identified by production data assessment and confirmed by the operators. The reasons of this extraordinary working way are not cleared. Each furnace has a turn-on time, where the inertia reaches certain levels of temperature. This duration is not perfectly established and varies around ±20% for the different observed working weeks. The dependence of the HTP over the die-casting process, which precedes the HTP, may create situations in which the load is not ready. Therefore, scenarios in which the input load "suffers" a delay of one or more stage-times may be generated. Besides, other operation factors may affect the load input. In this regard, and based on the production data compilation (input time, number of parts, kind of parts, etc.), the input time may be modified for the analysis of a new scenario without delays. This time value represents when the batch is introduced to the first furnace.

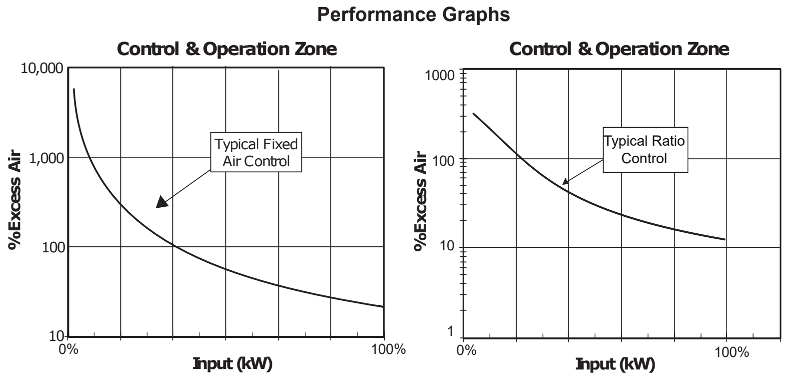
Definitely, the production depends on the customer's demand, and, as a consequence, a different demand generates different consumption profiles. In fact, in terms of quantity/weight of aluminium-alloy which is treated (high correlation to the energy consumption), the total treated weight may vary more than 20% among working weeks.

The parts must remain for a certain time at the required temperature, this restriction is tracked by the (specific-to-process) KPIs called STTS and ATTS. The current stage-time is selected to accomplish these requirements. The parts are arranged into steel baskets prior to be introduced into the furnace. The furnaces heat the charge by means of burners. These burners have specific working conditions( determined by building-default) which are explained in the data sheets. Besides the burner size, these burners are constricted by other apparent power restrictions, which seem to limit the maximum energy provided by these devices. The first stage of the solution process is responsible for providing heat to the entering load. An internal door was originally built, which isolates stage 1 and 2 at the SF, in order to prevent the cooling of the next stages. Currently, the internal door is always opened. The furnaces are not perfectly isolated from exterior, fissures or gaps in the enveloping wall, attributed to the non-perfect closure of the doors or to the roller conveyors' cylinders, were visually identified. These gaps are product of the normal use of these kinds of devices, due to the heavy loads (weights) they support. The burners are fed (comburent or oxidant agent) by air at ambient temperature. The furnace is depressurised (below the exterior pressure) in order to avoid leak flows. The baskets and parts are also introduced at ambient temperature.

### 4.3.3 Device characteristics

Within the two furnaces and the quenching stage the main devices that command, control or participate in this process are the following: burners, roller conveyors, baskets, centrifugal fans, chimneys and all the internal sensors which log data or provide warning-alerts if a product characteristics are not under normal conditions.

- **Solution and Ageing Furnace:** The HTP consists of two furnaces: SF and AF, divided in 9 and 7 stages, respectively. The other main devices are distributed inside these furnaces. The number of stages of each furnace determines the duration the parts (the batches or, in short, the load) remain at the furnace according to the established time-interval for the stage-time.
- **Quenching Tank:** This sub-process consists of a pool of water in which the load quickly reduces its temperature after the SF. The load is introduced by a vertical elevator connected to the roller conveyor. This step is fed by compressed air, which is introduced by the bottom of the tank/pool, to increase the forced convection. After the load reaches the required temperature (under 40°C), the parts go up and wait for the remaining time interval. In this period (the remaining time) the parts drain by gravity (without forced actions).
- **Burners:** The main heat generator of these processes are the burners. The SF and the AF heat generation systems are composed of 6 and 4 burners, respectively. The first burners (in the production process direction) are the most powerful in their respective furnaces. The remaining burners, 5 at SF and 3 at AF, present lower nominal powers. The burners' fuel-air ratios follow the ratio adjustment of design. This adjustment is a fixed air control for the AF burners and a specific ratio control for the solution ones, as shown in the performance graphs of the burners datasheets in Figure 4.5. In this regard, the datasheets present other performance graphs in order to characterise both the ecological aspects and the behaviour of the provided energy. The burners are commanded by PLCs (Programmable Logic Controller) which track the temperature of the circulating air of their respective burning sections. These PLCs establish the power which each burner generates. The introduced excess air follows the previous commented ratio according to the power provided by the PLC, as shown in Figure 4.5.
- **Centrifugal fans:** In order to prevent temperature peaks and to increase the heat transfers (by improving the convective mechanisms), several centrifugal fans are installed inside the furnace, at each burner section. Centrifugal fans are constant-displacement or constant-volume devices, meaning that, at a constant fan speed, a centrifugal fan moves a relatively constant volume of air rather than a constant mass. This means that the air velocity in a system is fixed even though the mass flow rate through the fan is not. Besides, these fans act as a heat source due to their energy losses. This energy is not very relevant for the solution process, but it can make a non-negligible contribution to the ageing furnace.
- **Roller conveyors:** The load, batches of parts and baskets, is transported by means of a set of roller conveyors (as schemed in Figure 4.6. This element is



a) Fixed air control

a) Ratio regulator adjusment

**Figure 4.5** – Datasheets: Performance of the burners. Excess air control.

split in many stages for each furnace (one per batch section) which may work individually. Once the next stage is empty, the preceding roller section starts to work (if it is commanded in this sense) to move the load to the next stage. The main energy-related feature of this item is the generation of relevant thermal inefficiencies. These inefficiencies are attributed to the infiltration air (due to a non perfect closure with the exterior) and the thermal bridges.

- **Baskets:** The baskets are the fixture in which the parts are placed in order to be introduced into the furnace. The baskets, which are introduced by pairs in each batch, are made of stainless steel. The baskets are introduced at ambient temperature, therefore, the furnace needs to heat this steel weight. In this regard, around 40% of the energy absorbed by the load is spent for heating the steel basket. The basket dimensions and structure, in combination with the part shapes, are the main limitation of the batch load. Different number of parts may be introduced in each batch according to the different geometry of the parts (as shown in Figure 4.6).

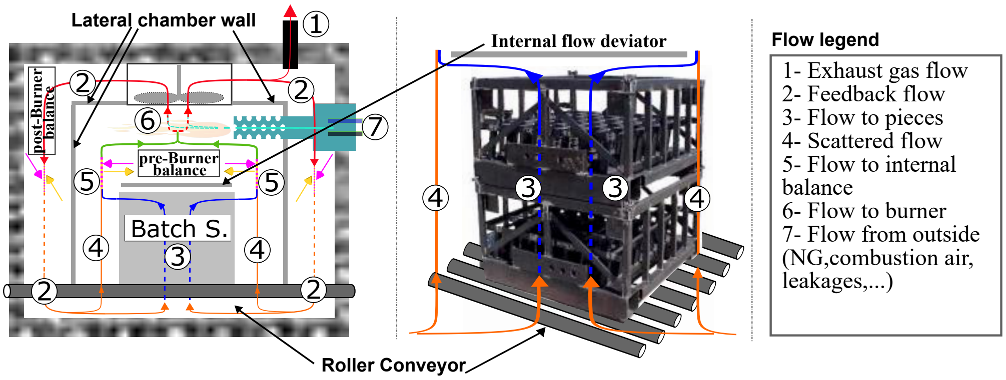


**Figure 4.6** – Schema of the furnace chambers and some devices representation.

- **Chimneys or stacks:** The stacks collect the exhaust gases of the furnaces and direct them to the exterior (disposal). The heat losses at the collectors and pipes represent up to 15% of the total energy of the solution stack gases. In the AF the heat losses attributed to the piping and exhaust collection are not as relevant due to the minor operating temperature (around 160°C in front of 540°C). The solution stack losses are measured in a point located several meters over the furnace. These ducts, pipes and collector generate the chimney stack (negative variation of pressure) which provides the internal (negative) pressure of the furnace chambers. This stack is controlled by a static damper adjusted to the nominal working conditions. Non-tailored adjustment would conduce to high negative pressures within the chamber, which would allow high infiltration air flow through the infiltration area (due to the non-perfect closure of the doors, grooves near the burners, or gaps at the conveyor rollers).

- **Batch chamber:** The structure of the batch chamber is designed to provide the heat requirements without damaging the parts (temperature peaks). In this regard, two structures must be highlighted: the internal flow deviator and the lateral chamber (as shown in Figure 4.6). These two elements direct the hot gases inside the furnace to the batch base and isolate (for direct radiation flows) the load from the burners flame.
- **Sensors:** The main sensors are the position sensors, which assess if a batch is located in a specific section, and the temperature sensors. They are situated all around the furnace. The temperature sensors are located above and under the load. The values of the ones located over the load are shown on the furnace control screen. The other values are used for warning purposes (in case the temperature exceed some limitations).
- **Combustion air feeding fan:** This fan feeds the combustion air of the burners. The fan takes air from the environment, makes it go through a filter, and directs it to the burners according to their requirements. The increase in the air pressure is low, around 40 mBar. Considering an isentropic compression, the temperature rise would not be higher than 3 °C, however, the pipes and valves located between the fan and the burners remove the heat obtained.

### 4.3.4 Main restrictions or limitations

From the analysis of the device characteristics, the process information and the production characteristics some restrictions, attributed to physical limitations or imposed production rates, are identified. The most restrictive ones are commented below:

- STTS and ATTS: These time values cannot be reduced more than 20% and 25%, respectively (in comparison to the current times).
- Basket Load: The load of each basket cannot exceed the 150% of the maximum current load in order to remain under the upper limit of the furnaces.

- Internal Pressure: The internal pressure of each section cannot get near (5 Pas) the exterior pressure due to security reasons.

- Air Temperatures: The solution and ageing furnace convection air temperature (after the flame) must not exceed 600° C and 200° C, respectively. These restrictions only apply to furnace limitations. The parts' restrictions are delimited by the T6 Aluminium alloy technical considerations.

- Part Temperatures: The solution part temperature must not exceed 544° C in order to prevent partial melting or deformations of the parts. In the ageing furnace this restriction does not apply. However, as it is previously commented in Section 4.3.1, the temperature level may affect the part's mechanical specifications.

- Annual production: The annual production is fixed by the factory strategical plan. In spite of the fact that some measures or changes in the process may increase the productivity (rate of production), the total production of the factory is kept constant for the subsequent evaluation of the measures.

## 4.4 Data Analysis and Assessment: Mass and Energy flows assessment

Based on the previous facility analysis which corresponds to the first step of the methodology (Scenario Selection) and supported by this next step the "Data Analysis and Assessment" (explained at Section 3.2.3), the energy flows of the process are identified and quantified.

### 4.4.1 Data transcription and measurement error

For this case study a continuous permanent measurement, monitoring and tracking system, such as the system provided by the EnMSs, is not installed. Therefore, several portable data-loggers and temporal devices must be implemented during a long representative interval time. In this regard, the portable loggers, which are shown in Figure 4.7, were installed for both main processes (SF and AF). Besides, an in-depth understanding of the process and of the involved phenomena is required in order to characterise and understand the circumstances and events happening during the manufacturing process. This information is required for the selection of the measurement time-step.

The time step must be selected after an in-depth process knowledge acquisition in order to identify and characterise the involved production and operational events which affect the main variable profile or the process modus operandi. In this regard, the shortest time step required for the analysed processes were around 4 seconds. This time step split the shortest event into 7-8 parts, allowing a good characterisation of the events involved in the analysis of the main energy variables.

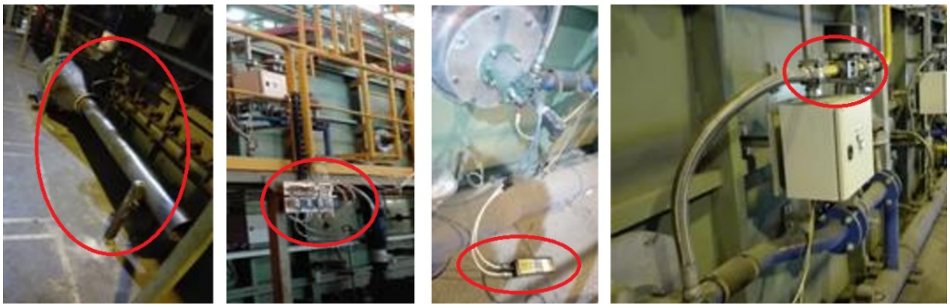


**Figure 4.7 –** Portable monitoring system for main variables data acquisition.

The first step consists of ad-hoc measurements, in order to define the processes from an energy perspective and to be able to reflect the energy consumption related to operational variables and to production strategies. The main measurement mechanisms are as follows. Pitot technology was used for measuring the combustion air flow rate and the fumes flow rate at chimney. The burner gas flow rate was obtained from pressure drop measurements in the burners' integrated orifices. Flue gases temperature, ambient temperature at factory and ambient temperature at air supplier were also logged. Factory Relative Humidity was measured by means of planar capacitance technology. Finally, an external local meteorological station provided pressure measurements.

The main critical variables of the process, in order to tackle the dynamic modelling and assessment, were the burners' energy consumption and the mass flows. In this regard, two kinds of error were introduced in the measurements: Transcription errors, attributed to the translation of the datasheet information, such as in Figure 4.8 (tracking of pressure drop to real power), and monitoring-device error, attributed to device measurement error.

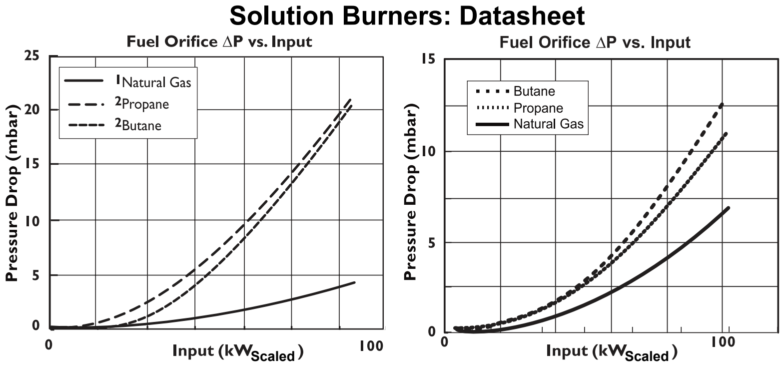


**Figure 4.8 –** Datasheets: Pressure drop-Power relation for solution burners.

The errors of measurement of the sensors (GEMs) used for the mass flow and power monitoring, were less than 1% of nominal design. Therefore, for nominal load conditions the measurement errors were considered negligible (lesser than 2%), both for all burners (solution and ageing) and for mass flow measurements, as shown in Figure 4.9. Even for half-loads the burner power errors were kept in an acceptable range (lesser than 5%). However, for very-low loads the relative error considerably increases, reaching values up to 80-90% of the measured values (as shown in Figure 4.9 for low values of power and mass flow).

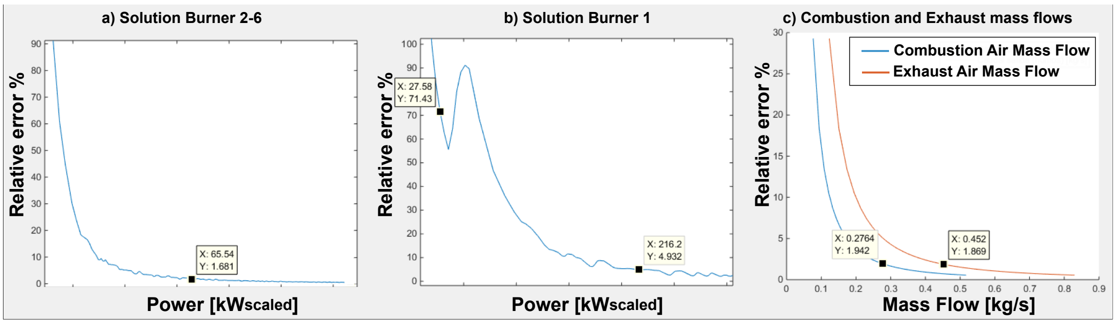


**Figure 4.9 –** Example of relative errors for some main variables.

With the aforementioned data, energy related variables were calculated. The energy consumption of each burner $[kW]$ was obtained by referring the differential pressure to the data sheet of the furnace manufacturer (Figure 4.8). The volumetric flow rate $[m3/s]$ of air-to-burner supplier and stack gases were obtained by means of flow density, flow temperature, and differential pressure.

The Data acquisition and Monitoring step opened the way to the most important section of the proposed methodology, the integral modelling of the process. An intensive analysis of data was first carried out in order to develop the process models.

### 4.4.2 Mass and Energy flows assessment

The two main consumers of energy of the HTP are the SF an the AF. The solution process represents 85% of the total natural gas consumption of the HTP, whereas the ageing process supposes the remaining 15%. The power consumption measured at the monitoring step for SF and AF is represented in Figure 4.10 and 4.11. This representation refers to a representative working week. As shown in the previous figures, the burner power consumption is extremely variable all along the working week. However, a pattern may be visually identified. This pattern corresponds to a basket input into a furnace. In the zooms typical patterns are isolated. Notwithstanding, several working anomalies, variations in the pattern or, simply, several working patterns may be identified along the period.

With the aforementioned data and energy assessment the main variables for the indicators are singled out and quantified, such as production, working time, theoretical

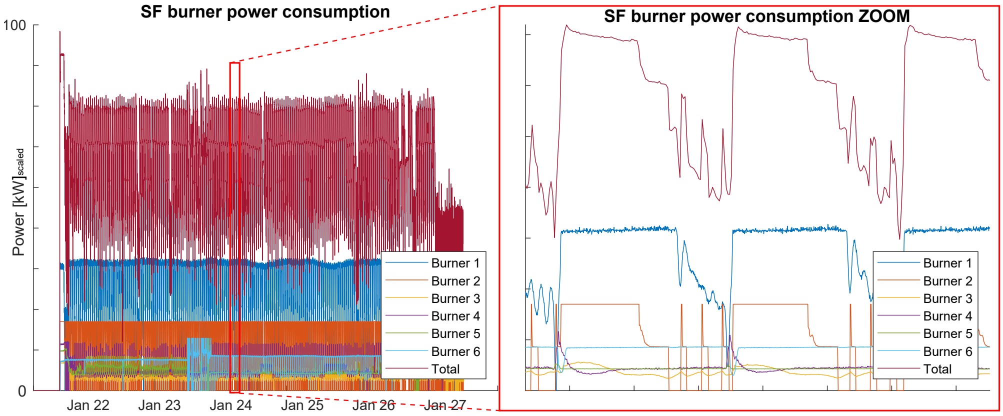


**Figure 4.10** – Power burner consumption: SF

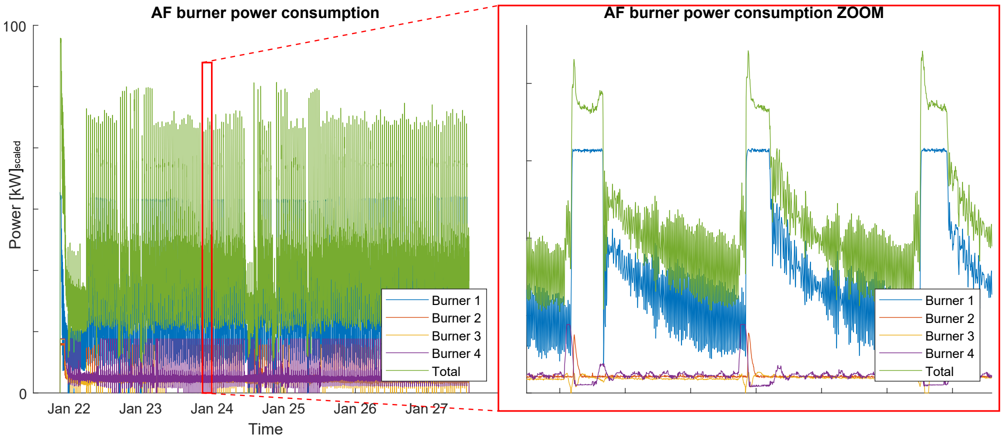


**Figure 4.11** – Power burner consumption: AF

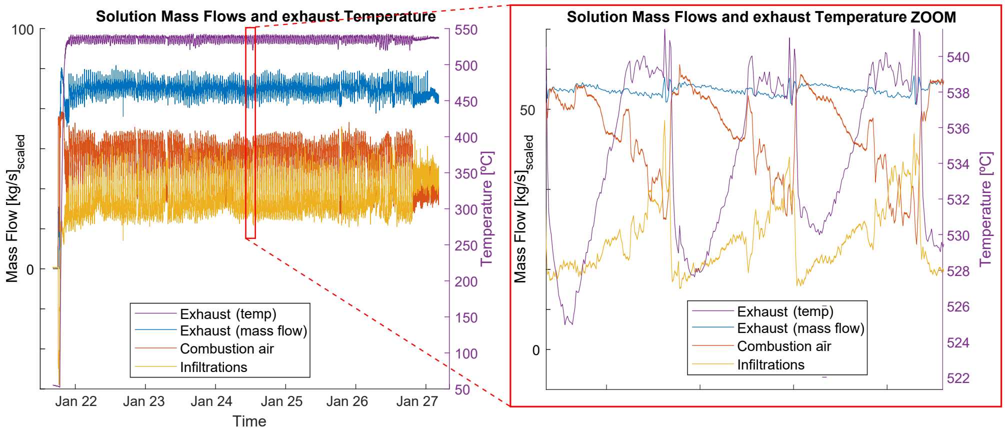


**Figure 4.12** – Mass flows and exhaust air temperature SF

energy requirements or energy consumption. This way, the overall energy efficiency of both furnaces and the specific consumption are calculated.

In the next group of figures (Figures 4.13, 4.14, 4.15 and 4.16) the patterns, which were previously identified, are isolated for the operating interval time. This interval, whose duration corresponds to the working stage-time period, starts when a batch is introduced into the furnace and ends when the same batch moves to the next stage of the furnace. In these figures, the profiles of the specific interval time for each main variable are represented. These figures show an example of results of the applied frequency analysis during a representative time interval. As it is indicated in the first figure (Figure 4.13), the colour-bar represents the frequency of repetition of the values (or within the interval of values), in which yellow-orange colours mean a high probability value and the blue ones point out less probable values.

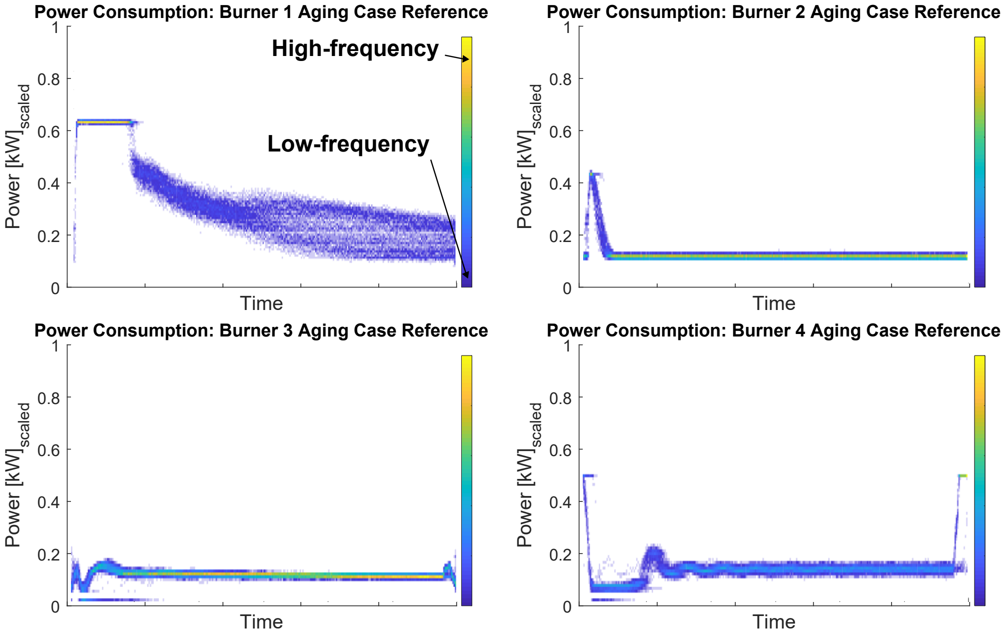


**Figure 4.13 –** Power burner profile from frequency analysis: AF

Then, the isolated behaviour is confronted to the identified events and the specific-event behaviours of the diverse phenomena are identified and quantified. In this process, several relations among variables or occurrences have been recognised. The more obvious and representative are the following:

- The power connection between the temperature measure of the chamber (related to the parts' load) and the energy level consumption of the first burners (both for SF and AF).
- The overall energy consumption and the link with the production (quantity of treated aluminium alloy).

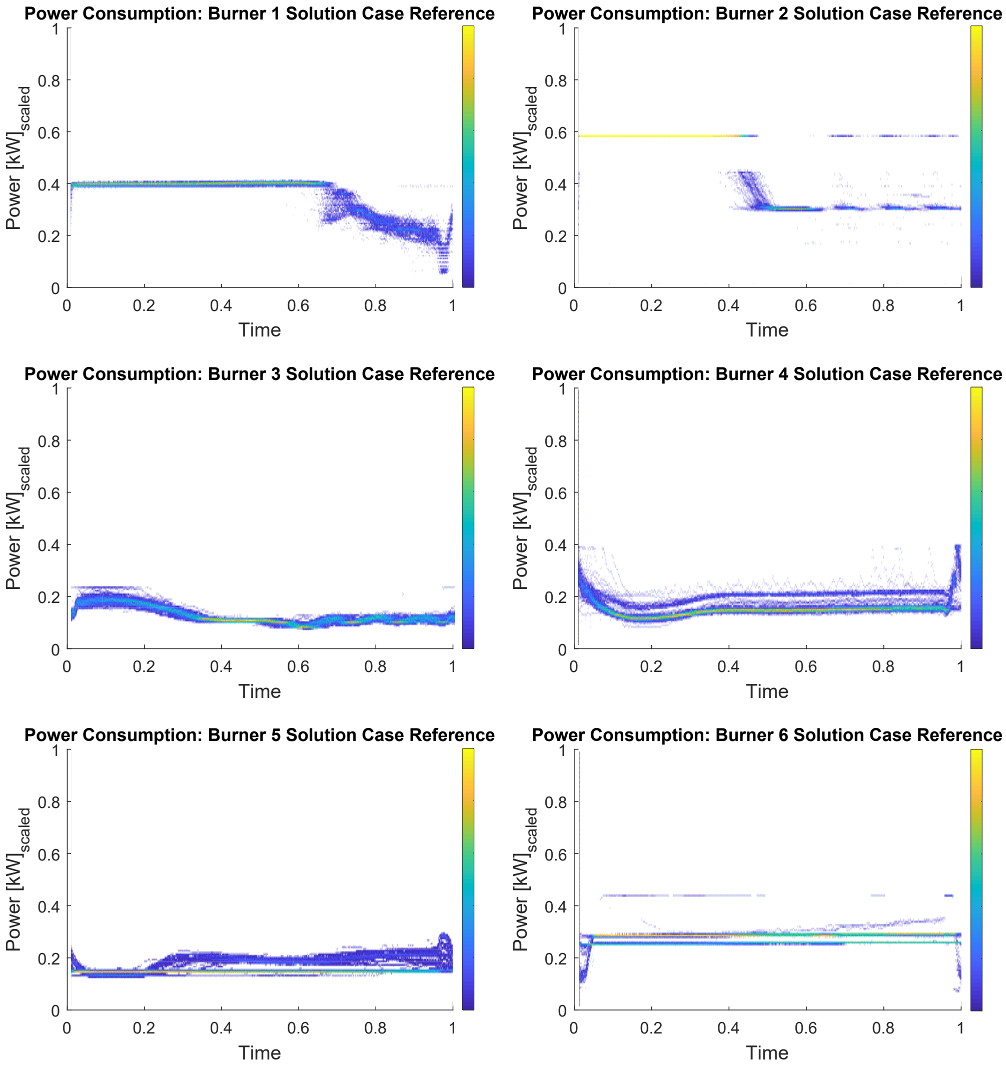


**Figure 4.14 –** Power burner profile from frequency analysis: SF

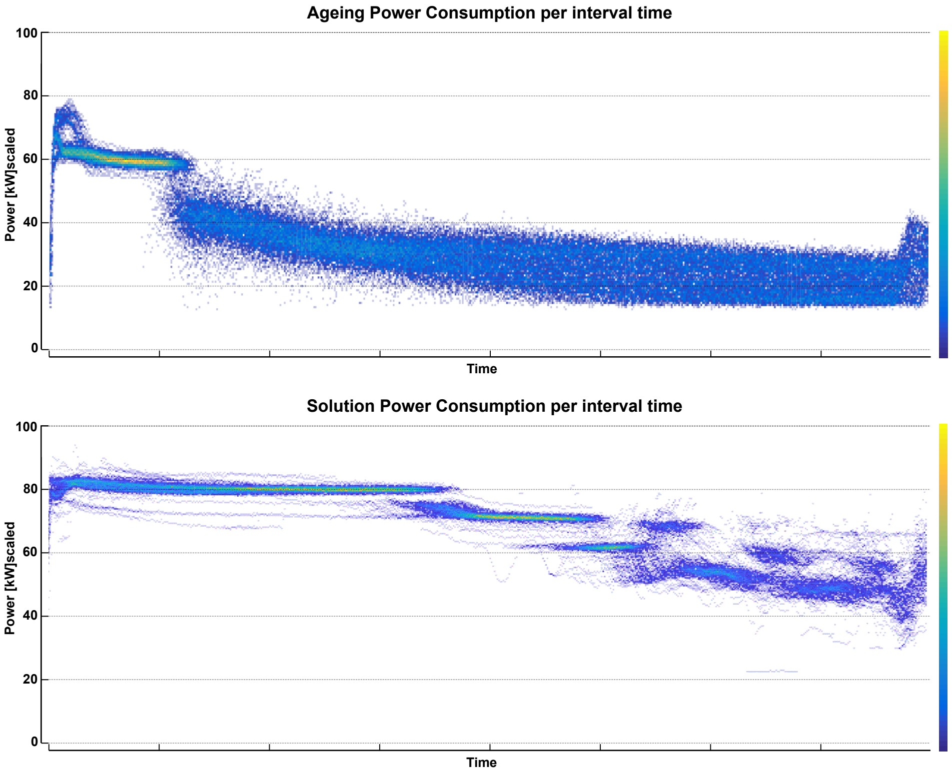


**Figure 4.15 –** Furnaces power consumption profile from frequency analysis: SF and AF

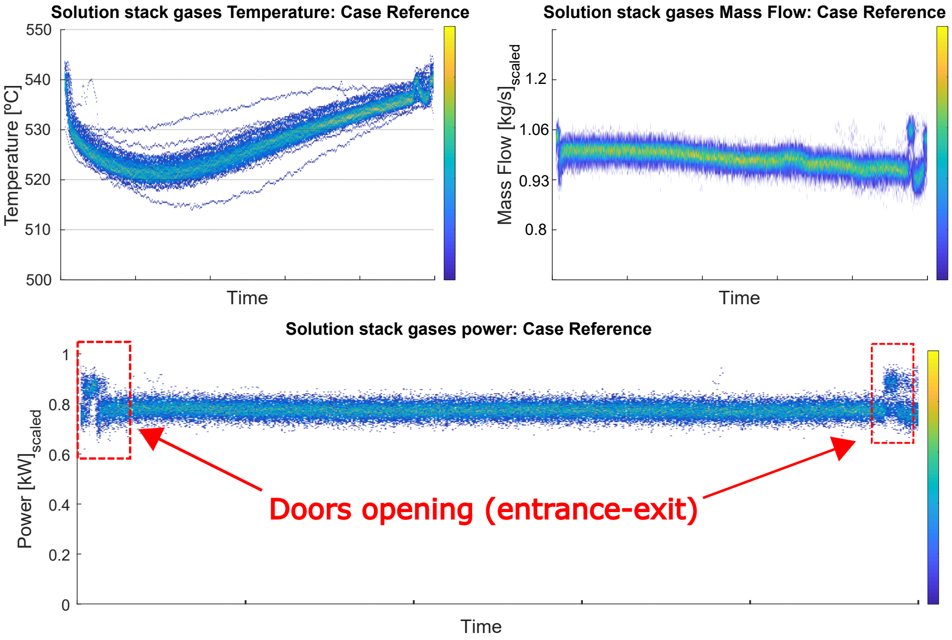


**Figure 4.16 –** Stack gases power, temperature and mass flow profile from frequency analysis

- The increase of the solution stack gases when doors are opening.
- The linkage among the power of the burners, the internal pressure of the chamber and the overall infiltration air.

On the one hand, some events show high correlation parameters (close to Sperman Rho = 1), such as the relation of infiltration-door openings, which can be directly measured. In this regard, for the infiltration-door opening step, the stack gases remain practically constant with the exception of the two intervals whose duration corresponds to the temporary lapse of time in which the doors remain open. Indeed, this event may be directly observed in Figure 4.16 in Solution Stack Gases Power Figure - Door Openings and, to a lesser extent, in Solution Stack Gases Mass Flow. In this regard, the period in which the doors are opened is isolated and assessed and, then, the additional infiltration air flow is quantified. Both, the overall time of opening and the net mass flow introduced, differ between the entrance and exit door. The opening times are around 40 and 30 seconds, whereas the average additional mass flow ratio is around 8% and 10% of the nominal stack gases flow for entrance and exit openings, respectively. The causation between the air infiltration and this event is clear, showing conclusive results and obtaining the increase of infiltration air derived from this event.

But on the other hand, some events which may have a strong theoretical background (and in theory should be identified) may be covered up by other reactions/ocurrences with higher effect in the same variable, such as the relation between weight and power (whose relation can not be directly visualised on the frequency figures, but statistically has a high significance), the ambient temperature and the consumption or the individual burner power and the total stack gases mass flow.

Besides, an intensive analysis of the non stationary events is carried out in order to identify relevant parameters for the integral modelling, such as the thermal inertia (obtained as the energy balance of the furnaces at switch-on step), the "natural" generated stack (approached at switch off step, when the burners are switched off but the furnace is hot) or the effect of unexpected events (such as a burner malfunction, a batch re-introduction or power blackouts).

These identified relations (for punctual transitory events or for stationary working conditions) are quantified with a statistical correlation analysis in order to obtain a numerical correlation among variables for all the specific scenarios.

Therefore, an in-depth statistical analysis of data is performed in order to link the gathered data with events and phenomena for subsequent modelling. Correlation analyses are carried out to quantify trends and cast aside wrong hypothesis (as it is explained in Section 3.2.3.2). The main and obvious hypothesis analysed is the possible link between the energy consumption and the furnace load. The obtained results of this analysis are shown in Table 4.1.

| | | Nº of experiments | Anomalies | Rho *1 | p-value (<0.05) *2 |
|---|---|---|---|---|---|
| First Solution | Pearson's linearity | ~600 | <50 | 0.1713 | 5.2818e-05 |
| Burner | Spearman's monotony | ~600 | <50 | 0.1808 | 1.9492e-05 |
| Second Solution | Pearson's linearity | ~600 | <50 | 0.1825 | 1.5517e-05 |
| Burner | Spearman's monotony | ~600 | <50 | 0.1782 | 2.4440e-05 |
| Third Solution | Pearson's linearity | ~270 | <50 | 0.0167 | 0.8053 |
| Burner | Spearman's monotony | ~270 | <50 | 0.0799 | 0.2403 |

*1 Values for Rho range from 0-1. Positive values indicate positive correlation. Values close to 0 indicate no correlation.

*2 p-values lower than 0.05 indicate that the hypothesis analysed is statistically significant.

Table 4.1 – Main results of weight correlation analysis for the SF.

