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Building Digital Twins to Overcome Digitalization Barriers for Automating Construction Site Management

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Abstract: Construction sites are highly unpredictable environments involving a wide variety of stakeholders with complex information exchanges, which lead to the well-known inefficiencies and unproductivity of the construction sector. The adoption of Building Digital Twins (BDT) in the construction site is a promising solution to this issue, by automating data acquisition and knowledge extraction processes and providing what-if scenario simulation capabilities. Furthermore, the current research sets the principles to define, replicate, and scale-up the architecture of a Building Digital Twin Platform (BDTP), conceived as a scalar ecosystem, which allows to seamlessly manage on-site construction processes, integrating cross-cutting domains for the construction site optimization (Progress monitoring, Quality control, Operational Health and Safety, Equipment control, and Production planning). The starting point of the research is a comprehensive diagnosis of on-site process inefficiencies and the barriers to its digitalization leading to the user requirements, which have been underpinned by questionnaires and interviews addressed within an open innovation user-centered approach around Living Labs. The research has been conceived following the Design Science Research (DSR) methodology and based on the Plan-Do-Check-Act (PDCA) analysis for the continuous improvement of the construction process. By means of the adoption of the standard Business Process Model and Notation (BPMN), based on the BDTP architecture, the research has resulted in BPMN workflows stemmed from the Digital Twin (DT) where the DT itself is an actor in a service-oriented data-exchange workflow. Moreover, the use of a BDTP can pave the way for the transition from user-driven construction management to hybrid management, coexisting with both human and digital actors and merging expert knowledge with artificial intelligence techniques.

Keywords: digital twin (DT); building digital twin (BDT); plan-do-check-act (PDCA); business process model and notation (BPMN); construction process; site management

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1. Introduction

Although, in many countries, the construction industry contributes significantly (5–10%) to the national Gross Domestic Product (GDP), poor productivity is considered a vital aspect of failure [1], being, for example, the poorest-performing sector in Europe in terms of productivity [2]. Given the challenges faced by the construction sector in embracing digital innovations and technologies, it is often considered among the least digitized industries, characterized by a sluggish pace in adopting innovations [3,4]. The global McKinsey Institute identified that the construction sector needs to improve both productivity and profitability [5]. These inefficiencies and weaknesses particularly affect the construction site process, although there are many influencing factors, such as design and planning problems, inadequate work methods, and planning of human and material resources or problems arising from safety control [6]. Accordingly, this research starts with the identification of the foremost barriers that arise in the construction site in order to address the measures aimed to optimize this phase of the building lifecycle.

The adoption and application of DT, a promising tool, although far from being widespread in construction, can enable scenario simulation-based planning and optimization [7] to optimize the process. Hence, a DT-driven strategy might increase the productivity of the construction sector through predictive analytics and help address many of the challenges faced by the sector [8]. In particular, the automation of the data acquisition and knowledge extraction enabled by the DT results is crucial to effectively tackle the on-site phase, one of the most critical in construction. This would allow real situational awareness through the simulation of the process in a virtual model for decision-making in real-time.

While a properly planned construction process is important for the productivity of the sector, it is equally important to verify that it matches the as-performed (i.e., the quality of the products and efficiency of the processes was as expected) for the diverse aspects of the site construction (schedule, quality, safety assurance…). Additionally, if a deviation in the plan is detected, this difficulty increases exponentially since the impact of this deviation must be assessed and corrective actions defined without losing quality or safety. Once the work process has begun, the capacity to react is very limited, greatly affecting productivity.

Therefore, one of the main objectives of this paper is to research the potential of DTs for the optimization and improvement of the on-site construction process' efficiency in all its domains based on a comprehensive diagnosis of the inefficiencies of this process and the barriers to its digitalization. The analysis of technologies for on-site digitization will allow the drafting of the requirements of the DT from the user's perspective. It is a matter of conceptualizing the optimal construction process, digitized and eventually automated that will overcome these barriers, establishing the basis for the development of a DT for the management of building construction processes, considering the real on-site context.

The study introduces a holistic and comprehensive methodology for implementing the digital twin concept in the construction of buildings, aiming to optimize the on-site construction phase. It establishes a conceptual framework for the BDTP, which enables the agents to track what is occurring on-site in real-time. In this way, they will be able to know the ongoing progress, the work quality, the worker's location, the state of the materials and equipment, and the safety conditions, among other aspects. Several methodologies, approaches, principles, and digital tools are leveraged in this paper to draft the DBTP architecture. The research relies on the PDCA analysis for continuous improvement of the process. Additionally, the elaboration of particular workflows through the standard BPMN representing the different subprocesses coincident on site and their interdependencies will lead to drawing the BDT for automation of the construction site management.

This DT-based approach is conceived as a scalar ecosystem of Digital Twin, which might span several sites or exchange information with city-scale DTs. This approach of the DT ecosystem allows the orchestration of information generated on-site in real time from different areas involved at the same time in the on-site construction.

In summary, starting from the research problem produced by the lack of efficiency in the construction sector, this research focuses on the recognized DSR Methodology, whose novelty lies in combining different systems and techniques used in previous research, such as PDCA, Living Labs, or BPMN. It aims to drive a common approach for a BDTP architecture intended to boost the automation of the on-site construction process, where both digital and human actors can interact through the platform. The research contributes especially to the state of the art due to the challenging application of DT-driven construction management, considering an innovative cross-cutting approach of the disciplines involved in construction management.

This research is underpinned by the approach addressed in the BIM2TWIN (Optimal Construction Management and Production Control) research project [9] funded by the European Commission. The developments made over the project have evolved herein towards a systematic methodology to draft the BPMN workflows of the construction process as a basis of the BDTP for construction site management.

The remainder of the paper is structured as follows: Section 2 addresses the background, concepts, and methods involved in the methodology. Section 3 presents the methodology adopted for this study. Section 4 presents the results of the research process. Section 5 provides the conclusions of the research conducted for the automation of Construction Management through the BDT conceptualization. Finally, Section 6 concludes the paper with an approach to the opportunities for the replicability and upscaling of the research findings.

2. Background

Considering the barriers and inefficiencies of the sector, the use of Building Information Modeling (BIM) methodology could allow for having 3D virtual models for designing and planning the construction process. At present, the BIM methodology is focused on the design phase, not fully exploiting its potential in the on-site construction process. Aiming at automated site management through Digital Twins, the BPMN 2.0 [10] graphical standard has been used for designing and validating the process workflows, which were optimized and particularized through a methodological development based on BIM and DT. This process of continuous and optimized improvement of the site process is based on PDCA (plan-do-check-act or plan-do-check-adjust), a systematic process to obtain valuable learning and knowledge for the continuous improvement of a product, process, or service. This conceptual framework developed in this study allows the integration of the BIM methodology in the construction process itself by using it concretely in Occupational Health and Safety (OHS) and Planning and Quality control activities, among others.

2.1. Construction Site Process

The construction industry encounters noteworthy challenges in relation to the strategic planning and efficient project management of construction projects, with a particular emphasis on the construction on-site [11]. Monitoring progress during this phase ensures that the construction aligns with the project specifications, meets the required standards, and adheres to the scheduled timelines. Moreover, there is the challenge of aligning with the functional specifications of the installations. This monitoring activity plays a pivotal role in achieving high-quality construction and typically represents the lengthiest phase in the project management life cycle during on-site execution.

Currently, the construction phase faces a lack of digital tools for effectively monitoring work progress. Despite the emergence of some digital tools designed for this task [12,13], they are often employed in isolation with manual input of information by users. Furthermore, their integration within the construction industry is constrained, as evidenced by a mere 12% of organizations recognizing the implementation of a comprehensive operational processes' digital transformation strategy [14]. Effective oversight and regulation of a project play a crucial role in guaranteeing the efficiency and positive outcomes of the execution procedure. Data derived from monitoring activities are indispensable for tracking information pertaining to quality, safety, efficiency, and productivity. However, the predominant methods employed to oversee the development and progression of tasks primarily involve manual procedures and depend on visual inspections. This manual approach makes the control process susceptible to errors and is time-consuming [15]. In addition, the challenging aspect of the project lies in the inadequate collaboration and communication among all stakeholders, making it challenging to effectively control the project's progress. The inadequacies in overseeing and monitoring construction activities lead to 75% of cost overruns in the construction process, attributed to shortcomings in construction management [16]. Generally, building contractors utilize Critical Path Method (CPM) scheduling tools for project planning. Nevertheless, the CPM approach requires skilled and experienced personnel to define task durations and relationships between them [17]. Despite the visualization capabilities of CPM tools, they lack effective mechanisms for automatic work planning adjustments [18], necessitating manual data entry.

The lack of work planning and management of equipment, construction machines, and materials often results in work stoppages due to the loss, unavailability, or unknown location of essential materials and machinery. The timely and adequate supply of materials significantly influences the successful execution and quality of the work. Conversely, inadequate material supply leads to work discontinuity, reduced worker performance, execution disorder, and the presence of unfinished tasks, consequently causing quality issues. This situation arises because the completion of work is hindered by the existence of other incomplete tasks. At present, in the construction sector, the planning, supervision, and monitoring of the use of machinery and materials are based exclusively on the knowledge and experience of site managers or foremen. However, these decisions are made with constrained awareness of real-time on-site conditions and amidst significant indefiniteness [19–21]. Several studies indicate that the major inefficiencies in controlling equipment on construction sites stem from inadequate control and planning of large equipment and machinery, particularly cranes or equipment for significant earthworks during the foundation and excavation phases of a building [22–24].

Lack of safety measures and risk prevention in the construction workplace results in a minimum of 60,000 deaths worldwide [25]. Recent research shows that a considerable portion of safety risks remain unacknowledged and unaddressed within intricate and dynamic construction environments. Additionally, construction personnel frequently overlook a considerable portion of potential hazards within their workplace, posing challenges to effectively managing the safety conditions of this process on-site [26,27]. In this line, different studies have been conducted, demonstrating the potential of BIM-based tools in facilitating the entire construction life cycle and in occupational health and safety [28,29]. However, the use of these tools in the construction sector is still very limited and, in many cases, non-existent.

Based on the construction site process presented and the identification of the main and most important fields or areas of the process, it has been possible to identify the domains on which this study focuses in order to optimize the on-site construction phase, as follows: Progress monitoring, Quality control, Operational Health and Safety, Equipment control, and Production planning.

2.2. Building Digital Twin (BDT)

A DT is a virtual replica of a physical asset, and one of its main features is the ability to simulate its behavior under different input data and working conditions. In contrast to theoretical simulations, which rely on different input assumptions, a digital twin is fed with real data coming from the physical world by means of sensors or other inputs. The concept is not entirely new, as in the 1960s, NASA introduced the concept for the first time in the Apollo mission [30]. But in recent times, its potential has become more evident thanks to the maturity reached in artificial intelligence (AI), Big Data, and the Internet of Things (IoT), within the umbrella of Industry 4.0.

The DT concept has a direct translation to the construction industry, where the physical asset is a building, or any built asset, or any of its constituents; hence, the concept of BDT has been recently coined under the umbrella of the Building Digital Twin Association (BDTA) [31]. It has strong links with the BIM concept, which was born at the end of the last century but only started to gain real popularity and adoption after 2010, with the advancements in digitalization and computational power. However, there is frequently a lack of clarity regarding the distinction between BIM and DT or BDT, with these terms often treated interchangeably. BIM is concerned with portraying the physical or functional attributes of a constructed asset (hierarchy of objects and spatial relationships, attributes, and geometrical representation). In contrast, a DT focuses on the operational aspect of the asset (how it behaves and evolves) by linking the virtual model to real-time data.

