POLITECNICO
MILANO 1863

ABC^PhD Doctoral Programme
in Architecture, Built Environment
and Construction Engineering

Lean Construction 4.0
a new paradigm to support the adoption of Industrialized Building Systems and the digital transition of SMEs

Doctoral dissertation of
Marco Cucuzza

Major academic discipline:
ICAR/11 - Produzione edilizia

Supervisor:
Prof. Gabriele Masera

Co-Supervisor:
Prof. Marco Imperadori

Tutor:
Prof. Matteo Ruta

2022 - 34th Cycle

Abstract

Construction is a traditional sector where innovation is slowly adopted. The **digital revolution** enabled by the new 4.0 technologies is an excellent opportunity to reduce the productivity gap that building production has compared to other sectors (-1.8%). **Design for Manufacture and Assembly (DfMA)** and Building Information Modelling (**BIM**) are two approaches that can support **building industrialization,** and in particular **offsite** production, leading to a reduction of costs (-20%), time (-30/50%) and energy consumption (-30%), increasing quality (+20%) and security (+80%) at the same time.

This research introduces the new paradigm of **Lean Construction 4.0** as a theoretical framework for Small and Medium Enterprises (**SMEs**) in the Italian context. Its purpose is to promote the transfer of industrial concepts to buildings in the **Process, Project and Product (3P)** management activities through the sector's digitalization.

The **PhygitArk** and **Phygital Producer** are introduced as figures that can help overcome the current barriers to digitalization and the communication gap between the Design, Production and Construction phases. The instrument proposed to check and improve the digital level of companies is the **LC4.0 Assessment**, a spider chart - driven by the **Phygital Coach** - evaluating the performances of individual 4.0 technologies across the building life cycle.

Another specific application of the paradigm is the **Panelization Design Tool**, a Decision Support System for the Early Design Stage, to support the broader use of offsite panelized solutions to refurbish existing buildings envelopes. It compares prefabricated technological solutions (concrete and timber panels) to traditional insulation using the design optioneering instrument in a **BIM n-Dimensions** environment across the building stages: from the formulation of requirements to the design, production, construction, maintenance and end-of-life phases. The Horizon 2020 project BIM4EEB – a BIM-based fast toolkit for Efficient rEnovation of residential Buildings – was an opportunity to develop the research's theoretical framework about the guidelines for **Modern Methods of Construction (MMC)** adoption in Italy and digital-testing the tool on a real case study.

Keywords

Lean Construction 4.0, Phygital world, Offsite façade panel, Panelization Design Tool, Decision Support System, BIM nD.

Figure 1: Offsite Panel in Köln, 2022, Germany

Summary

Figure 2: Prefab brick facade - Copenhagen, Denmark

Executive Summary

Low levels of digitalization [1], fragmentation of the supply chain, traditional logic and structural slowness in the adoption of innovations [2] are some factors that explain the **productivity gap** that the Architecture, Engineering and Construction industry (AEC) has towards the other productive sectors (-1,8%) [3][4]. In this context, the fourth industrial revolution represents a great growth opportunity for the industry thanks to the introduction of digital technologies, which improve the information transfer process during the life cycle of construction products. Better choices can be taken according to data collected influencing the early design stage since the concept and driving design, production, construction, use, maintenance and end of life to a more effective and circular approach. Currently, the focus of industry 4.0 in the construction sector concerns the management of the built environment, thanks to the use of sensors and Internet of Things (IoT) that allow monitoring building performances, as highlighted growth trend perspective of the sector tripling its value in the next seven years (from 80.62 billion USD in 2022 to 328.62 billion USD in 2029) [5]. The creation of the **Construction 4.0 taxonomy** identifies and categorizes the main tech trends in the AEC sector by dividing them into different *Areas* (*Information, Digitalization, Product Optimization, Automation*) and *Management/Method of Analysis*, which refer to three *Objectives* (*Smart Production, Smart Manufacturing, Smart Use*).

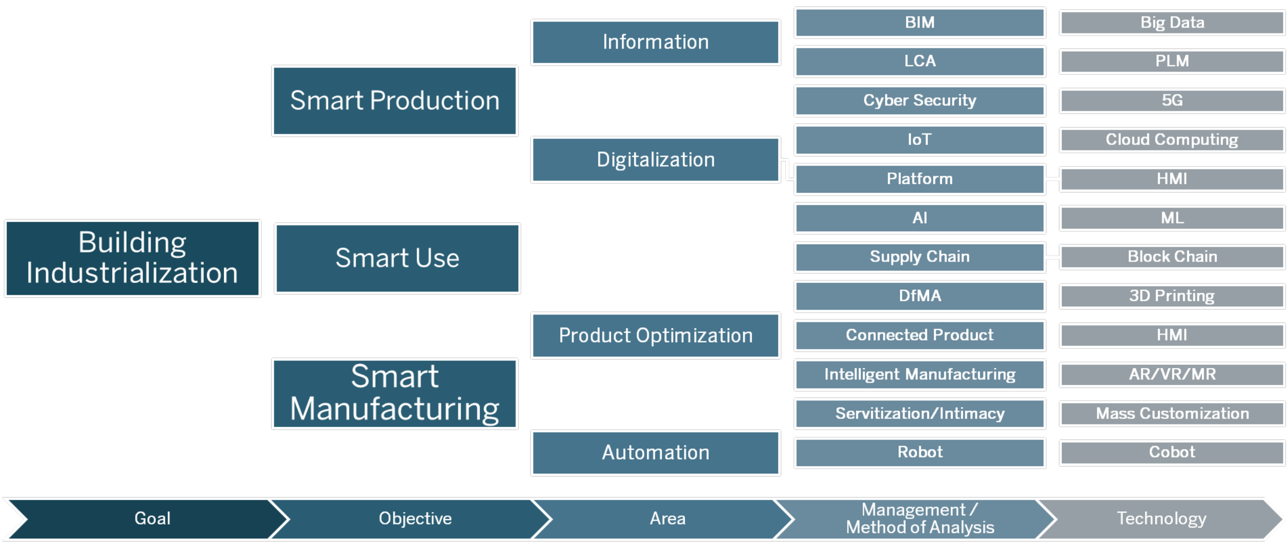


Figure 3: Construction 4.0 taxonomy

A market description helps in the understanding of the actual sector situation. Two coexistent and disruptive factors, such as the *Covid-19 pandemic* and the - partly consequent - *scarcity of raw materials* on the market, have accelerated the adoption of the fourth industrial revolution in process digitalization and production optimization. These instruments are fundamental to answering the challenging issues [6] of the increasing housing demand forecast for the future and the current need to reduce the environmental impact of highly energy-intensive buildings. The refurbishment of the old building stock cannot wait to achieve the decarbonization goal given by the EU and only the **Industrialized Building System (IBS)** can accomplish the renovation target as suggested by the *New European Bauhaus* [6].

Compared to other countries, the **Italian market** analysis [3] shows a more significant productivity gap due to the sector's high pulverization, mainly composed of *SMEs* with a low possibility to invest in innovation and a poor digital level, according to the *DESI index* [7]. On the other side, the presence of government funds for 4.0 investments (*Piano Industria 4.0*) and the tax deductions (e.g., *Superbonus 110%*) [8] to improve the environmental and seismic performance of existing buildings are good opportunities to embrace a sector revolution.

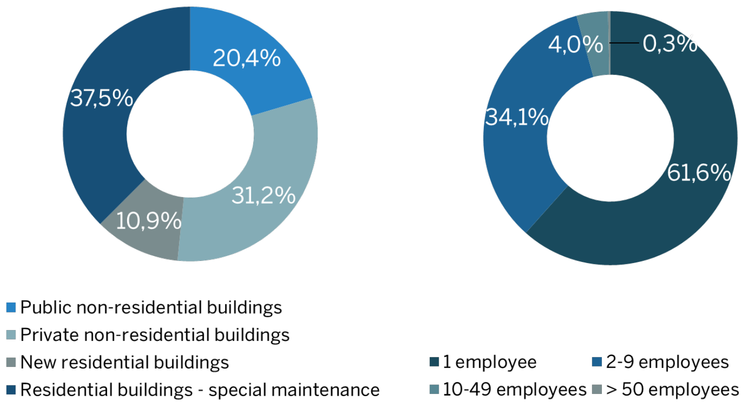


Figure 4: 2019 Construction Market in Italy is based on Refurbishment and SMEs [9]

This doctoral work proposes the **Lean Construction 4.0 Paradigm**: a theoretical framework for the digital transformation of the sector, leading to widespread industrialization at all scales, including Small and Medium Enterprises (SMEs), which is a crucial component of the sector in Italy [10]. The paradigm applies to three elements: **Process, Project and Product** in a Green (sustainable) & Blue (innovative) perspective.