A slight positive correlation is observed (rho=0.1713) for the energy consumption of the first solution burner . Despite the fact that the correlation is not quite high, its p-value (p-value=5.2818e-05) concludes that the correlation is statistically significant. In the same way, a small monotony correlation is shown for the first burner (rho=0.1808), which is confirmed by its p-value (p-value=1.9492e-05). For the second burner the results are similar. For the next burners, the analysis, as shown in Table 4.1 for the third solution burner, shows that there is not any correlation. These burners are not affected by the batch weight because at these stages the parts and baskets have already reached the set point temperature. Therefore, there is not fuel consumption destined for that end. These burners just compensate heat losses and their respective stack gasses. These results are similar for the AF. In this case, the relation is only statistically significant for the first burner, while the other burners support the stack and lateral losses of their sections.

The ambient temperature of the plant is also analysed in comparison with the total consumption. Variations of less than 20°C were identified when comparing day to night work shifts (both in winter and summer). Besides, seasonal variations were identified, which represents a variation of the overall temperature in around 10°C. A slight reduction of the energy consumption of the burners (around 3%) is observed when comparing the later night (5:00 hours) with the afternoon/evening (17:00 hours), as can be observed in Figure 4.17.

Several reasons may be responsible for the identified variation, such as the reduction of the lateral heat losses, the increase of the load input temperature as well as the increase of the temperature of the combustion air or the infiltration air and natural gas. Therefore, although the effect is identified and quantified, the identification of the main source, which is responsible for such effect, is not possible. This energy variation is the product of a combination of these events.

In this regard, this methodology, based in phenomena simulation, allows to recreate and reproduce the results of this temperature variation due to the physic phenomena modelling. The lateral heat losses are modelled depending on the ambient temperature of the plant (convection and radiation), whereas the energy of the flows (infiltration, natural gas and combustion air) is quantified by means of the bulk temperature. Despite the fact that the correlations or causalities have not been found, the proposed modelling, which allows to set the initial temperature of each element, takes into account this phenomenon for the simulation process.

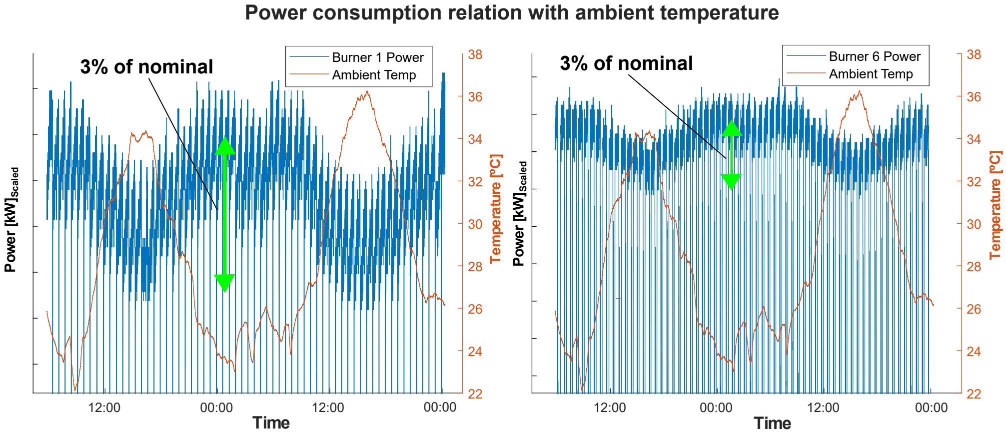


**Figure 4.17 –** Relation between the ambient temperature and the individual burner consumption for two burners in the same time interval

As it can be noticed in Figure 4.16, there is a slight decrease of the mass flow from the beginning of the time interval (start of the abscissa axis) to the end of the time interval (end of the abscissa axis). This decrease is expected to be product of the mass flow associated to the burner power, which also decreases at the end of the time interval (as shown Figure 4.15 both for SF and AF). The stack gases of the SF have a strong theoretical dependence on the input mass flow which the burners introduce to the furnaces. This dependence is guided by a simple mass balance equation (such as the proposed by the Equation 4.1). According to this simple mass balance, a priori, if the introduction of mass flow increases, the output should increase following the mass-flow-balance represented in Equation 4.1 (the solid mass flow, also known as load, is not represented here). The Natural Gas flow is small enough (several orders of magnitude) in order to ignore it. Nevertheless, the Natural Gas flow commands the heat power of the burner. Modifications in the power settings (activated by the logged temperature) cause the burner PLC to move over the curves of Control & Operation (as shown in Figure 4.5). Therefore, the total amount of Natural Gas flow and Combustion Air should follow the relation provided in this equation (Equation 4.1).

$$InfiltrationAir + NaturalGas + CombustionAir = StackGases \tag{4.1}$$

However, a non-expected (it does not follow the proposed hypothesis commented before) connection between the total stack gases and the burner consumption is identified in the solution process. Just as it has been identified, the Stack Gases do not follow this expected hypothetical exponential profile (through a direct follow-up of the curves of the technical sheet). Modifications in the power requirements, which change the Natural Gas flows, modify the Combustion Air flow and, ultimately, change the internal pressure of the furnace chambers. Each burner contributes to this effect with different behaviours, but this effect is mainly commanded by the first two burners in the SF. This is because the overall power variation mainly depends upon these two burners, due to the fact that they present higher maximum powers and higher variations (as it is shown in Figure 4.14), whereas the others barely present variations (the total power provided remain practically constant during the interval time). Besides, the relative position of the burners within the furnace may affect this behaviour.

In conclusion, a positive significant correlation has been identified in burner one whereas the second one presents a negative correlation. These correlations (relation of the power setting on the infiltration air flow) are stated as parameters and introduced into the model burners behaviour.

The AF does not show this kind of behaviour due to the type of excess air control which rules the burners. These burners are commanded by a fixed air ratio control, so, the introduced total flow (Natural Gas and Combustion Air) is practically constant. This typical behaviour avoids modifications of the chamber internal pressure depending on the provided power.

The thermal inertia is approached by means of the overall power balance of the furnaces (as shown in Equation 4.2). In order to determine the thermal inertia value (i.e. in order to determine the energy consumption required to reach a stationary situation in the furnaces) the measurement variables which are mentioned in Sections 4.4 and 4.3 were also monitored during many start-ups of the furnaces.

$$Burner + OtherSources = Inertia + Load + LateralLosses + StackGases \quad (4.2)$$

where $Burner$ and $OtherSource$ [kW] represent the power introduced to the furnace by the "burners" and "other sources"; $Inertia$ and $Load$ [kW] represent the powers which are absorbed by the "Inertia" and the "Load" and $LateralLosses$ and $StackGases$ [kW] represent the powers which are lost by the "surface" and the "chimney/stack".

Based on the energy balance of the furnace (presented in Equation 4.2) the Figure 4.18 represents a specific turn-on phase. The $Burner$, $Load$, $StackGases$ and $LateralLosses$ terms are known (measured or calculated by means of the data monitoring system). Therefore, if the system reaches the stationary state, the remaining energy (not accounted for the aforementioned terms) belongs to the $Inertia$ term.

In Figure 4.18 the transient analysis of a preheating-start period of the solution furnace is shown. Here, the "Burners Consumption" profile, the "Stack Gases" power, the "Lateral Heat Losses" and the power remaining from the energy balance equation from Equation 4.2, which represent the energy absorbed by the inertia and the load (if any), are depicted. The green squares represent the theoretical energy required to heat the load (baskets and parts) up to reach the process temperature. Once the load has attained the process temperature (with enough time), the lateral heat losses has become stable and the "Inertia+Load" term tends to zero, we can conclude that the furnace has reached the stationary state. Therefore, the energy that the "Thermal Inertia" of the furnace is able to store can be approached by solving "Inertia" term from Equation 4.2.

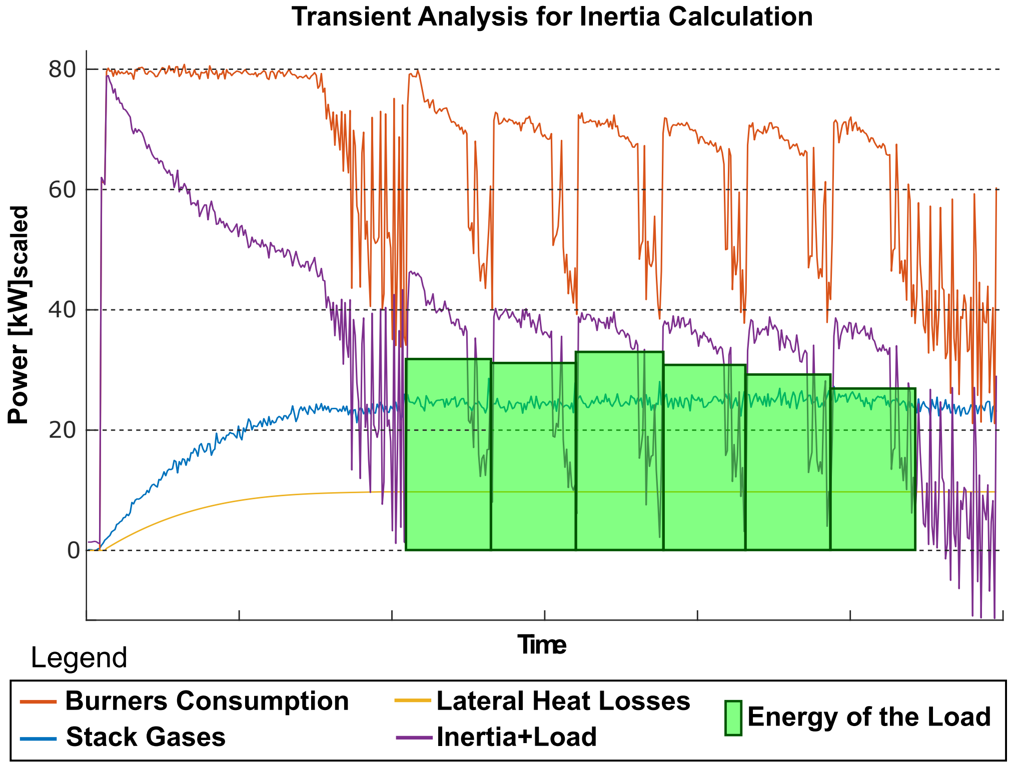


Figure 4.18 – Power profile of preheating-start transient period for the Inertia Calculation.

Therefore, the energy balance (energy consumption, lateral heat loses, stack energy, energy absorbed by load), which corresponds to the start-up period, provides the thermal inertia data. Several start-ups were analysed to determine the correct value. Finally, the total average inertia, which was obtained from several start ups, is around 1350kWh. This method has returned values in the range of 1200 kWh to 1450 kWh.

All the considerations and event relation identified in this step were evaluated and translated to valuable information in order to provide the characterisation of the behaviour of the manufacturing process.

## 4.5 Conceptual model and modelling

The conceptual models are generated as the replication of the process physics laws and as the parametrisation and virtual characterisation of the measured data. Besides, the production data is treated and translated to be an input for the models. The assumptions are based on reasonable analysis of literature-source information or on parallel event reproduction (if required) by a more specific modelling approach. This is the case of the internal pressure of the furnace, where Dymola models where developed to understand the pressure phenomena which happen in the furnace-stack system [188].

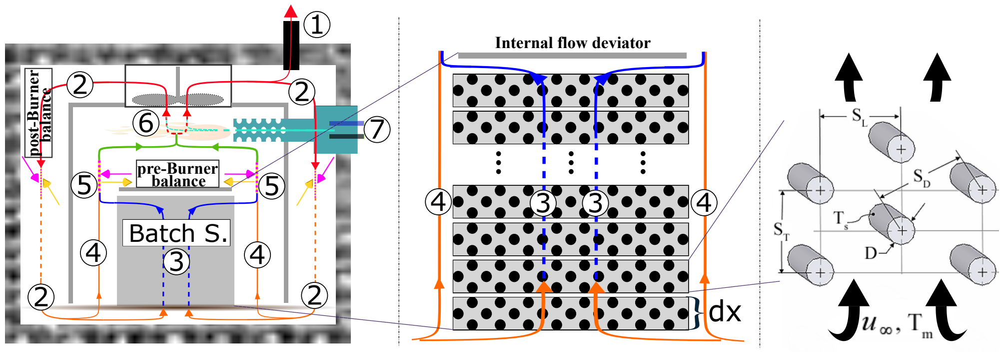
Some events, mainly those which are based on physics laws, are directly transcribed to the modelling language in MATLAB®. The input data is adapted to the code and introduced to the virtual system. Other events can not be related to physics based equations (or are too complex), and are approached by assumptions based on expertise, empirical data or literature review. This is the case of the infiltration air flow, which is monitored and then characterised to several equations and the if-else clauses according to the measurements and the events logged, as early mentioned and explained in the last Section.

Finally, all events and conditions identified as relevant are introduced to the models following the steps of modelling proposed in the Methodological approach in Chapter3, Section 3.2.4.

### 4.5.1 Energy Modelling: Overall perspective

The energy models must be detailed enough to consider the dynamics of the different stages in the process with the aim of minimising the error of the obtained process performance.

The proposed energy model is split into internal and external mass and energy balances. The mass flows corresponding to the internal balance are represented in Figure 4.19 (b). This internal balance takes into account the heat transfer from the furnace internal gases (flows 3 and 4) to the load (Load in Figure 4.19 (a)) and reproduces the thermal characteristics of the load (solid flow). There is an internal analysis for each Batch Section (9 sections for the SF and 7 for the AF). The Load (depicted as “Load” in Figure 4.19) is formed of steel baskets which contain aluminium parts inside. The external energy balance takes into account the inputs and outputs related to each burner section (Figure 4.19 a), allowing the energy variables (such as fumes energy and temperature) to be tracked. Both balances are interconnected between them. This division has been generated for replicability reasons (for future changing in the kind of load or modifications in the number of stages for other furnaces).



(a) (b) (c)

**Figure 4.19 –** Heat system schema: (a) Burner section, (b) Batch Section (c) Internal batch staggered geometry.

The mass flows [kg/s] on the burner section depicted in Figure 4.19 (a) can be defined as follows:

- Flow 1: Stack gases flow. The furnaces are in a low vacuum, when comparing to the exterior. Therefore, this flow contains combustion air and all the infiltrations.
- Flow 2: Circulation flow. This is the nominal flow that each centrifugal fan provides. This flow is several orders of magnitude higher in comparison with the stack gas flow.
- Flow 3 and flow 4. The flow 2 is split into a flow that goes through the Batch System, flow 3, and the flow that goes around the baskets, flow 4. Flow 3 is responsible for providing heat to the parts.
- Flow 5: This flow contains the sum of flow 3 and 4 just after the "batch system".
- Flow 6: Burner flow. This flow contains flow 5 and the combustion mix of the burner. The energy of the fuel is released. After that, this flow is split into Circulation flow (flow 2) and Stack gases flow (flow1).
- Flow 7: Combustion flow. This flow contains the stoichiometric air, the excess air and the natural gas. The measured infiltrations and the flow introduced occasionally due to door openings are also introduced in this flow.

The mass flow balance is summarised in this set of equations:

$$Flow1 = Flow7 \tag{4.3}$$

$$Flow2 = Flow3 + Flow4 \tag{4.4}$$

$$Flow5 = Flow2 \tag{4.5}$$

$$Flow6 = Flow5 + Flow7 \tag{4.6}$$

The infiltration air flow, during the stationary working process, is introduced through slits all along the SF and the AF (doors and roller conveyors). However, these multiple infiltration flows have been modelled as an additional air flow which is included in the combustion air flow of each burner. This additional air (infiltrations) flow has been quantified as the difference between the measurements of the burner inlet air and the stack gases mass flow. This air introduction follows a set of equations (Equation 4.7 and 4.8) which depend on the chamber internal pressure and the temperature of the inertia temperature (due to the stack effect[1]).

$$TotalInfiltrationFlow = InfiltrationArea * InfSp * Rho_{air} IT^{Factor} \tag{4.7}$$

$$IT^{Factor} = a + b * InertiaTemperature \tag{4.8}$$

where the $TotalInfiltrationFlow$ $[kg/s]$ represents the total infiltration air flow which is introduced into the furnace (SF or AF). The $InfiltrationArea$ $[m^2]$ term represents the normal surface of infiltration, which is approached by means of the measured infiltration flow (for a stationary working operation) and the internal pressure of the furnace. The $InfSp$ $[(m^3/s)/m^2]$ element represents specific infiltration (derived from Figure 4.20). The $Rho_{air}$ term is the density of the air at ambient conditions and the $IT^{Factor}$ element represents the empirical value of correction for the temperature of the inertia, in which $a$ $[-]$ and $b$ $[K^{-1}]$ are empirical factors and $InertiaTemperature$ $[K]$ is the average temperature of the furnace sections.

The $IT^{Factor}$ comes from the observed different behaviour of the infiltration air flow. This factor has its origin in the different value of the furnace draft effect which happens when the furnace is cold in comparison to when it is hot. Once the furnace reaches the stationary work mode (the thermal inertia is full) this parameter remains constant and approx to 1). The $InfSp$ value comes from the internal pressure of the furnace chambers, which, at the same time, depends on the total power of each burner (due to the dependency of the combustion air from the power).

The total infiltration air attributed to the infiltration area is split between the totality of the burner sections (represented in Figure 4.2- Burner Section-> Grey Square and Batch Section-> Red Square). The first and the last section present a higher contribution of infiltration air due to the presence of doors. The second burner section of the SF has a smaller contribution than the others, due to the fact that it only has one batch section, in comparison with the other, which contains two batch sections (higher dimension, and,

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[1] Stack effect or chimney effect is the movement of air into and out of buildings, chimneys, flue-gas stacks, or other containers, resulting from air buoyancy. Buoyancy occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences.

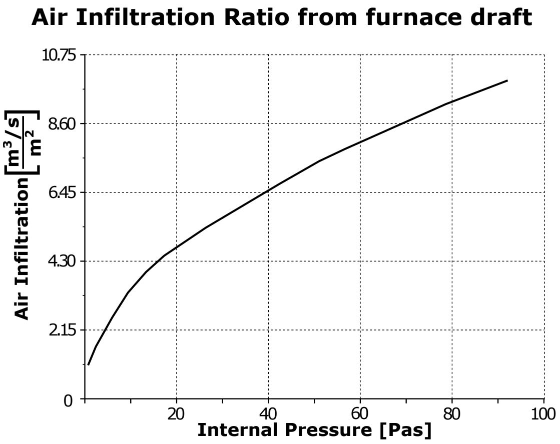

**Figure 4.20** – Rates of air infiltration resulting from furnace draft (adapted from [189])

for example, more roller conveyors cylinders). The specific air flow introduced during door openings is quantified by measurements and modelled as specific introductions during opening times in the first and last burner stages.

Flows 2 and 5 suffer an inter-burner balance in order to attenuate temperature differences among burners, after and before the combustion stage and stack gases exit. In these inter-burner balances, the flows of contiguous burners are interchanged. The interchanged mass flow is represented as $\dot{m}FlowB^i - Bi + 1$ in Figure 4.21. The interchanged mass flow, $\dot{m}FlowB^i - Bi + 1$, is a part of the total flow (Flow 2 and Flow 5) and depends on the difference of enthalpies of the mass flows. The difference of enthalpies of the consecutive flows (difference between the enthalpy of Flow 2 or 5 of the burner “i” and Flow 2 or 5 of the burner “i+1”) regulates the portion of mass flow that is exchanged. Therefore, each mass flow (Flow 2 and Flow 5) remains constant while the enthalpy of each mass flow changes. The modelling of the individual energy balance of each section includes this inter-burner balance term.

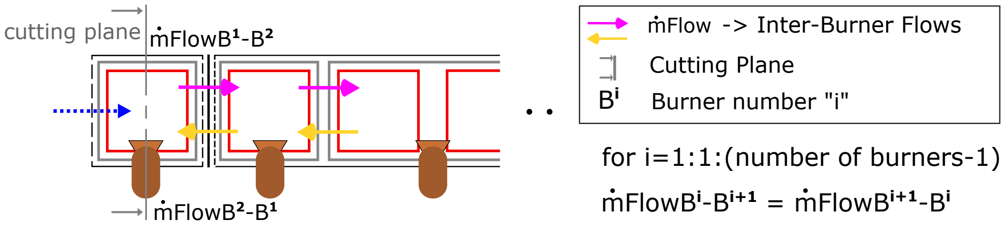

**Figure 4.21** – Inter-burners mass flow balance and cutting plane for Figure 4.19.

The dashed lines in Figure 4.19 represent the heat transferred to the inertia (in Flow 2) and the heat transferred to the system (in Flow 3). For pre and post burner balances, the mass flow of the burner section (Figure 4.19 a) is conserved individually, while the energy is distributed as a function of temperature and proximity parameters.

### 4.5.2 Energy Modelling: Internal heat transfer

To model the burner section (Figure 4.19 a), a generic batch system (Figure 4.19 b) has been reproduced, as proposed in Kang et al.[190], i.e. the parts' modelling has been addressed as an array with different configurations in order to prioritise the energy distribution and consumption. Therefore, the internal heat distribution of the part is disregarded. The proposed forced convection equations, synthesised as convective coefficient $h_{conv}$, are summarised below:

$$\overline{Nu}_{DFlow3} = C \cdot Re_{D,max}^{m} \cdot Pr^{0.36} \cdot \left(\frac{Pr}{Pr_s}\right)^{\frac{1}{4}} \equiv [-] \tag{4.9}$$

$$h_{conv} = \overline{Nu}_{DFlow3} \cdot k/D' \equiv \quad [W/m^2 \cdot K] \tag{4.10}$$

where $Nu$ $[-]$, $Re$ $[-]$ and $Pr$ $[-]$, are Nusselt, Reynolds and Prandt numbers respectively, evaluated at the medium temperature (and surface temperature for the $Prs$ term). Parameters $C[-]$ and $m$ $[-]$ have been selected from Bejan et al. [191, 192], according to convection conditions and the geometry of the system. The $k$ term represents the thermal conductivity of the medium, evaluated at the average flow temperature. $D'[m]$ is the adapted characteristic length of the part. The staggered tube bank distribution simplification (Figure 4.19 c) has been selected to characterise the parts-baskets distribution [191]. In this assumption, a squared distribution has been selected, where $ST$ $[m]$ and $SL$ $[m]$ are equal (from now on referred as $S$ $[m]$). $S$ $[m]$ value is the result of generating a cylindrical staggered mess fitting both the volume available (basket volume) with the mass inside this volume. $D$ $[m]$ stands for teh characteristic length of the part, which is associated to the shape of the part.

The $D$ length is selected around 0.02 meters, as an approximation to the average length observed for usual parts. If the introduced parts become more compact, or, on the contrary, present more holes, this parameter may change. In fact, this parameter does not depend on the density of the part. The characteristic depends on the maximum length that a specific part presents from the exterior to the core of the widest part section. The $S$ dimension represents the "density" of bars/cylinders which are into the batch volume. This parameter does depend on the overall density of the batch. A batch with a double weight would present a double number of cylinders (if the characteristic length is kept). However, this higher weight may not have an effect on the characteristic length.

As shown in Figure 4.19 a and 4.19 b, medium flows which do not go through the Batch System (flow 4) are taken into account for the energy balance. These flows are approximated by means of a scattering factor which links the fraction of medium that goes through the batch system and the fraction which goes around the “batch section”.

### 4.5.3 Energy Modelling: Lumped capacitance system

The model of the conveyed batch material is defined as a lumped capacitance system, as an analogy derived from related works [193], and as an adaptation of several heat transfer handbooks [190, 194]. It means that the temperature of the solid is spatially uniform, being only a time-depending function. To reach a compromise between real heat transfer and computational effort, a longitudinal division of the parts-basket system has been adopted. The heat transmission equations are the ones presented below:

$$Q_{trans} = h_{conv} \cdot A \cdot \left(T_j^{syst} - T_j^{flow3}\right) \cdot \partial x \cdot \partial t \equiv [J] \tag{4.11}$$

$$H_j^{syst} = H_j^{syst} + Q_{trans} \cdot \frac{1}{\rho^{syst} \cdot \delta V^{syst}} \equiv [J/kg] \tag{4.12}$$

$$H_{j+1}^{flow3} = H_j^{flow3} - Q_{trans} \cdot \frac{1}{\zeta^{flow3} \cdot \partial t} \equiv [J/kg] \tag{4.13}$$

where, $H_j^-$ is bulk enthalpy of the system or of the heat transfer medium at each longitudinal division and interval time. The $\rho^{syst}$ $[kg/m^3]$ and $\zeta^{flow}$ $[kg/sec]$ are density and mass flow evaluated at their corresponding temperature. $A$ $[m^2/m]$ and $\delta V$ are geometrical characteristics, specific internal contact area and volume, which depend on batch physical properties such as number of parts, part weight or part characteristic length. The transferred heat $Q_{trans}$ is calculated each time interval, $\partial t$ $[s]$, for each dimension interval, $\partial x$ $[m]$, by means of the convective equation, in which $h_{conv}$ $[-]$ represents the convective coefficient.

### 4.5.4 Energy Modelling: Overall energy balance

The heat balance of the overall system (SF or AF) consists of:

- **Surface heat losses of furnace (SHL [W])** which include radiation, convection and conduction losses [195] transferred to the ambient through the wall (discontinuous orange line in Figure 4.19 a), are accounted in Equation 4.14.

$$SHL = \sum_{i} A_i \cdot f_i \cdot [a_i \cdot (T_w - T_a)^{\frac{5}{4}} + 4.88 \cdot \varepsilon \cdot ((\frac{T_w + 273.15}{100})^4 - (\frac{T_a + 273.15}{100})^4)] \quad (4.14)$$

Where $A_i$ $[m^2]$ represents the area according to its typology (basement, lateral wall, roof, etc.) or diverse temperature conditions. $f_i$ and $a_i$ $[-]$ are parameters associated with the shape of the system. $T_w$ and $T_a$ are the wall and ambient temperature (in Celsius) and $\varepsilon[-]$ is the emissivity of external wall surface of the furnace.

- **Stack gases (SG [W])** whose energy is calculated as a function of mass flow (flow 1 in Figure 4.19) and flow enthalpy, as shown in Equation 4.15. Collector chimneys are located after the burner chambers. Therefore, exit temperature is assumed equal as post-burn temperature. Mass flow, enthalpy and gas composition fluctuate depending on the batch entries and the response of the burner.

$$SG = \sum_{i=1}^{Bur_{sect}} Flow1_i \cdot FluidEnthalpy(Comp., temp.)_i \quad (4.15)$$

Where $Bur_{sect}$ represents the number of burner sections of the furnace (Figure 4.2), $Flow1_i$ $[kg/s]$ represents the mass outflow of the section (Figure 4.19 a) and the $FluidEnthalpy$ $[J/kg]$ represents the specific fluid enthalpy at the specific conditions (composition and temperature).

- **Heat generators (HG [W])**, also referred to as Burners, introduce a certain flow of natural gas and air (as it is represented in Equation 4.16) to the furnace. This air flow is in clear excess in comparison with the stoichiometric ratio. Additionally, heat generators provide heat power to the furnace. This heat power heats this previous flow following the characteristics of the natural gas combustion. The final enthalpy corresponds to the heat power produced by the perfect natural gas combustion plus the enthalpy of these combustion gases at the moment the conditions are introduced. In this process the air is taken from outside at ambient temperature; the natural gas characteristics, temperature, pressure and composition, are provided by the supplier; and the burners are commanded by a heat power controller (also modelled for the energy modelling). As in the real case, the process is tracked by a temperature gauge in order to ensure the design temperature characteristic-curve avoiding extreme levels. The heat power controller covers the burners' restrictions or limitations, such as maximum heat power and minimum heat power, and, according to the temperature log, the controller regulates the heat power (natural gas mass flow).

$$HG = \sum_{i=1}^{Bur_{sect}} Flow7_i \cdot FluidEnthalpy(Comp., temp.)_i + NG_i \cdot LHV \tag{4.16}$$

$$Flow7 = NG + CA + Infil \equiv [kg/s] \tag{4.17}$$

where $Bur_{sect}$ represents the number of burner sections of the furnace (Figure 4.2). $NG$ $[kg/s]$ represents the natural gas mass flow provided by each burner. $CA$ and $Infil$ $[kg/s]$ represent the ambient air (combustion air) and the infiltration mass flows introduced by each burner. $LHV$ $[J/kg]$ corresponds to the lower heating value of the natural gas which is employed in the process. The $FluidEnthalpy$ $[J/kg]$ represents the specific fluid enthalpy at the specific conditions (composition and temperature). It considers the enthalpy of the three terms of the Equation 4.17.

- **Door opening heat losses (DOHL [W])** which are modelled as the radiation heat losses of a cavity to the outside [196], as it is shown in Equation 4.18. Besides, this event includes the air infiltration introduced by this opening. This last part is modelled, at the infiltration modelling section, by a parametric factor which depends on other energy and productive variables [188].

$$DOHL = Door_{state} \cdot Rad_{blackbody} \cdot \epsilon \cdot f_{rad} \cdot Area \tag{4.18}$$

Where $Rad_{blackbody}[kJ/m^2/s]$) represents the Stefan-Boltzmann black body radiation at the corresponding furnace temperature, $\epsilon$ $[-]$ is the radiation parameter emissivity, $Area$ $[m^2]$ corresponds to the total aperture area, $f_{rad}$ $[-]$ is the factor of radiation and $Door_{state}$ $[-]$ represents the degree of door aperture (lineal) for the specific time-instant. The air infiltration flow attributed to this event was measured and directly translated as a parameter introduced in the model when the event is reproduced. This flow is already included in Flow7, as shown in Equation 4.17.

- **Load [W]**, which absorbs energy in the way it is modelled in the energy balance described before. The parts are introduced into baskets at the beginning of each process for each batch. After the last stage of the SF and the AF, the baskets leave the system at the reached temperature. The overall heat balance considers both inputs and outputs.

$$Load = \sum_{i=1}^{Bat_{sect}} [\int_{dx} Q_{trans}]_i \tag{4.19}$$

Where $Bat_{sect}$ represents the number of batch sections of the furnace (Figure 4.2) and $Q_{trans}$ represents the power transferred to the batch (Equation 4.11). At some point the Load value may be negative depending on the part and air-to-parts temperatures.

- **Thermal inertia (TI [W])**, which represents the energy capacity content of the system environment, is accounted for in Equation 4.20 and 4.20. This environment consists of the diverse structures or materials that form the process devices. In the case of the furnace, the thermal inertia considers the furnace walls, insulations and refractories, the internal roller conveyor, the internal plate distributors, the burners, the doors, the stack collectors, etc. Thermal inertia effect is modelled as a furnace block that absorbs heat from the circulation furnace gases (Flow 2: Circulation flow). Regarding the heat losses (DOHL and LHL), they are included in the overall balance by the inertia term, because these losses are linked (subtracted) to this element. This is the reason why the DOHL and LHL do not appear directly at the overall balance (Equation 4.24), as they are already accounted for in this term.

$$TI = \sum_{i=1}^{Bur_{sect}} [QTI_{trans}]_i \tag{4.20}$$

$$[QTI_{trans}]_i = \Delta InertiaPower + DOHL \cdot f^1 l_i + SHL \cdot f^2 l_i \tag{4.21}$$

Where $Bur_{sect}$ represents the number of burner sections of the furnace (Figure 4.2), $f^1 l_i$ and $f^2 l_i$ are empirical parameters (obtained by means of an inverse modelling procedure) which represent where the losses act. The quantification of the real contribution to the lateral heat losses or to the door openings losses of each section can not be directly measured. Therefore, an inverse modelling method has been applied. A set of values for these parameters has been selected for a specific simulation, and, then, the results have been tested with the obtained data. After an iterative process, which is based on reasonable assumptions, a reliable set of parameters has been obtained. In this regard, the associated lateral losses for the first and last stage are higher due to the wider area. The heat losses regarding to door openings are also accounted for in the stages which contain doors (the first and the last). $\Delta InertiaPower$ $[W]$ corresponds to the net energy increase or decrease of the system inertia at the internal wall section.

- **Power supply by Other-sources (OSP)**. This term introduces the heat provided by the centrifugal fans or other devices which are situated inside the furnace. In this regard, the main secondary supply is the heat provided by the circulation centrifugal fans. The other sources may be associated to a fluid, such as a new hot flow introduction, or be generated by dissipation without being associated to a fluid, such as the heat provided by fans. All the sources considered are taken into account in OSP term (as shown in Equation 4.22).

$$\sum_{i}^{numberofothersources} OSP = OSP_{noFluidi} + OSP_{Fluidi} \tag{4.22}$$

$$OSP_{Fluid} = NewSourceFlow \cdot FlowEnthalpy(Comp, temp) \tag{4.23}$$

Where $OSP_{noFluid}$ $[W]$ represents the heat associated to a non-fluid source which is accounted as a simple power value. $OSP_{Fluid}$ $[W]$ represents the heat associated to a transported-by-a-fluid heat flow, as it is shown in Equation 4.23. $NewSourceFlow$ $[kg/s]$ and $FlowEnthalpy$ $[J/kg]$ correspond to the mass flow of the new introduced flow and its respective enthalpy (obtained for the fluid specific temperature and composition).

The Overall Energy Balance equation, according to the aforementioned terms, is presented below:

$$HG + OSP = TI + Load + SG \equiv [W] \tag{4.24}$$

This equation (Equation 4.24) is graphically represented for a specific time period in Figure 4.22 (the power values are scaled to maintain the confidentiality). In order to show the heat losses contribution, the $DOHL$ and $LHL$ are also depicted in Figure 4.22 despite the fact they are accounted for in the TI term. Some of the dynamic events which appear in this kind of processes (non-continuous thermal processes) are represented in Figure 4.22, such as the time-specific introduction of loads, the start-up stage, the transitory period[2] and other specific events (door openings). The TI factor may be positive or negative. The inertia “loses” energy the moment the cold (or cooler than the inertia) parts are introduced and, then, “recovers” energy when the parts and the circulating gases reach some levels of temperature. Once the furnace reaches the stationary working conditions, this phenomenon is practically limited to the first sections of each furnace, when the parts have not reached the nominal temperature yet.

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[2] Until reaching the nominal working conditions, which, in this case, is reached when all 9 stages have a load (baskets with aluminium parts).

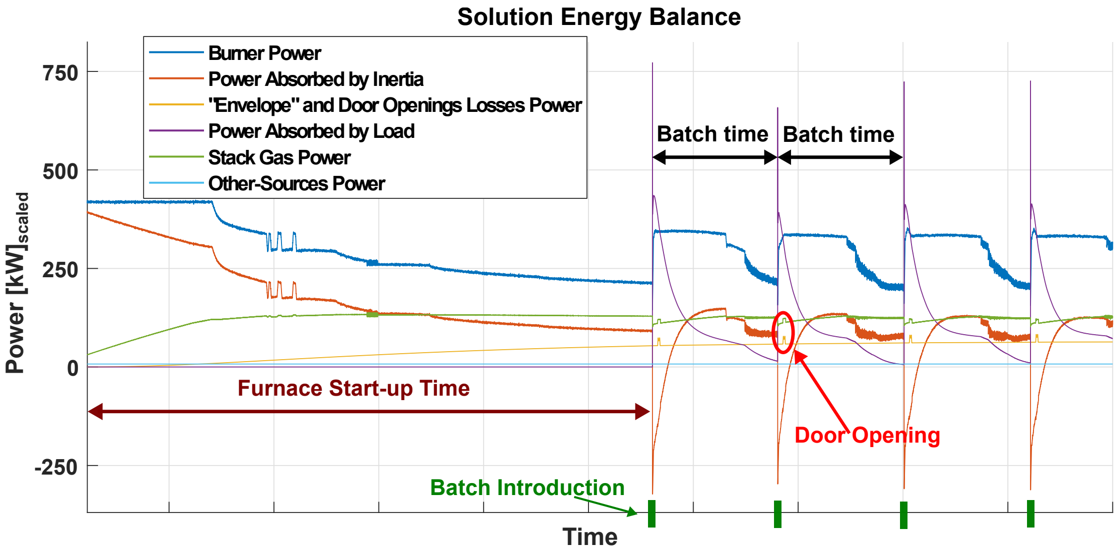


**Figure 4.22** – Energy Balance of the Solution Furnace: preheating phase and a section of the transitory period.

As it is commented before, there are several energy flows among the burner sections. Therefore, the individual energy balance of each section includes this inter-burner balance term. This mechanism is responsible for keeping the temperature in the furnace with low variability among sections, as it occurs in the real connected-sections of the furnace. The energy transferred in these flows is regulated by means of the interchanged mass flow ("$\dot{m}FlowB^i - Bi + 1$" term in Figure 4.21). This term is not included in the Overall Energy Balance equation (Equation 4.24), as the overall balance of these energy flows, when the furnaces are being assessed from a process perspective (in contrast to furnace section perspective), is zero/null.