Considering how this integration of real data is achieved, different maturity levels for a DT can be identified as follows [32,33]: (1) Descriptive: the DT collects data and informs about what has happened; (2) Informative: it analyzes and aggregates the data creating insights of higher value; (3) Predictive: based on a simulation model fed with the data it can predict what will happen in the future; (4) Prescriptive: it can create scenarios based on those simulations and propose or assist on the best decisions; and (5) Transformative: it can autonomously take decisions and implement actions.

As the DT maturity level increases, AI techniques, such as Deep Learning (DL) or Machine Learning (ML), are more strongly integrated into the DT. To achieve this, the DT must embed a knowledge model of the behavior of the physical asset, on top of which predictions are run through simulations or rule-based systems that embed expert knowledge. Thus, in the case of a BDT, the physical and functional representation provided by the BIM must be linked to the expert knowledge of the domain under consideration (building construction, operation, energy management. . .). A single BIM model could yield different BDT domain-specific BDT models, as presented in Figure 1, elaborated expressly by the authors to clearly represent this point (Figure 1), including concepts such as defect, quality, or delay for the construction process. Finally, this theoretical model must be fed with real-time data and interpreted for decision-making.

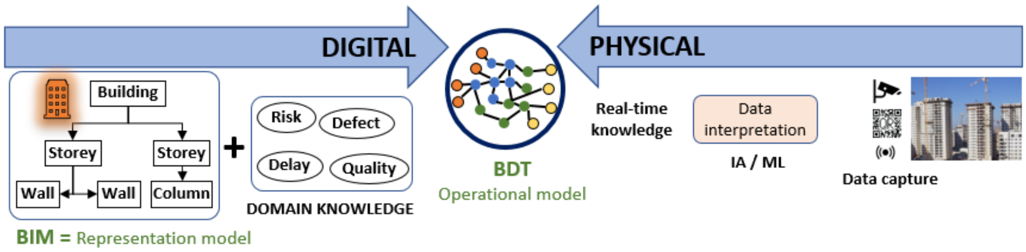


Figure 1. BIM vs. BDT.

2.3. BPMN

BPMN is a standard notation for modeling business processes using a common graphical notation. It uses a flowcharting technique that resembles activity diagrams in UML (Unified Modelling Language). The objective is to facilitate communication between technical users and business experts by offering a notation that is easily understandable to business users while still capable of representing intricate process semantics. It is widely used within buildingSMART International (bSI) [34] to model BIM processes. Thus, it seems a suitable tool for modeling the proposed DBT-driven construction process.

Although the standard is huge in terms of types of symbols, Figure 2 highlights the most relevant ones for this work: a pool is a graphical container for partitioning a set of activities from other activities, which could be organized in (swim)lanes, which represents participants (actors). Each actor performs tasks, which sometimes may be grouped into bigger subprocesses. Additionally, a task can be performed in a single step or in several loops or iterations. The workflow starts either manually or by programmed/scheduled or event-based actions, and the collaboration between actors is implemented through message or data exchanges. There could also be conditional gates to control the flow execution, depending on some conditions.

Then, each item can be further configured (Figure 3). For instance, a task could be specialized in a manual task (out of any digital context), a user task (performed by humans using digital tools, e.g., sending an email), a service task (e.g., invoking a web service), a business rule task (execute some business logic), and a script task (an automated activity).

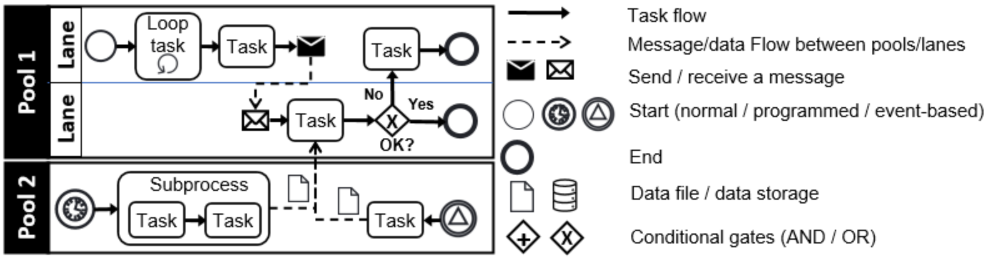


Figure 2. Main BPMN concepts applied in this research [10].

Figure 3. Task types in BPMN 2.0 [10].

2.4. PDCA (Plan, Do, Check, Act)

The PDCA continuous improvement and assessment system ("Plan–Do–Check–Act" or "Plan–Do–Check–adjust"), and beyond the original definition, the PDSA cycle (Plan-Do-Study-Act) represents a systematic approach formulated to acquire valuable insights and knowledge, contributing to the ongoing refinement of a product, process, or service [35]. Another term for this cycle is the Deming Cycle, named after W. Edwards Deming, who introduced this concept in Japan during the 1950s [36] as part of the modern Quality Control theory.

PDCA is a four-step management process (Plan, Do, Check, Act) intended to enable control and support continuous improvement in a product or process [37]. This is envisioned as an endless cycle, forming a feedback loop for teams to evaluate their capability to attain and enhance outcomes. It relies on a scientific approach, encompassing the proposal of a change, the execution of the change, the measurement of outcomes, and the necessary adjustments [38].

This methodology has been adopted in many disciplines, being a cornerstone in Lean Construction, which is based on the generation of maximum value through the removal of waste, focusing on streamlining the construction flows. The method PDCA herein applied is oriented to the continuous quality improvement of the construction process thanks to an iterative process, which, overall, starts from the planning of the process design (Plan) followed by the execution of the plan, in this case, construction of the asset (Do). This process is implemented with an expected outcome, which is then measured against the actual outcome and verified with the impact of the variance (Check). If there is a difference between the expected and actual outcomes, some countermeasures are drawn and integrated into the revised process, and the iterative process is continued for the continuous upgrading of the construction process. Particularly, the application of these principles for the continuous improvement of the construction site leads to substantial benefits due to the importance of short cycles of checking and implementing changes to improve the on-site construction.

Additionally, PDCA can be considered within a multiscale approach, i.e., applied to the whole process or subprocesses separately. The multidimensionality allows not only to plan long-term but also to specifically design check cycles in a short time, enabling to control the activities on a daily or weekly basis, as Lean Construction draws. These short periods require real or nearly real-time monitoring to be continuously compared with the expected information, predict the performance, and implement suitable changes to iteratively improve the process. Nevertheless, this information of the current state must be as accurate as possible to obtain valuable predictions.

The array of recently emerging technologies available for data gathering in construction sites, as well as the adoption of IoT systems, enables to obtain accurate and real-time information about the on-site process (Do). However, to obtain value in data, the information gathered needs to be properly managed in complex and interrelated processes. In this sense, powerful techniques for data assessment, such as AI and ML, allow us to smoothly check the results, compare them with the planned situation, and even predict future behavior (Check). The automation of the checking process makes it possible to iteratively adopt changes in nearly real-time, leading to a more efficient and lean process (Act).

Accordingly, the use of BDT intended to manage on-site construction gains leverage of real data monitoring and AI-driven technologies supported by Data Analytics. Therefore, the BDT-driven construction process fits the PDCA model for continuous improvement, and BDT workflows must be adapted to this purpose in order to implement continuous improvement cycles in on-site process management.

Finally, regarding the PDCA evaluation and continuous improvement system itself, this can be a compelling tool to apply to the scientific method to objectively measure the research's results if different sources of information are used. Moen et al. [39] describe the PDCA cycle as a progressive iteration of the scientific method, furnishing a structure for applying improvement methodologies and tools in accordance with the theory of knowledge. Therefore, it underscores the iterative learning process encompassing both deductive and inductive learning, offering a straightforward approach for individuals to empower themselves to initiate actions conducive to process improvement. According to this statement, the PDCA analysis has been applied in this research with the intention of fine-tuning the data, which is accomplished via the Living Labs ecosystem and contributing to the scientific method to make the process more replicable.

3. Methodology

The methodology presented in this paper intended for the adoption of BDT for the automation of on-site construction management is based on the DSR [40] approach. It focuses on the design and development of artifacts, processes, and systems with the explicit intent of improving the functional performance of processes and solving concrete problems [41].

In DSR, differing from explanatory scientific inquiry, academic research objectives embrace a more pragmatic perspective [42]. When dealing with problems associated with physical objects or specific issues, solutions can manifest through design drawings, 3D geometrical models, or engineering diagrams. For action-related problems, representations can involve flow diagrams and software solutions [43]. March et al. [44] described two fundamental activities that characterize the DSR approach: devising a solution and scrutinizing the effectiveness of that solution. According to Hevner et al. [45], a procedure inherently functions in an iterative and incremental manner, wherein the assessment stage furnishes vital feedback to the construction phase on-site, encompassing aspects related to both the development process's quality and the solution per se. The DSR methodology focuses on creating new solutions to specific problems, helping to solve application and relevance issues that arise in the construction sector.

According to Vom Brocke et al. [46], the DSR methodology is deployed through five stages, as shown in Figure 4.

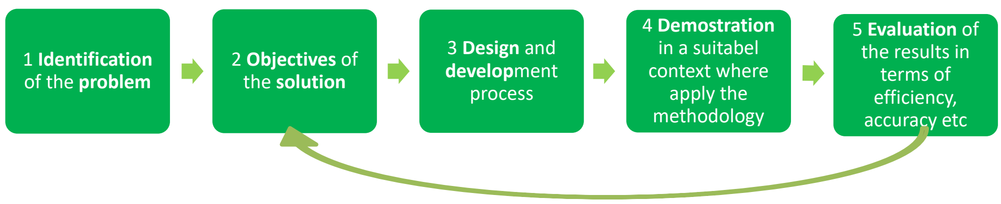


Figure 4. Stages of the DSR methodology.

The five stages of the DSR methodology are structured to provide a solution to the problem of inefficiency presented by the AECO (Architecture, Engineering, Construction, and Operations) industry, focused specifically on this research in the construction site (Physical Twin), with a global and comprehensive approach to the application of the DT concept. To this end, various resources are articulated, such as the Living Lab ecosystem, which helps to identify the different aspects of the problem and demonstrate solutions based on real cases that are applied and synthesized in different focus groups. The objective of developing the BDTP is supported by an iterative evaluation process through PDCA. But what is relevant and complex in the process is devising and optimizing among the different agents the Design and Development of the conceptual framework to develop the BDTP through workflows based on BPMN (filtered through the Living Lab and continuously evaluated by PDCA), as shown in Figure 5, which reflects the most relevant results of this article.