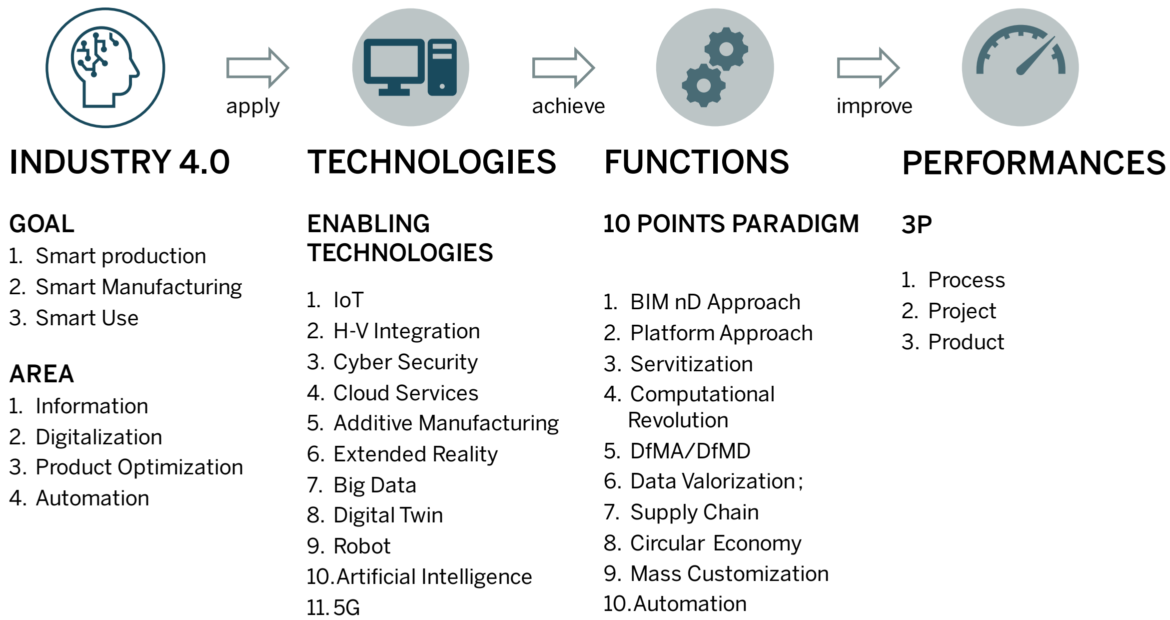


Figure 5: Lean Construction 4.0 Paradigm, from Technologies to Functions and Performances

By implementing the technologies and skills transferred from more industrialized sectors, the research work proposes a process to investigate the activities of companies and assess their level of digitalization in the three aspects of the paradigm, identifying gaps and weaknesses to be addressed with targeted strategies. This process is carried out by the companies themselves, supported by the **Phygital Coach**, namely an expert in building technologies, by the application of a tool (**LC 4.0 Assessment**) assessing the level of companies' digital maturity (**Digitalness**) in terms of *enabling* and *secondary technologies*, as well as reactivity during the building process phases (**Smartness**).

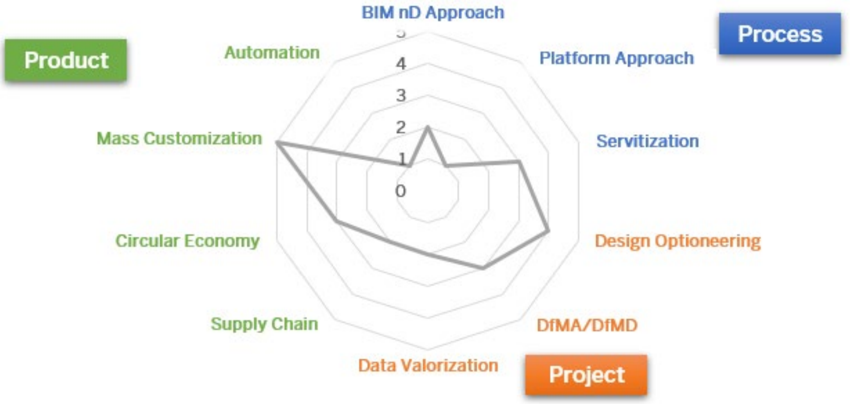


Figure 6: LC4.0 Assessment Radar, an instrument to measure the Digital Level of Companies

In addition, the research investigates a specific application of the paradigm regarding the adoption of **Modern Methods of Construction (MMC)** [11] and precisely of offsite technologies, such as for the retrofitting or new construction of envelopes able to address the growing demands in terms of performance. Acting on envelopes – responsible for 57% of the building energy losses – can better and faster achieve the global decarbonization objectives of a sector that emits 43% of European GWP [12]. From this perspective, **offsite industrialization** represents the best way to combine the building refurbishment need with the necessity to boost the sector's productivity. The market growth perspective of around 5.9% CAGR until 2030 demonstrates the increasing interest in this industrialized construction method allowed and enabled by the digital revolution. By applying **Design for Manufacture and Assembly (DfMA)** concepts [13] and a multidimensional **BIM approach (nD)**, it is possible to realize buildings and reduce the productivity gap by *lowering costs (-20%), time (-30/50%), resource consumption (-30%) and at the same time increasing quality (+20%) and safety (+80%)* [14]. The fine line between Physical and Digital dimensions [15] in the construction sector outlines the need for a hybrid stage: the Phygital World. It demands implementing the designer's profession, stressing the different architectural, technological, digital, productive and managerial skills that **PhygitArk** requires [16].

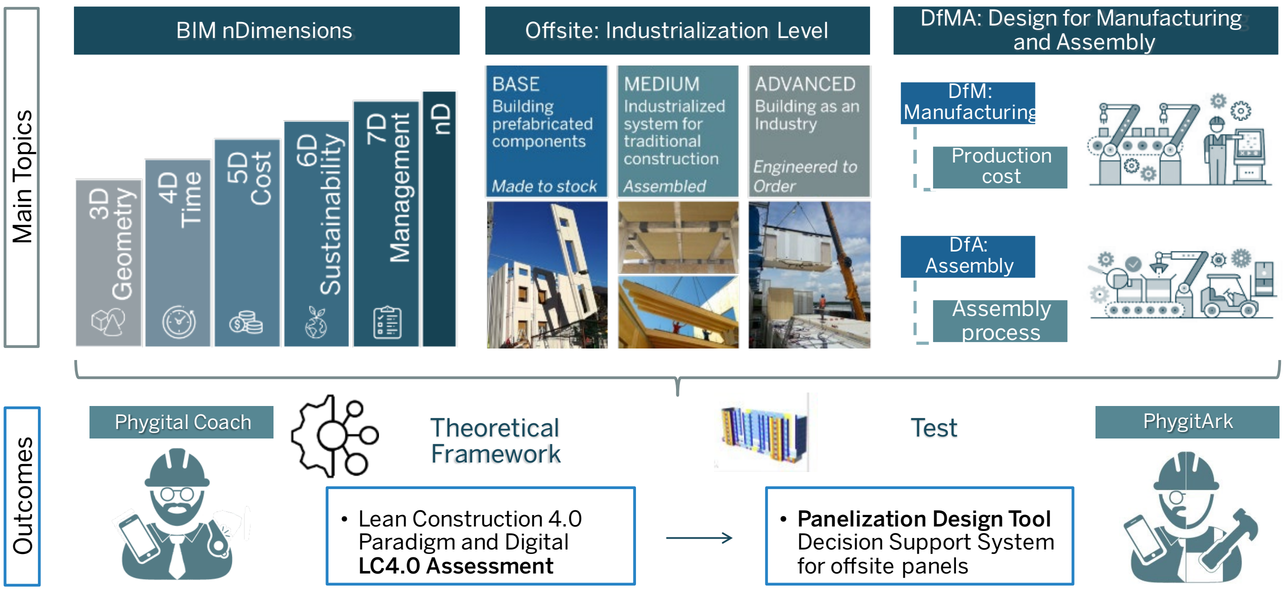


Figure 7: Lean Construction 4.0 Ontology, a DfMA and BIM n Dimensional approach to Offsite Manufacturing driven by Phygital Coach and PhygitArk

In the façade context, this figure represents the crucial link that facilitates the dialogue between design and production, involving companies from the project's preliminary stages and supporting decision-makers in the choice of the most suitable technological solution according to different parameters. This *holistic approach* to buildings is based on the digital revolution adoption as a game changer for the sector thanks to the data valorization and a new value proposition for more industrialized constructions thanks to the **Knowledge-Based Engineering (KBE)** [17] approach to *Information Management*.