The Particular Energy Balance for the solution process is schemed in Figure 4.23, in which the energy balance of each "Burner Section" is broken down. This figure shows, for the entire working period, how the energy is distributed among each element. Each section has the same elements: Lateral Heat Losses, which represent the percentage of lateral heat losses which that section transfers to the environment (it includes the door opening losses and the surface heat losses); Burner Contribution, which represents the total energy that each burner provides to its respective section (for simplification the other sources energy, such as the fan contribution, have been taken into account here); Stack Gases, which represent the stack gases energy associated to this burner (the losses attributed to the infiltration have been taken into account here); Inertia, which represents the energy that the system accumulates (it only represents the $\Delta InertiaPower$ term of Equation 4.21); Inter-burner flow, which represents the amount of energy which is transferred to other sections (the direction of the arrow indicates the direction of the energy flow, therefore, if the percentage is negative, the direction would be the opposite); Load Parts, which represent the energy transferred to the parts; and Load Basket, which represents the energy transferred to the steel baskets.

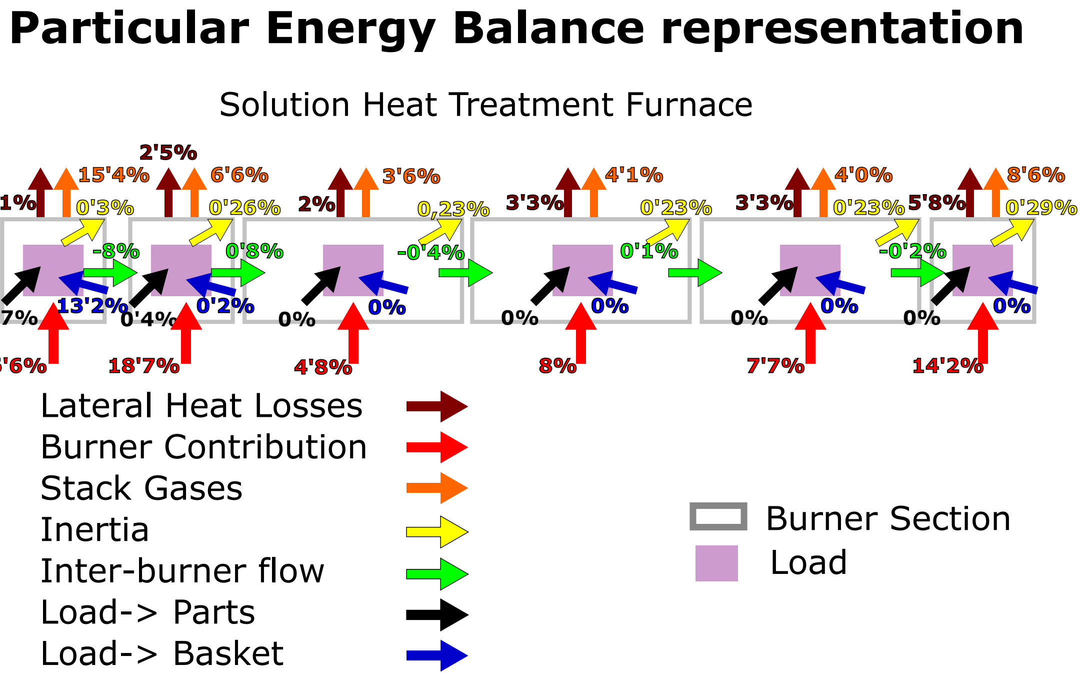


**Figure 4.23** – Overall energy balance for each section of the solution process.

The energy balance is conserved for each section (grey squares in Figure 4.23). The input energy is represented by the Burner Contribution, whereas the other elements are "outputs". Therefore, for each section, the sum of non-red arrow values agrees with the red arrow value. In this regard, the sum of Burner Contribution terms makes the 100%, which represents the energy required for the process.

Table 4.2 shows the overall energy balance for the entire system (all the furnace sections) for each phase of the process (Preheating, Transitory, Stationary and Shut-Down). Each phase is individually analysed for each aforementioned element i.e. "Lateral Heat Losses", "Burner Contribution", "Stack Gases", "Inertia", "Inter-burner flow", "Load-Parts" and "Load-Basket". Besides, the "particular contribution" represents the relative consumption of each phase in comparison with the overall consumption for the entire system. The "Inter-burner flow" follows the sign criterion of Figure 4.23. In this regard, a negative sign represents that an energy flow moves to the sections at left.

In conclusion, all the identified relevant phenomena are modelled. However, almost all the phenomena depend on the way of working of the furnace. This manner of working is represented in the production modelling.

| | Furnace Phases | | | |
|---|---|---|---|---|
| | Preheating | Transitory | Stationary | Shut-Down |
| Particular Contribution | 2’5% | 5% | 90% | 2’5% |
| Lateral Heat Losses | 8’7% | 21’7% | 23’6% | 37’1% |
| Burner Contribution | 100% | 100% | 100% | 100% |
| Stack Gases | 38’3% | 42’5% | 42’8% | 67’8% |
| Inertia | 55’6 | 3’6% | 0% | 0’1% |
| Inter-burner flow | -1’3% | -0.3% | -0’4% | -0’4% |
| Load Parts | 0% | 20’8% | 21’7% | -0’6% |
| Load Basket | 0% | 13’9% | 14’5% | -0’4% |

Table 4.2 – Overall energy balance for each phase of the solution process.

### 4.5.5 Production Modelling: Process way of working and Model input

For this case study, the main model input is the production (solid flow). The energy models, which reproduce the furnace behaviour according to the production input, are responsible for tracking the load requirements and for complying with the process restrictions. This production input is defined as a quantity of material (aluminium parts and steel baskets) and the time in which these batches are introduced to the first step of the first furnace (SF), as it is logged in the real factory. This production input is introduced to the model as an array of treated material weight and the introduction times in which these weights enter the furnace. For the simulation process, this array may be generated randomly (within some margins) or may come from real production data. Besides, some production conditions must be determined in order to launch the simulation, according to the specific observed modus operandi parameters. These modus operandi parameters describe the diverse states of operation that each device may present. By default, a set of parameters is selected for simulation (which corresponds to normal working conditions). In order to recreate the correct working conditions, the observed working modifications for a specific working period (such as burners nominal power anomalies, burners disconnections, ambient temperature or pressure controller damper state) must be introduced in the models. This introduction is by means of the specific parameters which are related to these working modifications. Therefore, these parameter modifications should be identified, adapted and introduced for the simulation process.

As it is stated before, the production depends on the customer’s demand. Due to this criterion, the total weight treated may vary more than 20% from one working week to another. The production model is capable of introducing these different production profiles and, ultimately, aspires to be able to optimise the production parameters which are accessible and modifiable by the operator. This optimisation, in real time simulation, would be implemented by following predictive clauses. The final behaviour of the part temperature depends on the future load which will be introduced in the furnace after the load under evaluation/optimisation is introduced. These clauses should be able to predict working patterns according to the expected production.

### 4.5.6 Economic Modelling: EEM costs and savings

The economic modelling of the process has been carried out by following the guidelines which are explained in Section 3. The employed indicators are quantified by calculating/figuring some cost for the proposed EEMs. The savings are directly obtained through the cost difference between scenarios. The baseline energy consumption (or productivity) is compared to the energy consumption of the process under the influence of the effects of an EEM. This difference is measured in terms of monetary cost.

As it is explained in Section 3.2.4.3, the cost (cost of preliminary activities, capital expenditures and operating expenditures) of the "ranged" EEMs may not follow linear trends. The "ranged" EEMs are those which can be applied with a different degree of implementation (such as infiltration area reduction, temperature increase of the burners combustion air flow or internal-external pressure controlling - with high or low margin of security-). Several non-linear assumptions have been introduced in the economic models in order to evaluate cost synergies among measures. In this regard, those measures which affect the same phenomenon may reach and optimal (which may be measured with the LEEC indicator $cost/kWh_{saved}$). The economic impact on the maximum contracted power is not taken into account for the economic analysis in order to simplify and reduce the assumptions.

Some economic assumptions for a specific degree of implementation (if any) are presented in Section 5 at the same time as the proposed measures are explained in detail.

### 4.5.7 Ecological Modelling: Harmful emissions

The ecological modelling of the process has been carried out as it is proposed in the Methodology Chapter 3. The employed indicators consider the amounts of emissions generated by the production process. In this regard two harmful particles have been assessed: carbon dioxide ($\mathrm{CO_2}$) and nitrogen oxides ($\mathrm{NO_x}$).

The $\mathrm{CO_2}$ emission is quantified by the straight translation of the consumed energy (Natural Gas or electrical energy) to the associated emissions of these sources. The $\mathrm{CO_2}$ emission factor account considers the entire life-cycle of the fuel-source, which includes extraction or transportation in the case of fluid or solid fuels.

The $\mathrm{NO_x}$ is approached by means of the performance graphs of the burners worksheets in concordance with the instantaneous power. The $\mathrm{NO_x}$ emission data is given for specific nominal conditions (such as percentage of $O_2$ or the temperature of the firing chamber) and adapted later to the process conditions (such as real $O_2$% or real combustion temperature).

$NO_x$ emission data is given for:

- Ambient combustion air 70°F (20°C)
- Less than 370°C firing chamber
- Minimal process air velocity
- Low fire input adjusted to the minimum Input On-Ratio (between 1'5 kW and 15 kW for the HTP burners)
- ppm volume, dry @ 3% $O_2$
- Neutral chamber pressure

The emissions are clearly influenced by the furnace parameters, such as chamber conditions, fuel type, firing rate or combustion air temperature.

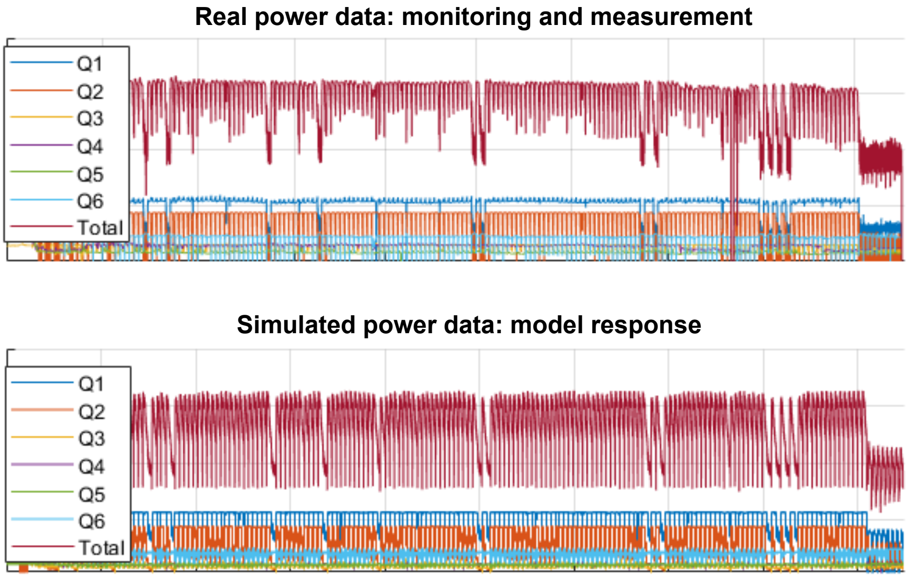
Other harmful emissions, such as carbon monoxide (CO) and the unburned hydrocarbons, are largely influenced by chamber conditions and, therefore, are not taken into account for the study.

## 4.6 Validation & Verification

As it is explained before, the validation and verification are, essentially, the comparison or testing processes to determine if the simulation result is consistent with its specifications or satisfies the requirements. For this case study the simulation results are endorsed by historical data validation in diverse conditions, which presents an acceptable theoretical medium-low degree of subjectivity.

The validation and verification of the conceptual model are accomplished due to the fact that the theories and assumptions underlying the conceptual model are physics-approach based phenomena (as commented in Section 3.2.5), such as convection coefficients, heat conduction, advection or lumped-capacitance. The model's representation of the problem entity, the model's structure, the logic of the model's processes, as well as the mathematical and causal relationships are "reasonably" selected for the intended purpose of the model. In the same way, the simplifications assumed are then corroborated by parallel analysis or studies, such as the internal pressure modelling [188].

In this regard, the model error is, at most (for all the historical-weeks-periods which were analysed), less than 7% for total consumption, and less than 9% for individual burners consumption and for other mass-flow rates. The error occasionally may increase by reducing the time sample, due to non-identified variations in the burners' energy supply. Ultimately, for almost all the analysed weeks, the errors are below the aforementioned worst case, showing, on average, errors lesser than 5%. However, the trends and the reactions to events are tracked with high fidelity (Figure 4.24).


Real power data: monitoring and measurement

Simulated power data: model response

**Figure 4.24** – Power validation for one-week period of working for SF. Q1 to Q6 represent the burners.

The comparisons between the real and simulated stack gases' temperature and mass flow are shown in Figure 4.25. As it can be seen, the mass flows of the simulation track the measurement behaviour of the measured data very well. In this case, the "noise" of the measurement is high. Notwithstanding, the trends and overall values are very similar and the expected relative error is, on average, lower than 6%. This error is very close to the expected error, which may be generated by raw data measurement and the subsequent conversion to mass flow units, provided by the sensors. The mass flow is measured at the top of the chimney, the vibrations generated by the normal working mode may generate the aforementioned interference.

In the validation of the stack gases temperature, the simulation profile presents some deviations in comparison with the measured one. The temperature deviations are ranged below 30°C for the most critical section, which is situated at the very beginning of the interval time (as shown in Figure 4.25 for temperature values). Despite the identified absolute deviations, in relative value, the error is contained below 7%, due to the high temperature values of the stack fumes. In this regard, the difference between the simulations and the real measurement may be attributed to two factors: the measure point and the inertia of the chimney. The measure point of the stack gases is several meters over the furnace. However, the stack gases temperature is calculated in the models to be at the very beginning of the chimney. The energy losses, which are generated at the chimney, are accounted for the measurement data (Figure 4.25). However, they are taken into account as an average value (15%). This value is approached with a simple study of the radiation heat transfer mechanism for the exposed area until it reaches the measurement point. This result agrees with the theoretical maximum temperature which is expected for the process (around 540°). The inertia of the chimney is not taken into account for the simulation values. Therefore, the temperature variations would be damped and the simulation values would be nearer to the measurement values.

In conclusion, the main variables are reproduced with high fidelity and the trends (attributed to events or phenomena) are followed in an accurate manner.

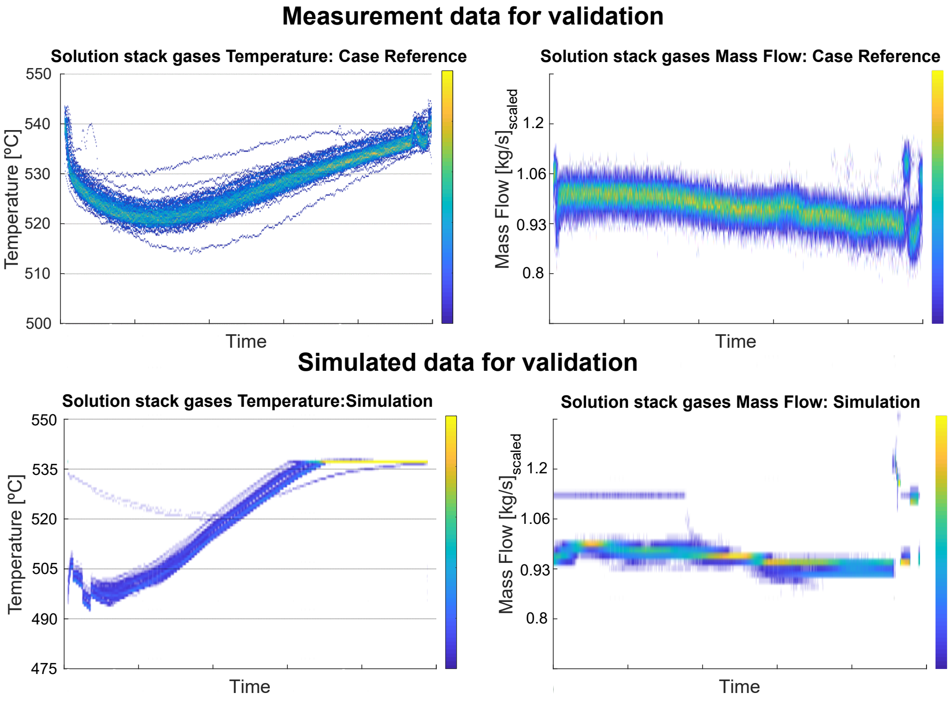


**Figure 4.25 –** Temperature and mass flow validation for one-week period of working (compressed in frequency plot) for SF.

## 4.7 Case Study Conclusions

As it is shown in this chapter, the process under study covers all the main proposed requirements. This process has a high variable production input, which generates diverse ways of working. Besides, it is a fuel-fired process in an energy intensive industry. The process consists of several sub-processes which are related to each other. Therefore, it meets the conditions of the processes in which the gap has been identified.

The proposed methodology is applied to this factory, in which the set of processes under study have been selected. As it was expected, the energy and material flows (non production flows, such as stack gases, fuel, infiltration, etc.) present profiles with manifold variations.

From the data analysis and assessment a high dynamic behaviour has been identified. The energy and mass flows depend on many physics-based phenomena (such as combustion, heat transfer phenomena, pressure-based infiltration phenomena, etc.) and production events (such as production modifications, unexpected specific ways of working, device failures or modifications, etc.), which have been characterised in order to generate the models. The nature of the models employed in this work implies that several assumptions have to be made, which synthesise and simplify reality [103, 48]. The energy modelling and characterisation has been carried out by means of compiling information about the process. This process information, besides being provided by the monitoring system, has been based on the comprehension of the device's way of working and also on the process' knowledge gathered for this purpose.

Finally, and following the proposed steps of the methodology, the generated models have been validated and verified. As it was expected, the verification is practically achieved due to the features of the process modelling. The validation of the results has been carried out by means of direct comparison (and error calculation) with historical data. The priority has been to correctly follow the trends of the energy and material flows instead of the perfect value correlation. This modelling aims to acquire a good compromise between complexity and replicability [157].

Therefore, the process has been correctly reproduced and modelled at the same time as all the relevant flows have been identified. A new energy modelling by simulation procedure for non-continuous thermal processes is developed and applied to a representative case study. This fact opens the door to an in-depth identification and the subsequent evaluation of hypothetical EEMs.

# 5

# Energy Efficiency Assessment

**Summary**

*This chapter expounds the simulation results of the different proposed scenarios. The first part of this section introduces all the EEMs which were identified as relevant and plausible. All these potential measures are contextualised and diverse course of action, which includes a wide variety of measures, is established. The simulation results for the different course of action is widely explained. The energy, production, economic and ecological features of each scenario are described in detail. The last part illustrates the tool developed to ease the introduction and implementation of EEMs in the industrial environment.*

## 5.1 Energy Efficiency Measures potential

This section identifies and analyses the specific EEMs which are identified for the case study (a Heat Treatment Process in an Aluminium Die-Casting plant). The first part identifies and accounts for the characteristics and limitations of the EEMs related to the case study in detail. Then, diverse course of action is proposed with the aim of providing different kinds of scenarios.

### 5.1.1 Energy Efficiency Measures identification

Once the case study is modelled and validated, this step consists of proposing modifications, device improvements or working changes in order to improve the energy efficiency by means of reducing the energy consumption or improving the productivity. These actions are called EEMs. The ranges of implementation of the EEMs have to fulfil the aforementioned overall requirements (commented in Section 4.3.4) or tackle the way to remove these restrictions.

In line with the mass and energy flows previously assessed and according to the stated restrictive considerations, a series of proposed measures are presented in the following pages (for determined implementation values).

- **Operation-schedule tracking:** The input introduction-time may suffer delays, as it is shown in Section 4.3.2. In this scenario the times in which the load enters the furnace are to be the same as the theoretically selected (i.e. the stage-time to cover the HTP requirements). Therefore, the result of the simulation of this scenario quantifies how much these delays affect in terms of consumption and productivity (according to the selected indicators). The analysed scenarios correspond to a 50% of current delay reduction and a 100% of current delay reduction (scenario with no delays). The analysis of this EEM, which mainly affects the operating level, quantifies the energy savings and impact of a perfect operation‘s schedule. This measure, which at the maximum level of application prevents input anomalies, is named Zero Anomalies, ($\mathrm{ZA}_{\mathrm{EEM}}$).
- **Tactical planning modification:** The HTP process works as a continuous process, from Monday to Friday, as it is shown in Section 4.3.2. This EEM scenario proposes a tactical change on the planning and analyses the production results by means of a different planning strategy, such as two-weeks of continuous production (10 working days - 4 rest day) or monthly production (20 working days - 8 rest day) in comparison to the current working schedule (5 working days - 2 rest day). This EEM reduces the energy consumption of the switch-on stages and the times in which the furnaces are cooled (natural cooling) and heated up (forced heating by the burners), reducing the stress attributed to these temperature variations. In addition, the time duration in which the furnace is being pre-heated or switched off is reduced, which causes reductions in the labour time. This EEM mainly affects the tactical level with minor consequences on the operational level. On the contrary, and in order to carry out the practical implementation of this measure, the numbers of operators or the existing working shifts would be modified. These modifications would generate cost overrun, new operator incorporations or discomfort among the operators due to the variation on the working shifts. This measure, which assesses the hypothetical implementation of diverse tactical planning, is labelled Tactical Planning ($\mathrm{TP}_{\mathrm{EEM}}$).

- **Production charge:** The parts are arranged in the baskets according to the different geometry of the parts. Therefore, a different number of parts may be introduced. Modifications in the basket internal structure or in the parts' arrangement may provide room for the introduction of more parts in each basket. The proposed hypothetical scenarios increase the overall load in the baskets around 2.5%, 5% and 7.5%. This increase is carried out in the lighter batches (those with minor weight of aluminium alloy). The real arrangement of the parts is not taken into consideration. This EEM only tackles the energy savings and the impact on the energy behaviour attributed to this increase, without considering how to increase the parts in the real baskets. On the contrary, this measure would affect the previous processes (such as, melting, degassing and die casting, as shown Figure 4.1 in Section 4.1), by increasing their production rate, or would require an increase in the batches of stocked parts, by arranging a new stock area in the plant layout. This measure, which evaluates the increase of the aluminium load in the basket, is called Load Increase, ($\mathrm{LI_{EEM}}$).
- **Turn-on time reduction:** During the turn-on time the furnaces reach the minimal conditions to start working. This time varies from week to week. The reduction or enlargement of this time affects the beginning of the production. The burners seem to work at maximum power until the circulation air temperatures, for each section, reach the nominal (or minimal acceptable) working temperature, around the solution temperature: 540ºC. There is evidence that the turn-on time could be reduced. This measure, which controls the duration of the preheating period of the furnaces, is denominated Turn-on Duration, ($\mathrm{TD_{EEM}}$).
- **Initial charge:** By default, the process is designed to work without any load in the initial step of turn-on (when the furnace is pre-heating at the beginning of the working week). However, some load can be introduced without harming the expected mechanical properties of the parts. This situation has been identified in the data monitoring step and in the process knowledge acquisition. The characteristics of the furnaces allow the introduction of an initial charge, both for the SF and AF. In the SF, the burner of the first stage is larger than the following ones. For this reason, a initial charge would "delay" the pre-heating time of the first stage, or, if the pre-heating time is kept, would reduce the temperature of the inertia. These effects are identified and confirmed in the data acquisition phase. The rise of the hypothetical energy consumption and the increase of the pre-heating duration time are crossed with the savings and the productivity increase in order to estimate the correct impact of this measure. The scenarios analysed for this EEM include the following situations: a scenario with additional initial charge in the first stage and a scenario with additional initial charge in the first and second stage. This measure, which analyses the assumption of beginning the process with load inside the furnaces, is labelled Initial Charge, ($\mathrm{IC_{EEM}}$).
- **Shortening stage-time** (Temperature-time restrictions)**:** As it is stated in dif-

ferent studies, such as the presented in [186, 197], the solution and ageing process duration tend be overestimated, which allows potential time reductions. The time the parts remain in each furnace is determined by the number of stages (construction parameter) and the stage-time. The STTS and ATTS indicators are very related to this duration. These indicators start to count the time when the parts arrive to nominal process temperature. Several scenarios, which recreate stage-time reductions from 1% to 25%, are reproduced and analysed. Then, the STTS and ATTS are evaluated in order to quantify how much these changes affect the indicator values in comparison to the baseline values. This measure reveals the potential of these scenarios. However, an empirical analysis of the mechanical properties of the parts should be assessed to confirm the aforementioned studies and to ensure that the requirements are reached. The modification to the ageing process stage-time, as a solution dependent process, without modifying the solution stage-time would entail several logistic problems and vice versa. In this regard, any modification to the stage-time is applied in both furnaces. The quenching stage does not mean a problem as the time required to drop the temperature is several orders of magnitude lower. This measure, which reduces the stage-time in order to tune the STTS and ATTS, is named Time Reduction, ($\mathrm{TR}_{\mathrm{EEM}}$).

- **Fixture size** (weight and material properties)**:** The baskets, which are introduced with each batch, are made of stainless steel. These baskets are introduced in the furnace at ambient temperature. Therefore, the furnaces need to heat this steel weight. The modification of the material composition generates differences in weight and in heat capacity. For the baseline scenario, around 40% of the energy absorbed by the load (baskets plus parts) is employed in heating the steel baskets. The recreated hypothesis is that the baskets are made in other materials (with its consequent heat capacity modification), such as carbon fibre or ceramic material. A typical carbon fibre composite fixture is between 10% - 20% the weight of a metallic fixture in order to maintain the same level of strength [198]. Therefore, the energy related to fixture heating may be reduced between 74% - 88% of the current theoretical energy [199]. In this sense, with carbon-fibre composites, the energy reduction may reach values around 80%, maintaining the basket properties. This energy reduction is the direct comparison between the average required energy for heating the current steel baskets and the energy required for the proposed new baskets (for the nominal process temperature, i.e. from 25°C to 540°C and to 160°C). However, other energy or production benefits may appear, such as the STTS and ATTS increase or the reduction of the roller conveyor consumption. This measure, which studies the effect of replacing the current baskets with ones whose thermal properties are better, is called Fixture Substitution, ($\mathrm{Fx}_{\mathrm{EEM}}$).

- **Burner sizing** (excess air considerations)**:** A complete combustion requires that the furnaces are supplied with excess air. Commonly, the minimal level of excess air is around 10% to 15% in the case of natural gas fuel. As the excess air is increased, both carbon monoxide (CO) and unburned hydrocarbons emissions are reduced. However, this excess of introduced air flow (at ambient conditions) is heated at the burning process and exits the system through the chimney (mass-balance) reducing the energy efficiency of the furnace [200]. Currently, the burners are not working at nominal conditions (default nominal power). In consequence, the excess air ratios are far away from the nominal working excess ratio (as shown in Figure 4.5). The excess air ratio, of the solution burners are for the reference case on average: 28%, 20%, 86%, 60%, 59% and 27% from the first to the sixth burner, respectively. The recommended ratios are around 11% of excess air. The solution burners are working with excess air percentages which triple, or even quintuple, the recommended ratios. The modification of the manner of working of the excess air introduction may allow to reduce these levels.

Besides, in a future substitution, or for a new plant, establishing the nominal power according to the future working conditions would reduce the heat losses by excess air. The planned scenarios include adaptations of the excess air to the real working conditions of the burners at different levels: individual total adaptation, individual partial adaptation, type total adaptation and type partial adaptation. The individual adaptation regulates each burner individually, whereas the type adaptation procures and adjustment according to the current types of burners. The "total" scenarios adjust the power to the observed limitations, whereas the partial scenarios mean that the maximum power is a specific percentage over the observed limit (within the interest of having a security margin for modifications). This measure, which provides a better burner size in adaptation to the measured behaviour and requirements, is denominated Burner Sizing, ($\mathrm{BS}_{\mathrm{EEM}}$).

- **Internal door 1st to 2nd stage:** In this typology of process, an internal door is commonly utilised to isolate the cold section (due to the cold load input) and the hot section (the stationary constant temperature section). Currently, the door is not being employed and, consequently, there is a leak of cold flow to other sections, which must be reverted by the other burners. This measure, which analyses the modification of the heating characteristics attributed to the internal-door work, is named Internal Door, ($\mathrm{ID}_{\mathrm{EEM}}$).

- **Infiltration area:** Excess air does not necessarily enter the furnace as part of the combustion air supply. The furnace system is not perfectly isolated from the exterior. This is attributed to the non-perfect closure of the doors, grooves near the burners, or gaps at the roller conveyor cylinders. A correct preventive maintenance, based on sealing tasks, may reduce this stationary infiltration area. In the scenarios analysed here, the infiltration area is reduced between an 8% to a 66%. This measure, which faces the reduction of grooves and fissures all along the furnaces, is labelled Infiltration Area, ($\mathrm{IA}_{\mathrm{EEM}}$).

- **Internal pressure:** Hot furnace gases are less dense and more buoyant than ambient air, so they rise, creating a differential pressure between the top and the bottom of the furnace. This differential pressure is the precursor of a natural draft or negative pressure in furnaces and boilers. Due to security reasons, the furnaces are maintained around certain levels of relative negative pressure in order to prevent hot flows from leaving the furnace. This pressure is usually controlled by a damper in the chimney circuit. This damper may be static (settled at the design or tune-up period) or be managed by a controller (which depends on the chimney flow or internal pressure). A variable damper operation to control chimney drafts in the fired heaters may be implemented. Several industrial services companies offer this kind of technology by means of electro-hydraulic damper drives[1] or multiple pneumatic operators[2]. In this regard, when changes in heater load and ambient temperature occur, chimney drafts occurring across the damper would change too. Getting close to the limit (without incurring in a security warning), reduces the total infiltrations in the furnace. For this case study a static damper is implemented. The scenarios proposed modify the negative-pressure to lower ones: reductions from 9% to 85%. This measure, which controls the damper settings in order to prevent excessive pressure differences (external-internal), is called Internal Pressure, ($\mathrm{IP_{EEM}}$).

- **Combustion air temperature:** As it is commented before, the burners are fed with ambient air, which is provided by fans. Raising the temperature of the air introduced could assist the combustion mix and increase the energy efficiency [200]. The combustion air, provided by an air fan, goes through a filter prior its entrance to the burner chamber. This flow may be heated by means of an external device. In this regard, a heat recovery system may provide the required heat for the heating process. This measure consists of the evaluation of the energy savings and impact on the process phenomena behaviour (such as the $\mathrm{NO_x}$ generation) according to several temperature scenarios. This heat may come from low heat recovery systems in the plant or from the excess heat recovered by the Heat Exchanger System (HES) system (which is explained later). The heat requirements (of the air preheating) are analysed individually for each situation. This measure, is denominated Combustion Air, ($\mathrm{CA_{EEM}}$).
- **Burner working-way** (apparent power restriction)**:** With this factor adjustment the apparent restriction would be eliminated. With this modification the maximum power of the burners reaches the construction-default maximum power. This measure, which analyses the effect of removing the apparent power limitation of the burners is named Power Limitation, ($\mathrm{PL_{EEM}}$).
- **Load initial temperature:** The load is introduced at room temperature both in the AF and in the SF. After the die-casting step, the parts are cooled and

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[1] https://www.powermag.com/advanced-furnace-draft-pressure-control-using-electraulic-damper-drives/

[2] https://www.heatflux.com/smart-stack-damper

suffer a first inspection. Then they are arranged into the baskets and laid in the production queue. After the SF process, the parts and baskets are quenched and, therefore, practically return to ambient temperature. The main way to increase the load temperature is by means of a new preheating stage. The hypothesis of developing a preheating stage for the AF has been directly rejected by several reasons. Both the fewer energy saving potential and the practical impossibility of introducing a preheating stage between the oven and the quenching pool make the hypothesis economic unfeasible. Therefore, ageing process is not involved at all for this energy efficiency measure.

This proposal tackles the implementation of a previous stage in which stock-batches lay before being introduced to the HTP. This new stage preheats both the parts and baskets during the time previous to introduction. This preceding stage is an independent stage, in which stack gasses from solution HTP go through this stage chamber. This chamber is virtually designed as an additional furnace stage: hot medium is introduced from the lower side of the batch and leaves the batch from the top. As a first assumption, stack gasses are directly introduced to the preheating chamber, without a heat exchanger. The hypothetical scenarios identified are split into two sensitive parameters: percentage of mass flow employed and percentage of heat losses. This measure, which increases the part and basket temperature before the solution furnace, is labelled Preheating Stage, ($\mathrm{PS_{EEM}}$).

This new device has been modelled similar to the furnace section due to the modularity of the models (as introduced in Section 3.2.4.1). It consists of one furnace stage but replacing the heat generator model by the selected energy source. The other considerations and features assumed for the furnace section (as described in the previous modelling subdivision Section 4.5) are reproduced for this system. Therefore, the thermal inertia of the new system, the infiltration air flow and the lateral heat losses are assumed and taken into account for the new system.

- **Waste Heat Recovery System:** The ageing heat furnace requires energy to heat the batches to ageing temperature (around 160°C degrees). This quantity of energy is considerably lower than those available in the stack gasses of the solution process (as it is shown in Figure 5.1). Therefore, a heat recovery system solution is proposed in order to supply this amount of energy. The HPHE technology has been selected due to energetic and economic reasons [201]. WHRS specific features are introduced later, in the results section. In this regard, for the next sections, the nomenclature (among HPHE, HES and WHRS) follows the criteria set forth below. Waste Heat Recovery System term (WHRS) includes the heat exchanger and all the piping and connections among processes and devices and it is already included in a heat recovery scenario. Heat Exchanger System (HES) trem also includes the heat exchanger and the piping, however, it is not already framed in a recovery scenario. Finally, Heat Pipe Heat Exchanger (HPHE) term only takes into account the heat exchanger, which, in this case, is based on heat pipe technology.

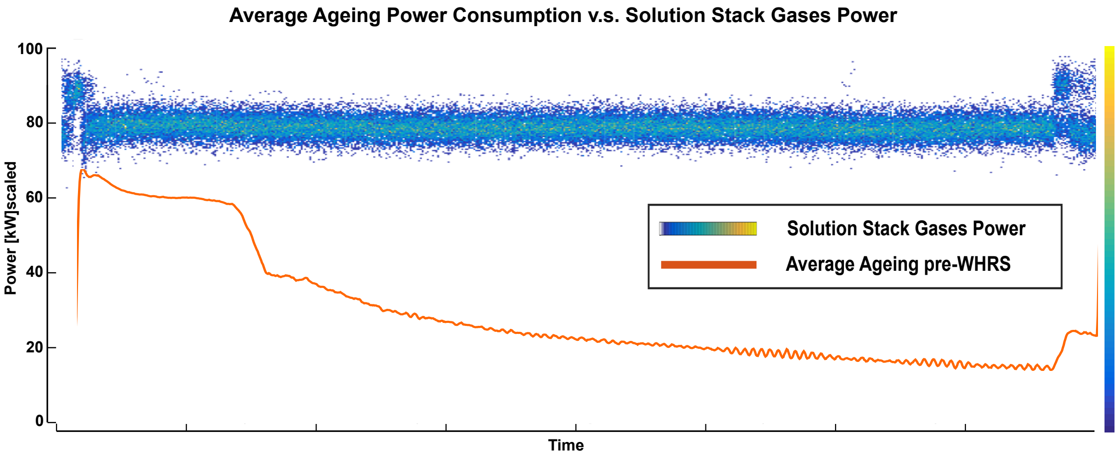

**Figure 5.1** – Power comparison between solution stack gases flow and ageing requirements.

The proposed heat exchanger recovers the energy [202, 134] from the exhaust gases of the solution process and directs (the energy) to the ageing process. The flue gases flow is directed from the stack collector to the heat exchanger, in which the HES transfers its thermal energy. This recovery system is based on heat pipe technology [203]. A heat pipe transfers thermal energy passively from a hot to a cold stream through a boiling condensation cycle inside a hermetically sealed metal tube. In this way, heat from the hot area can be transferred very efficiently to a cold part of the pipe. This technology is schemed in Figure 5.2. The heat exchanger is fed, at the cold side, by air at ambient conditions or by the exhaust gases of the ageing process. These both scenario are analysed.