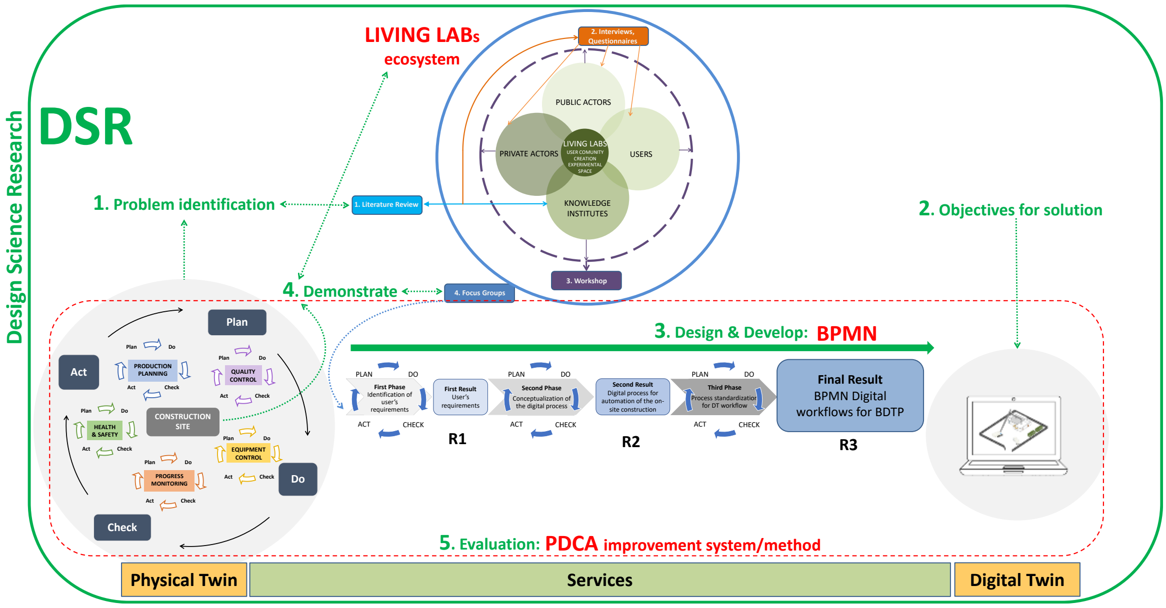


Figure 5. Abstract Graphic of the DSR Methodology applied to this research.

This research has been supported by the philosophy of Living Labs, introducing a novel concept to address the collaboration among stakeholders, aiming to integrate the four helixes of society: final users, governmental entities, private entities, and educational institutions (Figure 6). The Living Labs ecosystem strives to foster innovative processes where users actively engage as participants rather than passive recipients. Serving as a practical testbed, they respond to pre-identified needs through surveys, interviews, and workshops involving stakeholders [47–49]. Living Labs have been utilized in the past to support the integration of cutting-edge technologies in the construction industry [50]. Additionally, they have played a crucial role in the creation of sophisticated integrated platforms grounded in BIM, as exemplified in this specific instance [51].

Within this overall context of the DSR methodology, which allows the tackling of the drafting of a BDTP structure for optimizing the construction site management, the current paper especially contributes to the third stage of the methodology, Design and Development of the solution to the identified problem. The approach for the development of the solution is herein addressed in the research as an array of steps that result in intermediate and final findings, as presented in Figure 7, elaborated by the authors for this purpose. Each step of the process leads to a standalone outcome, which feeds to the following step, giving the BPMN workflows as the main outcome, setting the basis for a BDTP architecture intended to automate construction site management.

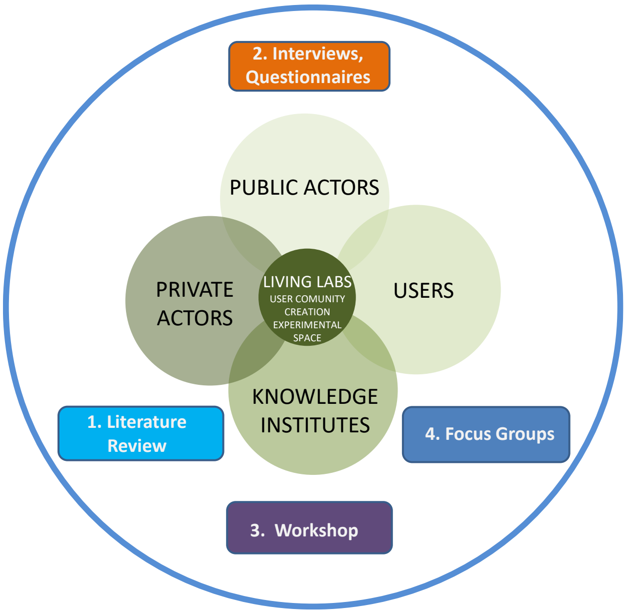


Figure 6. The Living Lab ecosystem used in the methodology reflects the first steps of the research.

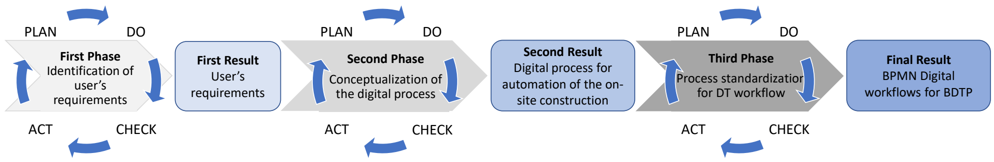


Figure 7. Deployment of the Design and Development Phase of DSR into Phases and Results based on the PDCA improvement process.

The three steps of the aforementioned process are summarized hereafter:

- Identification of user's requirements for Building Digital Twin. The objective in the first phase is the achievement of the necessary User Requirements to improve the execution process of the construction site. These have been defined from documentary analyses and literature reviews by conducting surveys, interviews, workshops, and focus groups on the Living Labs;
- Conceptualization of the digital process for on-site construction. The identified requirements lead to the second phase, where the digital process is conceptualized and broken down into tasks performed by actors to meet the requirements previously defined. In this stage, the tasks, agents, exchanged information, and dependencies between tasks have been outlined and represented using a graphical language;
- Process standardization for Digital Twin workflow. The DT is a technological solution that has the capability to help improve the construction process and manage new digital processes and their integration with other existing ones. Therefore, this technology, which entirely fits the goal of this paper, has been considered the cornerstone of the research, leading to the design and development of the solution as part of the DSR methodology applied in this research. This phase consists of standardizing the digital processes for automation and providing a solution to the identified requirements in a way that is compatible with the architecture of a DT. For this, BPMN notation has been utilized as a suitable solution for defining the workflows that drive the BDTP architecture for construction site management.

Additionally, the PDCA analysis was applied at each stage in order to fine-tune the results and minimize bias. This involves applying an iterative process of checking and validating the information elicited by the stakeholders based on the user's perspective as part of the context of Living Labs.

The current research provides intermediate results that are standalone and valuable independently for contributing to the State of the Art: the user's requirements for BDTP and the Digital process for automation of the on-site construction. Beyond these results, the main findings of the research are the generic BPMN diagrams for on-site construction management, according to the PDCA stages of the process.

3.1. Phase 1. Identification of User's Requirements for Building Digital Twin

Using the DSR approach, the research methods used in this phase included documentary analyses and literature reviews, as well as surveys, interviews, workshops, and focus groups. These initiatives are nurtured within the Living Lab's ecosystem, wherein the identification of inefficiencies in on-site construction processes, along with the recognition of barriers and opportunities for digitizing the construction sector, transforms into a collaborative and consensus-driven process. This approach ensures that digital products (platforms/software) are tailored to meet the needs of end users. The constant feedback from users facilitates testing and evolution, aiming for the most optimal version in each specific case.

According to the prescribed procedures of the DSR methodology, an initial step involves conducting an exhaustive literature review encompassing all facets relevant to the research's objective development. The state-of-the-art analysis focused on issues related to the usual practices and procedures during the on-site construction phase, the digital transformation of construction, and specifically, the identification of shortcomings, methodologies, or frameworks pertaining to site administration, engaged stakeholders, the dynamics between processes and entities, and related facets. The extensively scrutinized body of literature has particularly delved into the subsequent domains: prevalent practices in on-site construction, oversight of work advancement, regulation of work progression/quality, identification/prevention of safety and risks, coordination and oversight of equipment deployment, strategic planning of resources and tasks, and DTs. The key aim of scrutinizing the literature is to precisely identify critical inefficiencies influencing the construction phase and delineate the primary barriers hampering the implementation of digital technologies in construction activities. This forms the foundation for defining user requirements for the BDT platform.

Based on the review of the existing literature concerning construction processes, the current practices within the sector and their inefficiencies have been discerned. Then, a questionnaire was formulated to delve deeper into the understanding of inefficiencies impacting the construction phase and the obstacles hindering on-site construction digitization. The questionnaire was disseminated at the European level, incorporating participation from select Latin American countries to encompass a diverse array of perspectives. This outreach involved contacting companies in the construction sector engaged in various phases of the construction process and leveraging social networks. All the questions in the questionnaire have been formulated to maintain the same structure. In order to carry out a quantitative analysis of the results obtained in the questionnaires, a numerical scale was assigned to the different answers (ranging from 0 to 10, with 0 indicating no importance at all and 10 representing the utmost importance). This approach facilitated the acquisition of a numerical assessment regarding the significance of various aspects under consideration. As required by the DSR Methodology, this assessment obtained has been contrasted with personnel involved in the construction phase on-site by means of several workshops and interviews carried out in three countries (Finland, France, and Spain) using the Living Labs ecosystem created. In this way, the quantitative results have been transformed into qualitative results by addressing the four helixes involved in the Living Labs, governmental entities, private entities, and educational institutions in relation to the end users of the construction works phase. Thus, the requirements from the user's point of view have been specified in an active way and based on their experiences in previous related cases and have been adjusted by applying PDCA.

In fact, the platform requirements have been categorized into the four groups defined by the PDCA method. PLAN establishes the requirements and needs that will be necessary before the start of the work on the BIM model and in the planning of the construction site, such as the level of detail, detailing the specifications of the expected results, defining the activities necessary to achieve the objective of the platform, establishing the objectives and processes necessary to achieve the necessary results, etc. DO includes the necessary requirements during the construction phase, indicating the different information to be displayed on the platform in real-time or in specific time periods for the correct development of the construction process. CHECK encompasses the specifications and requirements of the platform necessary to verify and control the proper development of the construction site so that, if it has not been achieved, it will be necessary to plan again. Special emphasis is given to this step, as it is estimated that the automation of this process on-site can allow great progress and improvement. Finally, ACT includes the requirements related to the necessary actions to be taken after the analysis of the control results and to make the necessary changes to ensure the correct development of the construction site.

Based on the prioritization of site needs and inefficiencies, areas for improvement, and barriers to implementing this digitization, an initial outline of high-level general user requirements has been formulated. These requirements will undergo further refinement to delineate specific details and specifications of the BDT Platform. This user-centric approach aims to design a platform that addresses the actual needs from the perspectives of various stakeholders engaged in the on-site construction process.

3.2. Phase 2. Conceptualization of the Digital Process for On-Site Construction

The second step of the methodology consists of drafting the on-site construction process based on the user's requirements, where the whole process has been deployed into tasks, which are performed by actors in which any kind of information is exchanged. This procedure has been driven by the DSR methodology, supported by the Living Labs ecosystem and the PDCA systematic process. It is based on the stakeholders' elicitation, implementing iterative and incremental procedures for improving the process's performance to obtain specific solutions.

Therefore, the process must be conceptualized and broken down into tasks in order to normalize the representation. In fact, a process is just a sequence of concatenated tasks performed to reach a goal. These tasks need actors to be tackled and an information flow managed by the actors to be undertaken. Additionally, the dependencies between tasks lead to the sequence that, together with the agent and information exchange, finally entails the process.

The points for improvement have led to the definition of user requirements for a BDT, which allows for the optimization of the construction site management. To fulfill the requirements previously identified for the Phases (P, D, C, A) and for the technical domains, specific tasks to be managed through the BDTP must be outlined. Answers to questions such as how, what, who, and when to perform the activities intended to accomplish the requirements drive the process, defined by tasks, agents, information, and dependencies.