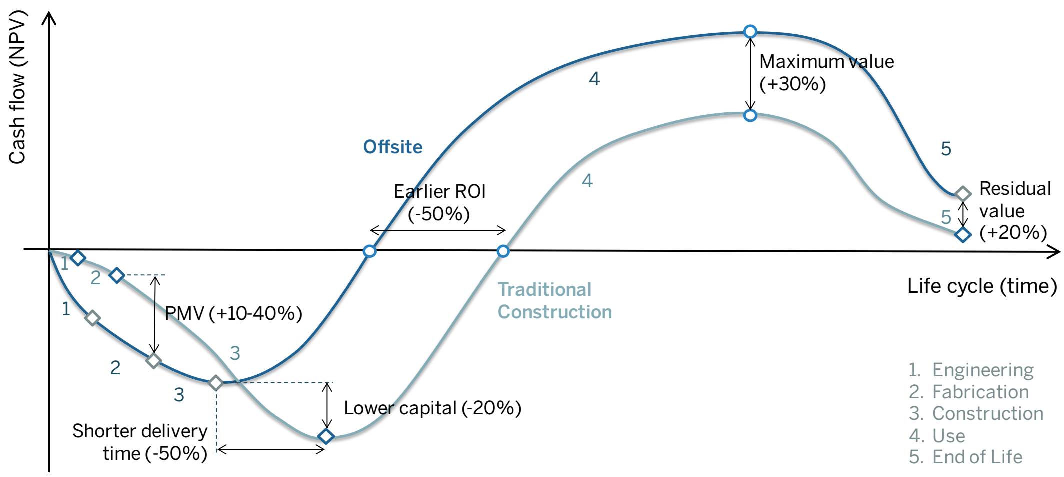


Figure 8: the Offsite Construction value proposition across the building lifecycle

For these reasons, this doctoral work develops the **Panelization Design Tool (PDT)**, *a decision support tool for the Early Design Stage*, helping different actors involved in the design-production-construction and management process of high-performance facade components. Thanks to a script able to analyze the existing geometry and collect the various desires/ limits identified by the client, the architect, the engineer, the manufacturer and the builder, various *technological solutions for the prefabricated envelope* (steel, wood and concrete) can be compared through quantitative indicators.

Figure 9: Meta-technological recladding options to compare in the Panelization Design Tool

Analytical scores assess each technology's effectiveness, grouping them by type according to their **BIM nDimesions**, as disciplines subdivision. *Geometric (2D), structural (3D), time (4), economic (5D), sustainable (6D) and management (7D)* parameters are the drivers that each involved stakeholder analyzes according to its priorities without losing the whole vision of the project. Therefore, the PDT is intended as an **open platform** based on parametric design tools that can be easily implemented with further and additional modules to expand the involved disciplines (e.g., safety, seismic and fire protection). This optimization process aims to avoid arising risks from the late decision about technology, causing losses in terms of efficiency and overall quality. It focuses on making initial decisions that are as much as possible data-driven instead of a priori.

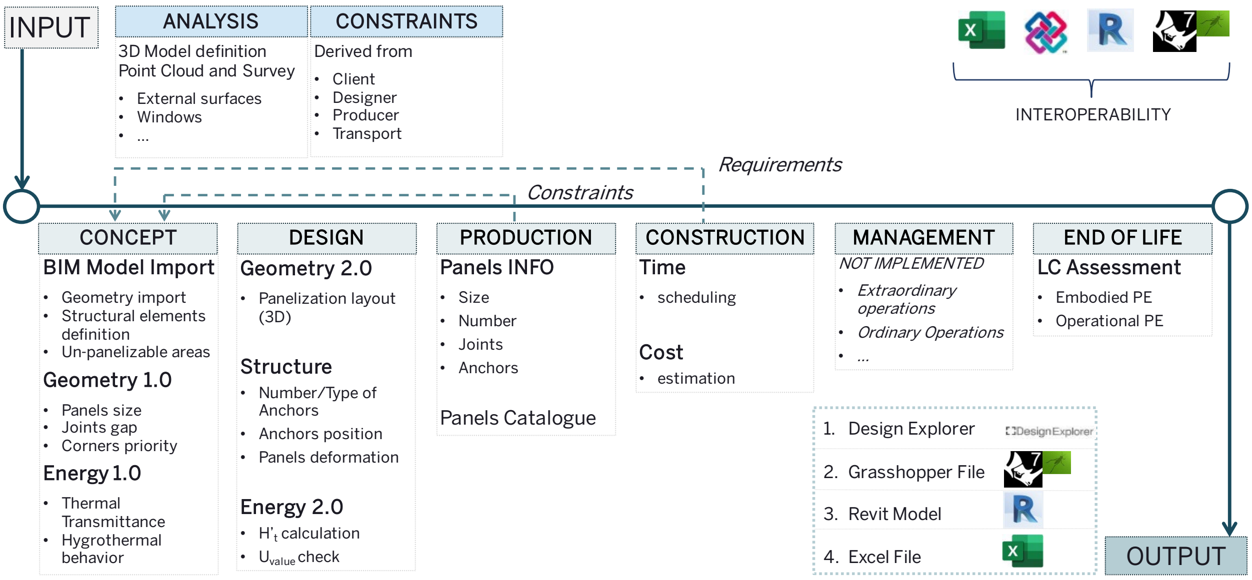
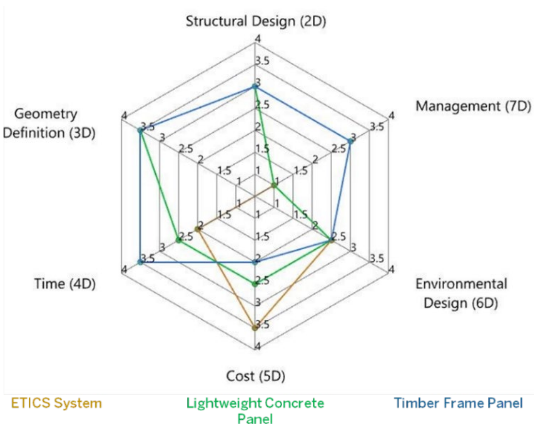


Figure 10: Panelization Design Tool Process Mapping for an informed decision in the Early Design Stage

The proposed **Decision Support System** was tested on a case study of the Horizon2020 project *BIM4EEB – a BIM toolkit for fast-track renovation of existing buildings* [18]– thanks to which it was possible to identify gaps and critical issues in the application and dialogue phases between the different actors. The PDT application on this building's typology underlines how parametric design can be applied functionally and efficiently not only to iconic architecture but also to common residential buildings to be renovated, which are the primary target to ensure the achievement of Europe's decarbonization targets.



Structural Design (2D):
- Number of anchors / m2 (no./m2);

Geometry Definition (3D):
- Number of total panels / Total cladding surface (n/m2);
- Number of panel types / Number of total panels (-);

Time (4D):
- Installation time [h/m2];

Cost (5D):
- Total cost [€/m2];

Environmental Design (6D):
- Thermal transmittance U (W/m2K);
- Global average heat exchange coefficient H't (W/m2K).

Management (7D):
- LCA [PEREN/PETOT].

Figure 11: BIM nDiagram, the synthetic radar instrument of the Decision Support System

Figure 12: Dortheavej Modular Residence, BIG, 2021, Copenhagen, Denmark

1. Introduction and methodology

"The beginning is the most important part of the work."

PLATONE

Abstract:

Industry 4.0 is an overused word in 2022, applied to several fields, so why investigate this topic? The research background gives a picture of the context and the scientific interest in the construction world in this specific area. The description of the **thesis goal** is driven by the **Research Questions**, which are splitted into **Horizontal** (4 broader concepts) and **Vertical** requests (4 specific and tailor-made, plus 8 sub-ones), which find answers during the text. Each research question is linked to a primary **Objective** (4) and 4 **Sub-Objectives** that find answers in the following chapters. The **methodological approach** applied and a short description of the following steps complete the research overview in this chapter, which can be intended as a **reader's guide**.

Contents:

Expected results:

- Research Background
- Identification of the thesis goal
- Statement of Horizontal and Vertical Research Questions
- Accounting main and sub-Objectives
- Description of the applied methodology
- Summary recap
- Reader's guide

Keywords:

Research Background, Goal, Research Questions, Objectives, Method, Structure

1.1 Problem statement

At the beginning of the 2020s, disruptive technological innovations have influenced all sectors worldwide except the building market: Industrial 4.0 innovations have limited application in this field [2].

This research aims to start a broad investigation path to understand how digitalization, automation, robotics and advanced manufacturing technologies and tools can be realistically applied in the 2020s building construction processes by providing significant innovations. The need is to suggest a possible solution to fill the productivity gap that the Architecture, Engineering and Construction (AEC) sector has with respect to the other manufacturing compartment, pushing the adoption of an industrial approach also in this field. The purpose is to respond to future social, economic and environmental challenges, particularly in a market like the Italian one, characterized by the prevalence of risk-averse small and medium enterprises with a limited budget for implementing innovative processes.

Starting from this general objective, the research aims to:

- Identify the main areas for integration of digitalization, advanced industrialization (offsite solutions), automation and robotics in real building processes;
- identify multiple problems/barriers related to their application in a typical Italian / European context and considering the Industry 4.0 targets;
- assess the multiple benefits of the potential innovations, considering social, economic and environmental challenges of the building sector;
- define development trends and possible new schemes and tools to be introduced over standard construction processes for more effective integration of such innovations.