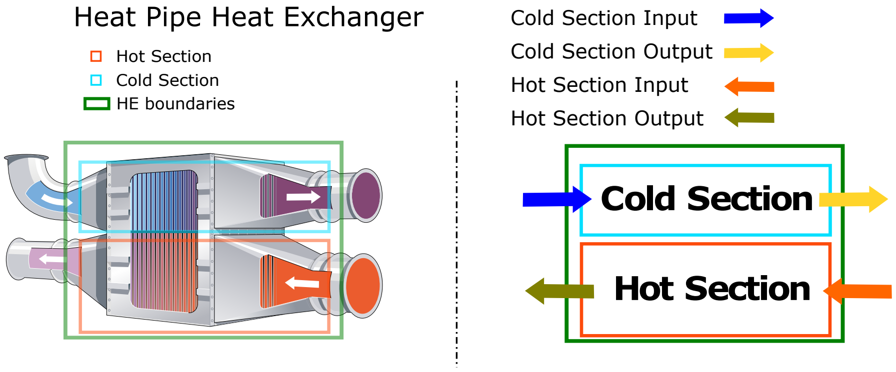

**Figure 5.2** – Heat Pipe Heat Exchanger [204].

In these scenarios the energy consumption profile of the ageing burners, depicted in Figure 4.15, is attempted to be provided by the energy of stack gasses of the previous process (i.e. solution heat treatment, depicted in Figure 4.16). As opposed to the solution process, the ageing process requirements are more relaxed, imposing less restrictions to the medium temperature. This measure, which is presented as the main strategy to improve the energy efficiency of the process according to the selected energy and operational criteria, is framed in a further assessment for real implementation. This measure, is named Heat Exchanger System, ($\text{HES}_{\text{EEM}}$).

The proposed EEM, the acronym, the characteristics, the initial ranges analysed and the suggested costs are summarised in Table 5.1. Several degrees of implementation within the proposed range are then assessed in order to acquire an in-depth knowledge of the behaviour of the system (sensitivity analysis). The costs, represented in Table 5.1, refer to the intermediate (in bold) value of the range, and the OpEx term represents the monthly operational expenditures. These assumptions are only utilised for the combinatorial analysis in order to behave a optimisation according to a monetary criteria. Some values are obtained from public documents or approached from technology suppliers report.

| | **Acro.** | **Range** | **EEM Purpose** | **CapEx** | **OpEx** | **CPa** |
|---|---|---|---|---|---|---|
| $\text{WHRS}_{no-recicr.}$ | HES | - | Provides energy to AF from SF disposal. | 35300 | 50 | 0* |
| $\text{WHRS}_{recirc.}$ | HES | - | Provides energy to AF from SF disposal. | 35300 | 50 | 0* |
| Zero Anomalies | ZA | no-**half**-full | The entry time period remains constant. | 0 | 50 | 500 |
| Load Increase | LI | 1%-**2’5%**-8% | A greater number of pieces is introduced. | 0 | 50 | 2500 |
| Turn-on Duration | TD | 5%-**12%**-24% | Turn-on time reduction. | 0 | 50 | 2500 |
| Initial Charge | IC | $1_{st}$-$1_{st}$ & $2_{nd}$ | Load at the beginning stages. | 0 | 50 | 0 |
| Time Reduction | TR | 2’5%-**5%**-22’5% | The entry time period is reduced. | 0 | 50 | 4000 |
| Combustion Air | CA | 65°C-**150°C**-3750°C | The combustion air temperature is increased. | 10000 | 250 | 3000 |
| Fixture | Fx | - | Changing of the baskets fixture. | 25000 | -50 | 5000 |
| Burner Sizing | BS | $\text{type}_{\text{part}}$-$\mathbf{indi}_{\mathbf{part}}$-$\text{indi.}_{\text{tot}}$ | Adapts the burner power. | 10000 | 250 | 3000 |
| Internal Door | ID | - | The inner door starts to work regularly. | 0 | 60 | 1000 |
| Infiltration Area | IA | 8%-**33%**-66% | The infiltration area is filled or reduced. | 5200 | 100 | 1000 |
| Internal Pressure | IP | 9%-**18%**-85% | The internal pressure is adjusted | 0 | 100 | 1000 |
| Preheating Stage | PS | Total-**Partial** | The load temperature is increased. | 10000 | 250 | 3000 |

Table 5.1 – Individual EEMs proposed and analysed.

These proposed EEMs are modelled as modifications on the previous models, such as input variations or clause modifications of the internal blocks. The technical considerations of the new (post-EEM) energy behaviour of the proposed EEMs are widely explained in Section 5.1.2.

### 5.1.2 Courses of action

Therefore, three courses of action (based on the EEMs identification) are determined: the WHRS arrangement, the individual assessment of the proposed EEMs and the economical assessment of the combinatorial hypothesis.

This section accounts for the EEMs features and implementation consequences. First, the main strategy of the main course of action, as shown in Figure 5.3, is explained. Afterwards, the secondary strategy, which introduces other EEMs, is described according to the selected measures for the combinatorial analysis. Finally, the remaining EEMs which are not selected for this main course of action (dashed line in Figure 5.3) are presented at the expense of the main strategy (the WHRS).

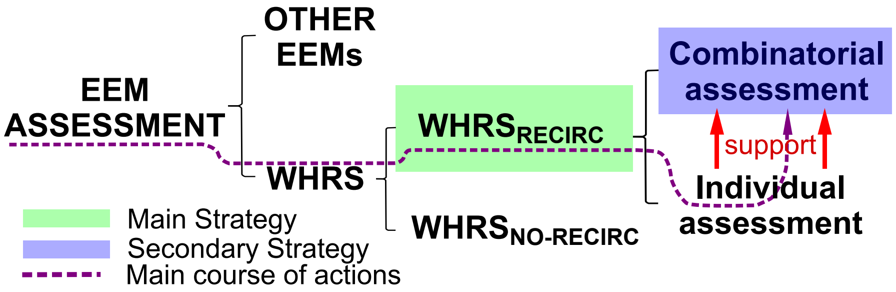

**Figure 5.3** – Course of action.

### 5.1.2.1 Main Strategy: WHRS

As it is stated before, the main course of action is the implementation of a WHRS, based on HPHE technology, with the objective of recovering the energy of the solution gases, as shown in Figure 5.4.

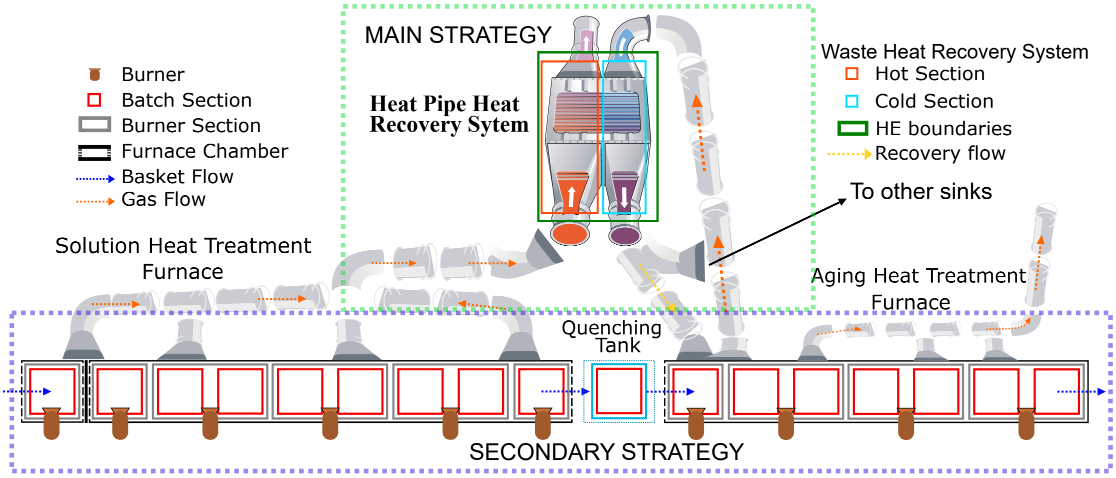

**Figure 5.4** – HTP and WHRS. Strategic course of action.

A WHRS [134], represented in Figure 5.4, is a system which transfers heat from process residual outputs at high temperature to another part of the process or to another process. The energy is recovered from the hot flow to the cold one [202]. For this case, an indirect heat exchanger has been selected, both flows are not mixed. Therefore, the heat exchanger may be split into two sections: the Hot Section and the Cold Section (orange and blue squares in Figure 5.4). The heat transfer fluid of the Hot Section is the exhaust gases flow of the solution process. For the Cold Section two alternatives have been analysed: ambient air feeding (at ambient temperature) and the re-circulation of the AF stack gases. Finally, as it will be later exposed, the re-circulation hypothesis is selected. For the final solution, the fluid of the Cold Section is the exhaust air of the ageing first collector. This first collector gathers the flow attributed to the first burner and the infiltration flow ascribed to the first furnace section. Therefore, the temperature corresponds to the exhaust gases of the ageing process, around 150-160°C. The WHRS recovers energy from the SF exhaust gases in order to direct the recovered energy (employed to heat the exhaust air of the first AF stage) to the AF, as shown in Figure 5.4. After this recovery, the exhaust gases of the SF are dropped to the ambient at lesser temperature. The design characteristics of the gas-to-air HPHE selected are the following:

- Nominal Hot Section inlet temperature 450ºC.
- Nominal Cold Section inlet temperature 25ºC for the $\text{WHRS}_{\text{no-recir}}$. Nominal Cold Section inlet temperature 150ºC for the WHRS with AF exhaust gases recirculation.
- Nominal air outlet temperature of Cold Section higher than 310ºC.
- Nominal Hot Mass Flow around 0.438kg/s $\sim$ 1580kg/h.
- Nominal Cold Mass Flow up to 0.5kg/s $\sim$ 1800kg/h.
- Nominal air outlet temperature of Hot Section Out higher than 130ºC (To be above sulfuric acid dew point in order to avoid corrosive scenarios).

With these nominal conditions, a HPHE model has been developed. However, the SF, which performances as a dynamic system, may bring variability in this nominal working conditions (due to slight variations in the stack gases mass flow and temperature). The HPHE characteristics and output variables, such as heat transfer effectiveness, Cold Section outlet temperature and Hot Section outlet temperature (final exhaust to ambient), depend on inlet characteristics. As far as the working conditions move away from the nominal point, the HE output variables (mainly the air outlet temperature) and characteristics (mainly the HPHE effectiveness) will also be modified. If the temperature of the exhaust gases increases (more source energy), the available energy for the ageing process will be increased. However, the HE effectiveness of the WHRS will decrease. Therefore, the variability of the SF will affect the energy recovery, both in quantity (total energy) and in quality (temperature). This behaviour is represented in Figure 5.5. Similar approaches have been implemented in order to cover other deviations of the main dependant variables, such as the ratio of Hot Mass Flow and Cold Mass Flow or the Cold Section inlet properties (temperature and mass flow).

The HPHE energy variables, which affect the ageing system, are the mass flow and outlet temperature of the Cold Section. The energy transferred to the AF is dependent of these two variables. The Cold Mass flow value and the Cold Section Outlet temperature are selected considering a compromise between the cost of the HPHE and the energy

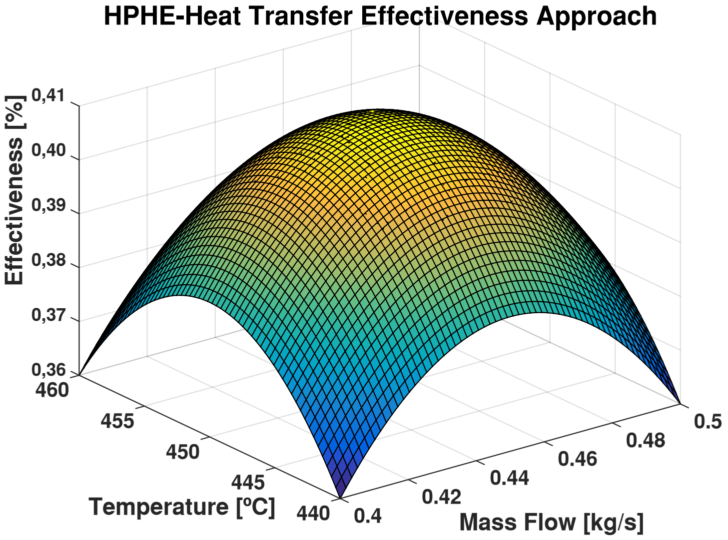

**Figure 5.5** – HPHE effectiveness according to Hot inlet temperature and Hot inlet mass flow.

benefit. This energy benefit comes from the savings attributed to a lesser use of the ageing burners. This solution requires the analysis of some production considerations as well, apart from the analysis of the WHRS from an energy point of view,. The solution process and the ageing process are not synchronised, the beginning of the ageing process is temporarily displaced from the beginning of solution process. The SF and the AF have the same stage-time, but the quenching stage is optimised to reduce the HTP total time and generates this asynchronism between the beginnings of stages. Despite the furnaces are continuous, the introduction of the batch in each process does not occur at the same time. A "critical section" is clearly identified in which the energy source (stack gases) is very just above the sink requirements (AF requirements). The AF thermal requirement may not be satisfied by the stack gases of the SF at this critical section (Figure 5.6).

In addition, the WHRS introduces a delay into the recovered heat flow due to the thermal inertia of the WHRS and the length of the ducts. This delay represents less than a 10% of the predefined stage-time. Besides, this thermal inertia softens the hypothetical temperature peaks (or valleys) which are produced by the SF exhaust gases variations.

These issues can only be analysed by means of a dynamical analysis provided by highly-flexible models, such as the ones described in the previous section (Section 4.5). By means of these models, the performance of a HPHE is reproduced to recover the heat from the SF gases and to transfer it to a new flow which will feed the AF. The HPHE takes as entry the entire mass flow of the solution furnace. The losses from stack beginning and collector are estimated to be 15% of the solution stack gases energy. The peak effectiveness, obtained for nominal conditions, is around 40%. The suggested

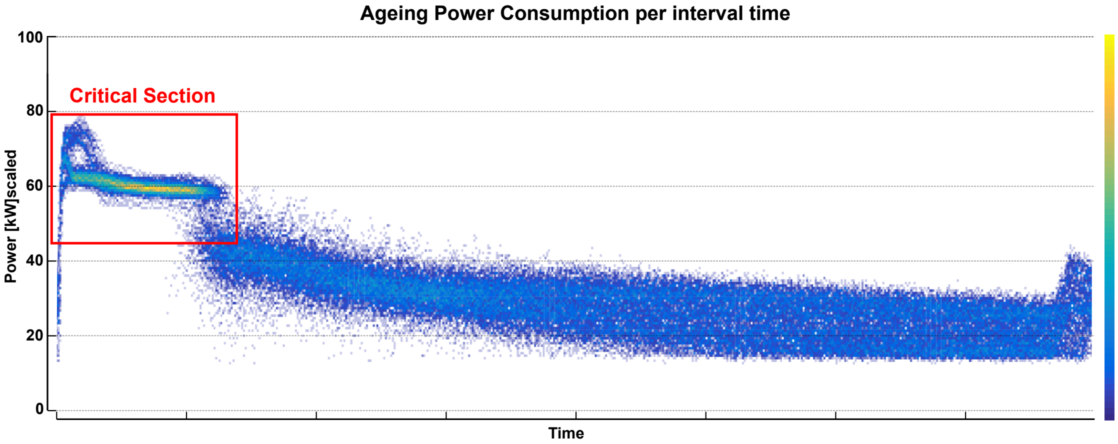

**Figure 5.6** – Ageing Pre-energy efficiency Assessment requirements: Critical section of the interval

place to introduce the recovered heat to the system is just at the first stage (as shown in Figure 5.4), after the flow deviator (depicted in Figure 4.19). Despite the fact the HPHE is modelled as a new block, the introduction of the new heat source to the existing models is modelled as a slight modification in the already developed models.

#### 5.1.2.2 Secondary Strategy

The selected EEMs for this secondary strategy are evaluated in combination with the main EEM: the WHRS. Therefore, the evaluation of the individual assessment results (Figure 5.3), whose results set the base of the sensitivity analysis, provide the information of how these measures individually work in combination with the main EEM for the entire range. The selected EEMs for this secondary strategy are the followings: Zero Anomalies ($ZA_{EEM}$), Load Increase ($LI_{EEM}$), Time Reduction ($TR_{EEM}$), Combustion Air ($CA_{EEM}$), Internal Door ($ID_{EEM}$), Infiltration Ares ($IA_{EEM}$), Fixture ($Fx_{EEM}$) and Internal Pressure ($IP_{EEM}$) (from Table 5.1).

The dynamic behaviour of the WHRS, which modifies downstream the AF, is analysed in combination to several EEMs. These measures may also generate modifications to the dynamics of the process. These dynamics modifications may affect the WHRS way of working or design, such as variations of the exhaust mass flow of the SF or the energy/power behaviour of the burners. DUe to this fact, an iterative adjustment is required to fit the WHRS to each range of EEMs. For example, a reduction of the infiltration area of the AF reduces the consumption according to the reduction of the infiltration air mass flow. Therefore, the energy required by this process is minor and, consequently, the nominal power of design of the WHRS can be reduced (which implies cost reductions).

This individual assessment provides design information and sets the variable behaviour trends, which allows to select the correct range for complying the combinatorial assessment criteria. These trends, behaviours and re-designs are explained in Section 5.2.2.

Ultimately, the best combination of measures to optimise the selected factors is proposed. The optimised factor may be economic, energy, ecological or a production factor (such as maximum energy reduction, shortest SPP, highest ROI, $CO_2$ emissions, etc.) or a weighted combination of them.

The optimisation process is approached as a heuristic iterative simulation process, due to the high variability of the production inputs and the dynamic behaviour of the manufacturing process. Some measures may have an important impact on a specific control parameter. This impact may be incremented or reduced by a combinatorial package of measures. Each proposed package corresponds with five different measures selected to optimise the required factor. The heuristic iterative procedure is required to get closer to the relative optimum. This optimisation process analyses and selects the combinations and proposes new configurations by modifying a EEM parameter.

As it was explained before, this work reproduces the real modus operandi of the manufacturing process for a specific period. Therefore, a relevant period must be selected in order to accept or refuse a course of actions. For this reason, any modification may be analysed and verified individually, hindering and extending the optimisation process. This fact generates high amount of data with high computational work. On the basis of the preliminary results, the selection of measures for each package may be directed/guided to save time and computational work. This guidance is tackled by the analysis of the preliminary results, in which the impact is individually assessed. The ranges proposed in Table 5.1 may be exceeded in the combinatorial packages due to synergies among measures.

Five "packages" of EEMs are obtained in order to reach the next five different goals: minimisation of the SPP, maximisation of energy reduction, minimisation of the HES sizing, maximisation of the production and the conservation of the current STTS and ATTS. The last one is the most conservative goal, the process is minimally affected. Both the process STTS and ATTS, the internal pressure, the $NO_x$ production, the production plan (number of treated parts) and the basket composition remain invariable.

#### 5.1.2.3 Other EEMs

This course of action analyses the behaviour of the implementation of some EEMs at expenses of the main course of action: the WHRS evaluation. In this section, EEMs, such as Turn-On Duration ($TD_{EEM}$), Initial Charge ($IC_{EEM}$), Burner Sizing ($BS_{EEM}$), Power Limitation ($PL_{EEM}$) and Preheating Stage ($PS_{EEM}$), are evaluated. These measures are only evaluated for the SF. However, the AF system may be affected indirectly.

These EEMs are excluded from the main course of action due to diverse reasons. The $PS_{EEM}$ measure is incompatible with the main strategy because of the both measures are hypothetically provided by the same flow. The scenarios proposed in the Energy Efficiency Measures identification (Section 5.1.1) are analysed in Section 5.2.4.

The BS measure includes the replacement of the current burners or, at least, an in-depth modification of the working parameters through changes at the burners PLC (Programmable Logic Controller). In the same way, the PL measure avoids the identified apparent restriction. Both kinds of EEM act at the same device, i.e. the burners. Consequently, the BS and PL measures are jointly addressed. The evaluated scenarios are the following:

- Scenario 1: The restriction is eliminated. The burners can work up to the design limits.
- Scenario 2: New burners are proposed, with lower nominal power designs, in order to fit the current apparent power restrictions. The data sheet curves (such as the ones shown in Figure 4.5) are modified.

The remaining measures mainly affect the transitory phases of the process and the results may be practically extrapolated without considering further iterative adjustments. The TP, TD and IC are measures which practically do not affect the process normal development. The PS affects drastically the process, making strong modification both in the common manner of operating and in the energy flows. The uncertainty which this last measure generates, is one of the main reasons to dismiss it for an in-depth analysis. Despite the fact that the temperature profile of the parts at the heating stage (from 25 to 540°C) does not suppose strong limitations, the implementation and design of this new additional chamber generates technical and layout problems.

## 5.2 Energy Efficiency Assessment Results

The main results, according to the case study, are commented and analysed below. After the EEMs identification (exposed in Section 5.1.1), this section splits the hypothetical ways to face the EEMs into 4 subsections:

- **Preliminary assessment**, which is responsible for analysing the modifications of the system for the main EEM, the WHRS based on a HPHE. Here, the sizing and the main features of the WHRS are established. The two proposed hypothesis for the recovery system have been analysed: ambient air feeding or re-circulation of AF exhaust gases.

- **Individual Assessment of EEM**, which evaluates the EEMs one by one in combination with the WHRS measure.
- **Combinatorial Assessment**, which optimises the selection of EEMs as well as the EEM working ranges according to an introduced multi-criteria selection (economic, ecological, production or energy).
- **Other EEMs**, which individually analyses the results of the previously proposed EEMs (in Section 5.1.2) .

In this section, the EEMs and the scenarios proposed in the courses of action (in Section 5.1.2) are compared to the Baseline scenario (BL) or to the Heat Exchanger System scenario (HES).

### 5.2.1 Main Strategy: WHRS arrangement analysis results

As it is commented in Section 5.1.2.1 there are proposed two options to arrange the WHRS: feeding it by air at ambient conditions or by redirecting the exhaust gases of the first stages of the AF to the WHRS cold input.

As it was introduced before, this methodology not only provides energy or economic results of the suggested measures, but also allows to know and to adopt the most suitable manner of working of the processes and devices in the new situation. In this case study, the method of providing heat to the parts in the AF changes. The energy supply of the AF, which were previously provided by the NG combustion in the burners, partially disappears. A new different energy flow becomes the main heat supply. Therefore, a new configuration setting for the heat sources of the furnace has been considered and adapted to the models for the two proposed cases. These proposed configurations are designed to fulfil the requirements of the Ageing Treatment at the same time that the consumption of the burners is reduced.

#### 5.2.1.1 No re-circulation

The energy results (energy consumption, energy recovered, stack gases energy, etc.), the new behaviour of the burners, and the new energy distribution are explained in this section together with the economic impact of the $\text{WHRS}_{\text{no-recir}}$ according to the selected production input (representative working week under study). For this scenario, the WHRS is designed to provide/introduce heat in several places of the AF. The mass flow distributor, which is placed after the Cold Section output of the HPHE, splits the recovered flow to several introduction points which are located all along the furnace. This complex HES distribution attempts to control the heat distribution in a better way. These flow rates, which are directed to each one of these introduction points, are established by means of a set of valves, according to the consumption (burners consumption) which were previously observed for each section. Therefore, the section which presents higher requirements (before the EEM) will be provided with higher quantity of recovered flow. Then, a minor iterative process to optimise this distribution is carried out.

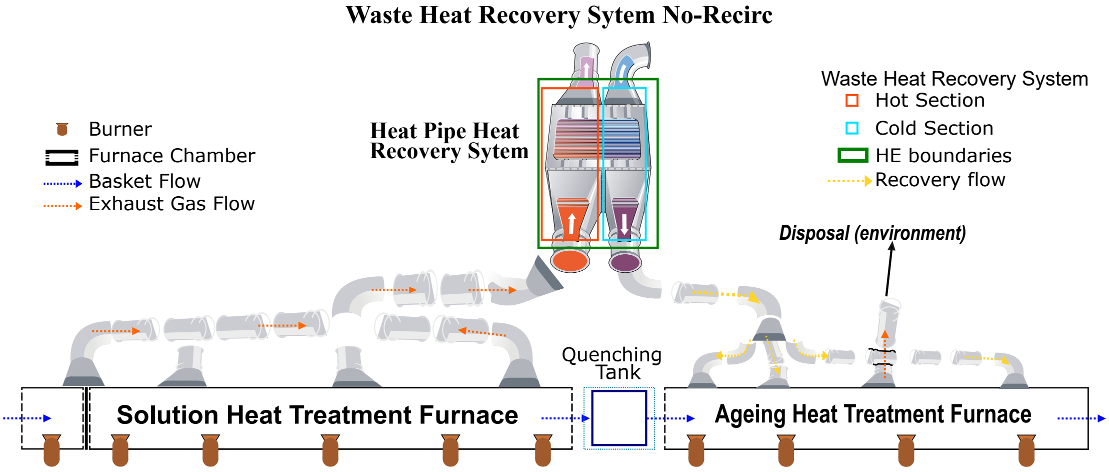

**Figure 5.7** – HTP for WHRS$_{norecir}$ hypothesis.

The total energy consumption of the furnace and the breakdown of the device modus operandi indicators (as described in Section 3.2.4.2.2) are analysed for each burner in the following pages. The new consumption profile, which is calculated by simulation for the selected working week, is compared to the pre-WHRS$_{\text{no-recir}}$ average consumption (orange line), as it is depicted in Figure 5.8. Very low values of energy may be observed in the last part of the burners consumption profile (Critical behaviour section in Figure 5.8). In this section, the entire energy which is required by the furnace is practically provided by the WHRS$_{\text{no-recir}}$. The simulation results shows a quasi-constant energy profile provided by the WHRS$_{\text{no-recir}}$, as it is depicted in Figure 5.9.

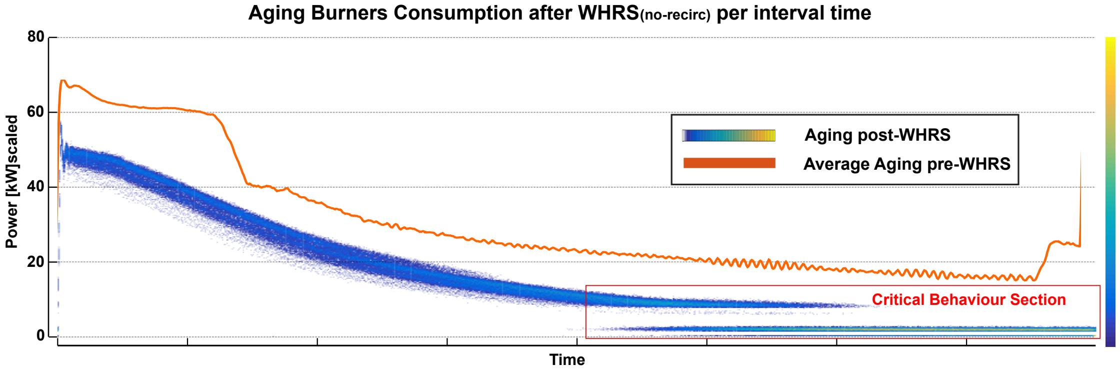

**Figure 5.8** – Burner energy consumption of the Ageing process after the WHRS$_{norecir}$.

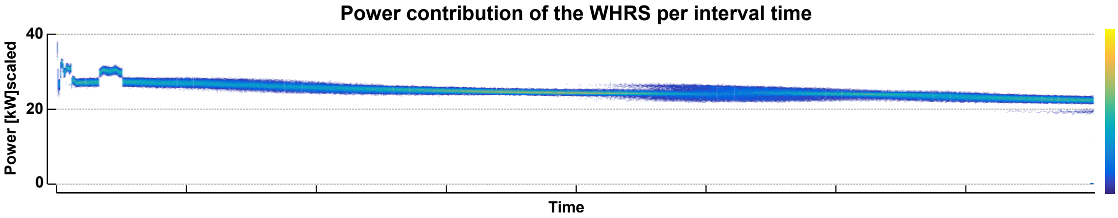

**Figure 5.9** – Energy contribution of the WHRS$_{norecir}$.

The total reduction of the energy provided by the burners is around 55%. In the last part of the interval time, the natural gas consumption is almost zero, as can be seen in the “Critical Behaviour Section” of Figure 5.8. The energy contribution of the burners fluctuates between “off” and “minimum input”. This is the reason for the discontinuities which are shown in the figures.

With this "range" of the main EEM the energy consumption has been reduced to 45% (when comparing with the previous energy consumption). However, the energy characteristic of the process has been changed. Before the measure implementation, the mass balance (in relation with the "fluid" flow) of the furnace was commanded by the infiltration air flow, the Natural Gas flow, the combustion air flow and the stack gases flow (as shown in Equation 4.1). After the measure implementation, a new term, called as $NewSource$ mass flow, is introduced (as shown in Equation 5.1). As it is commented before, the AF burners work as a constant air excess ratio, therefore, unless a burner is shut down, the combustion air remain constant. The natural gas flow is negligible in terms of mass flow. The infiltration air remains practically constant, in the same levels observed in the pre-EEM operation. The final adjustment, to ensure the previous levels, is carried out by acting on the static damper of the pressure controller. Consequently, the stack gases mass flow increases with this new term (which ultimately corresponds with the Cold Section air flow of the WHRS$_{\text{no-recir}}$). Besides, the energy losses of the stack gases flow increases (due to the exhaust temperature practically remains the same). As a result, the energy requirements of the process increase, as it is shown in Figure 5.10.

$$InfiltrationAir + NaturalGas + CombustionAir + \mathbf{NewSource} = StackGases \quad (5.1)$$

Even if the required energy has increased, now it is provided, to a greater extent, by the WHRS$_{\text{no-recir}}$. In energy and economic terms, this fact represents an overall energy saving. Nevertheless, this measure increases the energy of the exhaust gases of the AF opening the possibility to further recovery energy options, as it is shown in Section 5.2.1.2.

The temperature profile of the parts is controlled to ensure the compliance of the

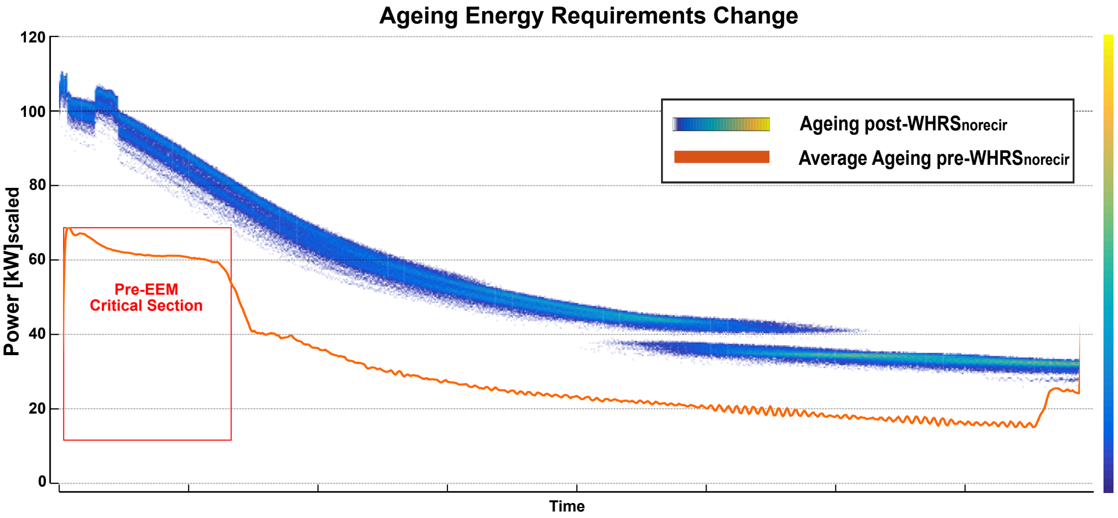

**Figure 5.10** – Energy requirements modification for the AF after the WHRS$_{norecir}$.

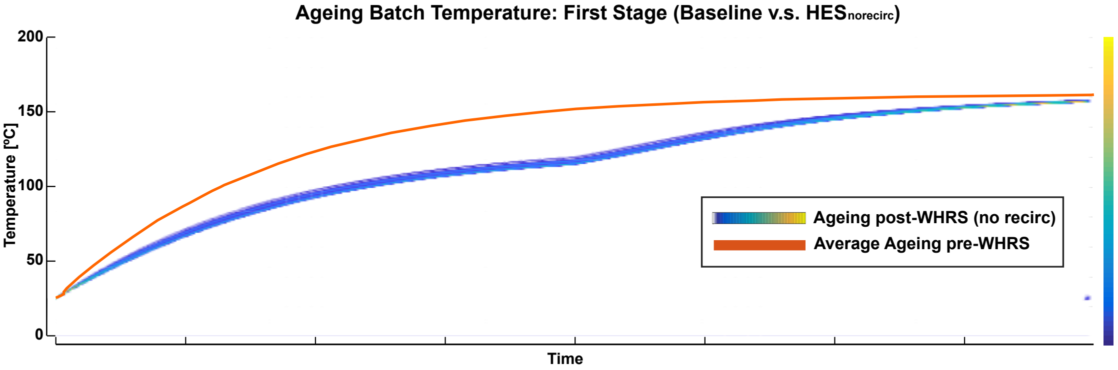

**Figure 5.11** – Batch temperature (first stage) for the WHRS$_{norecir}$ scenario.

temperature requirements of the parts. The temperature of the parts suffers slight modification (as shown FIgure 5.11), but the parts remain between the limitations. The compromise of the selected design variables allows to keep the temperature under the limit without introducing any regulator. To sum up, the energy of the SF exhaust gases flow is also modified. The model simulations shows that the SF exhaust gases go to ambient, after the $\mathrm{WHRS}_{\text{no-recir}}$, with less temperature (Figure 5.12) due to the recovered energy.

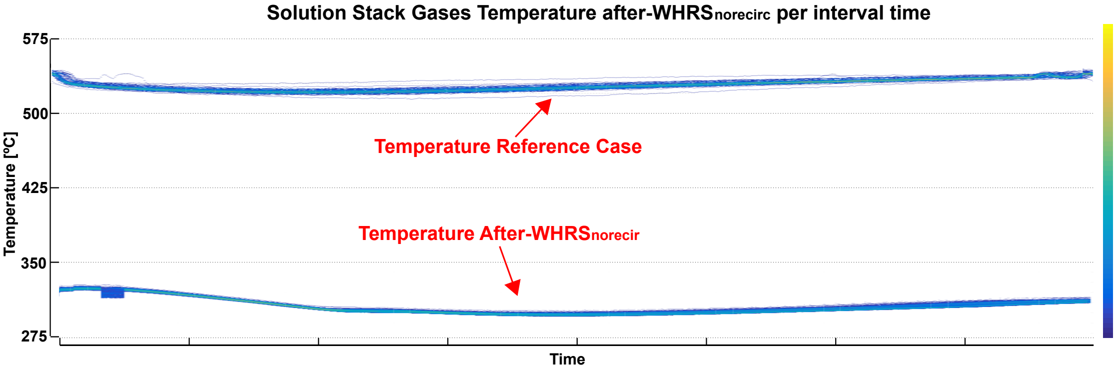

**Figure 5.12** – Solution Stack Gases Temperature after the $\mathrm{WHRS}_{norecir}$.

Thus, the expected energy savings for the HTP, which are calculated by means of the energy modelling by simulation for the case reference period, reaches 300 MWh/year (9000€/year EUROSTAT natural gas price [44]). The *CapEx* is around 17.5k€, referenced to a price of $183€/kW_{recovered}$. This value is obtained by means of the extrapolation of different project costs [extrapolation made from cost data of HPHE providers (Econotherm[3], Faco[4]) and projects (USA2008, India2010, Canada2012) [5] ranging from 5kW to 1200kW]. The cost of preliminary activities related to the $\mathrm{WHRS}_{\text{no-recir}}$ installation are approached to a 45% of the *CapEx* cost and the *OpEx* is assumed as a 5% of the *CapEx* cost during the first 5 years, and a 10% during the rest of the lifetime. In this way, for a 20 years lifespan, with a previous year for the initial preliminary activities of research, the LEEC obtained is 0.93 cents€/kWh, that must be compared with 3 cents€/kWh. The SPP obtained for this solution, without taking into account the first year that may be needed for preliminary activities in which no energy savings are obtained, is around three years.