In the particular case of the construction site, those components of the process are defined as answers to the following questions:

- How can the target of meeting the requirement be reached, and which concatenated tasks can help achieve this specific goal?
- What is the information (input/output) exchanged among tasks, and how is it managed between the agents?
- Who are the actors involved in the activity? These can be staff interacting with information managed on site, but also digital agents who can gather information and send orders in an automated way;
- When the activities must be performed, in other words, what is the sequence of the process and the chronological dependencies among tasks?

By means of the application of these steps, the construction site process can be organized into tasks, which leads to the generation of a product (in this case, a building). Each task has assigned a starting and ending date and some resources to execute it (material, equipment, and staff labor hours), and it is related to the predecessor and successor tasks. This representation helps to check the status of the task at any time by comparing the as-performed with the as-planned model in terms of deadlines, deliveries, use of resources, and bill of materials. In order to conceptualize the process, it is necessary to define different semantic concepts that allow for the standardization of the graphic representation in each layer. These concepts are defined in Table 1.

Table 1. Main semantic concepts of the construction process.

Concept	Definition
As-planned assignment	Connect a task with a resource (specifying amount and units). In the as-performed process, it is mirrored in the as-performed consumption.
BIM object	A physical object as designed in BIM modeling software.
Company	Represents either the constructor or any of the subcontractors/suppliers.
Equipment	The equipment assigned to a task will be on a zone, have a status (in use, idle. . .), move through a path, etc.
External factor	Anything that influences the progress of the construction and is not part of the project (weather, traffic. . .). It should be categorized and assigned some attributes.
Inspection	Any activity carried out to assess that the as-built and as-performed matches the as-designed and as-planned.
Issue	Any deviation from the as-designed and as-planned with respect to the as-built and as-performed. All tasks should be associated with an inspection, which will be assigned to a person and could produce a list of issues.
Labor (crew, trade)	Human resources required for a task.
Material	It represents the actual quantity of a given material on-site.
Order	An allocation of a given resource by assigning it to a company (link with the supply chain).
Path	A set of sequential locations where a vehicle or person moves on-site.
Person	Any human participating in the process.
Product	A whole unit to be installed (a wall, a stair. . .) or a part (a layer of a wall, a finishing. . .).
Resource	The tangible inputs required to perform a task (labor, equipment, and material . . .).
Risk	Anything that endangers the operational health and safety.
Site	The physical location or area where the construction activity occurs.
Task	An activity with a start/end date, use of resources, and responsibility, which delivers a product.
Task dependency	The dependencies of a given task (the requirements for that task to be executed).
Work package	High-level grouping of related tasks (excavation, structure. . .).
Zone	Spatial divisions of the site according to the phase or to the tasks performed.
***As-performed consumption**	The actual assignment of resources incurred in an executed task (in the planning phase).
***Completed work**	Any as-built element part of the final building.
***Delivery**	An order that has been executed.
***Operation**	An executed task. The as-performed counterpart of an as-planned task.

Note: Concepts applied only in the Verification Phase are marked with *. The rest are general concepts.

The conceptualization of the process gains leverage using the PDCA analysis applied to the construction site management. The PDCA method is a cornerstone in the research for the development of the two key activities in DSR: building a solution and evaluating the solution, as it also complies with the principles of iterative and incremental. In this research, PDCA has been applied to the research on two different levels: for managing the construction process and implementing the methodology of the research itself, as explained below.

On the one hand, at a higher level, this PDCA methodology has been applied to the follow-up of the construction process, which has been structured in four steps (Plan, Do, Check, Act). This is because current construction planning and management in construction can be conceptualized as a sequence of interconnected PDCA cycles closely tied to the construction process through digital twin information systems. These feedback loops allow for observation and monitoring across various temporal scales of cycle time [52]. The correspondence of the PDCA cycle with the on-site construction processes can be understood as follows:

- Plan: Create the as-designed BIM model with the required level of detail and the as-planned activities (production planning), along with other information such as safety planning, site zoning, etc.;
- Do: Carry out the construction activities and day-to-day management (Quality control, Operational Health and Safety, Equipment control);
- Check: Verify that the as-performed process matches the expected plan (progress monitoring);
- Act: When deviations are relevant, modify the models and create new versions of the as-planned/as-designed" to adapt to the as-built/as-performed reality.

Moreover, the on-site process can also be structured into five domains as mentioned above (Progress monitoring, Quality control, Operational Health and Safety, Equipment control, and Production planning). Additionally, the PDCA methodology can be considered multi-scalar, i.e., applied to the whole process, to each phase of the construction process (P, D, C, A), and also to the technical domains, being also the disciplines interrelated through the PDCA cycle for continuous improvement as shown in Figure 8.

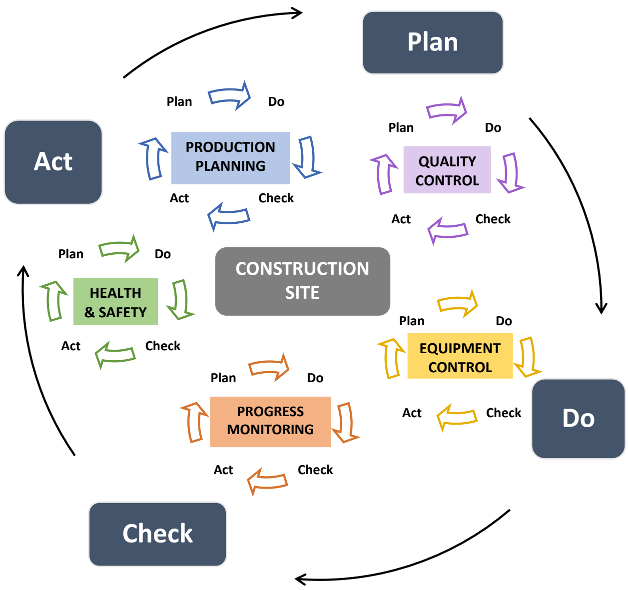


Figure 8. PDCA methodology applied to the management of the on-site construction process and subprocesses.

On the other hand, PDCA analysis intervenes at a different level, intended to fine-tune the preliminary results of the research. It is applied to each step of the methodology for the design and development of the solution (Users' requirements definition, Conceptualization of the digital process, and Process standardization for DT Workflow) in order to gain objectivity of the outcomes since different sources of information are used.

The different stages of a BDT-driven construction process can perfectly fit with the PDCA model; thus, this methodology is adequate to depict the different workflows and processes leading to the design of the BDT architecture. Figure 9 illustrates how the information can vary in the BDTP according to the outcomes of several PDCA cycles. The "DO" is the time arrow that moves, dividing the past from the future. At each timestamp of the "DO", the captured status is checked against the plan, and if deviations are detected and are considered significant, an "ACT" process will trigger creating a new branch for "PLAN" (only to the future, since all past planned events will be locked and stored for future analysis).

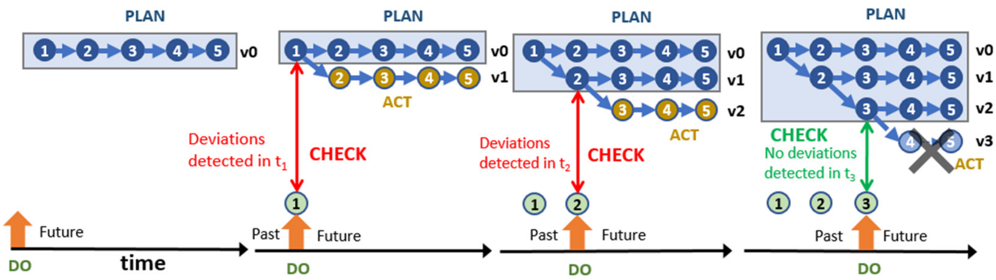


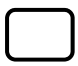
Figure 9. PDCA cycle in different instants.

3.3. *Phase 3. Process Standardization for Digital Twin Workflow*

The next step consists of defining a standard approach to represent the workflow of a PDCA sequence by means of BPMN templates. The first thing to highlight is that BPMN is traditionally used in the AECO industry to model user-driven processes, i.e., how the interactions and data flow among the participant actors (architect, engineer, building owner...) occur. What this paper proposes is a Digital Twin-driven BPMN workflow where platform-based architectures have priority over user-to-user interactions. This approach is a novelty in the literature (e.g., the search TITLE-ABS-KEY ("digital twin" AND BPMN AND PDCA) in Scopus just yields 12 outputs, and looking into the results, there is no real connection in the papers.

The standard BPMN 2.0 has been used as presented in the background, but for better understanding and readability of the diagrams, the convention reflected in Table 2 has been selected.

Table 2. Customization of BPMN to the research.

Concept	Symbol	Meaning
Task		Human tasks performed manually/visually or with software (design, build, install, inspect...). It mostly covers the "manual task" and "User task" of Figure 3, and in some cases, the "business rule task".
		Tasks automatically performed with no human intervention, either physical (e.g., autonomous robots or equipment) or software processes. It can be mapped generally to the "service task" and "Script task" of Figure 3.
		A task also automatically performed but indicating that the concept is still quite experimental or directly non-existing. It represents a future scenario.
Data		IFC model.
		Specific information about the outcome of a process (OK or with errors/warnings) or generic information.
Process		In addition to the line width, the start and end of a process are denoted by green and red background colors, respectively.

With this in mind, the template followed in this research is proposed in Section 4.3 of the results, which can be particularized to the desired AECO process under study.

4. Results and Discussion

Based on the aforementioned methodology, as described in this chapter, the main result of the research is the configuration of the BPMN workflows integrating the technical domains involved in the construction site process for comprehensive construction management through a BDTP (R3), which is presented below.

Likewise, some intermediate outcomes were also reached by the study (R1 and R2). On one hand, they lead to the final result of BPMN workflows for Building Digital Twin (R3), but on the other hand, the results by themselves can be used in a standalone way, contributing to the state of the art about BDTs.

The results, described in detail in the following subchapters, are summarized as follows:

- R1. Requirements for the Building Digital Twin Platform. From the assessment of the inefficiencies of the construction phase and barriers towards digitalization, the requirements for a Building Digital Twin, which integrates all the technical domains involved in the construction site process, are elicited from a user's perspective.
- R2. Digital process for automation of the on-site construction. Simplified diagrams with the agents, tasks, exchanged information, and other entities, as well as dependencies among them, are represented for the different phases of the construction phases (PDCA) as a reference of graphical notation leading to the process automation.
- R3. High-level BPMN Digital workflows of the on-site construction processes towards the architecture of the BDTP. The BPMN workflows are organized according to the standardized structure of Digital Twins, which encompasses the technical domains addressed on-site and the phases of the process (PDCA), which are the main outcomes of the research.

4.1. Users' Requirements for the Building Digital Twin Platform

Through an in-depth investigation of the present construction procedures and an extensive analysis of relevant research publications [9], it has been determined that the on-site construction process exhibits significant deficiencies impacting key aspects of the overall construction phases, as developed in the first two sections of this article.

Adhering to the proposed methodology, the collected questionnaire responses have been systematically compiled and scrutinized, involving participants engaged in the construction phase across over 15 countries, thereby encompassing a diverse array of professional profiles (Table 3). This comprehensive approach has enabled the derivation of conclusive insights into the real problems and inefficiencies of on-site construction.

Table 3. Survey respondent profiles.