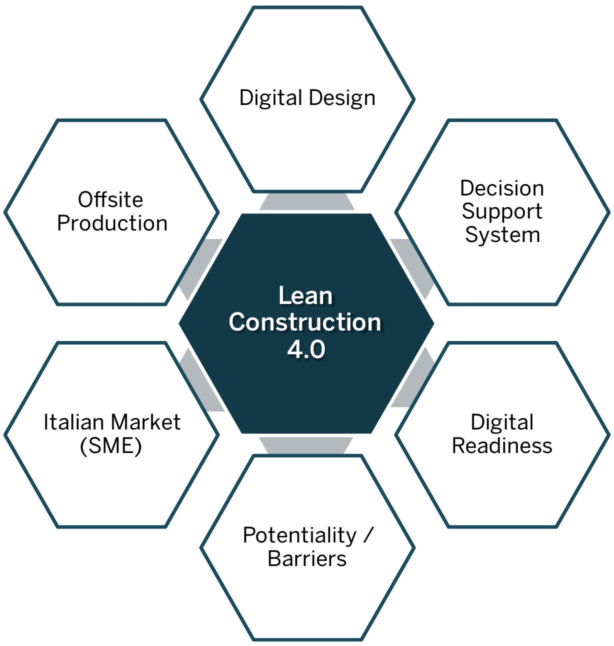


Figure 13: Lean Construction 4.0 research fields

1.2 Methodology

The definition of the problem statement figures out the main research goal [§ 1.2.2.1], which generates four broad research questions [*RQ 1, RQ 2, RQ 3, RQ 4*, chapter 1.2.1.1]. From these questions, the two general objectives are defined [*Obj 1, Obj 2*] with four sub-objectives [*Obj 1.1, Obj 1.2, Obj 1.3, Obj 2.1*] which helps in the definition of the vertical research questions [*RQ 1.1, RQ 2.1, RQ 3.1, RQ 4.1*, § 1.2.2.1]. The chapter continues with the description of the Research Method applied [§ 1.2.3] and finally, the Research Structure [§ 1.2.3] exploits the path which drives the thesis.

1.2.1 Research Goal

How to apply industry 4.0 to the construction sector? This is the primary investigation query that concerns many fields of the AEC sector, covering all the building life-cycle process. Questions are divided between Broad Questions (global scale for all enterprises sizes) and Vertical Questions (local focus, SMEs size) to identify the research focus. The first ones aim to understand the environment of the 4.0 revolution in the building sector, while the second ones are strictly related to the new paradigm definition and the application of its instruments.

1.2.1.1 Broad research questions: Construction 4.0 Environment

RQ 1. What are the potentialities/barriers to Construction 4.0 at a global/local scale?
RQ 2. How can different companies (Small, Medium) adopt Construction 4.0?
RQ 3. Where to act to take the AEC sector in a new era? What are key building process phases?
RQ 4. What are the different levels of action (Production, Project, Process) to evaluate?

1.2.2 Objectives

The purpose of the research is double: theoretical and practical. The first focuses on defining a new paradigm for Lean Construction 4.0 (§ 4.1) allowing Italian Small and Medium Enterprises (SMEs) to adopt the digital revolution in the building sector. First, it is essential to define the 4.0 level of companies and the purpose of the Lean Construction 4.0 Assessment set-up (§ 5.3). Two figures are defined with their own set of competencies to facilitate the adoption of this paradigm: the Phygital Coach for the companies' improvement of Smartness and Digitness (§ 4.2.3.2) and PhygitArk (§ 4.2.3.1). This second role model allows the adoption of Modern Methods of Construction (MMC) for new/refurbishment buildings (§ 3.4.4) by testing the information flow [12] defined to achieve the second practical intent of the thesis. This purpose is to apply the Design for Manufacture and Assembly (DfMA) and Building Information Modelling (BIM) approach in the façade design optioneering method with a more informative and data-driven decision-making tool: the Panelization Design Tool (PDT, § 6.3). The open platform system will be able to adapt, modify, change and evolve the structure flexibly according to the requirements of different supply chains.

Obj 1 Outline **Lean Construction 4.0**, a new theoretical paradigm for the digital transformation of the AEC sector's Italian Small and Medium Enterprises (SMEs).
- **Obj 1.1** Set up **LC4.0 Assessment**, a digital-level assessment of companies.
- **Obj 1.2** Define the **Phygital Coach** figure with its skills to drive the LC4.0 Assessment.
- **Obj 1.3** Define the **PhygitArk** figure with its skills to boost the 4.0 transition of manufacturing.

Obj 2 Figure out opportunities in **MMC adoption** through digital instruments (BIM approach) for DfMA objects (prefab elements).
- **Obj 2.1** Create and describe the **Panelization Design Tool (PDT)**, a Decision Support System (DSS) to apply the design optioneering method in façade design.

1.2.2.1 Vertical Questions: Lean Construction 4.0 paradigm development and applications

RQ 1.1 What are the possible instruments to facilitate solutions (schemes and tools)?

RQ 2.1 What figures can help in the adoption of the digital revolution in the AEC sector?

RQ 3.1 Companies Assessment: LC 4.0 Assessment

- **RQ 3.1.1** What are the enabling and secondary technologies enabling the digital revolution for enterprises?
- **RQ 3.1.2** How to evaluate the digital level of companies across the building process stages?
- **RQ 3.1.3** What are the appropriate KPIs to assess their overall digital score?
- **RQ 3.1.4** Is the score effective in evaluating their digital performance?

RQ 4.1 Panelization Design Tool (PDT)

- **RQ 4.1.1** How to apply Modern Methods of Construction for new construction/refurbishment? Why push the adoption of offsite panels to reclad existing buildings' envelopes?
- **RQ 4.1.2** How to effectively compare different panel technologies? Which instruments can be applied?
- **RQ 4.1.3** Which KPIs are useful to evaluate a panel technology?
- **RQ 4.1.4** How can non-technician decision-makers such as businessmen easily understand analytical results?

1.2.3 Research Method

The vision behind this research is based on the question of how to apply industry 4.0 to the construction sector. The problem statement analysis highlights the urgency of accelerating building production with fewer resources and much more quality to satisfy the home request coming from the population growth. The action strategy concerns not only the new buildings' construction but especially the action on the old existing building stock, which has a strong refurbishing need [19]. The vision driving the research methodology relies on the peculiarity of the AEC sector, where the research method should be based on innovations coming from the industrial world much more than theoretical investigation. For this reason, the scientific approach adopted is built on the correlation method [20], which involves direct observation, opinion pool, surveys, interviews, single cases study, etc., to understand the problem statement, the gap to fill into the sector and barriers to new approach adoption. These limitations suggest a new theoretical paradigm (Lean Construction 4.0) with a practical instrument (LC 4.0 Assessment) to help its adoption. The same scheme is adopted for the specific intervention area identified for the panelization of existing buildings (Panelization Design Tool). Some tests verified the scalability of both the proposed tools as the first validation of the created instruments. Results, paths, concepts and processes are explained with the help of graphics and schemas developed by the author when it is not indicated otherwise.

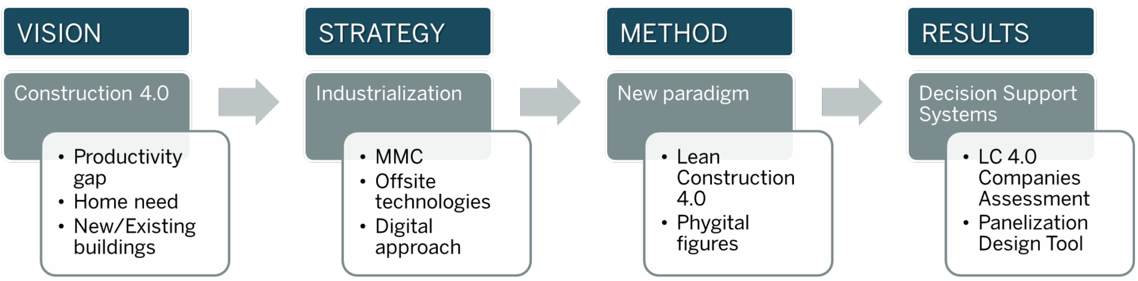


Figure 14: Research Method

1.2.4 Research Structure

The literature review of scientific studies allows understanding Industry 4.0 concepts deeply (Chapter 0). Then the focus is moved to construction, buildings and all the related aspects (Chapter 0). The few results in the academic world for the construction phase and the requirement of market data coming directly from contractors push the research on grey literature, such as reports and studies from companies (§ 0). The best practice collection, (§ 0) and the companies' interviews (§ 10.1) allow for defining a more applicable path in a 4.0 perspective [4], [14], [21]–[25].

The proposed theoretical framework (Lean Construction 4.0, Obj 1 - Chapter 0) is tested through the application in an innovation leader country such as Denmark of the original instrument (LC 4.0 Assessment, Obj 1.1 – Chapter 0) developed as the first main research output to test the digital level of companies. A worldwide Corporate (Velux, § 0) is a case study useful to understand the feasibility of the outline and where SMEs can introduce themselves in the market as stand-alone actors or suppliers for big players (RQ 2).