In Table 5.2 the different working ways of the AF prior and after the WHRS installation are shown by means of the effectiveness-operative indicators. In the nominal working way of the pre-EEM the second burner is off. As it is reflected, burners are working very far from the nominal working way. Consequently, the first burner consumption is reduced a 47% [from 47% to 25%, i.e. (1-25%/47%)% = 47%], the third

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[3] http://www.econotherm.eu/

[4] http://www.faco.it/index_en.php

[5] http://streblenergy.com/products/heat-exchangers-and-heat-pipes/
http://www.econotherm.eu/images/econotherm-flyer.pdf

| | Pre-WHRS | | | | | Post-WHRS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ML | NL | $xL^{100\%}_{40\%}$ | $xL^{40\%}_{20\%}$ | $xL^{0\%}_{0\%}$ | ML | NL | $xL^{100\%}_{40\%}$ | $xL^{40\%}_{20\%}$ | $xL^{0\%}_{0\%}$ |
| Burner 1 | 47% | 10% | 47% | 52% | <0.1% | 25% | 0.7%* | 25% | 19% | 37% |
| Burner 2 | 0% | 0% | 0% | 0% | 100% | 0% | 0% | 0% | 0% | 100% |
| Burner 3 | 25% | 1%* | 4% | 68% | <0.1% | 5.5% | 0.9%* | 1% | 6.6% | 73% |
| Burner 4 | 37% | 1%* | 13% | 86% | <0.1% | 16% | 1%* | 1.2% | 11.5% | 5.2% |

* This percentage near to 1% corresponds with the switch on step.

Table 5.2 – Energy behaviour of the AF.

one a 78% and the last one a 57% (reductions of the ML from Pre-WHRS$_{\text{no-recir}}$ to Post-WHRS$_{\text{no-recir}}$). These reductions correspond, in sum, with the 55% of the previous total energy consumption.

Besides, the implementation of the WHRS$_{\text{no-recir}}$ allows turning off the burners in several intervals (as shown the $xL^{0\%}_{0\%}$ indicator in Table 5.2). The first burner (the most powerful) remains off during the 37% of the time. The third and fourth remain off during the 73% and 5% of the interval time, respectively. Before the EEM, the burners did work almost never under the 20% of the nominal load[6] (1%, 28% and 1% for burners 1, 3 and 4, respectively). However, after the EEM the burners are mainly working in these conditions (44%, 92% and 87% for burners 1, 3 and 4, respectively).

However, burners are not designed to work in these very low loads (Critical behaviour section in Figure 5.8). The design parameters at these loads introduce high quantities of excess air (500%-6000%), as it is reflected in the burner characteristic datasheets (Figure 4.5). The burners are currently working with a configuration set adapted to the current specific behaviour. The simulated working way of the burners is modelled to reply this configuration set. However, there is evidence to think that the current configuration is not the best configuration set for the burners with the new WHRS$_{\text{no-recir}}$ since some burners oscillate between “off” and “minimum load” in some intervals. This raises a new branch for future work that should be analysed before the final development of the Energy Efficiency Assessment of the process, as will be shown in the next sections.

#### 5.2.1.2 Re-circulation

From the results obtained previously, a new opportunity of improvement has been identified. The energy of the stack gases of the AF has been increased. Therefore, a new solution has been proposed: the re-circulation of the AF stack gases to the Cold Section input of the WHRS, as it is shown in Figure 5.13. Unlike the previous case, the mass flow distributor after Cold Section output of the HPHE only directs the flow to one introduction point, which is situated near the first burner. This HES distribution

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[6] This indicator, which corresponds with $xL^{0\%}_{20\%}$, is obtained as the remaining percentage that the burner are not working in the other ranges, i.d. $xL^{0\%}_{20\%}$=100% - $xL^{40\%}_{100\%}$+$xL^{20\%}_{40\%}$

is proposed to simplify the piping construction tasks and to minimise the number of furnace modifications. Then, the exhaust gases flow of this section is redirected to the Cold Section input (as shown in Figure 5.13).

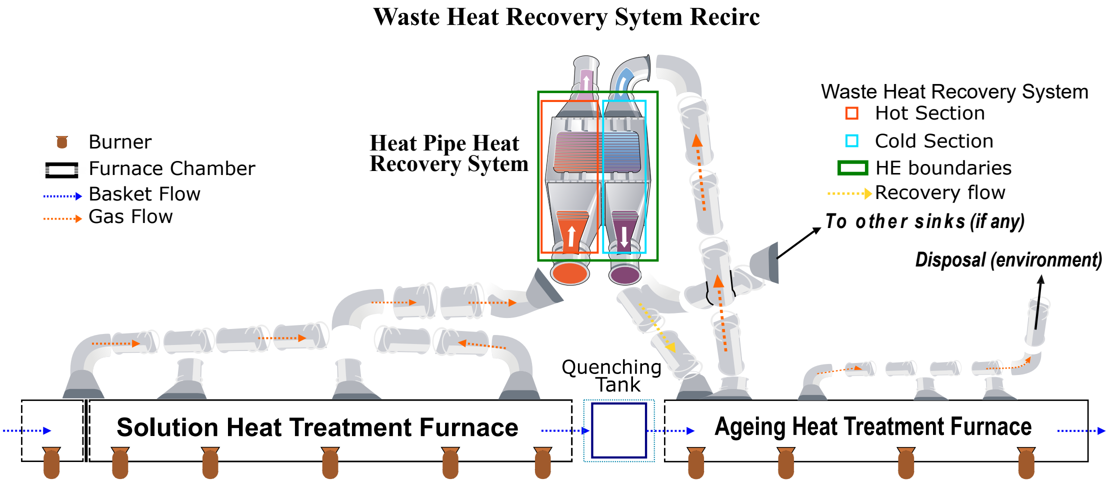
Waste Heat Recovery Sytem Recirc

**Figure 5.13 –** HTP for WHRS$_{recir}$ hypothesis.

The total energy consumption of the furnace and the breakdown of the device modus operandi indicators (as described in Section 3.2.4.2.2) for each burner are analysed in the following paragraphs. The new consumption profile, calculated by simulation for the selected working week, is then compared to the pre-WHRS$_{\text{recir}}$ average consumption (orange line), as it is depicted in Figure 5.14. The energy contribution of the burners is reduced drastically (as it is shown in $Agingpost - WHRS_{recirc}$ representation in Figure 5.14). An exceptional behaviour (in comparison with the constant profile observed in other periods) has been identified ("Burner 1: Exceptional behaviour" in Figure 5.14). In this period, the temperature of the solution exhaust gases decreases due to the new cold load entry and, in some cases, the first burner of the AF must be switched on to track the expected temperature profiles of the ageing load. This "switched on" implies that the burner one introduce the consequent combustion air[7] (cold air) which amplifies the effect.

The analysis of the main proposed EEM (i.e. the WHRS with re-circulation of the AF exhaust gases to the Cold Section entry of the HPHE measure) brings the results presented below. Unlike to the previous scenario, the critical behaviour section disappears due to this distribution only provides heat to the first burner section (as shown Figure 5.14). Therefore, the other sections are not practically affected, and the working way of these burners (from second to fourth burner) remains roughly unchanged. The simulation results shows a quasi-constant energy profile provided by the WHRS$_{\text{no-recir}}$, as it is depicted in Figure 5.15.

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[7] The ageing burners work as a constant combustion air burners. Therefore, the cold mass flow introduced to the system is the same for low or high values of burner power.

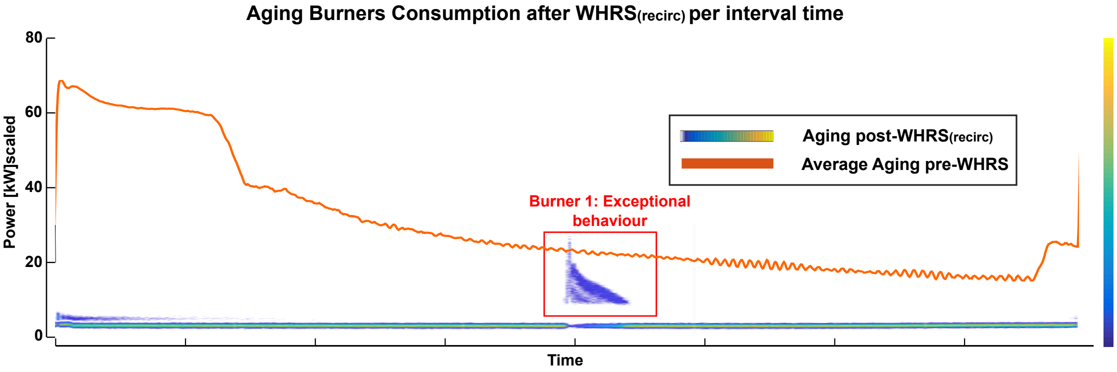

**Figure 5.14 –** Burner energy consumption of the Ageing process after the WHRS$_{recir}$.

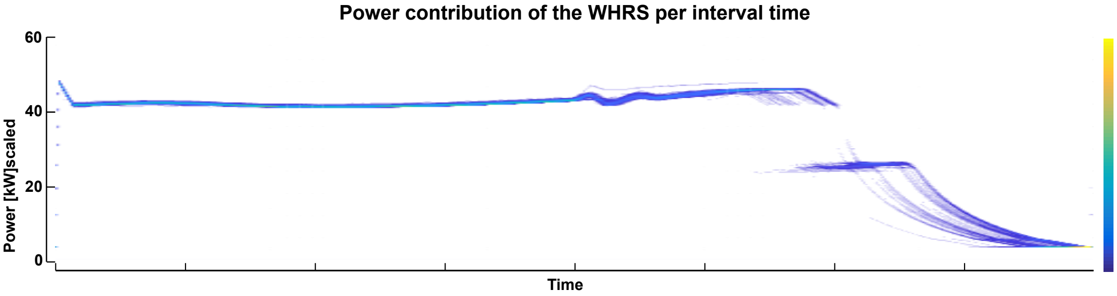

**Figure 5.15 –** Energy contribution of the WHRS$_{recir}$.

As a consequence of the WHRS implementation, the energy consumption has been reduced to 10'5% (when comparing with the previous energy consumption). However, as already advanced (and based on the same phenomena as in the previous case) the energy requirements of the process have been modified. The same reasoning and equations (Equation 5.1) set forth for the previous case are repeated in this scenario. However, unlike the previous case, the behaviour is drastically different. This is attributed to the change of the method of working of the first burner from "low load" to "switched of". Thus, the combustion air flow associated to this burner disappears. As a result, the energy requirements of the process are strongly modified, as it is shown in Figure 5.16.

As it can be seen in Figure 5.16, there are three distinguishable sections in the energy requirement behaviour in comparison with the baseline. In the first period, which correspond with the Pre-EEM Critical Section, the pre-EEM requirements are higher than those of the baseline. This is because, in the Baseline scenario, the power is employed to heat the combustion air. However, in this new scenario, the new heat source is a mass flow which is already at high temperature (therefore, it does not require energy to increase its temperature). In the second part (until the power contribution decrease), the new heat system provides the same energy flow until the parts reach the required temperature. Then, a control valve is activated and the mass flow of the new heat source (the WHRS) is reduced in order to not exceed the temperature restrictions. This mass flow reduction, in addition to the fact that the first burner is switched off

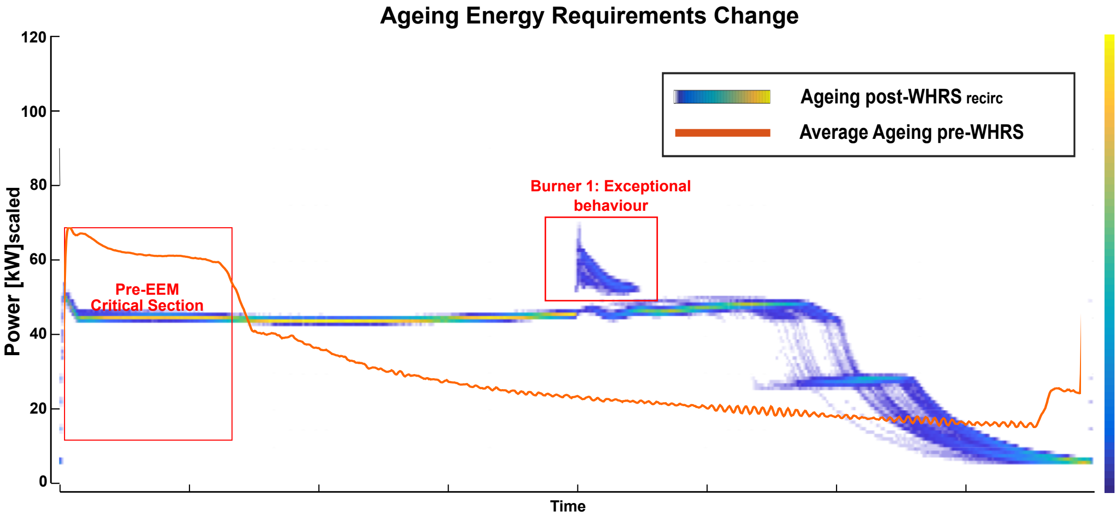

**Figure 5.16 –** Energy requirements modification for the AF after the WHRS$_{recir}$.

(and, therefore, it does not introduce cold combustion air), creates the situation shown in the last section of the Figure 5.16. Here, the energy requirements of the furnace are lower than the energy requirements of the baseline for the same section. This is due to the heat losses are minor. The combustion air mass flow and the new heat source mass flow, from Equation 5.1, have been reduced. Therefore, these low values of energy allow to keep the furnace under the expected limitations.

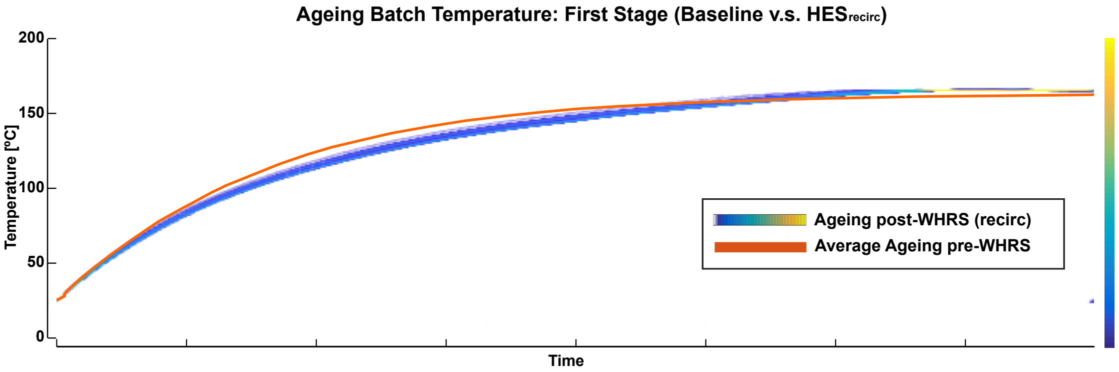

**Figure 5.17 –** Batch temperature (first stage) for the WHRS$_{recir}$ scenario.

In the same way as in the previous case, the temperature profile of the parts is controlled to ensure the compliance of the temperature requirements of the parts. Unlike the previous scenario (without re-circulation), the parts temperature better tracks the expected profile (as shown Figure 5.17).

In Table 5.2, the different working ways of the AF prior and after the WHRS installation are shown by the effectiveness-operative indicators. In the nominal working way of the pre-EEM the second burner is off. However, for this scenario this second burner is activated. As it is reflected, the burners are working very far from the nominal working

| | Pre-WHRS | | | | | Post-WHRS$_{recirc}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ML | NL | $xL^{100\%}_{40\%}$ | $xL^{40\%}_{20\%}$ | $xL^{0\%}_{0\%}$ | ML | NL | $xL^{100\%}_{40\%}$ | $xL^{40\%}_{20\%}$ | $xL^{0\%}_{0\%}$ |
| Burner 1 | 47% | 10% | 47% | 52% | <0.1% | <0.1% | 0% | 0% | <0.1% | 96% |
| Burner 2 | 0% | 0% | 0% | 0% | 100% | 0.7% | 0.4% | 0.1% | 0.2% | 98% |
| Burner 3 | 25% | 1%* | 4% | 68% | <0.1% | 0.8% | 0.6%* | 0.1% | 0.2% | 99% |
| Burner 4 | 37% | 1%* | 13% | 86% | <0.1% | 20% | 0.9%* | 0.2% | 61% | 6% |

Table 5.3 – Energy behaviour of the AF.

way. Consequently, the first burner consumption is reduced, practically, by 100%. The second one begins to work but only at 0.7% of the nominal load. The third burner is reduced by 97%, and the last one by 57% (reductions of the ML from Pre-WHRS$_{\text{recirc}}$ to Post-WHRS$_{\text{recirc}}$). The final consumptions correspond, in sum, with the 10.5% of the previous total energy consumption.

Besides, the implementation of the WHRS$_{\text{recirc}}$ allows turning off the first, second and third burner all along the process duration. Only the fourth burner remains working during the 94% of the process duration. This burner works between "off" and 20% of its nominal load during 32% of the process duration. Besides, it works below half the nominal design load ($xL^{0\%}_{50\%}$) during the 99% of the process duration.

Finally, with the HES configuration of this scenario, the overall energy consumption of the HTP decreases 13'6%. However, this EEM only affects the AF, which generates a relative energy efficiency improvement of 89'5%, according to baseline. The AF is only consuming 10'5% of the baseline values. These energy savings represent 448 MWh / year. From now on, the relative energy efficiency is given according to HES values. The greenhouse gases emissions are reduced in the same proportion as the consumption, around 13'6%. The main characteristics of the way of working remain invariable.

The HES works at 73% of its capacity, this means that during some periods the energy of the solution gases is not recovered. The HES reduces the workload to avoid overheating the parts. This EEM returns a SPP of 28'4 months. The LEEC attributed to the measure is 27'6€/MWh for the first three years. However, it is quickly reduced to 21'7€/MWh for a six-year evaluation period. The ROI indicator behaves in the same way, reaching values of 25'4% and 144% for three and six-year periods respectively. Bearing in mind the economic factors, this implies that the cash flow becomes positive at 28'4 months (the investment is already recovered), while, for the third year, all the investment and 25% more of the invested amount would be back in the coffers. During this period, the price/cost of the used energy would have been equivalent to 27'6€/MWh.

In practice, the first, second and third burner stop working, meanwhile the fourth only has to provide the lateral and infiltration heat losses. This scenario is the starting point for the next section. All the additional measures, which are proposed in for the secondary strategy, are applied in addition to this measure: the WHRS with recirculation of the AF stack gases.

### 5.2.2 Secondary Strategy: EEM Individual Assessment

In this section, the EEMs proposed in Section 5.1.2.2 are evaluated. As a first step, the baseline (current method of operating) is established and the HES proposal, just as it has been proposed in the project summary, is evaluated. After that, the proposals of the secondary strategy are individually evaluated. The last part analyses the EEM packages proposed in the last part of the Section 5.1.2.2.

Some courses of action were identified as a consequence of the in-depth analysis of the processes, the comprehension of the modus operandi and the behaviour of the devices. These measures have been individually analysed and as a support to the first strategy measure: the WHRS.

The first branch of action affects the production way and the process restrictions. In this sense, the following measures are proposed: the removal of anomalies on the entry time (ZA), the basket load increase (LI) and the reduction of the time of the process (TR) [197, 186]. The increase of the batch weight depends on the part typology. The last measure (process time reduction) affects directly the STTS and ATTS. As it was explained, the parts must remain, at least, a specific time at the temperature conditions. However, there is evidence that the time selected may be overestimated [205, 186, 197]. Therefore, some limited time reductions should not modify the expected mechanical characteristic.

The second branch works on the surroundings of the processes without modifying the process characteristics or the production plan. In order to reduce the air infiltration flow, the following measures are suggested: the reduction of the infiltration area (IA) (attributed to the non-perfect closure of the doors, grooves near the burners, of gaps at the conveyor rollers) and the control of the internal pressure (IP). Besides, to increase the combustion air temperature (CA) of the burners is proposed. The heat employed to heat the combustion air flow may come from low-heat recovery systems in the plant or from the excess heat recovered at the HES. The main purpose of this measure is to assess the energy behaviour and the environmental impact of both furnaces (SF and AF). Some economic suppositions have been selected for the analysis. The heat requirements (for the air preheating) are analysed individually for each situation.

The measures of the third course of action act on specific devices. This part covers measures, such as the implementation of an internal door (ID) to separate the first and the second stage (to prevent cold intrusions to the heated parts) and the substitution of the steel basket fixture (Fx) with lighter ones [198, 199] (around 40% of the energy absorbed by the load is employed for heating the steel basket). In this sense, with fibre-carbon composites, the energy reduction may reach values around 80% at the same time that the basket properties are maintained. This energy reduction comes from the comparison between the average energy requirements for heating the current steel baskets and for the proposed new baskets [for the nominal process temperature (from 25°C to 540°C and to 160°C)].

All these measures are jointly reproduced with the HES measure. The proposed EEMs have been individually analysed for the whole range of application. This range of application has been defined based on reasonable production and device capacity characteristics. The cost of the EEMs increases non-linearly according to the range increment as adaptation to the real behaviour of the engineering costs (as it is explained in Section 3.2.4.3 and schemed in Figure3.14).

The analysed factors cover all the scopes assessed: energy, environmental, production and economic. The energy assessment includes the overall energy consumption of the heat treatment (weighted regarding to the HES baseline). The environmental outlook is represented by the $CO_2$ generation. The $NO_x$ generation is only discussed in the measures which modify the combustion characteristics (CA). The STTS and ATTS (time[8] that the parts stay at the process conditions), the total time to treat the parts, the production rate and the HES working load represent the modus operandi of the process. The selected economic indicators, derived from these scenarios and the cost assumptions are the following: the economic savings, the SPP and the LEEC and ROI indicators for three-year period. Some results are confronted to the HES measure factors (100%) in order to keep the confidentiality of the production data.

The HES workload factor provides only the average HES workload in relation to its nominal design (Section 5.1.2.1). In this sense, it is also weighted according to the HES baseline in order to ease the understanding of the factor. Some measures modify the HES design, such as the nominal recovery power. Therefore, the workload factor will be referred to the new HES design. The new design capacity/features are commented individually for each case. A minimal modification for adapting the HES is then introduced to optimise the correct utilisation of the recovered heat, all the proposed EEMs are assessed by means of the procedure proposed in Section 3.2.6. The greatest energy reduction is obtained by the main strategic measure: the WHRS heat pipe based. In addition, other proposals stand out by providing great savings (Overall Energy Consumption in Table 5.9).

The results are summarised in Table 5.9. Each EEM behaviour and the selected ranges under evaluation are individually analysed in the following sections. The proposed "range" are those that fulfil (at any one time of the processes) the overall requirements (as referred to in Subsection 4.3.4). Each EEM affects the production and energy behaviour in a different way. Therefore, the impact on the economic indicators is different.

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[8] Outliers are excluded

### 5.2.2.1 Zero Anomalies

This measure is a very conservative EEM, which only affects to the operational tracking of the tactical plan. In this regard, the case reference has a set of anomalies which represents an increment of 3%, on average, from the theoretical established stage-time. The energy savings of the "full" implementation are rather low (53 MWh/year) for the analysed period. However, this measure has moderate improvements for the process total time (2'3% of reduction) and for the production rate (2'4% of increase) without affecting the process restrictions. Both solution and ageing relative energy efficiencies are affected by this EEM, which increase 1% and 3%, respectively, in comparison with the processes efficiencies of the $\text{HES}_E EM$ scenario. The HES workload slightly increases a 1'5% in comparison to the $\text{HES}_E EM$ scenario. During the anomalies, the batch stays longer than was programmed in the stage. In this "extra" time, the HES works at low power because the batch has already reached the temperature. If this time is eliminated, and a new load is introduced, then the HES returns to the nominal load. Despite the low energy savings, the economic results show acceptable improvements due to the very low costs of this measure. The Capital Expenditures (CapEx) are considered 35300€, which represents the capital cost of the WHRS, and the Operational Expenditures (OpEx) are approached to 600€/year for both cases i.e. "full" and "half" implementation. The Cost of preliminary activities (Cpa) is approached to zero due to this measure does not include any technological challenge and only represents very low organisational modifications.

### 5.2.2.2 Load Increase

The increase of the load of each basket will allow us to produce the same production with less batches, reducing the time in which the furnaces are working and, therefore, their consumption. The EEM shows moderate energy savings for an intermediate range: 194 MWh/year according to the Table 5.9 range (8% of load increase). The time restrictions remain practically invariable, notwithstanding, minimal reductions are identified due to in these scenarios there is more load (parts) to heat. The HES workload also suffers a slight increase. The HES needs to work longer at nominal conditions because the load (weight of treated parts) has increased. From the economic point of view, all of the economic factors increase while increasing the load; however, this increase is delimited by the theoretical basket fixture and parts shapes as well as the tactical plan. However, if the technical challenges of arranging more parts in each basket are leaded two strategies are identified: to increase the total production and to reduce the total process time. In the first strategy scenario, the manufacturing process may present a bottleneck which prevents the load increase. However, the annual production would be increased (by maintaining the working time). The second strategy scenario would modify the current working schedules, however, the process time would be reduced (by maintaining the total production). The results of the first strategy are presented in Table5.4.

|  | Baseline | HES$_{EEM}$ | LI-1% | LI-2’5% | LI-5% | LI-8% | LI-9% | LI-11% |
|---|---|---|---|---|---|---|---|---|
| Total Production | 100% | 100% | 101% | 102’5% | 105% | 106% | 109% | 111% |
| Production Ratio | 100% | 100% | 101% | 102’5% | 105% | 106% | 109% | 111% |
| SF Efficiency | 20’6% | 20’6% | 20’7% | 21% | 21’4% | 21’9% | 22% | 22’3% |
| AF Efficiency | 30’6% | 244% | 246% | 248% | 251% | 253% | 254% | 255% |
| Cpa | 0 | 0 | 2000€ | 2400€ | 3100€ | 4900€ | 6400€ | 10000€ |
| CapEx | 0 | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ |
| OpEx (annual) | 0 | 600€ | 600€ | 600€ | 600€ | 600€ | 600€ | 600€ |

Table 5.4 – Economic costs and Total Production increase for the analysed ranges of Load Increase EEM.

#### 5.2.2.3 Time Reduction

The main characteristic of this EEM is that the time the parts stay in the furnace is reduced. Consequently, the time which the parts remain at the critical restrictions is reduced (STTS and ATTS) as can be shown in Table 5.5. The simulation results exhibit that the reduction of the restriction parameters decrease faster than the time reduction (as it is shown in the STTS element in Table 5.5). This behaviour is attributed to the fact that the preheating time (time in which the parts increase their temperature to process temperature) remains invariable, as it is schemed in Figure 5.18. Therefore, while the preheating period is kept, the period in which the parts stay at the process temperature is reduced due to this time reduction. The specific energy efficiency of each process is increased (as shown Table 5.5). Thus, the overall consumption is reduced, reaching high values of energy savings (370 MWh/year according to the Table 5.9 range). Both the total time and the production ratio are directly improved. The HES working load is also improved because of reasons similar to those explained for the Zero Anomalies measure. On the one hand, this kind of measure shows one of the best economic results, due to the low initial investment. On the other hand, the risk induced to the mechanical properties should be assessed. The tactical plan is not critically involved. However, this measure would require a minor stock modification (increase of the stocked batches).

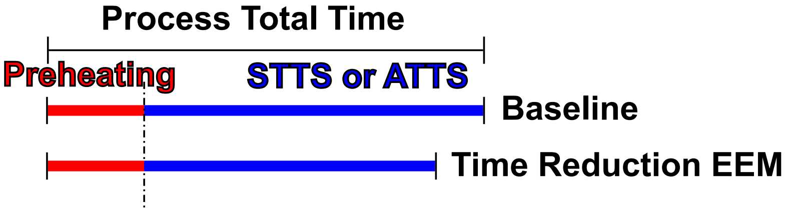

**Figure 5.18 –** Time reduction schema. Process restriction behaviour.

#### 5.2.2.4 Infiltration Area

This measure shows great results without modifying the process modus operandi nor the tactical plan. The highest energy saving is obtained with this EEM (430 MWh/year according to the highest Table 5.9 range, i.e. 66% of area reduction). The HES workload

| | Baseline | HES$_{EEM}$ | TR-2’5% | TR-5% | TR-10% | TR-12’5% | TR-15% | TR-17’5% | TR-20% | TR-22’5% |
|---|---|---|---|---|---|---|---|---|---|---|
| STTS | 100% | 100% | 97’3% | 94’5% | 89% | 86’3% | 83’5% | 80’5% | 78% | 75’2% |
| SF Efficiency | 20’6% | 20’6% | 20’9% | 21’2% | 22% | 22’3% | 22’7% | 23’1% | 23’5% | 24% |
| AF Efficiency | 30’6% | 244% | 255% | 267% | 288% | 298% | 306% | 311% | 307% | 291% |
| Cpa | 0 | 0 | 3850€ | 4000€ | 4250€ | 4460€ | 4700€ | 4950euro | 5350€ | 5770€ |
| CapEx | 0 | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ | 35300€ |
| OpEx (annual) | 0 | 600€ | 600€ | 600€ | 600€ | 600€ | 600€ | 600€ | 600€ | 600€ |

Table 5.5 – Economic costs and STTS variation for the analysed ranges of Time Redution EEM.

analysis of the Infiltration Area reduction also shows interesting results. This measure reduces the infiltration flow, and so also reduces the energy of the exhaust gases forcing a re-sizing of the HES. The hot section of the HPHE must be adapted to the new exhaust gases flows. The available energy of the solution fumes is reduced 34’3% for the proposed upper range of area reduction (Table 5.6). The enthalpy of the exhaust gases almost remains unchanged, due to the fact that the process temperature characteristics are not modified. Consequently, the cold part of the HPHE also needs to be adapted. The final CapEx, which includes the lower cost of the lower HPHE and the cost of the reduction of the infiltration area, reduction is approached to 37000€ (as shown Table5.6) and is already taken into account for the final economic analysis. The breakdown of the cost is the following: 26800 € derived from the HPHE CapEx (60’5 kW of nominal power), 10200€ derived from the Infiltration Area CapEx, 4200€ derived from the Cpa and around 2400€/year derived from the cost of maintaining this Infiltration area level.

| | Baseline | HES$_{EEM}$ | IA-8% | IA-16% | IA-32% | IA-49% | IA-66% |
|---|---|---|---|---|---|---|---|
| Fumes Power | 100% | 100% | 96’2% | 92’6% | 83’9% | 76’3% | 65’7% |
| SF Efficiency | 20’6% | 20’6% | 20’9% | 21’2% | 22’1% | 22’9% | 24% |
| AF Efficiency | 30’6% | 244% | 247% | 246% | 230% | 206% | 170% |
| Cpa | 0 | 0 | 1000€ | 1000€ | 1000€ | 1600€ | 4300€ |
| CapEx | 0 | 35300€ | 39200€ | 38400€ | 36450€ | 35500€ | 37000€ |
| OpEx (annual) | 0 | 600€ | 1200€ | 1200€ | 1200€ | 1440€ | 2400€ |

Table 5.6 – Economic costs and Solution Stack Gases Power for the analysed ranges of Infiltration Area EEM.

The energy efficiency of the solution process is highly improved whereas the efficiency of the ageing process falls. Despite the fact that the reduction of the infiltration area in the ageing process increases the efficiency, as it is shown in Table 5.6 (the ageing demand comes down), the heat availability of the HES also comes down. Therefore, the final ageing balance is negative due to the fact that burners have to provide heat which previously was provided by the larger HES. However, the overall balance, considering both the solution and the ageing processes, is very positive because the weight of the solution process in the overall consumption is much greater. The HES workload, which is referred to this new HES size, shows high working loads due to the reduction of the transferred nominal power. Thus, the HES is nearer to the nominal load than in other measures. This measure shows the best economic results, with short SPPs and high ROIs. On the contrary, a more accurate sealing supposes higher initial expenditures and maintenance costs, which are compensated more than enough by the higher savings.

#### 5.2.2.5 Internal Pressure

As in the previous measure, this measure affects on the furnaces infiltration flow, and, therefore, to the energy of the solution fumes (as shown Table 5.7). This EEM also presents the same conclusions (but different specif values) than the Infiltration Area measure regarding to energy, ecological, production and HES considerations. For the analysed ranges, from 9% to 85% of pressure reduction (Table 5.7), the HES size is reduced up to 17% for the maximum analysed range i.e. 85% of negative pressure reduction, whereas the energy saving obtained for this range of application is around 185 MWh/year. The economic indicators depend on the proposed cost and take into account the operation cost of the pressure control. A more accurate pressure control will supposes high expenditures and operation costs, as it is presented in Table 5.7.

| | Baseline | $HES_{EEM}$ | IP-9% | IP-18% | IP-26% | IP-35% | IP-55% | IP-65% | IP-75% | IP-85% |
|---|---|---|---|---|---|---|---|---|---|---|
| Fumes Power | 100% | 100% | 98’4% | 96’3% | 94’6% | 93% | 88% | 87’1% | 85’1% | 83’4% |
| SF Efficiency | 20’6% | 20’6% | 20’7% | 20’9% | 21% | 21’2% | 21’5% | 21’7% | 21’9% | 22’1% |
| AF Efficiency | 30’6% | 244% | 234% | 225% | 216% | 202% | 181% | 174% | 166% | 156% |
| Cpa | 0 | 0 | 1000€ | 1000€ | 1000€ | 1000€ | 1300€ | 2300€ | 5000€ | 9000€ |
| CapEx | 0 | 35300€ | 34900€ | 34400€ | 34000€ | 35600€ | 31600€ | 32100€ | 31600€ | 31200€ |
| OpEx (annual) | 0 | 600€ | 1200€ | 1200€ | 1200€ | 1200€ | 1200€ | 1200€ | 1800€ | 1800€ |

Table 5.7 – Economic costs and Solution Stack Gases Power for the analysed ranges of Internal Pressure EEM.

#### 5.2.2.6 Combustion Air

This kind of measure presents high energy savings and improves (or maintains) the process way of working (STTS and ATTS). The emissions (both CO2 and NOx) in other EEM are almost directly related to the energy consumption. However, this EEM considerably increases the $NO_x$ generation, as it is shown in Figure 5.8. For instance, the process goes —for the 330°C preheating scenario- from a specific generation of 0.19 kg-$NO_x/MWh$ to 0.26 kg-$NO_x/MWh$. Even so, the total $NO_x$ generation is only increased 3% due to the energy consumption reduction achieved.

| | Baseline | $HES_{EEM}$ | CA65°C | CA115°C | CA150°C | CA210°C | CA280°C | CA330°C | CA375°C |
|---|---|---|---|---|---|---|---|---|---|
| NOx emissions* | 0’19 | 0’16 | 0’159 | 0’168 | 0’1783% | 0’194 | 0’227% | 0’258 | 0’284 |
| SF Efficiency | 20’6% | 20’6% | 20’9% | 21’3% | 21’6% | 22’2% | 22’9% | 23’4% | 23’9% |
| AF Efficiency | 30’6% | 244% | 271% | 312% | 349% | 428% | 529% | 603% | 668% |
| Cpa | 0 | 0 | 3000€ | 3000€ | 3000€ | 3000€ | 3000€ | 3000€ | 3000€ |
| CapEx | 0 | 35300€ | 45300€ | 45300€ | 45300€ | 48100€ | 52700€ | 64800€ | 69000€ |
| OpEx (annual) | 0 | 600€ | 3000€ | 3000€ | 3000€ | 3000€ | 3000€ | 3000€ | 3000€ |

*** Measured in kg-**$NO_x/MWh$

Table 5.8 – Economic costs and NOx emissions for the analysed ranges of Combustion Air EEM.