Profiles of Survey Respondents	Percentage (Size)
Main Activity	
Constructor/Subcontractor	74% (229)
Technical (Architectural and/or Engineering)	13% (39)
Promotor	3% (8)
Public Sector	3% (11)
Other	7% (22)
Field of Work	
Execution and Monitoring	48% (149)
Quality Control	13% (39)
Production Planning	6% (19)
Occupational Safety and Healthy	3% (10)
Other	30% (92)

Table 3. *Cont.*

Profiles of Survey Respondents	Percentage (Size)
Role	
Technical Staff	48% (149)
Middle Management	35% (109)
Director/Management	13% (39)
Workmanship	1% (4)
Other	3% (8)
Company Size	
Large >250 employees	70% (216)
Medium <250 employees	13% (39)
Small <50 employees	13% (41)
Micro <10 employees	4% (13)
Age	
>60	4% (12)
50–60	19% (57)
41–50	38% (118)
31–40	25% (78)
20–30	14% (44)

Through this methodical process, conclusions have been drawn regarding the primary issues and inefficiencies prevalent in on-site construction (Table 4). Simultaneously, the identification of key barriers obstructing the integration of technology or the transformation to digitalize construction procedures has been accomplished.

Table 4. Prioritization of inefficiencies based on the impact on the construction on-site process.

Inefficiencies in the Construction Site	Average Value
Inadequate work planning	8.32
Constant adjustments and changes	8.15
Insufficient control over the implementation phase	8.15
Limited collaboration among involved agents in the work phase	7.97
Challenges in acquiring skilled workers and subcontractors	7.92
Lack of communication in task assignment	7.77
Material shortage or late supply	7.39
Difficulties in controlling safety conditions	7.09
Issues in permission handling (authorization, restriction on work hours, etc.)	6.58
Project size	6.13
Consideration of external factors (weather, rain, temperature, wind, etc.)	5.77
Issues related to the location of tools, equipment, and machinery	5.76
Challenges in tracking the on-site location of staff members	5.39

Note: On a scale of 0 to 10, where 0 signifies minimal importance and 10 signifies utmost importance.

Concerning the inefficiencies within the construction process (Table 5), the questionnaire results highlight that the most impactful inefficiencies during on-site construction are “Inadequate work planning”, “Constant adjustments and changes”, and “Insufficient control over the implementation phase”. Conversely, issues related to “the location of tools, equipment, and machinery” and “Challenges in tracking the on-site location of staff members “ appear to be considered less impactful inefficiencies.

As for the barriers, the results of the survey show that not all of them have the same effect in preventing or hindering the implementation of digital tools. The results reveal the greater need to resolve some of these barriers with respect to others in order to improve the efficiency of the site through the digitization of processes. The main barriers identified were the “Urgent need for a complete reimagining of traditional on-site methodologies”, the existence of “Participation of multiple teams with distinct working procedures (used programs protocols, etc.)”, and the “Insufficient progress in the required technology and lack of compatibility between tools”.

Table 5. Prioritization of the main barriers impacting on-site construction digital transformation.

Barriers to the Digitization of Construction Processes	Average Value
Urgent need for a complete reimagining of traditional on-site methodologies	8.06
Participation of multiple teams with distinct working procedures (used programs protocols, etc.)	7.99
Insufficient progress in the required technology and lack of compatibility between tools	7.97
Limited expertise in the use of digital tools for tasks within the construction phase	7.73
Managing a significant dataset in both real-time and static contexts requires attention (data collection, storage, analysis)	7.64
Resistance to change prevails in the construction sector	7.57
Significant initial resources, time, and financial commitment are necessary	7.57
Digitalizing construction processes is hindered by technical complexities	7.31
Inadequate functionality of IoT systems in adapting to the dynamic nature of on-site work	7.16
Challenges arise in handling extensive data files in a nimble and operationally efficient	7.12
The learning curve is excessively sluggish, and the associated training costs are steep	6.85
The return on investment is not adequately demonstrated or is notably low	6.84
Traditional contracts often do not align with the current operational requirements	6.82

Note: On a scale of 0 to 10, where 0 signifies minimal importance and 10 signifies utmost importance.

Considering the quantitative and qualitative data obtained in this first phase of the DSR methodology through the surveys conducted worldwide and the interviews, workshops, and focus groups carried out inside the Living Labs ecosystem [9], the User Requirements that will serve as the basis for the preparation of the BDTP have been defined, adapted, and validated. As mentioned in Section 3 Methodology, the platform requirements have been classified using the PDCA method in these four groups, PLAN, DO, CHECK, and ACT, which are presented here in four differentiated tables. To facilitate the structuring of the BDT platform information, the requirements have been defined on the basis of the different user profiles. In order to optimize the classification of the defined user requirements, the exercise of relating each of them to the user profiles they will affect has been carried out. In this way, it can be determined which information or activities should be accessible to each of the user profiles. The classification of the different requirements and their linkage with the defined user profiles are shown in the following tables (Tables 6–9).

Table 6. User requirements for PLAN.

Requirement	Domains					Profile			
	PM	QC	OHS	EC	PP	DIR	MID	TEC	WOR
The elements of the BIM model must present at least a LOD 400. In addition to being defined geometrically in detail, its position, belonging to a specific construction discipline, it will have assembly information in terms of materials and labour required and also allows the possibility of including non-graphic information linked to the element.	√	√	√	√	√	▪	▪	√	▪
A work breakdown structure (WBS) of the whole project must be provided, specifying the required resources (trade, equipment, material) for each final task. Also, these tasks must allow define the start and end of task, and the deadline for changes	▪	▪	▪	√	√	▪	√	√	▪
In shorter term periods, the WBS granularity can be increase by splitting a task into more granular subtasks related to intermediate or temporary processes	▪	▪	▪	▪	√	▪	√	▪	▪
Any object in the BIM Model must be mapped to a product (Assembly/part) and consequently in tasks in the WBS. Thus, the changes to the design identified, will be included in the execution on site plan in terms of cost/quality/delay.	√	√	▪	▪	√	▪	▪	√	▪

Table 6. *Cont.*

Requirement	Domains					Profile			
	PM	QC	OHS	EC	PP	DIR	MID	TEC	WOR
There should be a deadline defined after which modifications in the design are not possible (they impact in cost/quality would be very relevant)	▪	▪	▪	▪	▪	▪	√	▪	▪
Tasks should have a clear definition of dependencies. To guarantee the execution of each task it is necessary to know if the precedent task is finished.	▪	▪	▪	▪	√	▪	√	√	▪
An Inspection Points Plan (IPP) must be defined for QA and it must be possible to link any product (BIM object) to a task and a point/milestone in the IPP and include instructions for QA process steps	√	√	▪	▪	▪	▪	√	√	▪
Provide more intermediate milestones for control of executed work and quality monitoring, to facilitate the detection of time deviations or execution failures.	√	√	▪	▪	√	▪	√	√	▪
Each required resource for a task must be mapped to orders to a provider (subcontractor or supplier) and scheduled well in advance. These planification time must be defined a short time and longer time	▪	▪	▪	▪	√	▪	▪	√	▪
The construction site (possibly a 2D map) should be correctly divided into different spatial zones according to the activity performed (circulation of heavy machinery, storage. . .) well in advance. In the initial stages of the project, the revision will be done every week, in later stages it will be enough with a revision/modification monthly, and there will come a point in the development of the work, in which will no longer be modified.	▪	▪	√	√	√	▪	▪	√	▪
All tasks should have a definition of the safety risks associated and the required measures and equipment (collective and/or individual)	▪	▪	√	▪	▪	▪	▪	√	▪
A model checking functionality should warn if inconsistencies or missing data is found (tasks not planned, products not linked to tasks, etc.)	√	√	√	√	√	▪	√	√	▪

Note: a requirement "√" is totally related to the domain, and a requirement " ▪" is not related to the domain.

Table 7. User requirements for DO.

Requirement	Domains					Profile			
	PM	QC	OHS	EC	PP	DIR	MID	TEC	WOR
Show resources needed (subcontracting/equipment/material) for on-going/next tasks	▪	▪	√	√	√	▪	▪	√	√
Show resources available on-site (subcontractors/equipment/material) and status (in-use, waiting. . .)	▪	▪	√	√	√	▪	▪	√	√
Show safety equipment needed for ongoing tasks	▪	▪	√	▪	▪	▪	▪	√	√
Show safety equipment available on-site. It should be possible to locate on a map or in the BIM model the health and safety equipment.	▪	▪	√	▪	▪	▪	▪	√	√
Show the status of ongoing orders and deliveries to avoid deviations.	▪	▪	▪	√	▪	▪	▪	√	▪
All resource flows (materials, equipment, etc. entering/leaving the site) should be registered and time-stamped for traceability purposes	▪	▪	▪	√	√	▪	▪	√	▪
Provide access to an updated task calendar in real-time, so that all site workers know which activities should be executed and can better control the correct development of the work and detect possible deviations and delays.	▪	▪	▪	▪	√	▪	▪	√	√
Show the localization on a site plan or BIM model of on-going tasks	▪	▪	▪	▪	√	▪	▪	√	√
Provide access to documentation (QA plans & other certifications) according to IPP	√	√	▪	▪	▪	▪	▪	√	▪

Note: a "√" requirement is fully reflected in the domains, and a " ▪" requirement is not reflected in the domains.

Table 8. User requirements for CHECK.

Requirement	Domains					Profile			
	PM	QC	OHS	EC	PP	DIR	MID	TEC	WOR
A system of automatic alerts should be created when any of the needed requirements is not met (required materials or safety equipment not present, deliveries not arrived, etc.)	▪	▪	√	√	√	▪	√	√	▪
Automatic conformity checking of collective safety protection	▪	▪	√	▪	▪	▪	▪	√	▪
Automatic detection of potential risks (e.g.: fall from heights)	▪	▪	√	▪	▪	▪	▪	√	▪
Automatic calculation of quantities of work executed	√	√	▪	▪	▪	▪	√	√	▪
Provide a tool for entering QA inspection results (photos, notes...) according to IPP	√	√	▪	▪	▪	▪	▪	√	▪

Note: a requirement "√" is totally related to the domain, and a requirement " ▪" is not related to the domain.

Table 9. User requirements for ACT.

Requirement	Domains					Profile			
	PM	QC	OHS	EC	PP	DIR	MID	TEC	WOR
For each modification (e.g. due to issues, defects, corrections. . . .), control the workflow of changes (who modifies, who validates...)	√	√	√	√	√	▪	▪	√	▪
Know at any time the deviation WRT as-planned (quantities, duration. . .), both the deviations that affect the deadlines and planning of the work, as well as the deviations in the use of materials and equipment associated with an activity.	√	√	▪	▪	√	√	√	√	▪
Automatic update of planning according to executed work (as-performed vs as-planned progress deviation)	▪	▪	▪	▪	√	▪	√	√	▪
All affected stakeholders should automatically receive updates on design/planning changes (new start/end of task, modified quantities, materials...) If a task planned don´t be executed, all the affected stakeholders must be informed in order to reschedule the work on site.	▪	▪	▪	▪	√	√	√	√	√
Understand the impact of each modification in cost and schedule and be able to reallocate resources onsite. An estimate of the costs and delays that a modification may cause in the work schedule should be available to facilitate decision making.	▪	▪	▪	▪	√	√	√	√	▪
Automatic update of associated resources (e.g. material, equipment, people) per task when a drawing (BIM model) is modified	▪	▪	▪	▪	√	▪	√	√	▪
It should be possible to update task status and reallocations onsite from a mobile device, including checking of proper performing (product/subassemblies) and quality steps	▪	▪	▪	▪	√	▪	▪	√	√

Note: a requirement "√" is totally related to the domain, and a requirement " ▪" is not related to the domain.