A practical application of LC4.0 consists in the Modern Methods of Construction (MMC, § 3.4.4) to fill the productivity gap of the AEC sector and specifically offsite panels for the building envelope. The designed Information Flow (§ 6.3.1) is validated by the Horizon 2020 European research project BIM4EEB (a Building Information Model-based toolkit for Efficient rEnovation in Buildings) [26]. It concerns the development of a BIMMS (Building Information Model Management System): a BIM toolkit for renovating existing buildings. One of this project's tasks is a fast-track BIM renovation tool using prefabricated panels for the façade retrofit.

Outside of the European project, but as an original outcome from this research, the Panelization Design Tool (PDT) (RQ 4.1, Chapter. 0) is designed to test the Decision Support System for the Early Design Stage selection of a façade technology in a real Italian case study.


Figure 15: Digital Revolution in Architecture [Adobe Stock]


Figure 16: Sandwich panels installation

2. Industry 4.0

"For the first time in history (1983, E.D.), it is now possible to take care of everybody at a higher standard of living than any has ever known.
Only ten years ago, the 'more with less' technology reached the point where this could be done.
All humanity now has the option of becoming enduringly successful."

RICHARD BUCKMINSTER FULLER

Scope:

The thesis starts with understanding what industry 4.0 is in **literature** and from companies' perspectives. To explain the Digital Revolution's impact, the innovation path is explored, starting from **Kuhn's theory** and focusing on **disruptive innovations**. A **Digital World** interpretation, a **glossary**, the **categorization of the technologies involved**, a pros and cons analysis and the description of the new mindset and **companies' architecture** required in the fourth industrial revolution complete the overview of this introductive chapter to the topic.

Contents:

Expected results:

- Industrial revolutions history
- Innovation theories overview
- Digital World Interpretation
- Deep understanding of Industry 4.0
- Critical analysis of digitalization
- Glossary collection
- Technological trends identification
- Benefits and limitations of Digital Revolution
- New organization description

Keywords:

Industry 4.0; Enabling technology; Innovation; Digital revolution; Market

The chapter concerns the introduction to the fourth industrial revolution starting from the previous three, their features and the impact on the period.

Industry 4.0, a term coined in Germany in 2011 [27], means production's digitalization process, changing the traditional supply chain based on human making. The new smart manufacturing innovates the process using information and digital technologies [28].

2.1 Industrial revolutions

The 4.0 number indicates that there are three previous industrial revolutions [29]:

1.0 The industrial period started in the 18th century with **mechanical production** based on water and steam power
2.0 The introduction of electrical energy took the industry into **mass labor production** (beginning of the 20th century)
3.0 The Internet revolution introduced **automatic production based on electronic** (the 1970s)
4.0 Cyber Physical Systems (CPS) production has become integrated thanks to **Digital Transformation.**

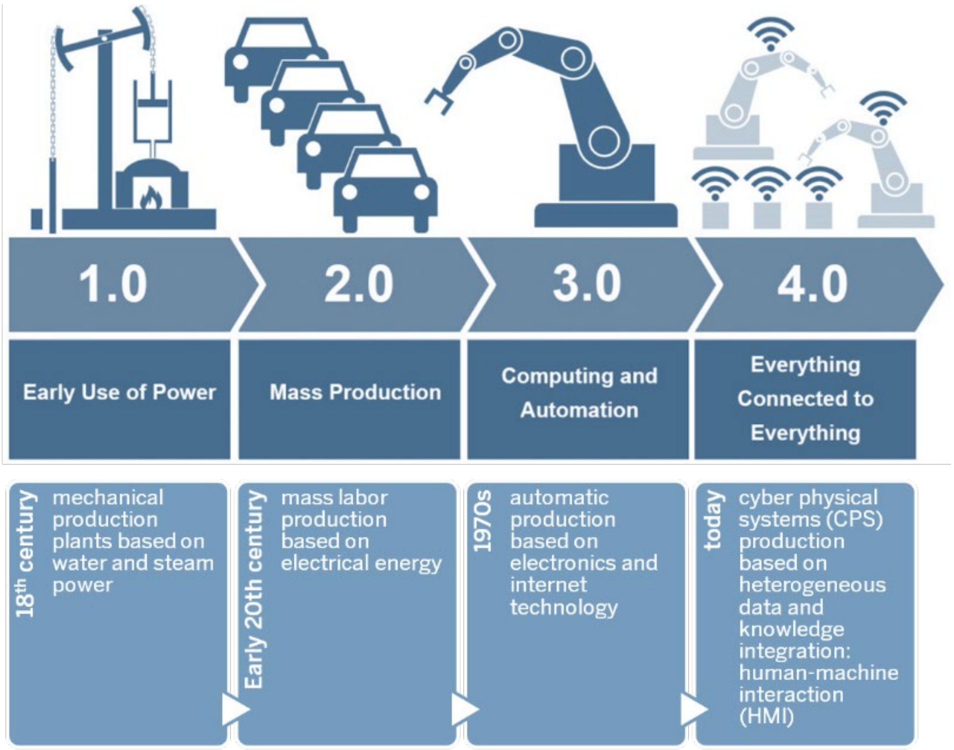


Figure 17: The four Industrial Revolutions features

2.1.1 The fourth industrial revolution

There are many definitions in literature for industry 4.0 or 4.0 Revolution; the most cited are:

- "*The integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes.*" [30]
- "*A new level of value chain organization and management across the lifecycle of products.*" [27]
- "*a collective term for technologies and concepts of value chain organization.*" [31]

- An industry where Internet of Things (IoT) and Cyber Physical Systems (CPS) communicate and co-operate with each other and humans in real-time and the Internet of Services (IoS), both internal and cross organizational services, is offered and utilized by participants of the value chain. [29]

The common part of all these definitions is the use of **technology** as an instrument to improve communication, information flux and production **optimization**. The **multidirectional communication** directly connects production to customers creating a **high customized product** [32].

Figure 18: 4.0 Cross Laminated Timber (CLT) Factory in Italy

2.2 What is innovation in the 4.0 era?

Innovation can be described as a social and cultural change that is not necessarily related to new technologies [33], [34]. According to this interpretation, there are two kinds of innovation:

- **Incremental** means "*doing more with less*" (*Buckminster Fuller Ephemeralization* [35], *Foster* [36]) or optimizing resource consumption to obtain the same product. It was born from *Popper's* theory about the cautionary approach through the *dubitative method* of what is already achieved [33]
- **disruptive**, introducing a new good that completely changes the market [37]

All the technologies involved in the 4.0 process are disruptive innovations [38] that offer a **higher service quality** without the concept of technology innovation property.

These innovations are great revolutions that moved people to adopt them quickly thanks to new and completely different technology from the actual marketing situation. Because of the marketing strategy of Corporates, which are investing in "sustaining innovations", they lose leadership when disruptive innovations arrive.

The genesis of this process is through a series of little innovators that realize new products or services. The winning revolution is the creation of a standard, becoming the reference point for the sector [39]. The inspiration for these solutions usually came from the **automotive** and **aerospace** industries, the innovation pioneers, activating a **technological transfer** process.

Disruptive innovation follows the **Paradigm Shift** theory of *T. Kuhn* [40]: the radical change of the current status due to a **Crysis** of the previous one. He and A. Einstein believe it is an opportunity [41]: the **Pioneer** - or innovation trigger – moment [37]. The new paradigm will become the standard only after the **Fast Second** adoption (the market leaders) and the **Third Generation** mass production begins (plateau).

The Covid-19 pandemic can be interpreted as the accelerator event in the digital revolution adoption of society, starting from the remote work and the new inventions created during the lock-down period for new (digital) necessities.

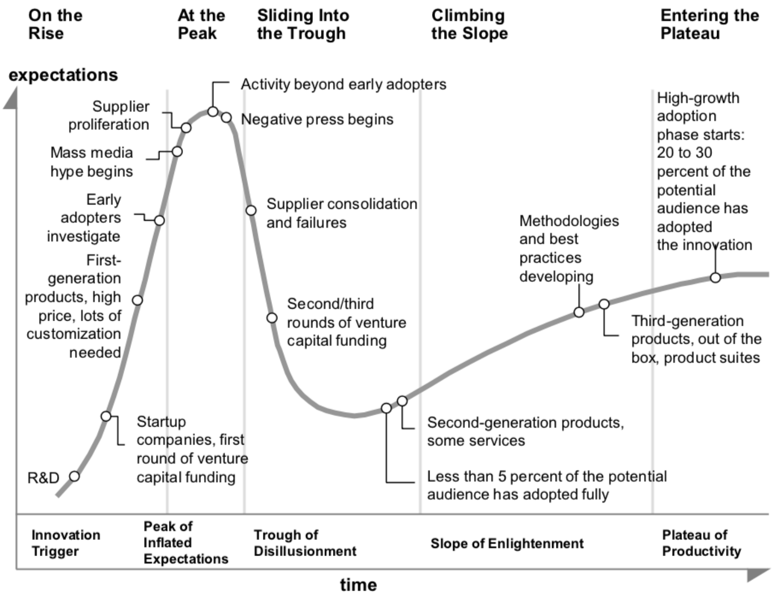


Figure 19: Gartner's Hype Cycles [37]

2.3 Digital world

2.3.1 A philosophic interpretation

Regarding the current society, *Bernard Stiegler* underlines the need to rebalance the theoretical and practical-operational aspects by creating interdisciplinary skills networks addressed to **Lifelong Learning**, intended as the continuous learning process of man during life [34]. The German philosopher analyzes the digital revolution pointing out the need to maintain a critical point of view on the technological instrument. The risk of virtual society is to convert the knowledge from "what is" to "what becomes", which means, according to *Heidegger*, moving from **Dasein** ("be ontologically in the world") to **Inforg** ("manager of Infomi[1]"), namely processing agents that consume instead of being (*Han* [42]). By the term "manager", it is assumed that effectiveness replaces the truth for the lack of time. This urgency forces to run behind the information, but it does not lead to any knowledge: everything is recorded without knowing it, living it and then without making a physical experience. Finally, reality is dematerialized. Therefore, the digital order de-realizes the world imposing the not-things, namely the information, as a value driver and, consequently, underestimating the concepts of tightness and durability as saving values from the post-factual society of information (*Hannah Arendt*).