For this measure the AF efficiency (which represents the ratio between the theoretical required energy utilised to increase the temperature of the parts from the ambient temperature to the process temperature and the real energy spent by the burners) increases to apparent illogical values (up to 668%). However, these values are attributed to the fact that the ageing burners practically do not provide energy. The expected maximum temperature -for these kind of processes- to transfer energy to the batches is around 300°C. Therefore, the heated combustion air acts as a new energy source. The heat provided by this source in combination with the heat provided by the WHRS is enough to heat the parts and keep the ageing temperature during the process. The energy supplied by the burners is negligible and it is only provided in exceptional periods.

From the economic point of view, this measure has the handicap of the high initial expenditures. Therefore, the economic results worsen the initial ones (HES). For this EEM, some devices and O&M costs have been supposed to obtain a comparative point of view. However, the real cost analysis related to this kind of measure will depend on the characteristics of the demanded heat to reach the selected preheating temperature. The power demanded for the 150°C preheating scenario is 28’2 kW and 3’4 kW for the solution and ageing processes respectively. The average combustion air mass flows for this scenario are around 860kg/hour and 100kg/hour, respectively. These ranges of power and mass flow may be provided on average by the HES, reducing the expenditures considerably. However, this evaluation requires a posterior and in-depth analysis.

#### 5.2.2.7 Internal Door

This measure, which proposes to isolate the first stage from the second one (SF), avoids cold flow incursions in heated parts, improving the solution restriction (STTS) by around 5%. From the energy point of view, this EEM shows a moderate energy saving (100MWh/year), which is generated by a better (more efficient) working method of the burners. The CapEx and the Cpa proposed for this measure are 36300€ and 1000€, respectively. In this measure, the annual OpEx is approached to 720€/year. The obtained economic results improve those of the HES baseline. This simple measure brings great production-economic results for a future combination with other EEMs. In this regard, this device (the internal door) is an element which is already built in the SF, but it is not currently in operation due to a process simplification. Therefore, restoring this device would not suppose a hard maintaining task. Besides, this EEM generates improvements in the time that the parts remain at the process conditions for the solution process. This measure not only increases the STTS up to 5’1% but reduces the temperature reduction of the second stage (in the SF) attributed to the cold load introduction in the first stage.

#### 5.2.2.8 Fixture

This measure affects radically the energy demand of the batches. Each batch requires certain amount of energy to reach the process temperature. This energy demand comes from both the steel basket and the aluminium parts. The parts contribution is indispensable for the process. However, the basket contribution is unnecessary for the process. For this reason, a totally substitution of the current steel baskets by other made of other material is proposed. The reduction of the heat capacity of these baskets will produce a high benefit, both in energy savings (up to 240MWh/year), environmental aspects (around 7% of $NO_x$ and $CO_2$ reduction), time restriction improvements (around 3% both for STTS and ATTS), and other energy and non-energy related benefits derived from the high weight reduction (roller conveyors, baskets transport, etc.).

In contrast to these benefits, this EEM entails high expenditures, and the HES workload is seriously affected. The CapEx and the Cpa proposed are 65000€ and 5000€, respectively. In this case, the annual OpEx, which is negative due to the expected savings derived from the reduction of the basket weight, is approached to -600€/year. This measure provides an operational cost saving. The hot supply of the HPHE practically remains invariable, but the cold side demand is drastically reduced. Almost 50% of the HES potential is not used. This behaviour provides additional opportunities to future combinations of measures or to future searches of energy sinks where the extra residual heat could be reused. The economic indicators suffer the handicap of the entire substitution, showing the worst economic results of the preliminary assessment. If the substitution is extended during the time, to the extend the old baskets break, then the amortisation would grow more quickly. The budget for basket replacing may be employed for the purchasing of this kind of baskets.

#### 5.2.2.9 Individual Assessment conclusions

For this course of action, a simple sensitivity assessment has been carried out to ease the combinatorial assessment approach and to guide the heuristic procedure. As it is introduced before, manifold simulations have been analysed, within the selected range, in order to understand the EEM energy behaviour. Some main parameters have been selected to summarise both the energy, production, ecological and economic behaviour for the entire proposed range. The Overall Energy Consumption is represented in Figure 5.20 as an energy indicator. The $CO_2$ and $NO_x$ emissions match the Figure 5.20 (with the exception of the Combustion Air EEM). The HES workload and the solution restriction (STTS) are represented in Figure 5.21 and Figure 5.23 as a productive indicators. The Monthly Economic Savings in Figure 5.22 in addition to the Simple Payback Period (SPP) in Figure 5.19 indicator complete the economic assessment.

In contrast to the energy savings results, some measures affect the current produc-

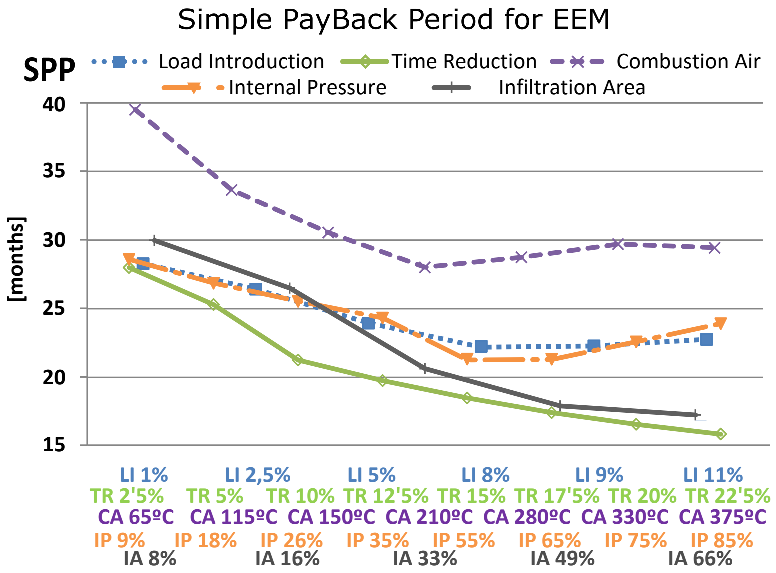

**Figure 5.19 –** Simple Payback Period for the EEM entire range.

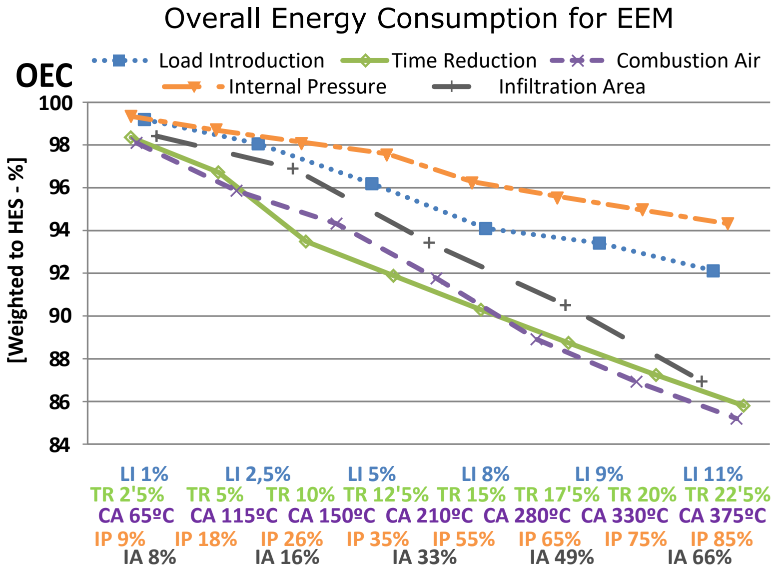

**Figure 5.20 –** Overall Energy Consumption for the EEM entire range.

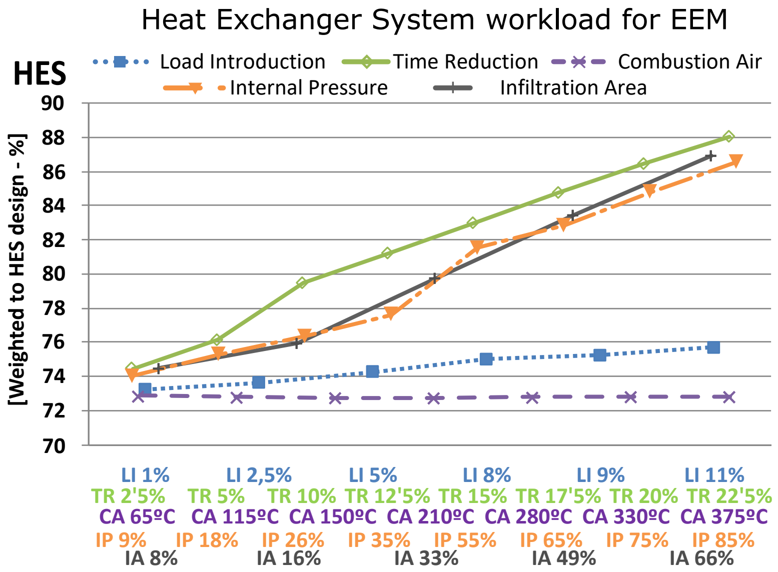

**Figure 5.21** – Heat Exchanger System workload for the EEM entire range.

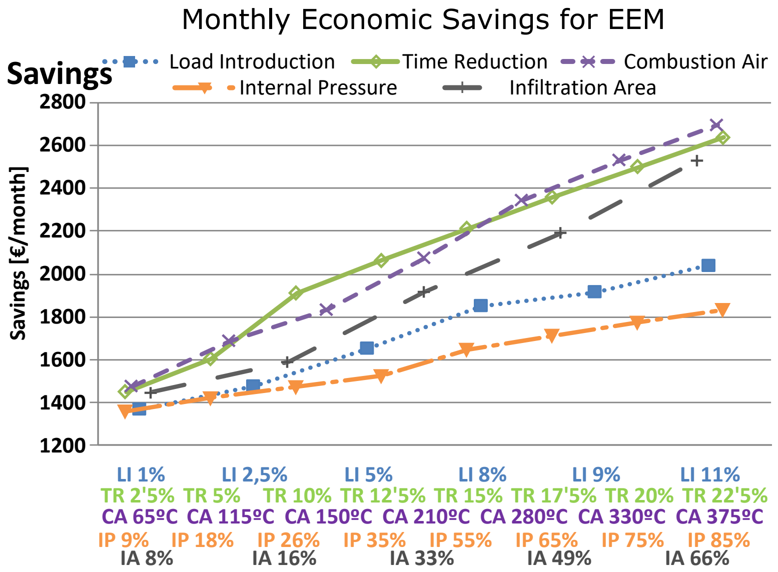

**Figure 5.22** – Monthly savings for the EEM entire range.

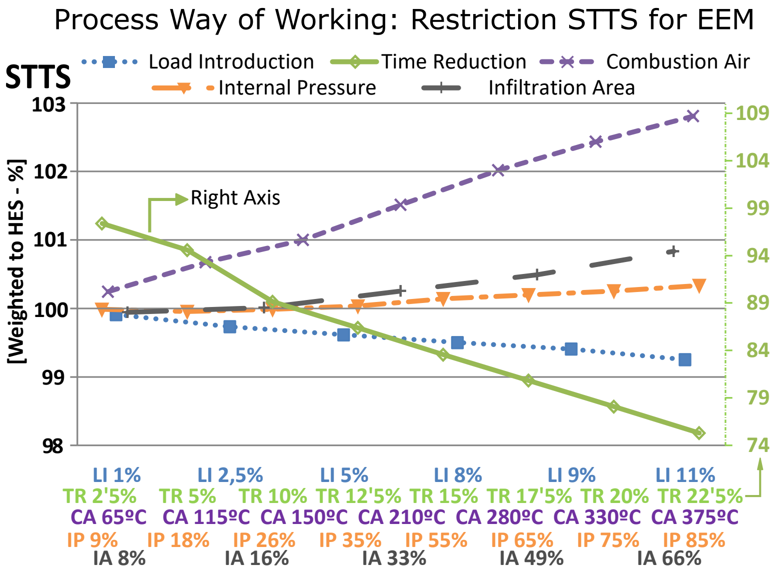

**Figure 5.23** – Solution Time-Temperature State restriction for the EEM entire range.

tion restrictions of the process, modifying the STTS-ATTS parameters. The measures that limit the time restrictions can be combined with measures that improve the time restrictions to create energetic-economic-production synergies by decreasing the risk of defective production.

| | | **Energy** | **Eco** | **Process Way of Working** | | | | | | **Economic Indicators** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Range | Consumption Overall [%] | $CO_2$ [%] Emissions | Restrictions [%] STTS | ATTS | Total time [%] | Production Ratio [%] | HES load [%] | Savings [k€/month] | SPP [months] | LEEC 3y [€/MWh] | ROI 3y [%] |
| BL | - | 113.6 | 113.6 | 100 | 100 | 100 | 100 | - | - | - | - | - |
| HES | - | 100 | 100 | 100 | 100 | 100 | 100 | 73 | 1.293 | 28.4 | 27.6 | 25.4 |
| ZA | full | 98.4 | 98.4 | 99.2 | 99.1 | 97.7 | 102.4 | 74.8 | 1.444 | 26 | 25.4 | 36.1 |
| LI | 8% | 94.1 | 94.1 | 99.5 | 99.1 | 100 | 108 | 75 | 1.852 | 22.3 | 21.8 | 58.7 |
| TR | 17'5% | 88.8 | 88.8 | 80.8 | 80.8 | 82.9 | 120.6 | 84.8 | 2.359 | 17.4 | 17.1 | 101.9 |
| IA | 66% | 86.9 | 86.9 | 100.8 | 98.1 | 100 | 100 | 87 | 2.530 | 17.3 | 18 | 91.7 |
| IP | 55% | 96.3 | 96.3 | 100.1 | 99.2 | 100 | 100 | 81.6 | 1.644 | 21.3 | 21.3 | 62.2 |
| CA | 210 °C | 91.8 | 91.8 | 101.5 | 99.8 | 100 | 100 | 72.8 | 2.074 | 28 | 27.9 | 24.2 |
| ID | - | 96.9 | 96.9 | 105.1 | 99.7 | 100 | 100 | 74.7 | 1.590 | 24.1 | 23.6 | 46.9 |
| Fx | - | 92.7 | 92.7 | 103 | 103 | 100 | 100 | 52 | 1.989 | 32 | 30.7 | 12.8 |

Table 5.9 – Main energy, production, ecological and economic results for the basic EEM for the range value which optimises the SPP (Figure 5.19).

Table 5.9 summarises the individual assessment. The obtained level of EEM implementation (column "Range" in Table 5.9) is the result from the minimum SPP for the proposed cost (CapEx,OpEx and Cpa) and to ensure that the process comply the overall process restrictions. The Overall Energy Consumption indicator takes into account the required energy to produce the expected quantity of load of the selected representative working week. This indicator considers the energy consumption of both furnaces. The prevented CO2 emissions follow this reduction of energy consumption (less natural gas is burnt). In this analysis the HES, which is represented by means of the HES load indicator, recovers all the energy available at the SF fumes.

### 5.2.3 Secondary Strategy: Combinatorial Assessment

On the basis of the results presented previously, a new assessment is proposed. The combination of different measures generates synergies in the process, which may go beyond the improvement of the individual EEM. On the contrary, some combinations of measures may cushion the overall effects. The final "packages" with their respective measure selection, the range and the costs are summarised in Table 5.10. Each combination of measures as well as their respective ranges of application are obtained by applying the procedure described in section 3.2.6. First, and based on the previous results (Section 5.2.2.9), "a priori" combination of EEMs and ranges are selected. This selection is guided by the criteria established for each combinatorial scenario. Several scenarios have been proposed in this first step for each proposed multi-criteria. Each scenario is expected to meet the multiple criteria introduced due to they are combinations of the individual scenarios analysed. However, these scenarios are simulated to ensure that the dynamic behaviours of the process and the measures do not deviate from the expected "a priori" behaviours. If a serious deviation is observed, the range (or even the set of the selected EEMs) is modified and simulated again. Once these scenarios fulfil the required criteria, a sensitive analysis (by slight modifications on the ranges) is carried out to probe that the solution is the relative optimum. Consequently, a final scenario (each combinatorial package) which optimises the established multi-criteria is obtained. The final results of these combinatorial packages are summarised in Table 5.11. The results of each combination are explained in the following sections.

| | **Measure package & Implementation Range** | | | | |
|---|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** | **V** |
| ZA | ✗ | ✗ | ✗ | ✗ | ✓ full |
| LI | ✓ 7% | ✗ | ✗ | ✓ 11% | ✗ |
| TR | ✓ 20% | ✓ 23% | ✗ | ✓ 22,5% | ✓ 4,5% |
| IA | ✓ 43% | ✓ 66% | ✓ 66% | ✗ | ✓ 66% |
| IP | ✗ | ✗ | ✓ 55% | ✗ | ✗ |
| CA | ✗ | ✓ 330°C | ✗ | ✗ | ✗ |
| ID | ✓ yes | ✗ | ✓ yes | ✓ yes | ✓ yes |
| Fx | ✗ | ✓ yes | ✓ yes | ✓ yes | ✗ |
| CapEx | 34000 | 94600 | 68400 | 72600 | 44500 |
| OpEx (annual) | 1320 | 2400 | 720 | -40 | 110 |
| CPa | 8500 | 13900 | 8000 | 12500 | 6300 |

Table 5.10 – Range and cost for the obtained combinatorial packages.

Five "packages" of EEM have been obtained to reach the next five different goals: minimisation of the Simple Payback Period (SPP), maximisation of energy reduction, minimisation of the HES sizing, maximisation of the production and the conservation of the current STTS and ATTS. The last one is the most conservative goal, the process is minimally affected. Both the process STTS and ATTS, the internal pressure, the $NO_x$

production, the production plan (number of treated parts) and the basket composition remain invariable.

The obtained ranges (degree of implementation) of the measures represented in Table 5.10 are a result which comes from the iterative heuristic procedure introduced in the methodology. This iterative optimisation (for the selected criteria) is mainly based on the preliminary approach (individual assessment) and supported by the process expertise and knowledge. For each case study, for 4 EEMs -among the 8 which have been proposed- and the main strategy -the WHRS- have been selected, in order to optimise the set of established criteria.

#### 5.2.3.1 Simple Payback Period optimum

This first scenario obtains the optimal combination to enhance the SPP economic factor. This optimum is totally dependent on the monetary weights that are attributed to the costs. Modifications or updating on the costs will determine the combination of measures and their range. In addition, measures with high CapEx are penalised. The measures obtained are as follows: the Load Increase, the Time Reduction, the Infiltration Area reduction and the Internal Door. There are some final solutions that reach similar values (months) of SPP, however, the CapEx parameters were higher[9]. For the proposed costs scenario and the selected measures this optimum shows a SPP of 12’6 months (as shown Table 5.10 ) and moderate (in comparison to other combinatorial packages) energy savings of 764 MWh/year.

The mass flow of the SF hot fumes is reduced by around 24%, and, consequently, its energy (due to IA and ID measures). Therefore, the HES size is reduced to a 76% of its original size (only WHRS implementation). This CapEx saving is already accounted for in Table 5.10. The HES workload maintains a good performance of 88’6% for the new size. The time-restriction parameters reach critical theoretical values (reductions of 20% for the solution process time and 25% for the ageing process time, as shown in Table5.11). However, these new conditions, despite being supported by researches, must be confirmed prior to implementation. The production ratio increase may be managed in two ways: accumulation of stock before the Heat Treatment Process or increasing the production rate before the Heat Treatment Process. This last way will modify the factory tactical plan. The accumulation of stock may represent a room/place availability problem which must be analysed.

#### 5.2.3.2 Energy saving optimum

This optimum sacrifices the SPP and the $NO_x$ production to reduce the NG consumption to the maximum. The four optimal measures selected are: Time Reduction, Fixture

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[9] In this regard, a "new" criterion was subsequently introduced to reduce the number of solutions.

change, Combustion Air pre-heater and the Infiltration Area reduction. Because no economic nor process-restriction indicators have been chosen for this optimum, all measures are selected in their maximum range. Only the "Time Reduction range" is delimited to secure theoretical values of ATTS and STTS. This optimum shows the highest energy savings, about 1865 MWh/y, at the expense of the SPP, which increases 21 months. Both solution and ageing efficiency increases considerably (around 70% and 50% in comparison with the energy efficiencies of the furnaces for individual implementation of the $\text{HES}_{EEM}$ measure). The HES size is reduced to the 66%, while the average workload is about 75% of its new nominal design.

#### 5.2.3.3 Heat Exchanger System size optimum

In this theoretical scenario, the size of the HES is reduced. This is achieved by reducing the ageing requirements (making the AF more efficient). The selected measures (as shown in Table 5.10) are the following: Infiltration Area reduction, Internal Pressure decrease, Internal Door restoration and the basket Fixture change. The overall energy efficiency increases due to the reduction of the infiltration flow provided by $IA_{EEM}$ and $IP_{EEM}$ implementation. In the same way, while the solution process becomes more efficient, then the solution exhaust gases which feed the HES, are reduced. Thus, the HES size reaches a reduction of 40%. The new nominal duty of the unit would be 56kW while the nominal heat provided to the ageing would decrease to 92kW. As a consequence of these modifications, the STTS greatly increases. The ATTS shows improvement to a lesser extent. From the economic point of view, this package improves the SPP of the HES measure by around 6 months. These results are similar to the results of the second package; however, the initial investment is clearly lower.

#### 5.2.3.4 Production maximum

The number of parts processed is increased in this package. Apparently, the measures that individually increase the production should be obtained at the measure selection process of this package. However, the Zero Anomalies measure, which increased the production directly, has been substituted by the Internal Door measure. This apparent incongruity is analysed below. The package measures consist of: Load Increase, Time Reduction, Internal Door restoration, and basket Fixture change.

In this scenario it must be emphasised that the Fixture and the Internal Door measures have been selected due to the fact that they provide reductions in both process restriction times. Therefore, in combination with Time Reduction measure, this measure allows us to increase productivity to a greater extent. This synergy between measures allows to transform the increase in the "time restriction", provided by the Fixture and Internal Door measure, into production increase by means of the reduction of process time through the Time Reduction measure.

There are two ways to increase the production: to increase the workload, and to reduce the production time. This is reflected in the total time (hours to treat all the batches), which shows a reduction of 22% in comparison with the reference time (Baseline), and in the production factor, which shows an increase of 42'2%. The energy consumption decreases strongly in comparison with other packages (savings of 1435MWh/year). The HES power shows higher values (average of 100kW of provided power), due to the fact that a higher production rate implies higher demands in the furnaces. However, the HES workload remains low, around 67%, due to the fact that the nominal power (153kW) is not modified. This package shows acceptable values in the economic indicators, improving the HES baseline SPP in 8 months. If there is an urgent need to increase the production, then it may be a better solution than installing another heat treatment line. This package of EEMs allows this situation.

#### 5.2.3.5 Conservative scenario

This package ensures that the critical conditions of the solution process remain unchanged. This package is not an optimal one, but it does fulfill a series of fixed requirements, while trying to optimise energy savings. Therefore, after fixing some criteria, the optimised factor is the "energy saving". The process conditions (to comply with the ageing requirements) of the AF are ensured based on the analysis of the part temperature profile (provided in the "Re-circulation" assessment in Section 5.2.1.2) and due to the relaxed restrictions of the ageing processes (to achieve the mechanical expected properties). The process conditions (in order to comply the solution process restrictions) of the solution process are ensured by keeping the current working "time restriction". In conclusion, from the point of view of the part, they remain the same time at critical temperature than in the current working mode for the solution process. Other conditions, such as the heating temperature profile and the internal pressure, remain similar to those of the baseline (BL). Within the prescribed limitations, this package brings moderated energy and ecological outputs. The energy reduction and the CO2 emission reduction are around 17'4% when comparing to the $\mathrm{HES}_E EM$ scenario. This energy reduction corresponds with 570 MWh/year. In spite of these moderate energy savings, the results of the economic indicators are excellent due to the low investment required for this package (as shown in Table 5.10). However, the monthly savings are low (less than 3000 €/month, as it is shown in Table 5.11) in comparison with other packages.

#### 5.2.3.6 Combinatorial final analysis

The results of this Energy Efficiency Assessment are summarised in Table 5.11. According to the introduced criteria, the Energy Efficiency Assessment returns a diverse combination of actions with a variable range of application. These scenarios have been selected to cover a wide variety of criteria, from very conservative scenarios (such as the scenario 5.2.3.5) to intensive-modification scenarios (such as the scenario 5.2.3.2).

| | **Energy** | **Eco** | **Process Way of Working** | | | | | **Economic Indicators** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consumption Overall [%] | $CO_2$ [%] Emissions | Time Restrictions [%] STTS | ATTS | Total time [%] | Production Ratio [%] | HES load [%] | Savings [€/month] | SPP [months] | LEEC 3y [€/MWh] | ROI 3y % |
| BL | 113.6 | 113.6 | 100 | 100 | 100 | 100 | - | - | - | - | - |
| HES | **100** | **100** | **100** | **100** | **100** | **100** | 73 | 1.293 | 28.4 | 27.6 | 25.4 |
| I | 76.8 | 76.8 | 80.3 | 75.8 | 75.2 | 133 | 88.6 | 3495 | 12.6 | 12.8 | 170.8 |
| II | 56.9 | 56.9 | 79.9 | 77.4 | 77.5 | 129 | 75.7 | 5378 | 21 | 20.7 | 67.3 |
| III | 74.7 | 74.7 | 110.9 | 102.3 | 100 | 100 | 72.6 | 3687 | 21.1 | 20.5 | 69 |
| IV | 70 | 70 | 80,8 | 78 | 78 | 142.2 | 67.1 | 4137 | 20.8 | 20.1 | 70.8 |
| V | 82.6 | 82.6 | 99.9 | 92.6 | 93.4 | 107.1 | 89.8 | 2942 | 18.6 | 18.8 | 83.9 |

*The values in bold are those that have been taken as a basis for the comparison / weighting.

Table 5.11 – Results of the combinatorial assessment EEM.

All the energy and behaviour results have been compared with those of the Baseline (existing way of working) in order to valuate the viability of the EEMs implementation. The technical way to reach each EEM (how to implement in real plant a specific EEM) is not covered in this study and the economic assumptions may differ for each case. The obtained energy and production results remain invariable for the analysed scenarios at expense of the economic interpretation of the implementation cost or factory specific requirements and restrictions. This Energy Efficiency Assessment allows to make posterior sensitivity analysis with economic variations.

Therefore, the results (range of application and selected measures) based on economic-indicators criteria may change, whereas the results (both energy, behaviour, and combination of measures) based on energy, ecological and production criteria will remain invariable at the expense of the selected economic conditions of the factory (cost of energy, operation and maintenance expenditures, etc.).

### 5.2.4 Other EEM

In this section other EEM are individually assessed to quantify in general terms the impact on the main variables, on the system environment and on the way of working. This group of measures is focused on the solution process. The parameter modifications or the code-blocks introductions are only implemented in the models of the SF.

#### 5.2.4.1 Preheating Stage

The introduction of a Preheating Stage ($PS_{\text{EEM}}$), which heats the parts before introducing them in the SF, affects the behaviour of the SF. This Preheating Stage (as it is shown Figure 5.24) aims to heat the load with the SF exhaust gases. This exhaust gases flow will be modified due to the new behaviour of the SF. Therefore, this dynamic system must be in-depth analysed in order to obtain the correct evaluation of the measure. In addition, this proposal re-uses the stack gases energy and, therefore, is not compatible at simultaneous time with the WHRS measure.

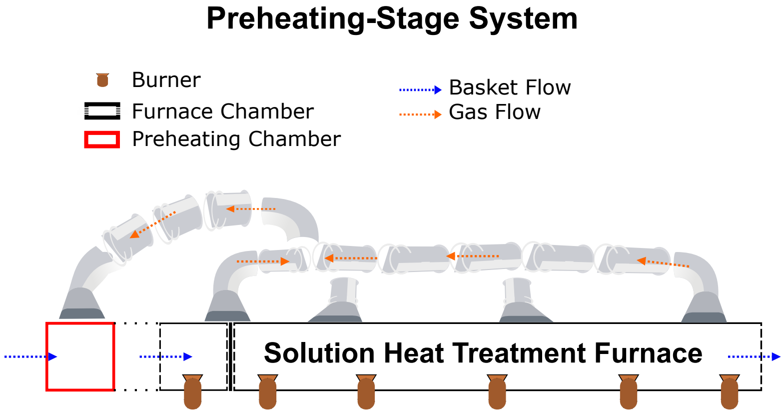

**Figure 5.24 –** Preheating stage and Solution exhaust gases circulation schema.

This alternative proposal modifies the stack gases characteristics of the reference case (i.e. the baseline without the WHRS). An intensive analysis of the stack gases at first step is required. The stack gases energy, the stack gases temperature (after and before the Preheating Stage), the batch temperature (at Preheating Stage and at first stages), and the new total energy consumption are analysed for each proposed scenarios. The three hypothetical scenarios of operating are the followings:

- Scenario 1: 100% of the solution stack mass flow with 100% of the stack gasses energy is employed. This scenario assumes that there are no losses from the collector to the preheating stage feeding point.
- Scenario 2: 100% of the solution stack mass flow with 90% of the stack gasses energy is employed.
- Scenario 3: 85% of the solution stack mass flow with 85% of the stack gasses energy is employed.

The proposed scenarios bring, in general, the following consequences: the energy consumption of the SF decreases significantly, the temperature at which the parts are introduced into the furnace increases considerably and the behaviour of the first and second burners is strongly modified. The main difference among scenarios is the final temperature at which the parts leaves the Preheating Stage. Reductions in the directed exhaust mass flow (from solution process) or assumptions of higher losses scenarios modify the final temperature of the parts (before entering the SF). Despite the fact three scenarios have been analysed all the figures correspond to the second proposed scenario (Scenario 2), which directs the entire flow from SF to the Preheating Stage and presupposes 10% of energy losses during this redirection.

Therefore, the power profile of the solution first burner (and the second in minor extent) moves to lower-load working profiles. This fact partially modifies the combustion air flow which the burners introduce to the furnaces. This event will provide a reduction of the exhaust gases. However, the same action reduces the internal pressure of the furnace, making the infiltration air flow of the furnace higher.

The energy of the exhaust gases of the SF is reused (third best option of the energy efficiency hierarchy, as it is shown in Section 1.3.2). Therefore, the temperature of the solution exhaust flow, after the preheating stage, is reduced. This measure generates a temperature profile after the Preheating Stage which presents a non-constant profile (as shown in Figure 5.25) when comparing to the baseline stack temperature profile (as shown in Figure 4.16). Notwithstanding, this variation does not present a bigger change due to the damper effect of the collectors and the big thermal inertia of the furnace.

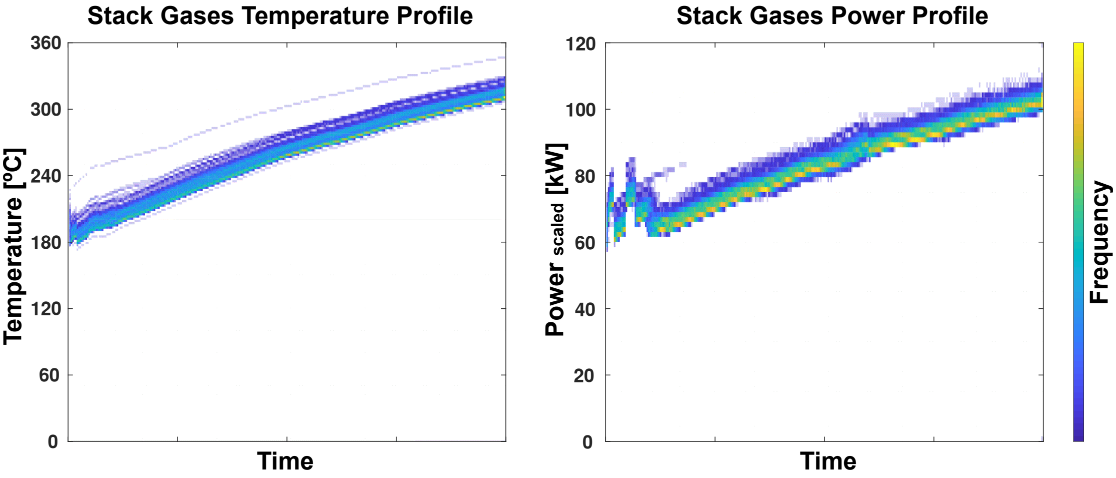

**Figure 5.25 –** Stack Gases properties after the Preheating Stage: $PS_{EEM}$ Scenario 2

In this regard, about 42%, 39% and 33% of the energy of the SF exhaust gases is reused for scenario 1, 2 and 3, respectively. The remaining energy of the Solution exhaust gases still presents acceptable values. However, the temperature profile is not very regular. This flow shows a ramp profile (as it is represented in Figure 5.25), making another recovery or recycle option more difficult.

As a result, the reduction of the combustion air flow, which is caused by the burner power reduction, is damped/cushioned or even counteracted because the infiltration and the excess air flows increase. The infiltration air flow increase is ascribed to the internal pressure increase, whereas the excess air flow increase is attributed to the low regimes in which the burners work for this new scenario. Consequently, the difference is not decisive, as it is shown in Figure 5.26. The stack gases flow even increases due to the new working regime of the burners. Notwithstanding, a new course of actions related to the better controlling of the internal pressure is raised. The lower variation of the burner power makes a more-accurate pressure controlling option possible.

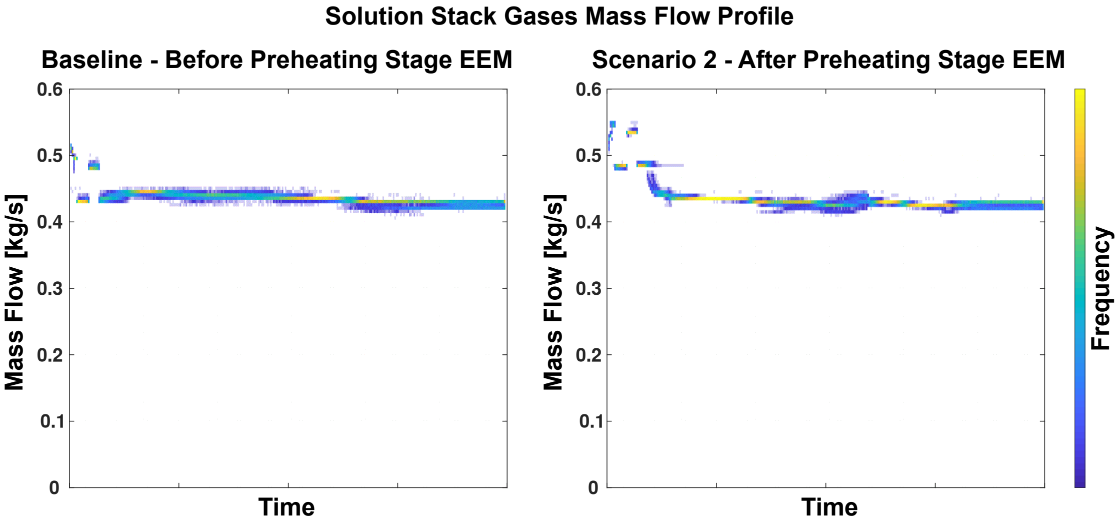

**Figure 5.26 –** Solution Mass Flow Variation due to $PS_{EEM}$ for Scenario2

From the production perspective, the Preheating Stage measure considerably improves the production indicators. For the Scenario 2, the STTS indicator increases 6% when comparing to the baseline. In addition, the period in which the baskets reduce their temperature (due to the air cooling caused by the new batch introduction) is completely prevented, as it is shown in Figure 5.28 at second stage square - azure colour. In the "Section Temp-Down", which is shown in Figure 5.27, the temperature of the parts remains practically invariable for the $\mathrm{PS}_{\mathrm{EEM}}$ Scenario, whereas the average temperature of the Baseline (purple line in Figure 5.27) presents a low reduction. Despite the fact that this reduction does not suppose any damage for the parts, the omission of this section may provide more temperature-stability for the parts.