The following convention has been used in Tables 6–9. PM: Progress Monitoring, QC: Quality Control, OHS: Operational Health & Safety, EC: Equipment Control, PP: Production Planning, DIR: director/management, MID: Middle management, TEC: Technical staff, WOR: workers.

4.2. Digital Process for Automation of the On-Site Construction

At this point, the requirement lists have been analyzed to better orient the real development in the DBT. The processes based on the PDCA Cycle have been conceptualized in different flows, which show the tasks, who made them, what information should be exchanged, and the dependencies between tasks, which are based on the concepts defined in Table 1. In addition, the tasks that represent the construction process are applied at different times, so it uses three different colors: blue to show the task in the long term, green for the short term, and orange for real-time.

4.2.1. Concepts for PLAN

The initial modeling/planning phase comprises the list of concepts depicted in Figure 10. We must note that not all the information is provided in a single stage. Rather, we could have an initial information level, which can be further detailed afterward (we cannot have a perfect project definition from time t = 0). Thus, the tasks can be split into detailed subtasks in shorter loops.

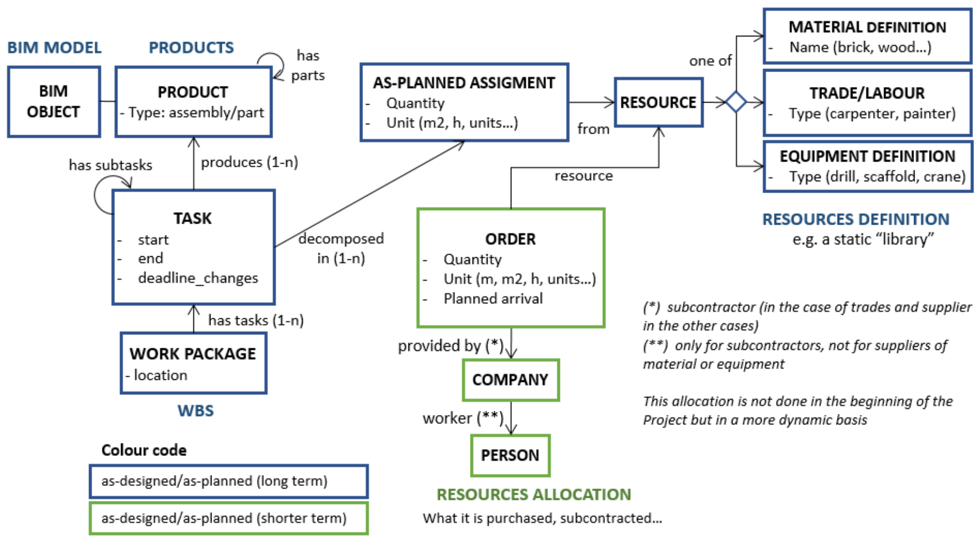


Figure 10. Preliminary entities (PLAN use case).

Additionally, tasks must clearly identify dependencies among them and other factors (Figure 11). This is critical for being able to assess the impact that any change or deviation in any task has on the rest of the project.

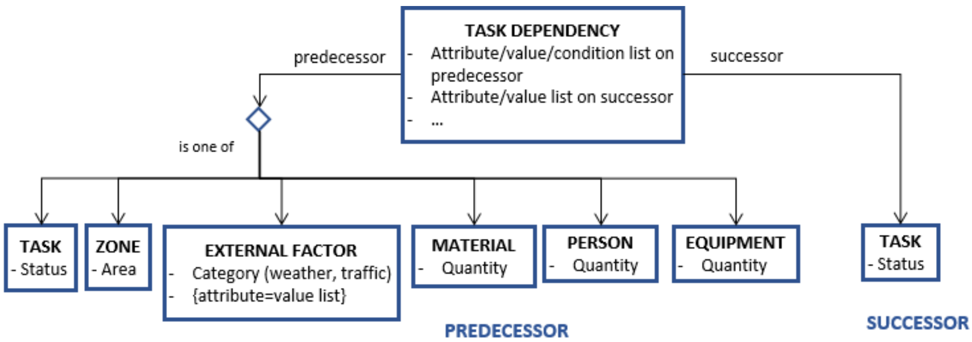


Figure 11. Task dependencies.

The possible types of dependencies between two tasks are as follows:

- Finish to Start: The predecessor's completion is a prerequisite for the successor to commence (the wall must be erected before cladding can start);
- Start to Start: The predecessor's initiation is required for the successor to initiate;
- Finish to Finish: The predecessor's completion is necessary for the successor to conclude;
- Start to Finish: The predecessor's commencement is a condition for the successor to conclude.

It is also required to model in advance how different tasks and external factors are associated with certain risks, and these, in turn, must define the safety measures to be applied in terms of collective or individual safety equipment (Figure 12), which should also be part of the BIM model (in line with the ideas of Prevention through Design or PtD).

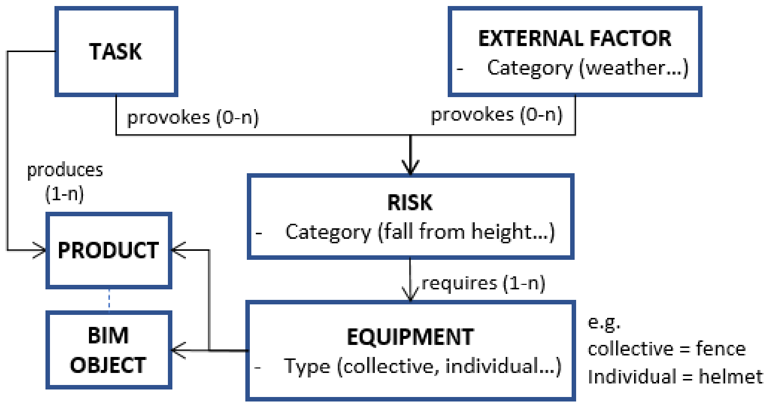


Figure 12. Definition of risks and planning of safety measures.

4.2.2. Concepts for DO

The functionalities of the DBTP in the DO use case will be mostly related to querying information about upcoming activities or receiving proactive information/notifications. Thus, the information managed will be essentially the same as for the PLAN use case, and there is no need to go further on that.

4.2.3. Concepts for CHECK

The concepts to be considered in the CHECK use case can be considered a mirror of the PLAN case (see Table 10 and Figure 13). In fact, most of the concepts are applicable, and some new concepts (in red in the next figure) are just a mapping as follows:

Table 10. Plan/check concept mapping.

PLAN	CHECK
Product	Completed work
Task	Operation
Order	Delivery
As-planned assignment	As-performed consumption

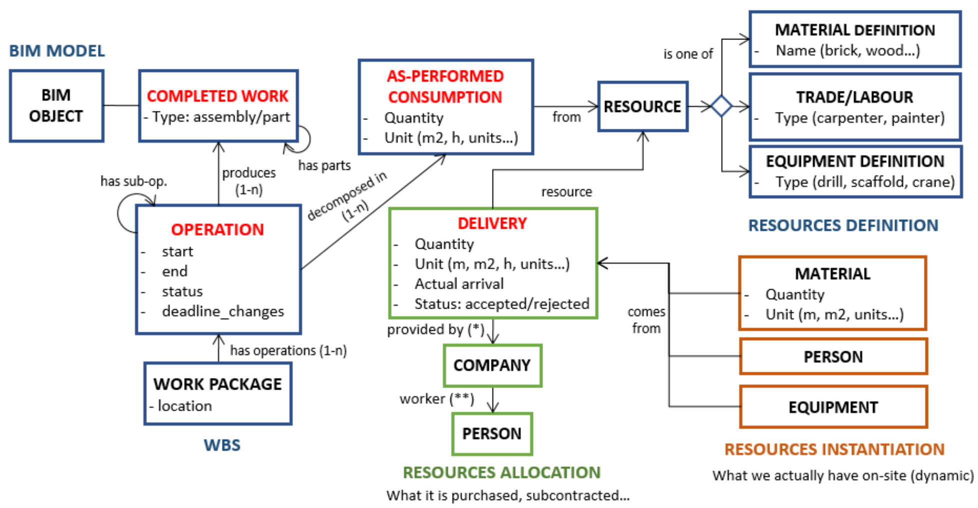


Figure 13. Preliminary entities (CHECK use case).

In the case of resources, we can see that in addition to which is assigned to a task and which is allocated to a supplier or subcontractor, we also have the real resources present on-site (linked to the Project Status).

Additionally, the CHECK use case is one of the cores of DT since most of the technical developments will be oriented to automatically capture and extract the knowledge about what is happening on-site. Thus, the action of checking the current status and reporting issues and deviations also imposes the need for some extra concepts.

4.2.4. Concepts for ACT

The ACT use case mostly deals with tasking decisions about how to handle the detected deviations, mainly to select the best re-planning alternative for the project (changes in products, resources, or scheduling). As such, it will mainly consist of generating new versions of the PLAN entities with their respective timestamp, so no additional concepts are required.

4.3. High-Level BPMN Digital Workflows of the On-Site Construction Processes towards the Architecture of the Building Digital Twin Platform

Firstly, the specific template agreed upon after evolving the BPMN standard to the needs of this research is presented as a base result (Figure 14), considering the DSR Methodology followed, which has evaluated and evolved the results in the Living Labs.

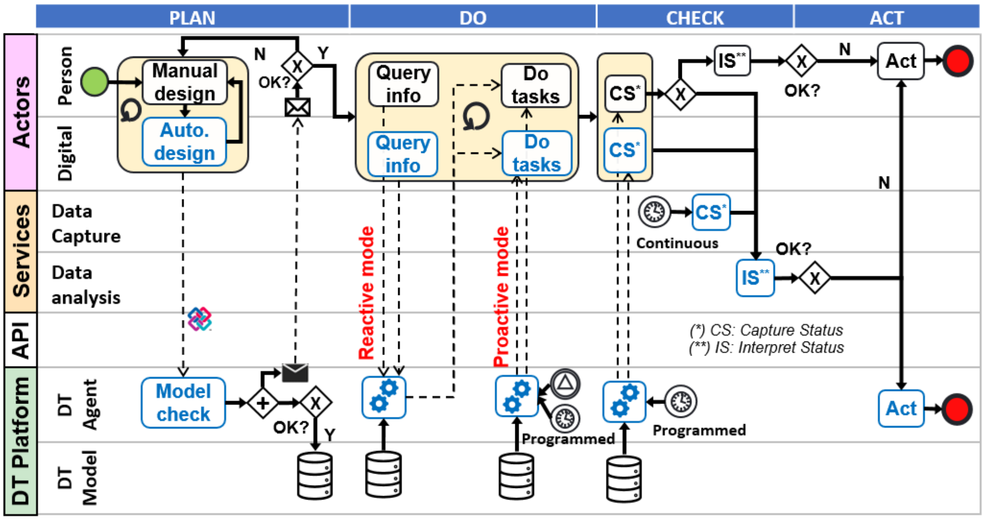


Figure 14. DT-oriented BPMN template proposed in this research.

The pool "Actors" represents the physical counterpart of the DT, where the business processes occur. Each actor (architect, building operator, . . .) executes a certain process or task. A distinction is made between human actors ("Person" lane), which are the majority currently, and "Digital" ones, which at some future moment will be the majority (a self-driving vehicle, a builder robot, etc.).