The **Inforg** should experience the knowledge phases by using new technological instruments. To attain **knowledge** intended as being aware, it is necessary firstly to gain **experience**, then **gather** (acquire data) and later process and **elaborate** the information to achieve the internalization of them and, from here, the possibility of transmitting concepts by communication (*G. Falciasecca* [43]). In a society that demonizes time, it is all about the undertaking, namely trying new experiences without internalizing them and making them their own. In other words, the process is interrupted at the first stage, transferring the gathering of information to digital tools and making people deprived of the possibility of processing and learning the data received. The transfer of human skills to machines risks subordinating the subject (man) to the instrument (technology), belittling the reality of *Homo Sapiens*. The human evolution in *Homo Ludens* (*Han*) has transformed the freedom of action of *Homo Faber* - which finds fulfillment in work for itself and thus emancipates itself from slavery, transforming personal freedom into time slavery. Thus, the man is catapulted into a post-history dimension in which there is the risk of suffering the choices passively without even making them. In this dictatorship of the time, it is fundamental to regain a homocentric dimension; without making it lag behind modernity, but operating according to the principles of *Festina Lente* or acting without delay but with caution (*Svetonio* [43]). The new dimension of freedom as consumption led to a logical shift of goods possession, typical of the 900, to one of experience: the more things you live, the richer you are, even superficially and without the information internalization. Hence, *Homo Ludens's* survival passes from the need to choose with care the information to preserve and look after since distinctive information is necessarily recognized as intrinsic value. The new **information capitalism** has replaced that of industry in which goods were material objects, while in this decade, they have been replaced by what can be shared according to a sharing economy logic translated on experiences. This new environment created in digital is defined as infosphere or "*the semantic space constituted by the totality of the agents and their operations documents where documents mean any type of data, information, knowledge codified and implemented in any semiotic format*" (*L. Floridi* [44]). This context defines a new historical era called **Hyperhistory**: it is characterized by the digital revolution that incorporates

[1] Infomi are defined Functions that elaborate information (Han) [42]

the three phases of information acquisition, processing and communication, the ultimate expression of which is artificial intelligence. The infosphere influences all levels from the digital point of view, starting from the single data passing to the processes and interesting the structure of society. The new hybrid environment between reality and virtuality is managed by **Digital Platform** (chapter 4.2.1.2), intended as something halfway between physical places and communication tools entirely based on **ICT** (**Information Communication Technologies**) [43].

Thus, to approach this complexity and identify the key **Infomi**, it will be necessary to develop multiple skills combining engineering pragmatism with a philosophical attitude through drawing the theoretical framework within which putting practical experiences. It is fundamental to respond to emerging needs by defining new requirements to be met by increasingly complex instruments guided and implemented by various actors. The latter needs a composite mind to coordinate them, as theorized by *Ove Arup* for the construction sector with the term **Total Design**, a definition of holistic design born in the years of post-war reconstruction (*A. Campioli* [45]). The necessary balance for managing such a powerful but neutral tool and the direction to be given it will be assigned to figures able to combine technical aspects with intellectual ones, without losing sight of the ultimate aim of human well-being.

Therefore, to better understand the extent of the digital revolution is necessary to define a vocabulary concerning the most used terms. Following the computer science logic, **data** (from the Latin datum, "fact") means a raw value inserted in a **context** with its meaning based on which information can be retrieved. Processing multiple data allows getting one or more **information**, which in turn are used to achieve other purposes such as making choices according to the **rules** defined.

2.3.2 Digital Glossary

Talking about the digital revolution, it is necessary to glossary three words: **digitization, digitalization** and **digital transformation** [46].

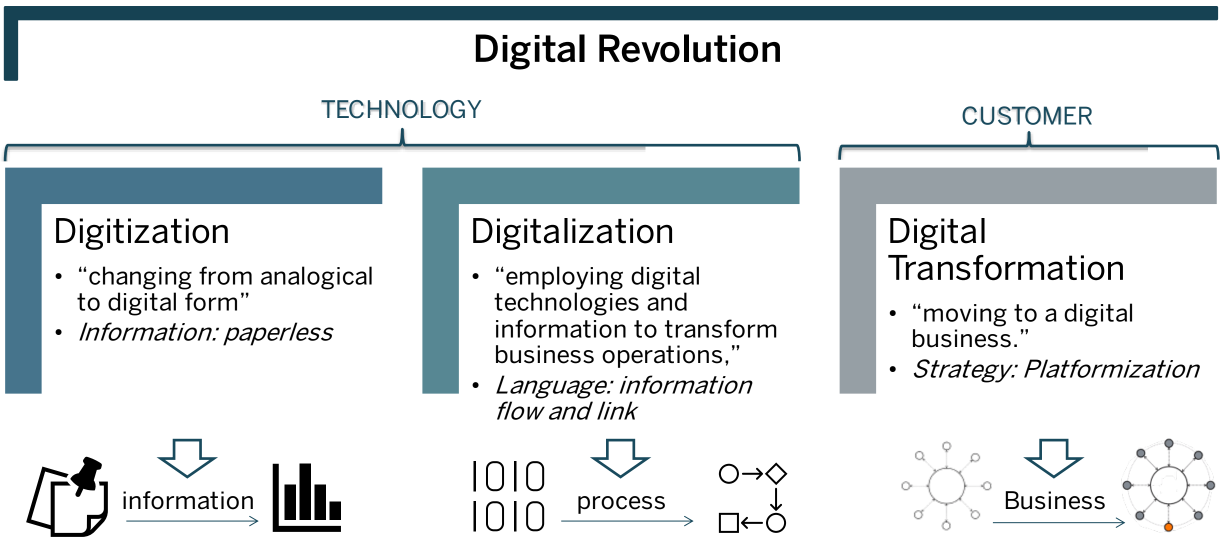


Figure 20: the Digital Revolution's glossary (Author's elaboration on [46]

The first is the switch from analogical to digital form (e.g., paperless); the second transforms the process through a new language adoption (information flow and link); digital transformation defines a new business strategy based on **Platformization** and **Servitization** instead of Product.

2.3.3 Enabling Technologies

The fourth industrial revolution defines the application of the digital revolution to the industrial process. **Nine** are the **enabling technologies** concerning production and manufacturing [27]:

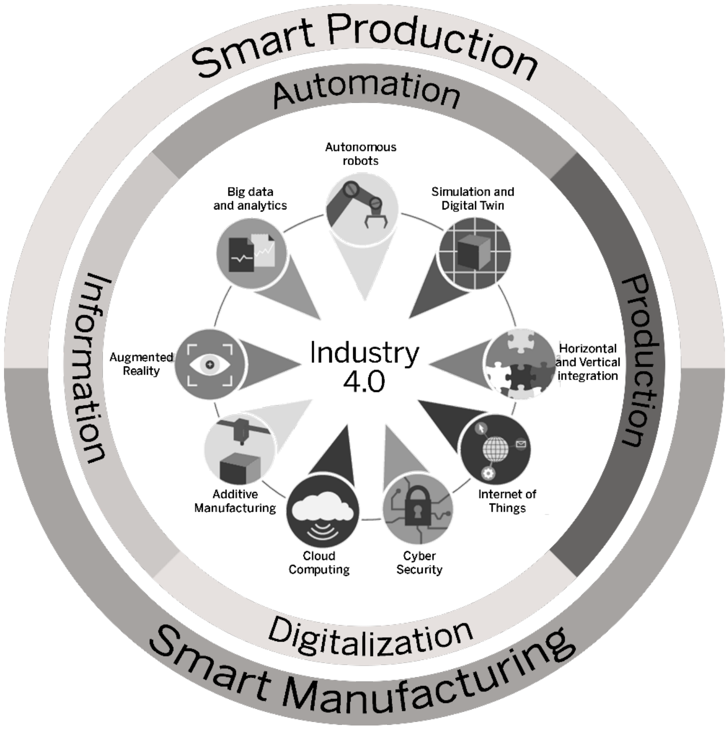


Figure 21: Industry 4.0 technologies and factory applications in the four main areas (Author's elaboration on [27])

1. **Advanced manufacturing solution**: interconnected and modular systems (automotive moving, advanced robots, collaborative robots or cobots).
2. **Additive manufacturing**: 3D printing systems to increase material efficiency and optimize energy consumption.
3. **Extended/Mixed Reality:** visibility systems to help humans in specific activities.
4. **Advanced Simulations and Digital Twin:** simulations to preview problems and interaction of machines by creating a Digital Twin.
5. **Horizontal and Vertical Integration:**
   - Vertical integration: thanks to IoT, products become active, intelligent elements that transfer information inside the production chain (between machines, systems and workers) and outside the customers' world.
   - Horizontal integration: collaborative manufacturing collects information for the supply chain creating a network between manufacturers, suppliers and clients as the German plan "Industrie 4.0" provides. In this way, companies increase efficiency and reduce costs.
6. **(Industrial) IoT**: inside and outside communication of the company thought a network controlling and optimizing every time and solution.
7. **Cloud computing**: open systems to collect data and interact.
8. **Cybersecurity:** access control to data and information is fundamental to protecting company know-how.
9. **Big Data Analytics:** ability to manage and use open data to predict the market future.