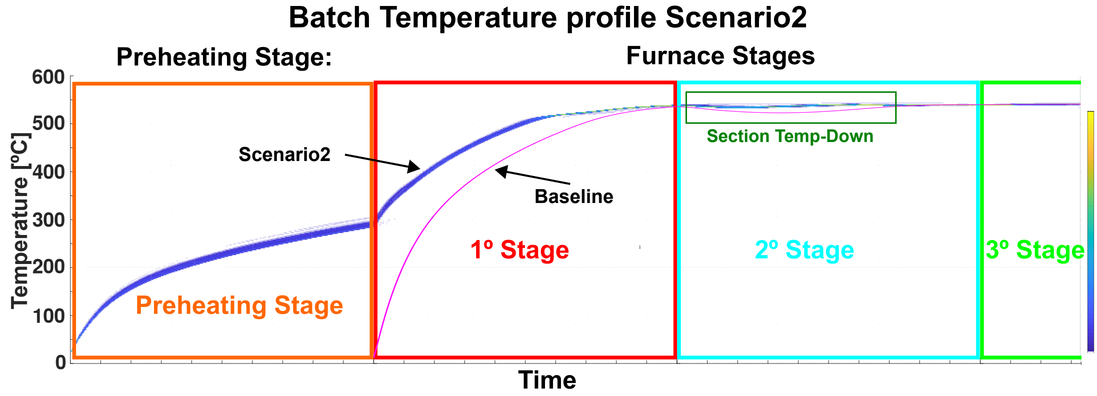

**Figure 5.27 –** Batch temperature profiles for the Preheating Stage (left) and for first SF stages (right): $PS_{EEM}$ Scenario 2

In conclusion, the baskets energy and temperature change their respective profiles compared to the reference case (Figure 5.28). The preheating stage raises the temperature of the batch to high levels, as shown in Figure 5.27, which allows the energy

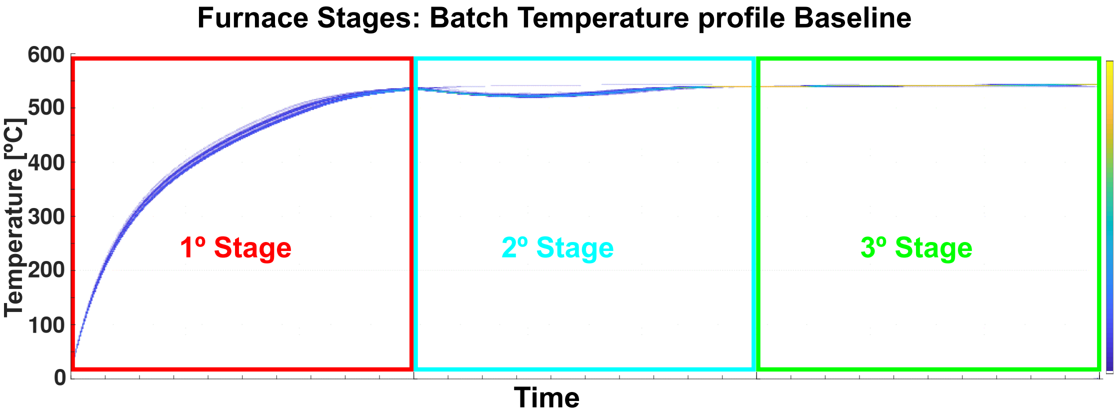

**Figure 5.28** – Batch temperature profiles for the SF first stages: Baseline.

contribution of first and second burners to be reduced. The energy savings of SF, according to the reference case, are about 21%, 18% and 14% for Scenario 1, 2 and 3, respectively, which correspond to annual energy savings of around 760 MWh/year, 660 MWh/year and 500 MWh/year. The AF is not affected at all by this measure.

#### 5.2.4.2 Turn-on Duration

This section tackles the duration of the turn-on of the furnaces. This time-period is employed to increase the temperature of the furnace to compatible-with-working temperatures. The proposed scenarios analyse the temperature of the inertia and how the parts comply the restrictions whereas the turn on duration is reduced. A common working week was taken as a reference. In this case reference, the turn-on duration (time until the first batch is introduced) was around 3 hours. Two scenarios of 1 hour and 2 hours reduction are analysed.

Evidently, reducing the time in which the burners are switched-on will provide energy consumption reductions. The energy savings associated, for one Turn-on phase, to these scenarios are around 371 kWh and 744 kWh for the 1 hour and 2 hours reduction scenario, respectively. This weekly values correspond to around 18 MWh/year and 36 MWh/year for the whole year of production. However, the temperature of the inertia (furnace) is affected. Besides, the restrictions-to-comply may be influenced due to this early introduction. These results are indicated in Table 5.12. The first part (left) of the Table shows the temperature of the inertia (which corresponds with the air temperature that the parts will receive). This temperature is split in the six identified sections of the SF. The second part (right) shows the STTS indicator (which controls the time that the batch remains at the process temperature) for the first three batches.

The simulation results show that while the inertia temperature (on average) is strongly affected by the measure, the STTS indicator is not practically changed. The

| | Temperature [°C] | | | | | | STTS [%] | |
|---|---|---|---|---|---|---|---|---|
| EEM | Section 1 | Section 2 | Section 3 | Section 4 | Section 5 | Section 6 | 1º batch | 2º batch |
| BaseLine | 522 | 467 | 436 | 491 | 485 | 477 | 100 | 100 |
| TD 1 hour | 493 | 420 | 392 | 445 | 429 | 411 | 99 | 100 |
| TD 2 hour | 418 | 352 | 311 | 322 | 290 | 263 | 98 | 99 |

Table 5.12 – Results of the $TD_{EEM}$ assessment.

main reason for this effect is that the inertia has not reached (on average) the "working" values, whereas the internal sections of the inertia (those surfaces which face the batches) have reached high levels of temperature.

Other additional advantage derived from this measure is the reduction of the total production time. However, this reduction is delimited to the turn-on reduction, so, it is completely negligible.

#### 5.2.4.3 Initial Charge

This scenario evaluates the theoretical case of introducing a load (set of baskets) before the furnace turning-on. The hypothetical turn-on duration has been kept. The analysed scenarios cover the situation of a previous load in the first stage of the SF and the situation of previous loads in the first and second stages.

The EEM under study affects the STTS indicator, the furnace temperature behaviour (until stationary conditions are reached) as well as the temperature-profile of the parts. The parts temperature profile experiments a slower growth compared to the baseline profile, as shown in Figure 5.29. However, the STTS indicators remain over the indicator average for the Baseline as the long switch-on time allows reach the required levels of temperature to be reached.

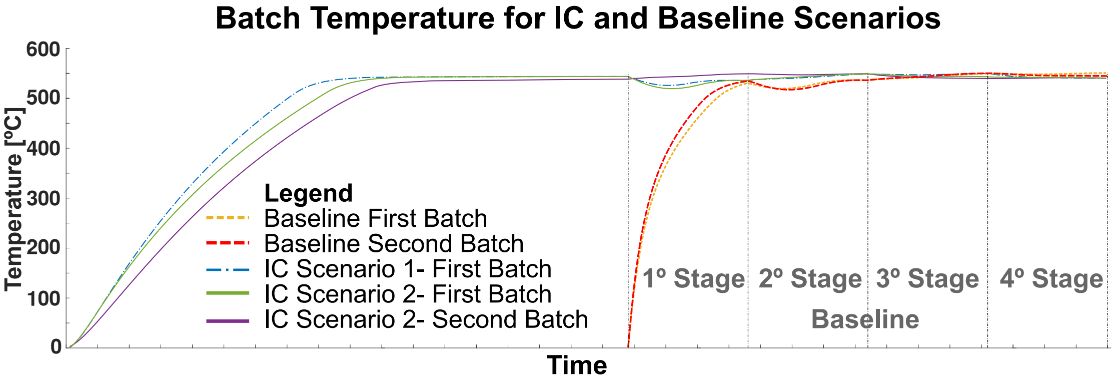

**Figure 5.29** – Batch Temperature profiles for $IC_{EEM}$ Scenarios

The "First Batch" temperature profiles for both scenarios (dashed blue line and green line in Figure 5.29) "lose" one stage-time attributed to the fact they are inside the furnace (at first stage) and must be moved at the first introduction. However, during the switch-on period they reach the process temperature and, consequently, it counts as a "first stage". The same phenomena affects to the second batch of the second scenario but in this case it "loses" two stage-times. Nevertheless, for the analysed case study, the switch on period still covers and counteracts this avoided processing time, and, even, improves more than 18% the time these parts remain at the specific temperature. This improvement is due to the fact the introduction of a new load does not reduce the temperature of this batch, in comparison with the baseline second stages, because it is very inside the furnace (3º stage).

The expected energy saving of this EEM derives from the time reduction associated to these initial charge as well as the heating savings during the switch-on time. These energy savings for the analysed scenarios are around 280 kWh and 590 kWh for each week of production, which correspond to 14 and 29 MWh/year.

In the same way as the previous proposed measure, an additional advantage derived from this measure is the reduction of the total production time. However, this reduction is delimited to the reduction of one or two batch-time intervals, so, it may be considered negligible.

#### 5.2.4.4 Burner Sizing & Power Limitation

Two different scenarios have been simulated for this analysis of this kind of measure. Each scenario presents diverse results due to the dynamics of the process changes, and, this, the manner of working is modified.

The first simulated assumption modifies the apparent power restrictions of the burners. The burners, in spite of the maximum-power design-characteristics shown in the data sheets, apparently show limitations. This measure ($BS_{EEM}$ Scenario 1) avoids these restrictions and the burners may work at its maximum level[10].

The results obtained by the simulation conclude, in the first instance, that the overall consumption is increased around 2%. This negative result comes from the new modus operandi of the burners. They are enable to work at their maximum, thus, they work in this point to reach the required levels of temperature as soon as possible (as it is commanded by the burners PLC). This behaviour makes it possible for the parts to reach the working temperature much earlier. Therefore, the STTS production indicator increases around 5%. Besides this positive effect, the section in the second stage (Section Temp-Down in Figure 5.30), in which the parts temperature decreases due to the introduction of a new cold batch to the first stage, is mitigated.

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[10] In the case of the second burner of the SF it was working above the maximum level, therefore, the limitation restricts the way of working to the maximum nominal design.

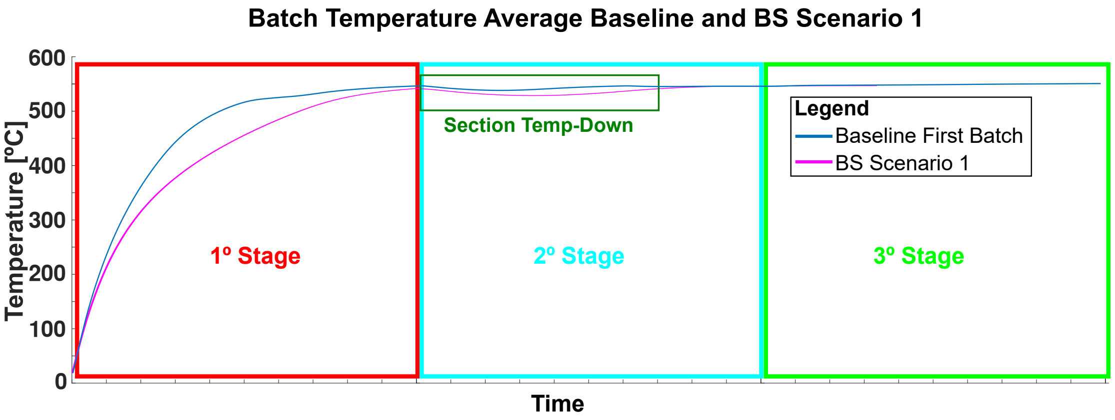

**Figure 5.30** – Batch Temperature Average for Baseline and $BS_{EEM}$ Scenario 1

A minor measure (in terms of process critical modifications), such as the reconditioning of the internal door between stage 1 and stage 2 of the SF would allow the increase of the STTS production indicator up to 9%. In this new scenario, reducing the total time of the process, as it is planned in $TR_{EEM}$, would keep the previous STTS and would provide the interesting energy savings which introduce this second measure ($TR_{EEM}$). Besides, this process time reduction would force the burners to work near to their nominal (first and second burner), which would generate minor additional energy savings. This is a clear scenario in which the implementation of different measures generates enormous synergies.

The second scenario proposal is to size the burners to fit to the current apparent restrictions. Therefore, the "new" burners would work near to their nominal. However, if the pressure system remains as the current one, it would result in higher pressures (due to the lower mass flow introduced) and higher infiltrations.

The energy savings obtained are around 1% of the total SF energy consumption. The combustion air mass flow has been reduced around 7%, where as the infiltration air mass flow of the SF has been increased more than 7%. However, the overall stack gases are decreased around 1'5%, which makes the energy consumption reduction possible. In this regard the hypothetical energy savings provided by the EEM are minimised by the relative worse pressure controlling. Therefore, the hypothetical impact of the $IP_{EEM}$ would be greater in comparison with other scenarios. In overall terms, other production features of the process, such as total time of production, production rate, STTS or part temperature profile, practically remain constant.

This is another example of how an EEM, which does not seem to provide good results (only 1% of energy savings), can be corrected by a synergistic approach of multiple action measures (implementation of other EEM). The behaviour of the burners is minimally affected by the EEM.

## 5.3 Energy Efficiency Assessment conclusions

The main conclusions derived from this Energy Efficiency Assessment are synthesised in this section. Once the process models have been generated and validated as well as all the relevant flows (energy and material), events and phenomena have been identified, the Energy Efficiency Assessment of the case study is carried out.

For this analysis some conditions, some economic assumptions and a wide variety of EEMs have been selected in order to obtain some specific optimums. The results show that there are high margins of improvement in manifold ways. The potential may reach up to 50% of the current energy consumption. This Energy Efficiency Assessment allows, based on some premises, to assess with a high degree of knowledge the processes and the entire production line once a EEM is implemented. This Energy Efficiency Assessment for the selected case study process is oriented to the analysis of the main measure, HES measure, and how other changes in the process, other modus operandi and the tactical decisions affect the HPHE design, the energy behaviour and the production plan.

Besides, other courses of actions, which include the analysis of other EEMs (which are not analysed for the main course of action) are assessed. As it is shown, each measure may act in a different way from each other. These actions generated by a specific EEM may generate synergies from several perspectives. On the other hand, some measures (which affect the same phenomena) may soften the sum of the individual described effects. The combination of measures do not modify the results as the sum of the individual results. In this regard, each combination of measures should be analysed in order to obtain the correct characterisation of the phenomena and, thus, the correct results.

The results (energy, economic, ecological and production) of each scenario are represented by means of summarising charts. The data or parameters represented in these kinds of chart can be easily modifiable. However, understanding the real process behaviour reached by the modification is not always an easy task. Some unwanted or non-expected conditions or situation may be "hidden" by the overall value of a specific result. This fact may be exemplified by means of the proposed case study. The main devices of the process are the burners. These burners work independently one of each other. However, the conditions which command the individual working of the burners are strongly affected by the other burners and other many factors. In this regard, one final solution which "apparently" presents good overall results may impose a situation where one device could work under undesired conditions. This is the case of the very low power loads situations which may present the burners working. Despite the fact of the burners are able to alternate very low loads with switch off phases in very low time periods is preferable to prevent this situation. For this reason, each scenario requires an in-depth analysis of all the involved phenomena and device to confirm that it is a favourable scenario

The potential of this Energy Efficiency Assessment, as it is represented by the manifold of scenarios analysed, is very high. An uncountable quantity of different scenarios may be assessed. On the other hand, the optimisation procedure becomes a non-perfect hard task due to the dynamic behaviour of the system proposed. The energy behaviour interaction among measures and range of measures generates an infinity of scenarios. The predictability of the results which come from a combination of measures is low. Due to this fact, the proposed iterative procedure for optimisation becomes in practice necessary. The proposed solutions and packages are obtained by heuristic analysis. The generation and analysis of these scenario results involve working time and computational power. This opens an opportunity to automatise the optimum selection and expand the criteria of the decision making process.

In order to fulfil one of the identified gaps, related to the overcoming of barriers, an easy-friendly environment to facilitate the proposal of scenarios has been developed. the aforementioned results obtaining, introduction of multi-criteria, the platform of scenario launching and the visualisation. This application is presented in the following section.

## 5.4 Energy Efficiency Measures Optimisation Tool for Decision

The aim of the proposed tool is to accelerate the pace of engineering and science introduction to the manufacturing process, and, consequently, the reduction of energy consumption and the increase of productivity. The tool is briefly presented in the following section and further details are provided in Appendix. All the results for the scenarios and hypothesis proposed in this Chapter have been obtained and simulated by means of the proposed tool (**E**nergy **E**fficiency **M**easures **O**ptimisation **T**ool for Decis**ion** - **$E^2$MOTion**). The tool allows to prepare the simulation by the simple introduction of parameters and preparing the internal scripts which are launched by the simulator. Then, it allows to compare results and parameters among the scenarios already simulated. Besides, for a deeper analysis of the energy and material flows, the tool provides a visualisation section in which any interval of the selected variable may be represented.

As it is stated before (Section 1.1.2.2), there remain problems to be solved in reference to the decision-making process and the accessibility to the scientific improvements in the industrial environment.

With this in mind, a user friendly tool has been developed to implement the advances provided by the proposed methodology and the derived Case Study advances. The tool has been developed in App Designer. App Designer provides:

- An enhanced user interface component set and design environment

- A robust programming editor and workflow
- The ability to create and share a standalone desktop or web app (requires MATLAB® Compiler™)

Measures for energy efficiency improvement have to be driven by business decisions and elaborated with help of the engineering domain [126]. Therefore, relevant research approaches need to provide decision support and business applicability with an industrial actor's perspective. Thus, the identification, evaluation and prioritisation of improvement measures need to be focused.

In this section an evaluation, comparison, what-if, and scenario simulation tool is presented. The tool allows the working parameters of the process considered to be modified and to introduce different ranges for the EEMs identified. As a result, different scenarios can be reproduced and the corresponding economic, ecological, productive and energy KPIs can be analysed. In conclusion, the tool allows to somehow automatise the methodology proposed in the previous sections. Although it has been developed based on the case study presented in Chapter 4, it could be easily adapted to any manufacturing process in which the methodology is applied.

The tool starts with an introductory window in which the tasks, those which the tool automatise, are presented. The different options to select are the following: simulation, visualisation and comparison, as it is shown in Figure 5.31.

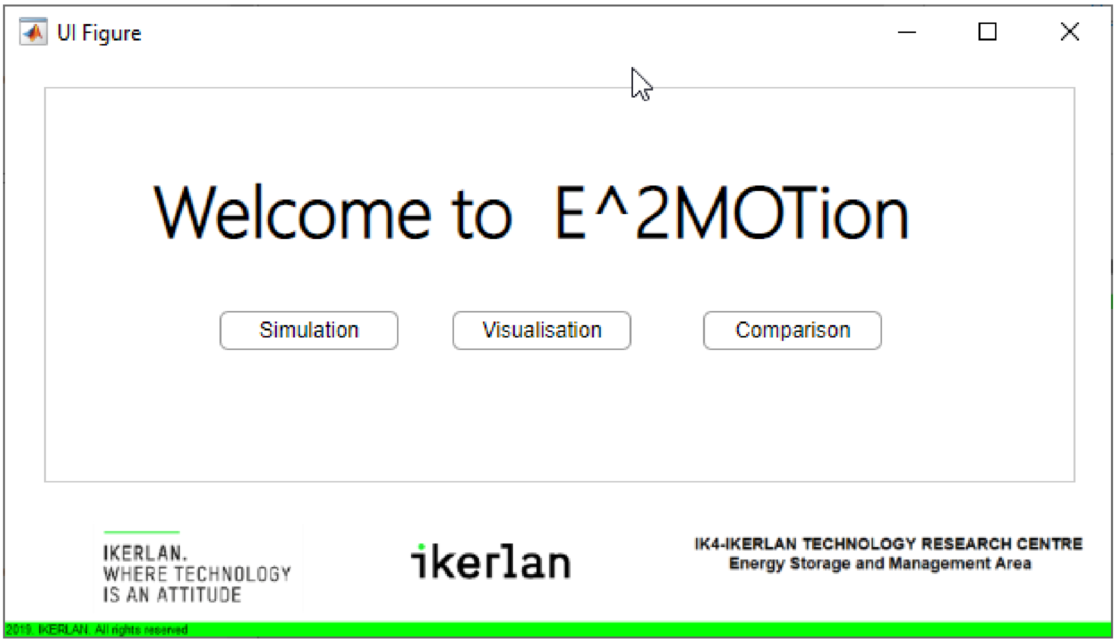

**Figure 5.31** – Initial window of the app EMOtion.

Once an option is selected, the tool guides through a variety of windows and panels to achieve the final required output. The first option i.e. simulation, guides the user through the simulation panels in order to reproduce the process with a set of new parameters chosen by the user. In the second option, i.e. visualisation, a wide range of parameters are able to be represented with the data from a selected file. In the comparison section the data from two different files are shown and analysed in comparison with the results of the existing process way of working, i.e. the baseline results. Furhter details are provided in Appendix A.

In conclusion, a user friendly tool is developed to ease the implementation of EEMs into the specific process under study. This tool is specific of the process. However, if the methodology is applied to another process, despite the fact the variables or indicators under evaluation would be modified, the platform support and the general features of the tool would be kept.

# 6

# Summary

**Summary**

*This chapter synthesises the work described in the previous chapters. The final conclusions derived from the proposed methodology and the compliance of the objectives are addressed. A discussion section is submitted, in which some limitations and other relevant considerations are illustrated. Additionally, an outlook of potential research fields is given, which could complement the presented work.*

## 6.1 Conclusions and Discussions

The purpose of this thesis is to develop a methodology for integral energy analysis of industrial processes and plants. This novel methodology generates a great contribution to the available background about Energy Efficiency and EEMs for non-continuous thermal processes as well as for modelling and simulation of these processes.

A novel energy modelling by simulation procedure for non-continuous thermal processes is developed and applied to a representative case study. This modelling aims to acquire a good compromise between complexity and replicability [157]. This procedure helps to manage the introduction of EEMs into industry by assessing the dynamic way of working of the selected process and the proposed EEM. The energy efficiency assessment carried out in this work provides a solution to reduce drastically the energy consumption and provides an analysis of the selected solution (WHRS) and the behaviour of the system. The installation of a WHRS will provide an opportunity to improve significantly the heat management inside the plant, to reduce the environmental impact and to reduce the energy bills.

This section includes a critical evaluation of the developed work is carried out. The first part of this section evaluates the methodology developed and compares it with the available state of the art in this topic. For this evaluation and comparison the criteria proposed by Thiede [44] and Heinemann [126] have been used. Both proposed criteria have been developed in order to evaluate both the multi-level and multi-scale features and the general methodological characteristic encompassed (integral evaluation of processes).

The first appraisal approach is carried out by following the evaluation steps proposed by Thiede [44]. This assessment covers diverse fields, such as the "Energy and Resource Flows", the "Fields of action", the "Evaluation" and the "Implementation". With this in mind, the score for each point is assessed and represented in Figure 6.1.

The proposed methodology takes into account all external energy sources and internal flows which can be considered as relevant. The process under study is completely evaluated (Completeness Score = 1). The dynamics of each relevant flow (either of material or energy) is deeply characterised. One of the core feature of the methodology is the capacity to reproduce high dynamic flows (affected by many phenomena and events) with high accuracy. It also takes into account the energy cumulative profile of the systems. In this regard both, the system dynamics and the dynamical systems perspectives, are more than covered by the energy and production modelling (Dynamics Score = 1). Due to the specific characteristics of the selected kind of processes to which the methodology is intended, the Technical Building Services (understood as Heat, Ventilation and Air Conditioning or compressed air system) is not taken into account in a deep degree. This fact occurs because the relative consumption of theses system is negligible in case of energy intensive processes (TBS score = 0).

This proposed methodology acts in each suggested field of action. From the technological point of view, the methodology includes, in the EEMs proposal and modelling, novel technological measures in many technical fields. In this regard, the methodology allows to implement and create non-existing measures or to adapt as required any measure, therefore, it presents a very high level of technological introduction (Technological Score = 1). Besides, the way the production behaviour is modelled allows to introduce a wide range of organisational concepts. The production variations, unexpected events, diverse modus opperandi (operational), tactical modifications and, even, strategic actions can be easily introduced and reproduced (organisational Score = 1). Finally, each process parameter, EEMs range and degree of measure implementation may be modified and, consequently, optimised. Furthermore, the methodology includes an optimisation procedure based on a multi-criteria input provided by the user (Optimisation Score = 1).

The evaluation procedure takes into account all the processes under evaluation from an integral perspective. In this respect, although this methodology provides an economical and ecological assessment, the degree of characterisation of these costs or the ecological considerations are not as broad as some approaches based on LCA. However, these criteria employed for the methodology are easily modified and many assumption inputs may be done ex post. This methodology supplies the conversion of different energy flows to GHG emissions and the generation of NOx of the heat generators. Therefore, the capacity of evaluation is still high (Economic and Ecological Score = 0.75). On the other hand, the suggested technical assessment comprises all the main technical considerations of the process under study. Thus, the restrictions of the process are modelled and tracked (Technical Score = 1). For the decision making process, all evaluation dimensions are considered simultaneously, which may lead to conflicts of goals. Besides the comparison/discussion methods for each scenario, other technical and technological considerations are taken into account. However, a platform to support the final decision, which provides the real final solution, supposes an ambitious challenge. The decision support is limited to guide the user and lead the user among the wide range of possibilities (Decision Support Score =0.75). This methodology is intended to limit the uncertainty of the process due to a physics-based modelling and a laborious characterisation task. As a consequence, the quality of results is ensured with either assuring that stochastic effects are not significant in the specific case or providing statistical confidence through sufficient simulation runs (Uncertainty Score = 1).

The implementation of the methodology is scored as follows. The transferability or replicability of the methodology for any case study is guaranteed by the proposed energy modelling. This energy modelling is based on blocks which are interconnected among them. Each block is independent and represents a sub-device, device, sub-process or process. Therefore, the expected adaptation to any process is carried out for any process conditions or devices (Transferability Score = 1). On the other hand, the effort required to implement this methodology is high. The methodology is developed in MATLAB®-Simulink®, which supposes higher learning and programming time, in comparison with static-simulation software, and higer cost in comparison with open-source software. The process is reproduced with high level of detail, and the process information as well as the result generation and assessment also demand high requirements. In order to ease the introduction of this methodology into the industrial environment, a user friendly tool has been developed. Considering that, the effort of the final user is considerably reduced, but the developer effort is still significantly high (Effort Score =0.25). Both the methodology and the proposed tool allow to visualise easily each measure or parameters. The MATLAB®-Simulink® environment allows to track the simulation variables during the running. Besides, once it is simulated, each variable or parameter of each scenario may be accessed in a simple way to obtain the required representation (Visualisation Score = 1). According to user needs, the visualisation may be focused on any field of the integral evaluation (economic, ecological, production or energy and material). Finally, to support the correct and target oriented applicability, the simulation approach should be ideally embedded within an appropriate comprehensive methodology which covers and provides support to the application cycle (validation, support for systematic improvement, support for data acquisition). This methodology is designed to cover all the cycle ((Application Cycle Score = 1)).

In conclusion, the evaluation method, which is proposed by Thiede [44], shows that practically all criteria could be correctly addressed by the methodology. Improvement towards the state of research hove been made in all categories for those which the methodology is designed. The average fulfilment of criteria is 0.83 (83'33%) which corresponds to the scores represented in Figure 6.1.

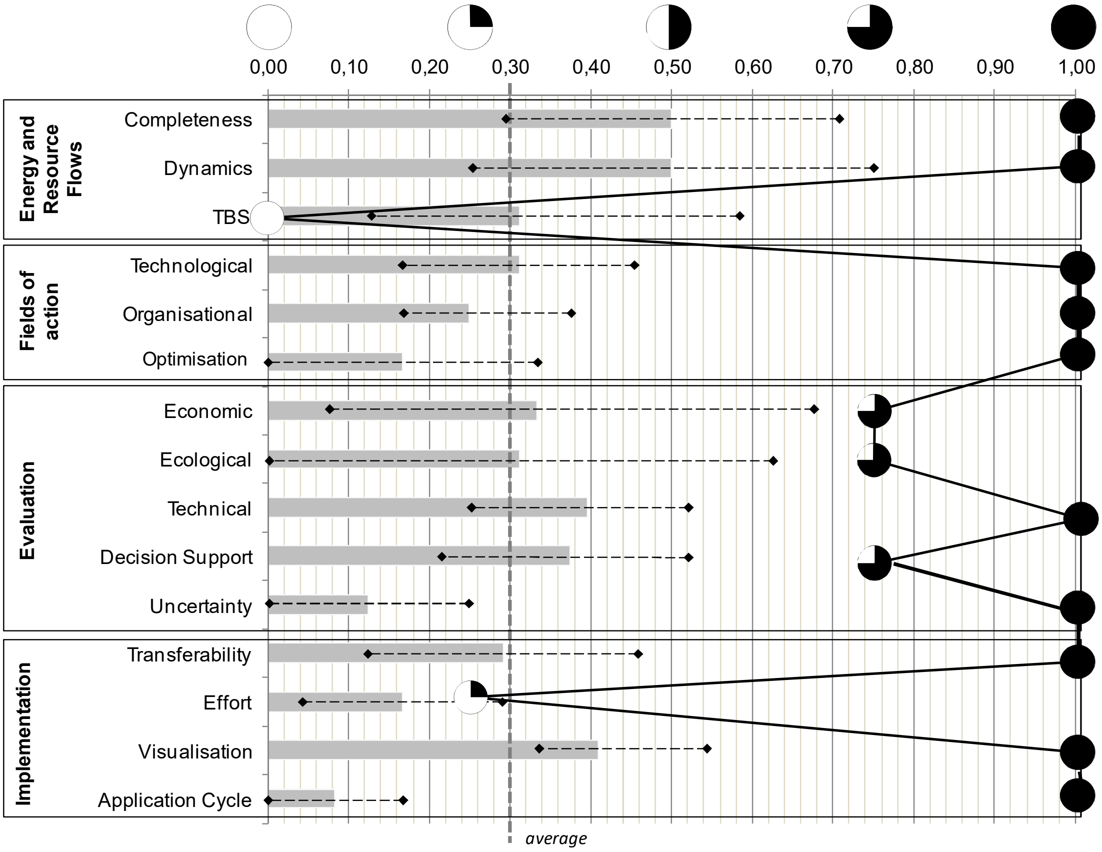

**Figure 6.1** – Comparison of the proposed simulation-based methodology with state of research (Thiede criteria [44])

Figure 6.2 shows the appraisal proposed by Heinemann [126], with which the proposed methodology is also assessed. The scope of the methodology under evaluation has different extent in terms of LCA or the spatial hierarchy an it is more specific for the aluminium die casting processes. In this sense, the analysis provided by Heinemann [126] is focused on LCA.

However, other points concerning to "data model quality" and "application" criteria may be adapted to provide a further evaluation of the methodological approach. This approach is similar to the one provided by Thiede (Figure 6.1), however, the application of other relevant appraisal method helps to confirm that the methodology is correctly evaluated. Notwithstanding, some criteria have been adapted in order to explain the characteristic of the methodology.

Therefore, despite the scope differences between the proposed methodology and this appraisal criterion, this evaluation approach is carried out. The spatial-vertical hierarchy corresponds to the range of application of the methodology. In this sense, the proposed methodology is expected to work from device level to factory, which covers practically all the levels in a specific industry (spatial-vertical hierarchy Score = 1). On the spatial-horizontal hierarchy perspective, the appraisal makes reference to peripheral systems such as offices, staff rooms or to Heat Ventilation and Air Conditioning system. Anyway, the proposed methodology is not intended for this purpose (spatial-horizontal hierarchy Score = 0), focusing on the "process". From the sequentiality criterion perspective, the proposed methodology does not take into account interactions among factories and does not relate value chains among them. Therefore, this parameter is not covered. However, the process, production line ans plant relation are addressed (spatial-sequentiality hierarchy Score = 0.5). The technological-primary shaping is a very specific parameter which does not apply for the proposed methodology. For this reason it is not represented nor scored. From the temporal scope, as it is commented before, the methodology covers the multi-time-scale perspective, i.e. operation, tactical and strategical. However, a LCA is not carried out by the suggested methodology (temporal-perspective Score = 1 and temporal-LCA Score = 0).

The gathered data about energy and resource flows of the observed system needs to be modelled in order to identify fields of action and derive measures to enhance the energy and resource efficiency of this system. The set of criteria named modelling quality evaluates the supported level of modelling detail. In this regard, this methodology assesses all the relevant flows and characterises them by means of the acquired measurements and knowledge (data quality-resource flows Score = 1 and data quality-data sources Score = 1). The structure proposed by the flows and the interactions among modelling blocks is dynamical. However, the modelling detail does not cover all the value-chain modelling, such as logistics, sales or service departments (model quality-modelling detail Score = 0.75 and model quality-structure of flows Score = 1).

From the application point of view, the transferability is ensured due to the modelling way based on blocks. The methodological approach results from a combination of methods. Several procedures have been implemented for analysis, data compilation or modelling. In the same way, the decision support is intended to introduce many criteria. As result, an excellent level of industrial applicability is reached (transferability Score = 1, methodology Score = 1, procedure Score = 1 and decision support Score = 1).

Finally, the evaluation method proposed for this methodology accounts for all the proposed sub-criteria suggested by Heinemann's appraisal (economic impact, physical mass flow,physical energy flow, environmental impact, Ex-post and Ex-ante perspectives, qualitative statements, quantitative comparable presentation, visualisation of energy flows and visualisation of material flows). Therefore, the final application evaluation score reaches the maximum level (Evaluation dimensions Score = 1, Evaluation perspective Score = 1 and display of results Score = 1).

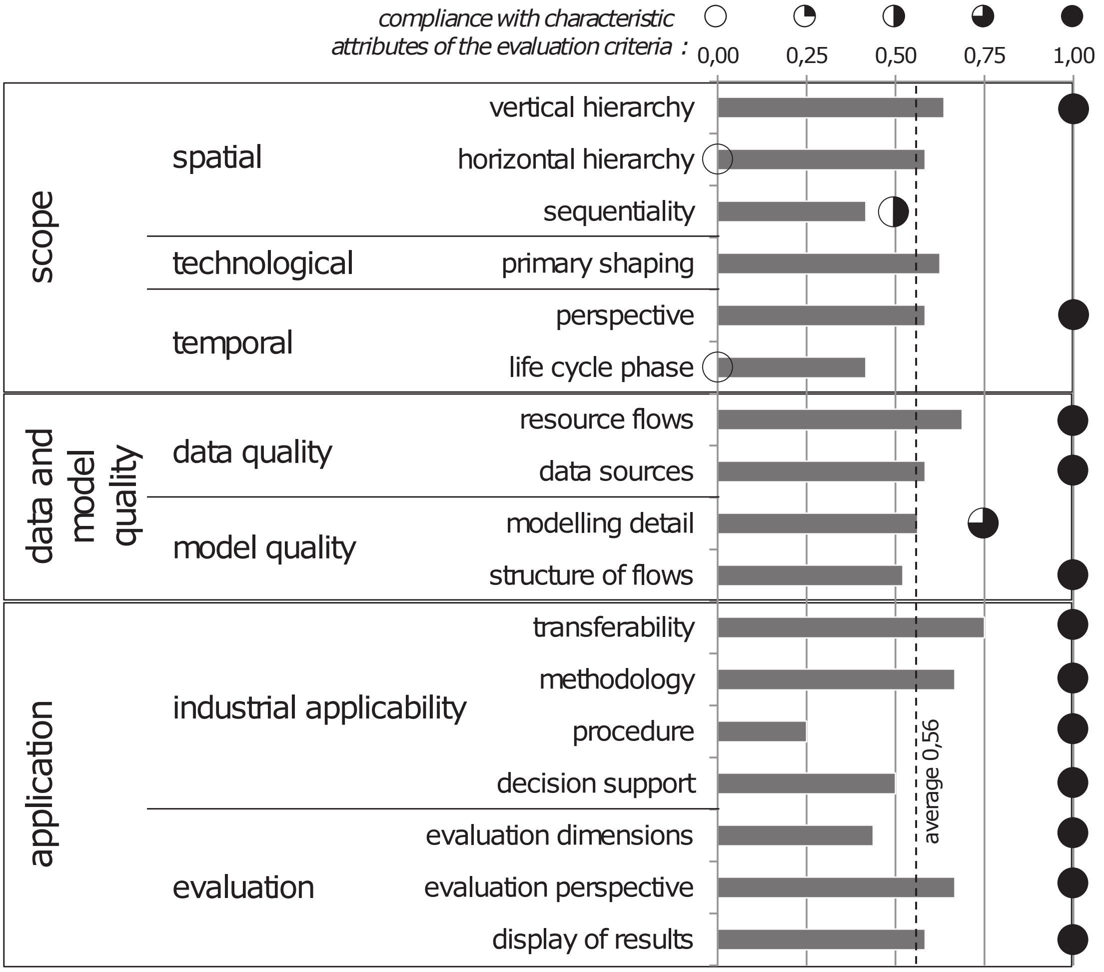

**Figure 6.2** – Evaluation of proposed methodology simulation-based against the state of research (Heinemann criteria [126])

In conclusion, this second methodology evaluation confirms the results provided by the first appraisal. The average fulfilment of criteria is 0.83 (82'81%) which corresponds with the sum of scores represented in Figure 6.2.