The pool "Services" represents the in-between layer between the physical and digital twins, where all the relevant data about the physical processes is captured ("Data Capture") and analyzed and decided upon ("Data Analysis"). The data capture can be manual or automatic (through sensors or IoT devices, smart products tagged with QR codes, etc.).

The data analysis layer will interpret the captured data, react upon it, and extract high-level actionable information to store it in the DT. AI techniques will have a prominent role here in the coming years.

The DT Platform is the digital counterpart of the real world, encompassing the following:

- DT Model: the backbone representation of the DT concepts, i.e., the information entities and their attributes and relationships;
- DT Agent. It is the brain that models the high-level process knowledge. It can also monitor the information and status of the BDT entities and trigger events, notifications, or other internal data transformation tasks.

Then, the conceptual sketch for each PDCA stage is reflected;

- Plan: the process (building construction, maintenance, or any other) is first designed, generally by humans, although (semi-)automated design processes must also be considered model-checking aspects;
- Do: during the construction process, two DT operation modes are considered: (1) reactive (actors query the necessary information to carry out the tasks) and (2) proactive (the DT informs about upcoming tasks, e.g., resources needed or missing, etc. and can anticipate to potential problems);
- Check: the correct fulfillment of the activities is checked, ideally also in a combined human/digital scenario. As before, the DT can proactively inform about the upcoming checks to be performed and its requirements, related elements, etc. The interpretation of the status (i.e., if something is performing wrong) can be performed by humans (expert knowledge) or by data analysis algorithms (e.g., Machine Learning);
- Act: finally, when a significant deviation, issue, or problem is detected, an action must be taken, typically by humans, but for a transformative DT (see Section 2.2), the DT itself can make autonomous decisions on how to respond to the issue.

In future AECO processes, the trend should be to have as many automated tasks as possible, i.e., to traverse the BPMN following as many blue boxes as possible.

This methodology applied to the construction site yields the schema depicted in Figure 15. The processes delivers building by assembling products, which are in turn created by transforming materials and using auxiliary resources (tools, machinery. . .).

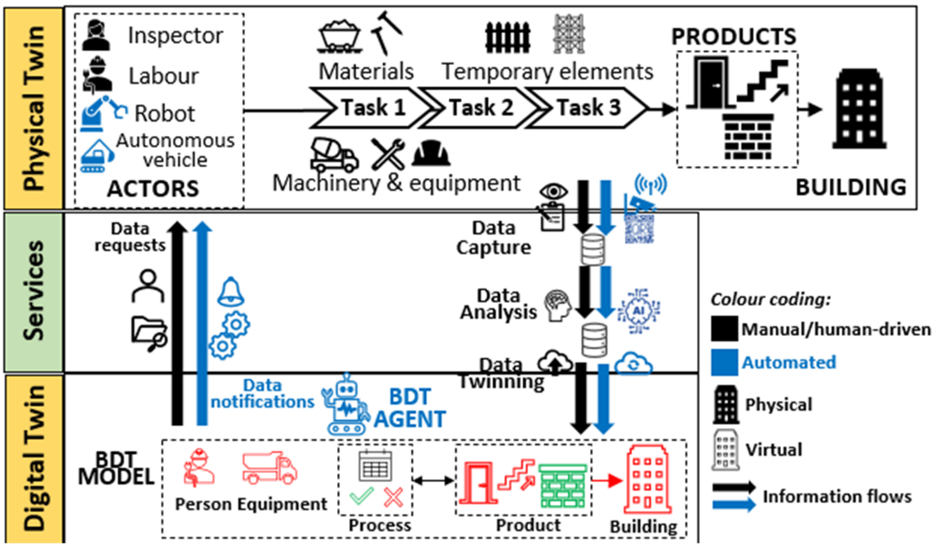


Figure 15. BDT concept and information flow in the construction site.

This process (carried out in the physical twin) can be just a single task (e.g., for prefabricated products arriving on-site) or a succession of connected tasks that yield temporary products (rebar, formwork. . .) and could require temporary elements (e.g., scaffolding, protective fences) removed once the building is finished.

Every on-site process (material, people, or machinery flows) is mapped to data flow with the DT, split into three steps, executed manually (black) or automatically (blue) as follows:

- Capture: manual (visual inspection, take notes, images. . .) vs. automated (sensors, surveillance cameras);
- Analysis: manual (expert knowledge) vs. automated (artificial intelligence);
- Twinning (reporting to the digital model): manual (upload files, etc.) vs. automated (automatic synchronization in the cloud, i.e., the BDT Model).

This approach is in line with recent proposals of the DTaaS concept (Digital Twin as a Service) [53], although in a broader sense, for industry in general.

For the standardized graphic representation by means of BPMN diagrams in each layer, it is necessary to start from the semantic concepts defined in the previous section, which was worked on in phase 2 of the development.

Finally, some DT-based BPMN templates generated in this research are presented, applying the generic template presented in Figure 14 following PDCA principles and particularized to a building construction process (thus DT, DT Model, etc. are represented as BDT, BDT Model, and so on). It includes the five considered domains (Progress monitoring, Quality control, Operational Health and Safety, Equipment control, and Production planning), although, in the Living Labs and requirements elicitation process, more detail has been put in progress and quality control. Due to its extension, the process is split into two diagrams, one for the Plan phase (Figure 16) and another one for the Do, Check, and Act phases (Figure 17).

Black boxes denote human-driven tasks, and blue boxes are automated ones. Additionally, solid lines indicate that software for that purpose is already available on the market, whereas dashed lines indicate that the concept is still experimental or non-existent.

Plan phase:

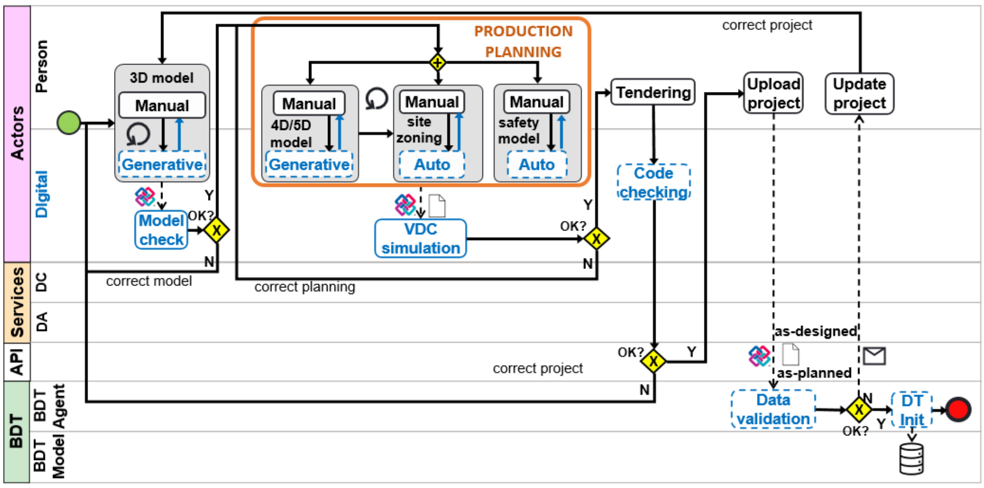


Figure 16. BPMN diagram for a BDT-based construction process (PLAN).

The planning phase covers mainly the building modeling in its various dimensions [54]. For simplicity, we will focus on 3D (the geometry) and the 4D/5D (scheduling and costs, including the work breakdown structure for each task, i.e., the materials, equipment, and labor needed). Additionally, the construction site must be spatially split into different functional zones (e.g., the materials storage, trucks, excavation area, etc.), which is derived from the activities performed and affects the safety measurements to be taken. Moreover, the related safety requirements must be defined (individual and collective protective equipment), where the temporary elements (fences, scaffolding. . .) are also modeled in BIM. All these aspects are inside the production planning domain.

Traditionally, these steps are carried out by designers and planners, following some iterations. However, emerging artificial intelligence trends enable us to envision a future where humans are assisted by automated designers/planners, usually referred to as Generative Design (GD). For 3D modeling, GD is starting to take the first steps [55], whereas GD for scheduling still seems limited to some theoretical studies [56], and the automation of site zoning and BIM/GIS integration is still experimental. In relation to safety modeling, both the automation of risk detection in a BIM model and the automated modeling of safety equipment are still in an emerging research state.

Parallel to the design, the checking of each aspect occurs, such as clash detection or user-defined validation rules for 3D geometry or data already supported by various vendors [57–59]. In the case of production planning, Virtual Design and Construction (VDC) [60] is used to simulate the construction process and detect task dependencies, bottlenecks, or spatial issues (e.g., not enough space for maneuvering a crane). Finally, when the project is accepted by the contractor, it must be submitted to the authorities for approval, and again, to check that a project fulfills all regulatory aspects is still mostly manual, although automated building permits are a popular topic currently [61–63].

During planning, the data capture and analysis are not yet meaningful since a physical reality does not yet exist. Thus, the project is directly uploaded to the DT platform, where all its internal representation (activities, tasks, resources, etc.) is created. Prior data validation ensures the consistency and completeness of the submitted information and reports issues (e.g., a task is not planned, an object is not assigned to any activity, etc.).

The Do/Check/Act phases are as follows:

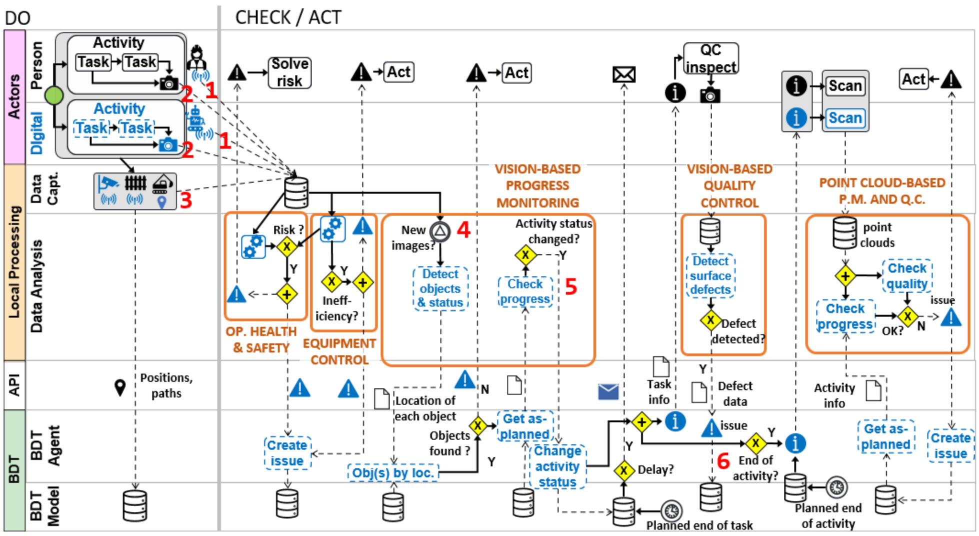


Figure 17. BPMN diagram for a BDT-based construction process (DO, CHECK, ACT).

The Do, Check, and Act phases are the ones where the BDT is really in place since the actual construction site is involved. In the “Do”, the construction activities introduced (e.g., building a column) are split into tasks (e.g., putting the rebars, the formwork, pouring concrete, etc.). In the future, we can envisage builder robots, autonomous vehicles, and other digital actors performing tasks.