2.4 Advantages and Challenges of 4.0 Industry

Analyzing all the concepts behind the 4.0 Industry, it is possible to summarize the positive aspects [30], [47]:

- **flexibility**: Artificial Intelligence (AI) gives automation a flexible, growing up, low cost possibility to make customer production,
- **fast track**: products and services are more rapidly coming to market,
- **productivity**: machine, workers, processes and energy increase their productivity,
- **quality**: fewer scrap due to higher control, check and regulation of functions,
- **competitiveness**: digital products and smart products are services with a higher value for customers,
- **de-risking**: processes are reliable, so the flux variation of revenue is smaller.

On the other side, the challenges are [48], [49]:

- **cybersecurity**: cloud computing and IoT mean that all the data are online and it is possible to steal it,
- **privacy risks:** all personal data online and full-time connection are risks for privacy because companies will use them for their profit, analyze human actions and habits for their business plan,
- **unemployment**: manual work decreases, so humans required for the industry are less,
- **reskilling workers**: a tiny part of the manual workers could be reskilled in more technical positions about technological aspects (new jobs as visual data designer, IoT architect, Data Science Manager, Cybersecurity expert, IT_OT integration manager, Industrial Big Data Scientist…),
- **machines are not ready** to complicate/non-repetitive tasks: they must be implemented,
- **costs**: initial capital to have this change is huge.

2.5 Smart Companies architecture

4.0 Revolution, like all disruptive innovations, requires a complete change in the industrial organization. It regards manufacturing and product in the new concepts of **Smart Manufacturing** and **Smart Product** that have the same origin: **technology innovations.**

Digital readiness [2] is the manufacturing technology index of the primary analysis divisions:

1. **execution**
2. **monitoring and control**
3. **technology**
4. **organization**

Each analysis is connected to many processes that are the backbone of the industry:

- **design & engineering**
- **production management**
- **quality management**
- **maintenance management**
- **logistics management**
- **supply chain**

All these processes are involved in the five main industrial areas. Every area has its own technical skills; the most important are the "Ability to define, implement and manage an industrial 4.0 technology take-up plan". Osservatorio 4.0 of Politecnico di Milano [50] selected 100 technical skills collected in 25 families referred to the five main areas:

1. Operations
    a. Process Improvement
    b. Planning and Coordination
    c. Smart resources management
    d. Enhancing process technologies
    e. Data analysis, Modelling, Simulation
2. Supply Chain
    a. Business innovation
    b. Smart Management
    c. Computer Science & Data Analytics
    d. Software platform use
3. Product-Service development
    a. Product/process innovation
    b. Smart Design
    c. Digital & Virtual instruments
    d. Services Engineering
4. Data Science
    a. Data Architecture
    b. Data Management
    c. Computer Science
    d. Data Analysis
    e. Visualization
    f. Domain knowledge
5. Information Technology/Operation Technology Integration (IT/OT)
    a. IT/OT alignment and business
    b. Platform and components platform
    c. Modeling and simulation
    d. Embedded Computing-Device Communication-HMI
    e. Standards and protocols
    f. Cybersecurity

Due to the technology revolution, the 4.0 companies' structure is now based on the digitalization of technical and production aspects. This change led to a new market based on three topics [27]:

1. **Digitalization** and integration of any simple **technical-economic** relation to complex technical-economic networks.
2. **Digitalization of products and services** offer.
3. **New market models** created by the new products-services.

These three mutually interconnected aspects in new companies' architecture are called RAMI 4.0 (Reference Architecture Model Industry 4.0). The 3D diagram merges data (left axis), function position (proper position), market and information communication (vertical axis), showing the integration of all these aspects.

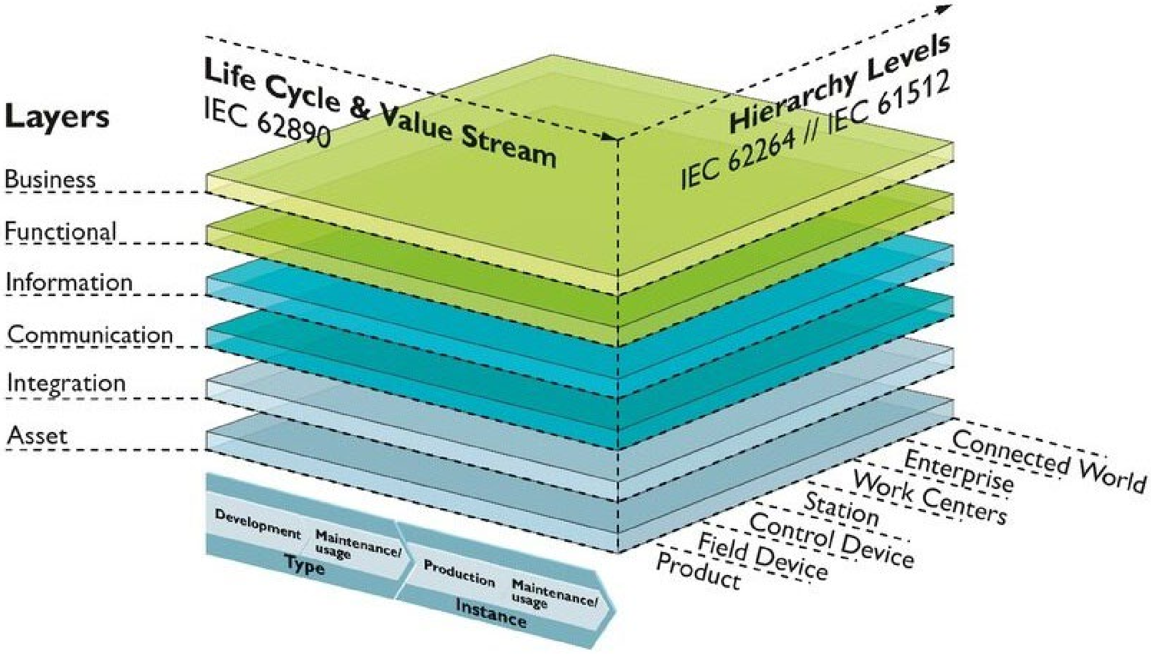


Figure 22: RAMI 4.0 (Reference Architecture Model Industry 4.0) 3D diagram [27]

The final purpose of the 4.0 industry is to create a **Smart Factory**, based on RAMI 4.0 architecture [51], able to have:

1. **Smart Production**: making an output (goods or services, tangible or intangible) for consumption (immediately or later) through resources (not necessarily machines)
2. **Smart Manufacturing**: producing final goods (tangible process) through men, machines, materials and tools (physical instruments) ready to be sold.

The difference between these two concepts is raw materials: the company owns them in production while manufacturing procures them. Because of their definition, all manufacturers are producers, but not all the producers are manufacturers: manufacturing helps in the transformation of raw materials into finished goods, while production is the process where inputs become outputs [52].

Production and Manufacturing are the two main concepts of industry 4.0. Both of concerning the four main innovative themes related to each other.

1. **Digitalization/digital transformation**
2. **Product optimization/customization**
3. **Information**
4. **Automation**

The four main concepts are based on communication technologies that need a **common language** to transmit data from production to all life cycles without limits on enterprises and countries.