The second part of this discussion section tackles the considerations assumed for the final solution of the Energy Efficiency Assessment. Besides, the compliance with the identified research objective also gets evaluated.

In this sense, the assumptions of the economic assessment are based on reasonable hypothesis and data obtained by public reports. However, both the accuracy of the expenditures as well as the cost trends for the range of implementation may vary in a real scenario. Beyond these hypothetical inaccuracies, the objective of this research is to prepare the tool for future EEMs, processes and plants. From the energy and production point of view, the energy modelling is endorsed by historical data validation in diverse conditions, which presents an acceptable theoretical medium-low degree of subjectivity [184]. Strong modifications of the initial scenario may distance from the energy real behaviour. Nevertheless, no evidence has been found to think that the energy behaviour of the process may change substantially.

The compliance of the main objectives (listed in Section 1.5) have been reached to a great extent. The energy efficiency of the manufacturing process is increased by means of the implementation of EEMs. These EEMs are identified, quantified and evaluated by means of the proposed methodology through the developed models. These models, which reproduce the dynamic behaviour of the system, provide the characterisation of all the relevant impacts which affects the new scenario system. Besides, a tool has been created to ease the Energy Efficiency Assessment and to put the industrial actor closer to this Energy Efficiency Assessment.

In addition, the specific objectives, listed in Section 1.5, are also fulfilled to a large extent. The analysis of the current situation and the state of the art in energy modelling and existing approaches is satisfactory addressed. Besides, a relevant case study has been analysed by the an accurate energy models of the developed methodology. Many EEMs have been analysed, taking into account the impacts on the system, and the fittest solution, based on multi-criteria, has been provided. Finally, a novel tool to control the simulation process and the results analysis step has been developed. Notwithstanding, the challenges observed for the fulfilment of these tasks, and some other new identified opportunities, have raised a wide variety of future working task.

Definitively, this methodology will advance on the existing state of the art as enabler for energy management in manufacturing [206], by providing supporting methods and tools and by assessing the manufacturing process paradigms.

Although this critical evaluation of the developed concept proves significant advances in comparison to the state of research, some open aspects can still be identified. Therefore, this section closes with an outlook on possible adjacent research topics.

## 6.2 Future Work

Although significant advances in comparison to the state of research have been achieved with the proposed methodology, some other diverse opportunities for future research have been identified. The optimisation process of the methodology still presents some gaps for improvement. The proposed tool is still under development and presents margin for improvement. The effort in time and cost to generate the models is still high. Besides, it has been identified that The extension of the methodology for operational tracking and control and planning of production could provide very useful results to this kind of processes. The improvements in the aforementioned fields would extend functionalities and provide better results.

Regarding to the optimisation approach for the methodology and tool, the considered ideas as so far are two: First, to automatise the heuristic process by an iterative procedure and to log the results in order to make "results maps". These maps will allow an approach, outside the simulation process, for optimisation or approximation to the optimum. Second, obtain solutions through weighted objectives and analyse how the results are affected by this weighting through an adapted sensitivity analysis. In particular, the proposed solutions and packages are obtained by heuristic analysis. The energy behaviour interaction among measures and range of measures generates an infinity of scenarios. The analysis of these scenarios involves working time and computational power. This opens an opportunity to automatise the optimum selection and to expand the criteria of the decision making process.

The proposed user-friendly tool includes simulation, comparing and visualisation sections which have been employed to obtain the aforementioned results. However, the optimisation process is not introduced yet. To introduce the statements and clauses utilised to reach the proposed final solutions according to the criteria introduced is still a not automatised task in which the "convergence speed" partially depends on the expertise and intuition of the user. Of course, the previous sensitivity analysis guide this optimisation process. Therefore, in combination with the previous future work, to integrate the optimisation tool by means of an automatised procedure would increase the value of the methodology.

The computational time to obtain all the results of the proposed scenarios is still high. A predictive tool, which is able to predict, in an accurate way, the dynamics of the processes (phenomena which are affected by the proposed modification) under study could reduce the computational time for obtaining the final solution. In this regard, some hypothesis, based on Artificial Neural Networks or similar, which could analyse simulation results and provide accurate predictions (or trends) for combination of EEMs, would generate valuable results and would reduce the computational time.

The methodology has been developed and planned to analysed hypothetical EEMs, in response to the gaps identified. However, several opportunities of energy efficiency improvement have been identified by modifying operational parameters and ways of working. The optimal way of working depends on these parameters in combination with the production input. As it is identified, the production input has high variations. In this regard, the methodology could be extended to provide operational real-time solutions in order to modify these parameters according to the specific production. Besides, hypothetical malfunctions or unexpected ways of working could be identified by comparison of the real measurements (in real-time) with the data/results provided by the simulation.

Besides, in general, the methodology could be improved by generating a deeper database of EEMs, by implementing it in a new case study, by including other relevant analysis (such as the Life Cycle Assessment) or by introducing the Technical Building Services characterisation.

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## 2017

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# Appendix A

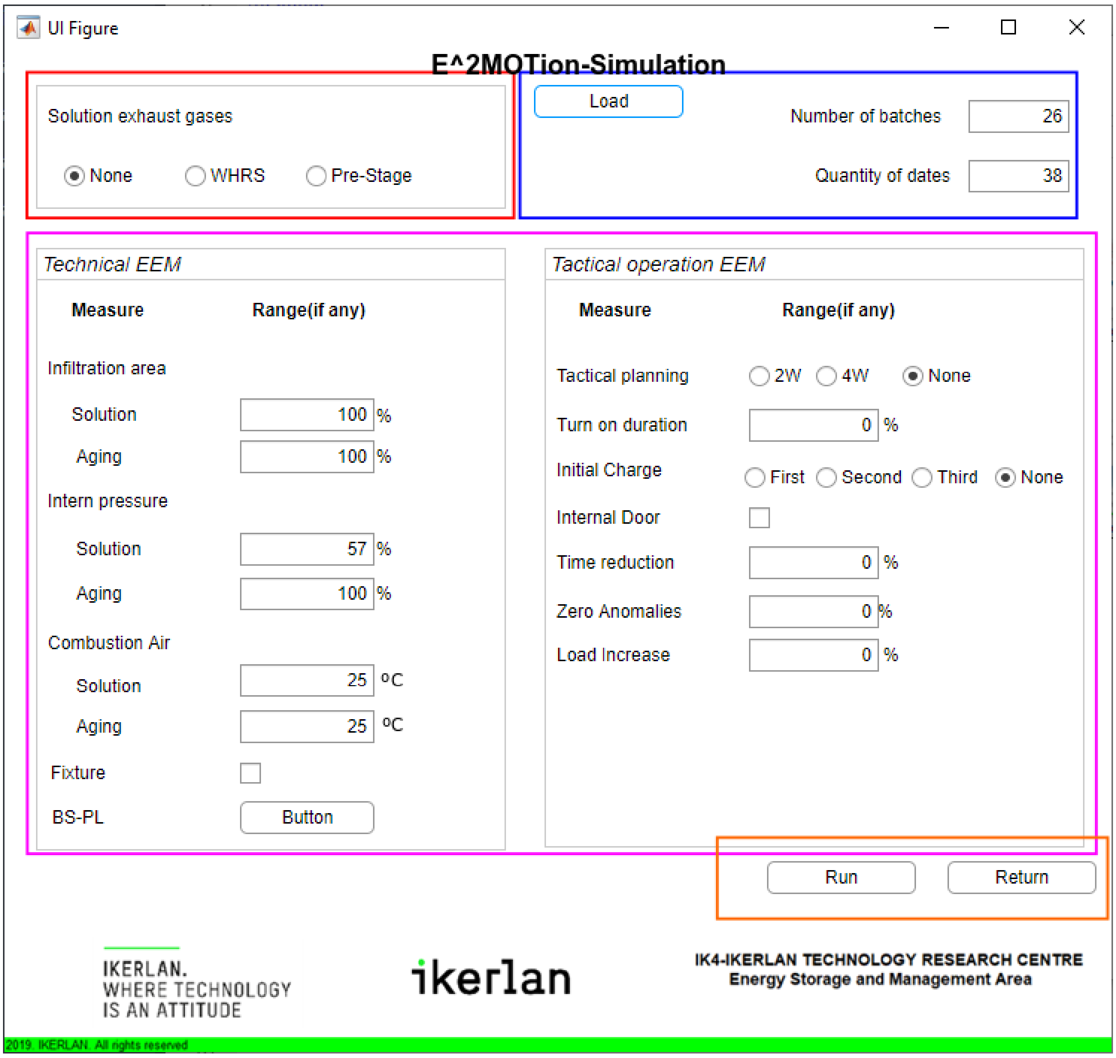
## Simulation

The first option is the simulation panel. This option allows the user to reproduce any scenario based on the identified EEMs. The main window of the simulation panel is represented in Figure A1, in which several sub-panels are represented (coloured squares are added later for a concise explanation).

Firstly, the tool requires the user to introduce the production input for the period under analysis. This production input is introduced by loading a .xlsx file which contains the values for the production load, by means of the "load" button as it is shown in the blue square in Figure A1. These data, are those which the modelled Case Study requires for including the different masses of the treated parts (amount in kilograms of aluminium parts) and the specific dates in which each batch is introduced to the first stage of the Solution Furnace. Once the file is selected, the number of batches different from zero is shown in an indicator called "number of batches" and the number of dates introduced is shown in "Quantity of dates". These indicators allow the user to obtain a small characterisation of the production input.

Once the production input is selected, the user has to select among the different options which have been identified for the main recovering flow, i.e. the exhaust gasses flow, as it is suggested in the proposed EEMs in Section 5.1.1. The options are to direct the gases to a Pre-heating stage, where load is preheated (following the respective proposed EEM), to direct this flow to a WHRS in which the energy of the exhaust gases is recovered and transferred to the Ageing Process or to keep on disposing this waste heat flow, as it is shown in the red square in Figure A1.

The last section includes the options of modifying the technical and tactical operation EEMs parameters, as shown in pink square in Figure A1, in which the user can introduce some parameter modifications. By default, this set of parameters corresponds with those of the baseline. Each parameter has to be introduced in a certain way according with the way it is modelled (temperature, percentage, option selection, etc.).



E^2MOTion-Simulation

Solution exhaust gases

● None ○ WHRS ○ Pre-Stage

Number of batches 26

Quantity of dates 38

*Technical EEM*

**Measure** **Range(if any)**

Infiltration area

Solution 100 %

Aging 100 %

Intern pressure

Solution 57 %

Aging 100 %

Combustion Air

Solution 25 ºC

Aging 25 ºC

Fixture ☐

BS-PL

*Tactical operation EEM*

**Measure** **Range(if any)**

Tactical planning ○ 2W ○ 4W ● None

Turn on duration 0 %

Initial Charge ○ First ○ Second ○ Third ● None

Internal Door ☐

Time reduction 0 %

Zero Anomalies 0 %

Load Increase 0 %

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**Figure A1** – Simulation window.

Finally, once the parameters of simulation and the production input are introduced the tool creates the internal script which generates the "launching" of the simulation by pressing the "Run" button (as shown in the red square in Figure A1). Once the simulation is finished, the tool opens a saving window to select the name of the simulation file. Next to the "Run" button there is a button called "return" so as to go back to the initial window.

## Visualisation

The next part of the tool provides the visualisation environment. The "visualisation" button in the main window guides the user through the visualisation selection steps in order to show the results. The previous section of the tool is able to save the data of each proposed scenario. In this part, the user can load a previously saved simulated scenario. The tool selects by means of the button "Load" a .mat file which contains the scenario data, as it is shown in Figure A2.

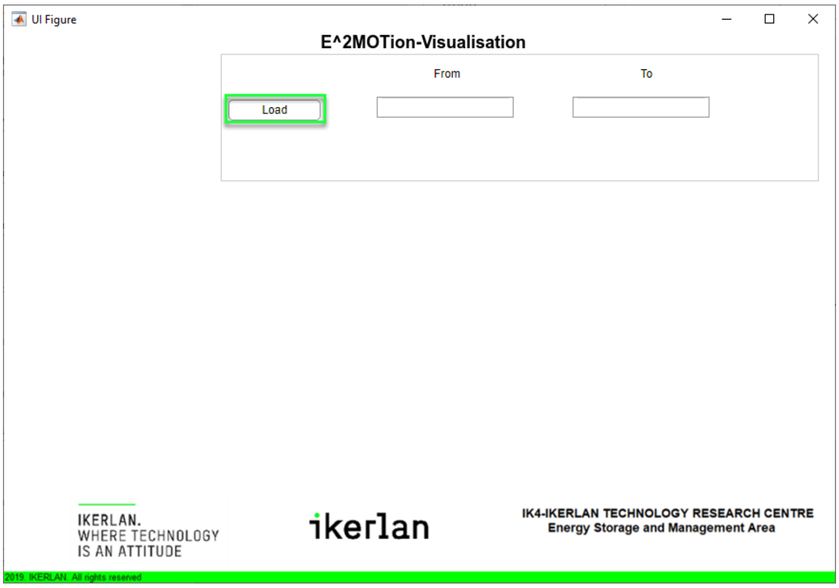
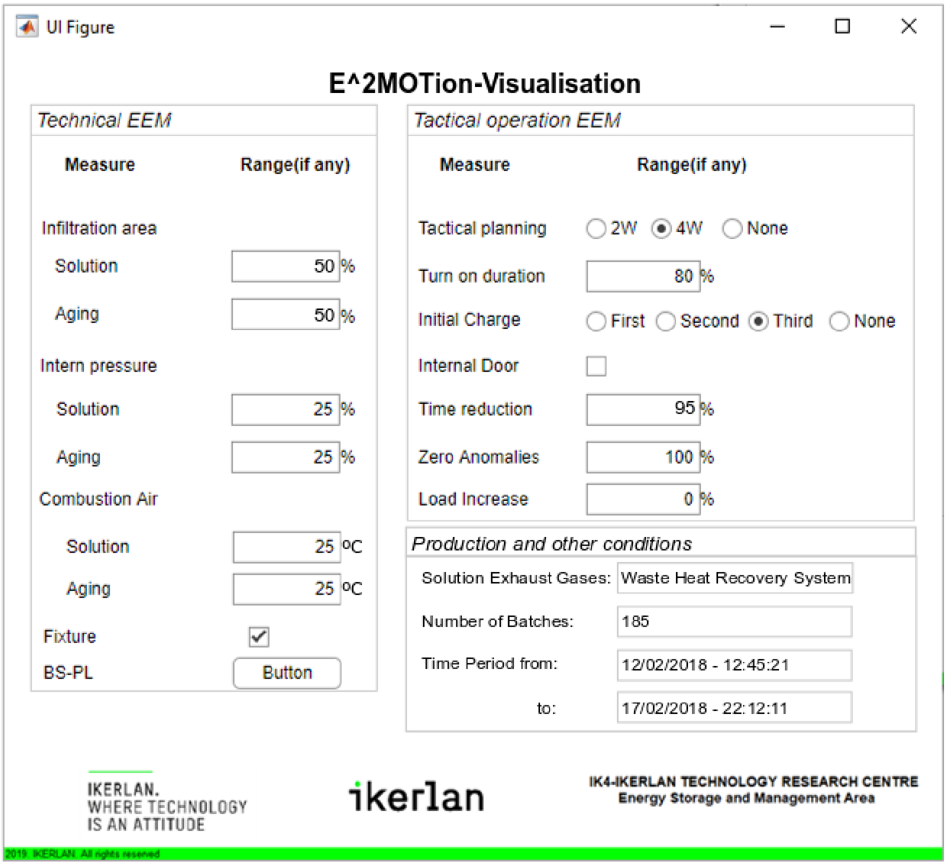


**Figure A2** – Visualisation window: parameters and production input introduction.

When the file is loaded, a new window displays the different parameters of the file that has been choosen. This new window is similar to the "Simulation window" and contains the technical and the tactical operation EEMs as well as the other simulation conditions. In this way, the user can ensure that the selected one is the correct file. This window is represented in Figure A3.

Then, the initial and final dates of the reproduced production load appear in the window the user was working before. A drop down with an amount of parameters appears in order to choose the required one to analyse. Up to three options may be



E^2MOTion-Visualisation

*Technical EEM*

| Measure | Range(if any) |
|---|---|
| Infiltration area | |
| Solution | 50 % |
| Aging | 50 % |
| Intern pressure | |
| Solution | 25 % |
| Aging | 25 % |
| Combustion Air | |
| Solution | 25 ºC |
| Aging | 25 ºC |
| Fixture | ☑ |
| BS-PL | Button |

*Tactical operation EEM*

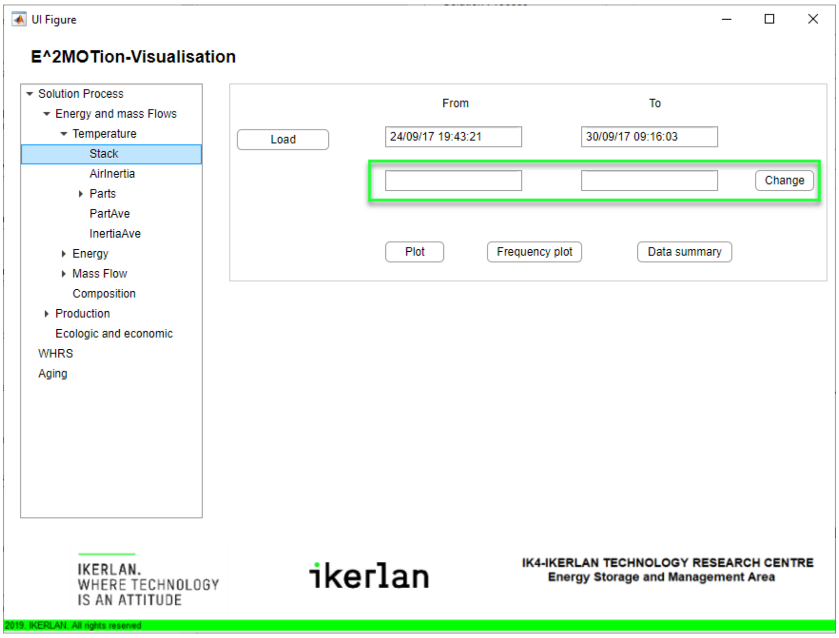
| Measure | Range(if any) |
|---|---|
| Tactical planning | ○ 2W ● 4W ○ None |
| Turn on duration | 80 % |
| Initial Charge | ○ First ○ Second ● Third ○ None |
| Internal Door | ☐ |
| Time reduction | 95 % |
| Zero Anomalies | 100 % |
| Load Increase | 0 % |

*Production and other conditions*

Solution Exhaust Gases: Waste Heat Recovery System
Number of Batches: 185
Time Period from: 12/02/2018 - 12:45:21
to: 17/02/2018 - 22:12:11

**Figure A3** – Parameters of the choosen file.

selected in relation with the kind of parameter. These options are: plot, stage-time frequency plot or show the data summary. For the "plot" option the user has to select the interval of depicting, if not, all the simulation interval will be depicted by default. All the identified and modelled variables are represented in this drop down system, such as energy and mass flows, production, or ecologic and economic indicators for each relevant process as shown Figure A4 (in this case: the solution process, the ageing process and the WHRS).



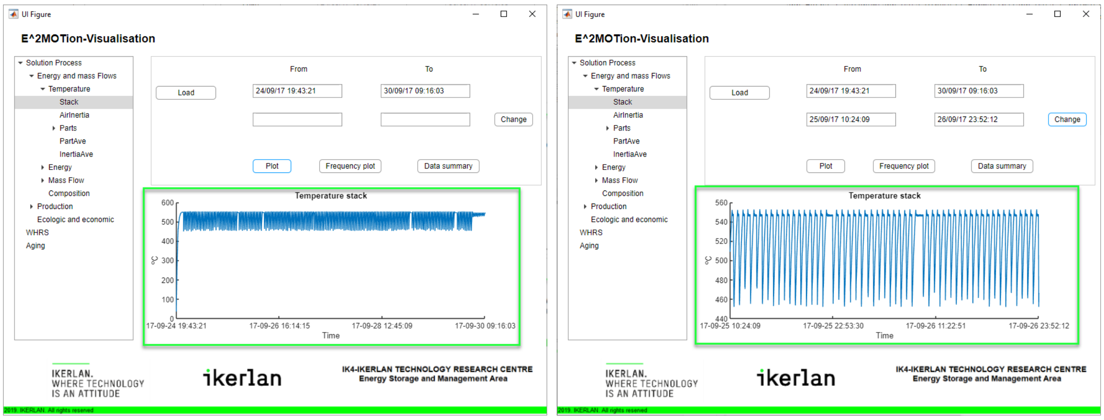
From: 24/09/17 19:43:21
To: 30/09/17 09:16:03

**Figure A4** – Parameters to choose to plot, frequency plot, or Data summary.

The three kinds of representations to visualise the data are shown in the next group of figures. In Figure A5 (a) the plot option visualisation is exemplified. The selected variable is represented for the entire period of the loaded simulation, whereas Figure A5 (b) the variable is represented for the period introduced by the user. Figure A6 shows the "Frequency plot" option, which corresponds with the frequency histograms for the theoretical stage-time (as it is represented in Chapters 4 and 5). Finally, the "Data summary" representation shows a new window with a table which contains the main data summary of the variable.

## Comparison

The next section of the tool is the comparison platform. This sub-tool requires to load three files to proceed with the comparison (red square shown in Figure A8). The first one is the baseline scenario with which the other two scenarios are confronted. The economic indicators are calculated for these two scenarios by means of a cost comparison.



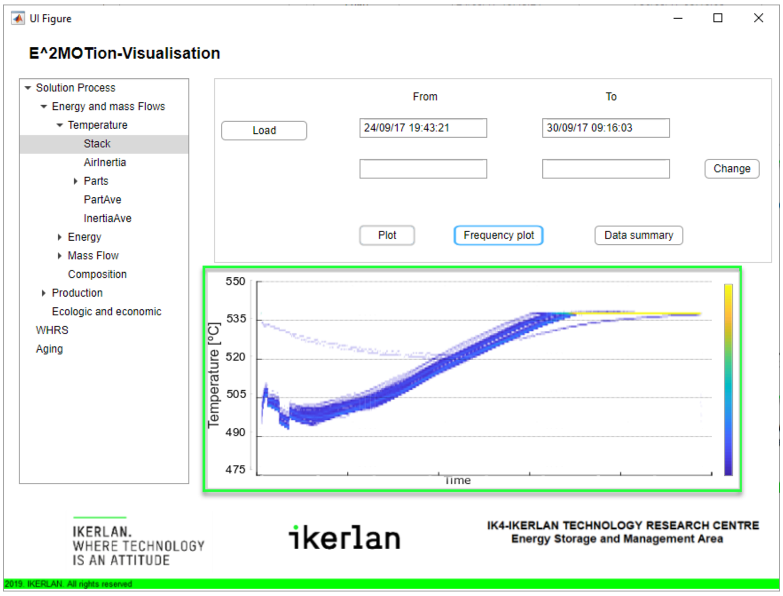
(a) From: 24/09/17 19:43:21 To: 30/09/17 09:16:03

(b) From: 24/09/17 19:43:21 To: 30/09/17 09:16:03; 25/09/17 10:24:09 to 26/09/17 23:52:12

**(a)** With the limit of dates by default of the file.

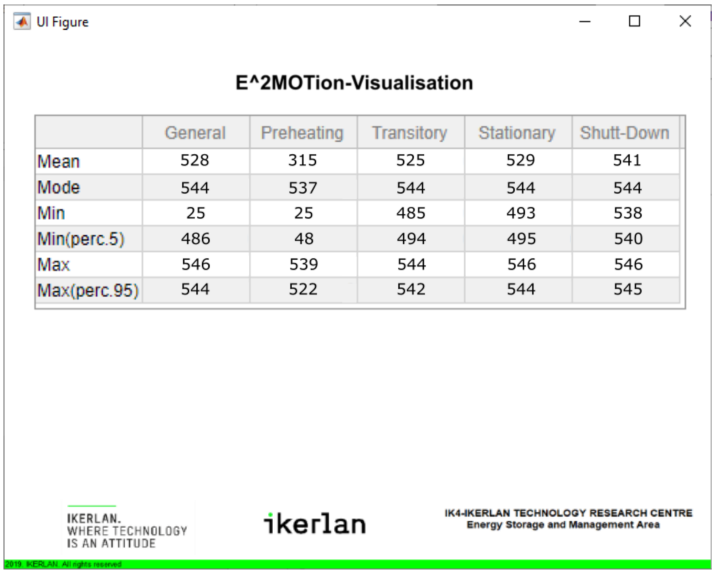
**(b)** With a limit of dates choosen by the user.

**Figure A5** – Plot of a parameter choosen by the user.



From: 24/09/17 19:43:21 To: 30/09/17 09:16:03

**Figure A6** – Frequency plot representation.



| | General | Preheating | Transitory | Stationary | Shutt-Down |
|---|---|---|---|---|---|
| Mean | 528 | 315 | 525 | 529 | 541 |
| Mode | 544 | 537 | 544 | 544 | 544 |
| Min | 25 | 25 | 485 | 493 | 538 |
| Min(perc.5) | 486 | 48 | 494 | 495 | 540 |
| Max | 546 | 539 | 544 | 546 | 546 |
| Max(perc.95) | 544 | 522 | 542 | 544 | 545 |

**Figure A7** – Table with statistical values of different stages.

Once the three files are loaded, the values of the different energy, ecological and production (purple square parameters in Figure A8) parameters appear. Besides, the respective (energy, production and ecological) relative differences are shown (orange square in Figure A8). For the economic assessment, the user has to introduce the expected cost of the two loaded scenarios (CapEx, OpEx and Cpa for the set of EEM included in the scenarios) in the table of the green square in Figure A8, although the tool provides some recommendations for these parameters. Once the economic costs are introduced, the "Run" button generates the economic KPIs (SPP, LEEC and ROI) and the remaining comparison results.

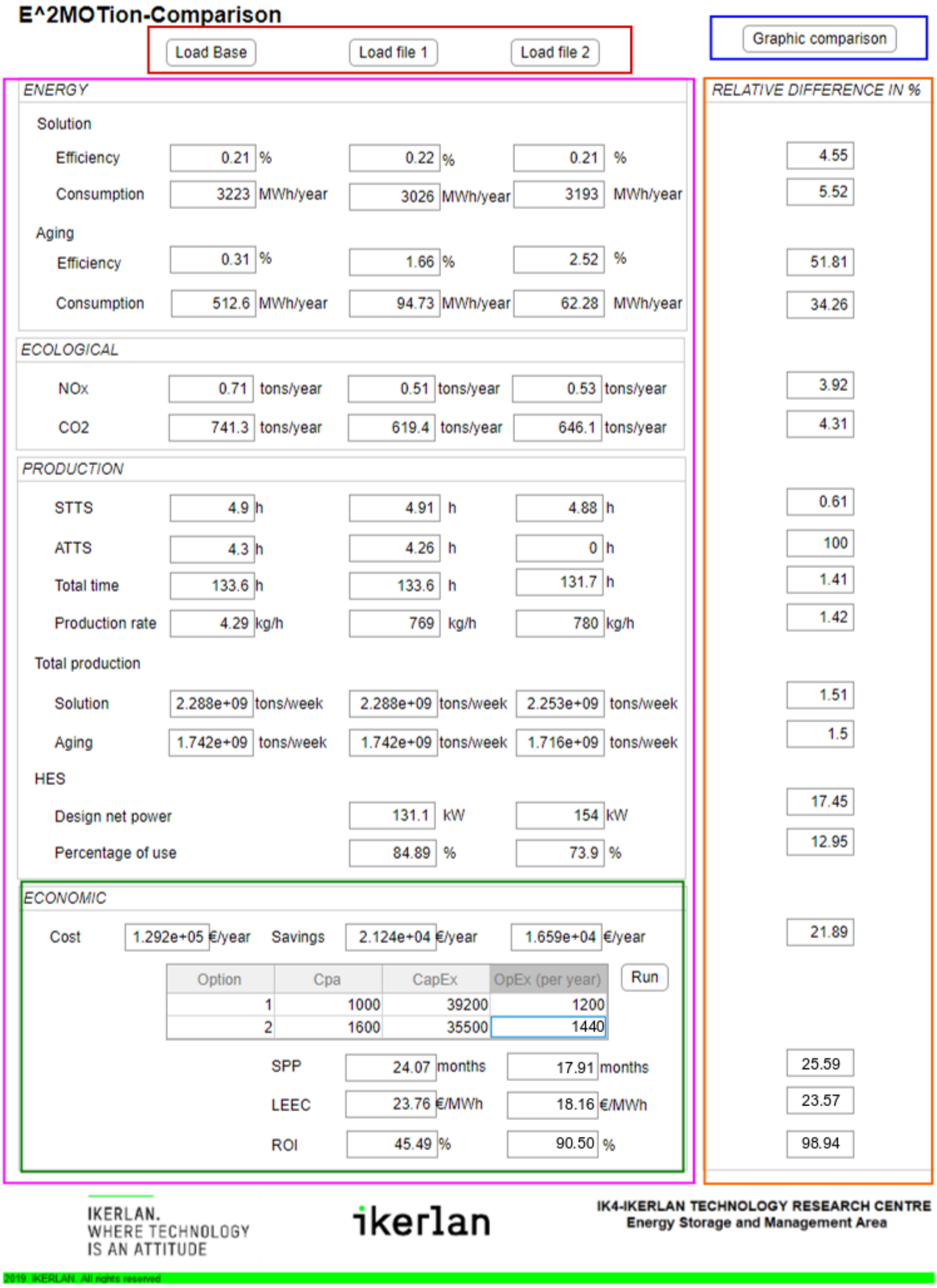
The relative difference in percentage of the values of the file 1 and file 2 have been calculated in the following way:

$$RD = \frac{F1v - F2v}{F1v} \cdot 100 \tag{6.1}$$

where $RD$ is the relative difference and $F1v$ and $F2v$ are the values of the parameters of the first and the second file.

Finally, there is another option to compare different results, which appears pushing the button "graphic comparison", as shown in the blue square in figure A8.

For this option, the user has to select a specific variable to be compared. This option shows a new window in which many files and a baseline file can be uploaded. The baseline file is only required if the user wants to represent the SPP, LEEC or ROI indicators. These indicators are calculated by comparison with the baseline's costs. Once



| | | | | RELATIVE DIFFERENCE IN % |
|---|---|---|---|---|
| **ENERGY** | | | | |
| Solution | | | | |
| Efficiency | 0.21 % | 0.22 % | 0.21 % | 4.55 |
| Consumption | 3223 MWh/year | 3026 MWh/year | 3193 MWh/year | 5.52 |
| Aging | | | | |
| Efficiency | 0.31 % | 1.66 % | 2.52 % | 51.81 |
| Consumption | 512.6 MWh/year | 94.73 MWh/year | 62.28 MWh/year | 34.26 |
| **ECOLOGICAL** | | | | |
| NOx | 0.71 tons/year | 0.51 tons/year | 0.53 tons/year | 3.92 |
| CO2 | 741.3 tons/year | 619.4 tons/year | 646.1 tons/year | 4.31 |
| **PRODUCTION** | | | | |
| STTS | 4.9 h | 4.91 h | 4.88 h | 0.61 |
| ATTS | 4.3 h | 4.26 h | 0 h | 100 |
| Total time | 133.6 h | 133.6 h | 131.7 h | 1.41 |
| Production rate | 4.29 kg/h | 769 kg/h | 780 kg/h | 1.42 |
| Total production | | | | |
| Solution | 2.288e+09 tons/week | 2.288e+09 tons/week | 2.253e+09 tons/week | 1.51 |
| Aging | 1.742e+09 tons/week | 1.742e+09 tons/week | 1.716e+09 tons/week | 1.5 |
| HES | | | | |
| Design net power | | 131.1 kW | 154 kW | 17.45 |
| Percentage of use | | 84.89 % | 73.9 % | 12.95 |
| **ECONOMIC** | | | | |
| Cost | 1.292e+05 €/year | Savings 2.124e+04 €/year | 1.659e+04 €/year | 21.89 |

| Option | Cpa | CapEx | OpEx (per year) |
|---|---|---|---|
| 1 | 1000 | 39200 | 1200 |
| 2 | 1600 | 35500 | 1440 |

| | | | |
|---|---|---|---|
| SPP | 24.07 months | 17.91 months | 25.59 |
| LEEC | 23.76 €/MWh | 18.16 €/MWh | 23.57 |
| ROI | 45.49 % | 90.50 % | 98.94 |

**Figure A8** – Comparison window.

the variable is picked (the options are the same that were represented in the previous window), the tool represent the selected variable for the uploaded options as it is shown in Figure A9.

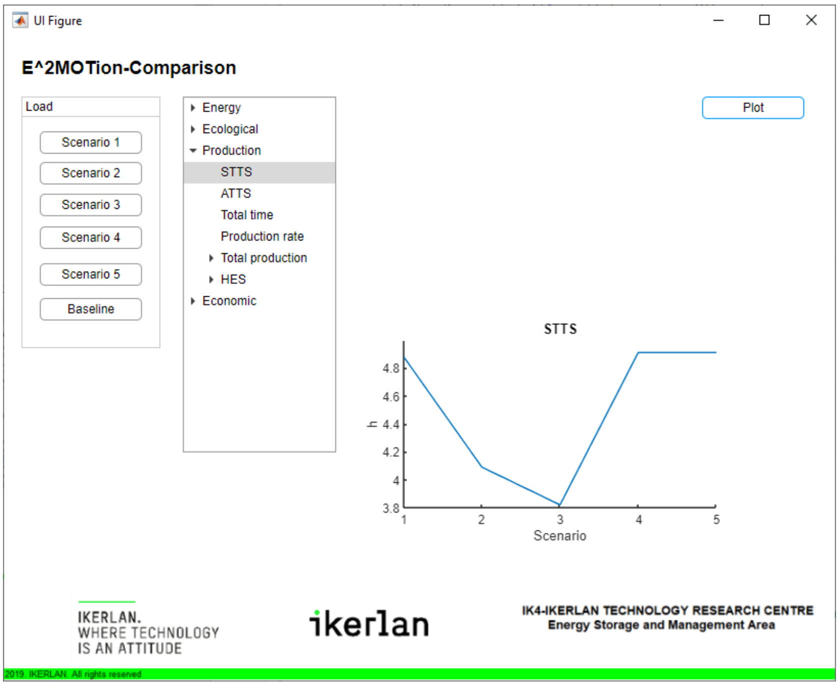


**Figure A9** – Graphic for each value of the choosen variable.

In the case of SPP, LEEC or ROI indicators, before plotting the values, a table appears in which the user has to introduce the Cpa, CapEx and OpEx values for each escenario, except for the baseline. Once all the gaps are filled in and the plot button is pushed, a graphic appears with the values of the parameter for each scenario. This graphic is interactive with the table and allows to modify the plotted data as the cost parameters are modified.