There would also be a data capture layer to record on-site data streams (see red numbers in Figure 17): (1) Actors (human or automated) emitting their location or the status of their protective equipment; (2) actors capturing the status of their tasks, e.g., though pictures, either on demand or automated with a helmet equipped with a camera; (3) images or videos coming from fixed cameras or selected locations, smart objects which emit their status or any change on it (a fence that has been opened, protective equipment that has been misplaced. . .) or heavy vehicles emitting their location.

The data analysis layer is a key component that progressively enables the replacement of human-driven interpretations with AI-driven knowledge extraction in the key domains represented by orange boxes (progress, quality, safety, and equipment use). Any high-level information and potential deviations from the expected status (defects, inefficient use of resources, safety issues. . .) are reported to the BDT through a standard API. By merging different domains, it will be possible to generate indicators, infer patterns, detect cross-dependencies between domains, and simulate what-if scenarios. Finally, data stored over several projects would serve as a knowledge base for future predictions.

This data analysis is a key element in unlocking the potential of BDTs to solve many of the inefficiencies in current construction processes. Particularly, in the methodological development and contrast with end users in BIM2TWIN, an approach on how to deal efficiently with progress monitoring (PM) and Quality Control (QC) was sketched as follows:

- QC is the key step since it represents the go/no-go decision, and PM should trigger all the notifications for QC, e.g., by automatically detecting when a task is finished;
- Vision-based PM enables a higher granularity on PM by detecting partial status (columns in rebar or formwork), in contrast to point clouds, which are only efficient for finished elements. Thus, QC can be performed more regularly, detecting issues earlier;
- Workers or inspectors would not need to record the task progress; they would just periodically capture images of their working zone (if not automatically performed), and computer vision algorithms would automatically trigger them (see 4 in Figure 17). If they detect a change in the task status, an alert for vision-based QC is launched (5) in order to identify surface defects such as cracks;
- Additionally, if it represents not only a task end but an activity end, it would launch an alert for point-cloud-based capturing (6) to obtain complementary information, such as geometrical defects (misplacement, deviation for vertical axis, etc.).

5. Opportunities for the Replicability and Upscaling of the Research Findings

The development of a BDT-driven process for construction management enables one to know what is happening on the construction site at all times, related to the workers, materials, equipment, tasks, and safety aspects, among others. This knowledge enables us to make informed decisions based on data.

The BDT must relate the information about the project design, the construction planning, and the performed work by comparison among the "as-designed", "as-planned", and "as-built" models in real-time.

Additionally, a set of construction management applications and services embedded in the BDT model, based on technologies such as AI and Machine Learning, will boost the automation of real-time knowledge extraction and pave the way toward hybrid human/digital workflows. The adoption of AI/ML is not just a theoretical vision; recent research highlights that specific approaches have already been proposed in the literature up to 2016. ML applications in the construction sector include artificial neural networks at 50.8%, genetic algorithms at 21.8%, composite models at 16.3%, fuzzy theory at 8.2%, and support vector machines (SVMs) at 2.9% [64]. Recently, the convergence of AI, Big Data, and IoT has revitalized the substantial potential of digital twins. This technological synergy propels Industry 4.0 advancements and catalyzes the transformative shift towards Construction 4.0.

ML, combined with the growing accessibility and affordability of IoT [65] solutions, provides a valuable tool for identifying errors and omissions in the design phase before construction commences. Additionally, designers can leverage ML to simulate diverse environmental conditions and scenarios, assessing the optimality of design elements and potential issues [66]. ML could change the way problems are addressed on-site.

Nevertheless, the potential application of the BDT goes far beyond a single site management platform and gains impact when multiple replicas of the BDT can be created in a multi-site management environment. We can imagine various instances of a site-BDT as part of a multi-site portfolio managed by a company, where the BDT not only learns from its own past but from alike sites and other parallel projects, enabling capabilities for benchmarking and self-tuning, as well as aggregating information to a database.

This idea is depicted in Figure 18. Each DBT instance (construction site) is composed of three logical layers (the physical twin, the digital twin, and the service layer) described in this paper. Furthermore, a BDT broker would coordinate the information exchanges between multiple sites, e.g.,

- If I have idle workers in site A today, I can send them to site B if an equivalent task is foreseen.
- If, due to some unexpected delay in the supply chain delivery, I am short of material in site A, but I have available stock in site B, which is not estimated to be used today, I can move it from site B to A.

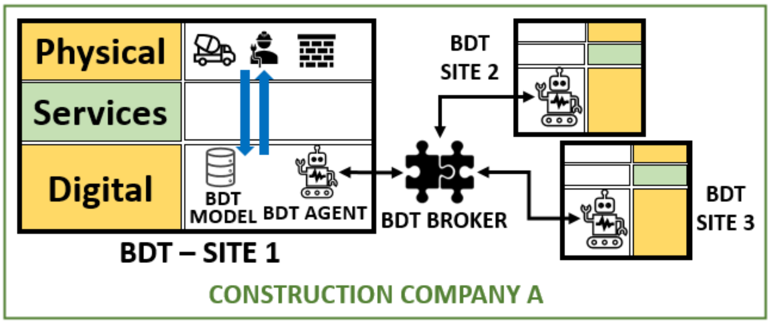


Figure 18. Multi-site management through BDTs.

We must not limit our imagination to connecting replicas of the same BDT architecture but even linking DTs of heterogeneous kinds. As stated earlier, a DT is any kind of virtual replica of a physical entity, which can be a manufacturing plant or even a whole city in any of its domains [67–69] (mobility and transportation, energy systems, urban planning, etc.), where the underlying data model is not BIM, but GIS (e.g., CityGML). The future scenario of an ecosystem of interconnected Digital Twins of various kinds has already been envisaged by several institutions (e.g., buildingSMART [70] and the Centre for Digital Built Britain [71]). The rationale behind this is that the value of data exponentially increases when it is shared across organizations and scales. Also, in the United States, the Digital Twin Consortium [72] has established technical guidelines and taxonomies and a series of requirements and new standards to improve the advantages of DT, demonstrating the utility of this technology. Some other documents, ARUP, and projects such as SPHERE [73] deepen into the DT ecosystem by means of the definitions of the DT in the industry aiming at better decision-making, learning and autonomy, and the standardization of the common work environment.

Thus, we can imagine the previous multi-site BDT instances aggregated upwards into a higher level through a Digital Twin Federator (Figure 19). The challenge here exponentially increases since the underlying domain model could be completely different, and they must agree on a shared and standardized APIS and vocabulary (e.g., through web ontologies).

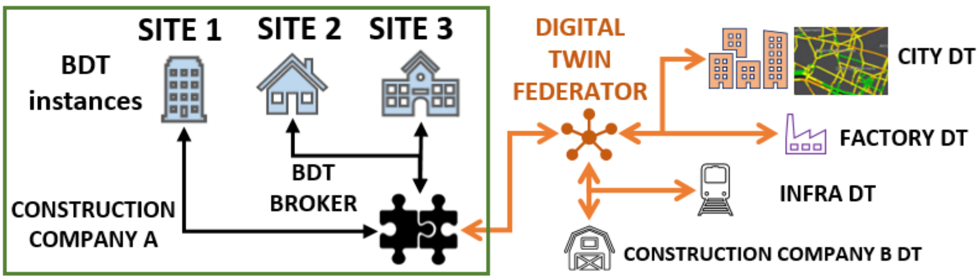


Figure 19. The BDT Platform as part of a Digital Twin ecosystem.

Boje C. et al. advocate for future semantic and intelligent construction platforms. On the one hand, the semantics are boosted by providing commonly agreed vocabularies and APIs. On the other hand, intelligence is ensured by leveraging AI for prediction and optimization applied to various vertical services, including the concept of AI-enabled agents [74].

6. Conclusions

The application of the DT concept to the construction industry is still in the early stages, compared to other industries such as automotive or manufacturing, although recent progress is noteworthy. In any case, the state-of-the-art applications are mostly oriented to building maintenance and operations, whereas their application to the building construction process is still in a very conceptual stage. Focused on this conceptual framework and based on the principles of DT, this work proposes a common approach to define the BDTP architecture, intended to manage the construction site process, starting from the identification of the users' requirements for a BDT, in a user-centered perspective. The widespread BPMN standards for the graphical representation of digital workflows have been used as a common language process and are very popular in modeling BIM processes.

The final goal of the BDT is to boost the automation of construction management and process optimization, leveraging the real-time information achieved from digital and human agents, technical devices, or vehicles that are exchanged into the BDT. Technologies such as AI or ML could be seamlessly implemented in the BDTP, helping to analyze deviations and predict future behaviors, enabling a smart decision-making process.

In summary, the main innovations addressed in this research can be summarized as follows:

- Shape the construction site process into five subprocesses according to the technical domains that they address (Progress monitoring, Quality control, Operational Health and Safety, Equipment control, and Production planning). The BDT allows for their management separately or as a whole since they are cross-cutting disciplines interconnected through the tasks and the agents;
- Apply the PDCA cycle in two levels in the research: firstly, the use of PDCA insight for construction management based on the lean construction principle, which enables the draft of the digital workflows of the processes according to the construction phases (Plan, Do, Check, Act). The second level of PDCA analysis is aimed at applying the research methodology, together with the DSR method, to reach as many precise and objective outcomes from the stakeholders' elicitations within a Living Labs ecosystem;
- Propose a standardized BPMN template based on the Digital Twin principles, where actors (humans and digitals), both at the physical twin side and the digital twin side, are represented and connected through a service layer for triggering the knowledge exchange through APIs and services in real-time;
- Propose a standardized set of digital entities that model the virtual counterparts, leading to the BDT architecture design, and are the basis for developing a data model through a property graph representation and an open and extensible layer of APIs;
- Draft an array of use cases that describe the specific implementation of each BPMN diagram representing the vertical domains and phases of the process, with a special focus on the data collection, agents (human and digital), and knowledge extraction in the selected domains. The key aspect is the detection of synergies between user stories and visualizing how the different applications and processes are linked to each other in a common high-level workflow;
- Pave the way for user-driven construction processes to hybrid processes, merging user activities and expert knowledge with artificial intelligence and computer vision algorithms, which boost and optimize the process. This can be achieved thanks to a new vision of the construction site, where the physical actors could be not only human but also any autonomous device/vehicle of smart products that can monitor the environment, capture data on their own, or even react and extract some knowledge by interacting among them;
- Finally, this approach underpins a broader context of future scenarios, where a Digital Twin is not an isolated piece for construction site management but takes part in Digital Twins ecosystems, in other words, coordination between various BDT instances and, even more, with heterogeneous DT at different spatial scales and technical domains, These ecosystems can be devoted, either to multi-site handling or multi-

scale management, including different urban scales and technical domains, such as infrastructures, city or territory, among others.

The work developed regarding the implementation of the DBT for the construction process automation, based on the assessment of the registered deviations, will allow in the long-term to extract KPIs that can serve as a knowledge base and training repository for automated learning techniques and the improvement of the construction site process. The adoption of BDT on the construction site will enable us to automate the process of data acquisition and knowledge extraction. Thus, it will help to supply more fitting and high-quality products in the future and learn from the errors detected, improving the quality of future projects. In this work, a BDT for progress monitoring, follow-up of the health and safety conditions, and supervision of work quality is proposed to optimize the construction process, help identify areas for improvement, and even reduce costs. But in the future, digital twins could even be used at urban or territory scales, enabling the identification of potential areas of environmental risk, such as air and water quality.

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