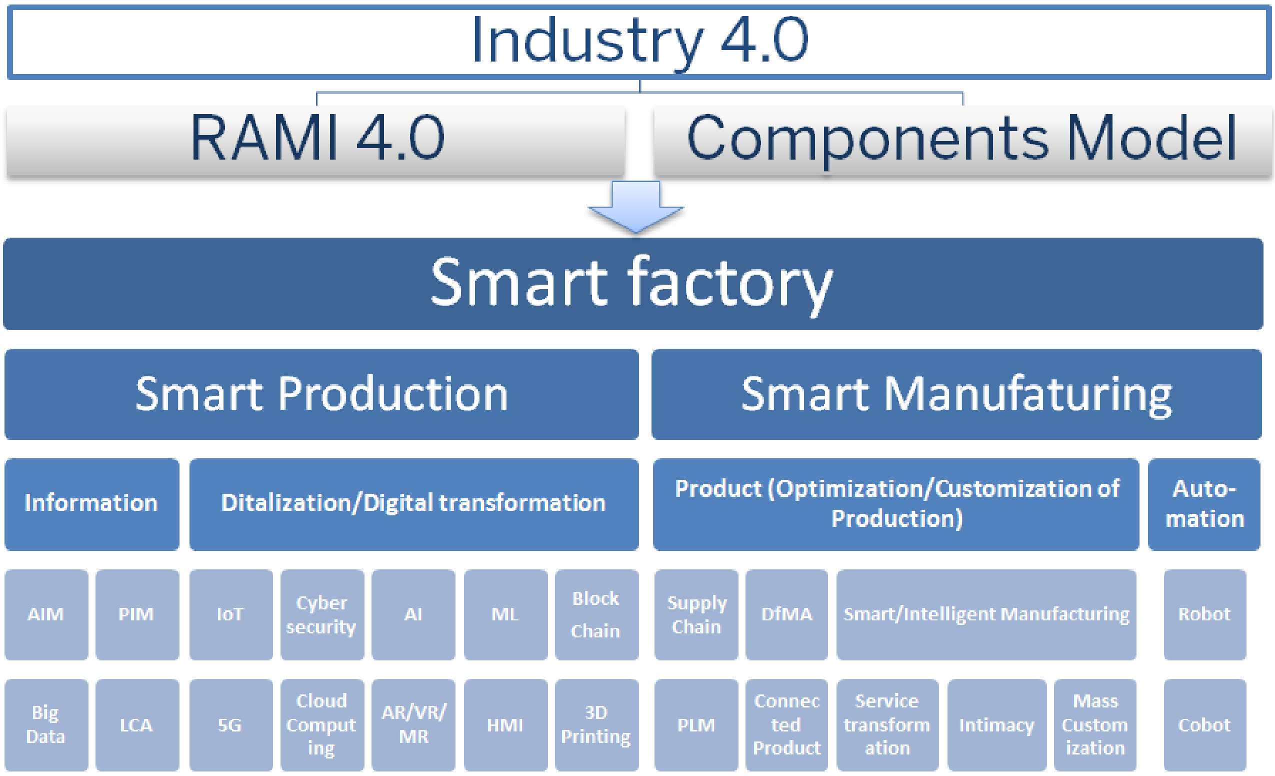


Figure 23: Industry 4.0 concepts table

Apart from their classification, all those aspects are linked by a common instrument with one single language: Internet. Technology becomes pervasive as well as products, packaging and transports are creating a **technologic ecosystem** that connects three levels of elements [48]:

1. **IoT: Internet of Things**, from physical products, factory elements, suppliers and warehouse
2. **IoS: Internet of Services**, from digital products and services
3. **IoP: Internet of People**, from customers

According to this split, the AEC sector presents an adding layer to Smart Production and Manufacturing consisting of the Use, as explained in the next chapter.

Figure 24: Unitized façade, UnipolSai Tower, MCA Architects, 2021, Milan, Italy

3. Construction 4.0

"Modernize or die."

MARK FARMER[2]

Scope:

The description of how industry 4.0 can thrive in the AEC sector and its different applications open the chapter as an answer to the main research goal. Starting from the literature review, the **Tech Trend Taxonomy** of digital instruments for buildings and construction defines three targets (**Smart Manufacturing, Production and Use**), plus four main **Areas**: **A. Digitalization and Digital Transformation** (§ 3.2.1), **B. Optimization and Customization of Production** (§ 3.2.2) **C. Information Models** (§ 3.2.3) and **D. Automation** (§ 3.2.4). From these concepts, it is possible to identify common **Methods of Application** and single **Technologies**.

A market analysis of the global and local Italian markets is provided to outline the diagnosis of the construction environment and understand the area in which actions are required [*RQ 2*] and the main opportunities. Identifying the productivity gap leads to the proposal of industrialization as a possible solution to achieve sector evolution. **Modern Methods of Construction (MMC)** represent a step ahead compared to the past industrial building prefabrication and **Lean Construction (LC)**. **Offsite production** (§ 3.4.4.1) and its pre-manufacturing value (§ 3.4.4.2) are two of the keys to implementing a new approach in the sector (§ 3.4.6), overcoming some of the barriers to the 4.0 adoption [*RQ 1*].

Contents:

[2] CEO of Cast Consultancy and a government-appointed champion of Modern Methods of Construction (MMC) in UK housebuilding

Expected results:

- Construction 4.0 description
- Literature review of construction 4.0
- Tech Trend Taxonomy: Explanation of technologies involved
- Productivity gap description
- Analysis of the sector's digitalization
- Identification of the Market need and opportunities
- Building industrialization features
- MMC introduction and comparison to LC and prefabrication
- 4.0 barriers and opportunities identification

Keywords:

Tech trend; Prefab; Industrialized building; Productivity; Modern Methods of Construction (MMC); AEC Market; Lean Construction

3.1 Literature analysis

In the construction sector, most of the cited technologies have short applications due to the structure of the building market and its supply chain. Many applications of these new digital tools concern the IoT application (Figure 25). The literature review on the database (Scopus) shows a significant relevance of predictive maintenance for asset management by the use of Digital Twin (DT) integrated into the **Building Management System (BMS)** [53][54]. It is an application of industry 4.0 strictly related to the use phase of a building, but what about the production and construction phases?

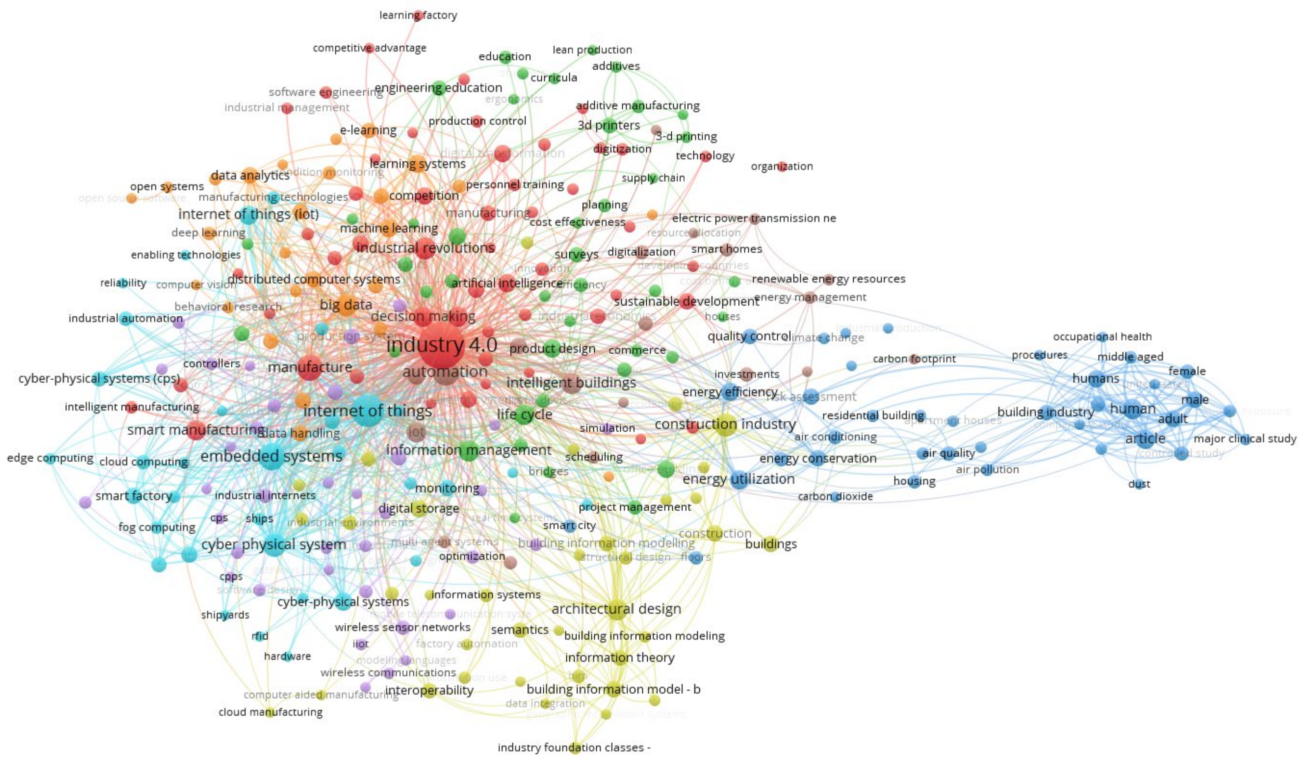


Figure 25: A literature review of Industry 4.0 and construction themes according to the used query (§0)

To have a fully real-time performance of the buildings/assets is necessary to go back to the beginning of the process, focusing on the design and construction phase. Although Digital Design is already applied for medium-large scale projects, there is a significant gap in the information flow between the three main stages of 4.0 application in the building sector. The research is focused on this information gap.

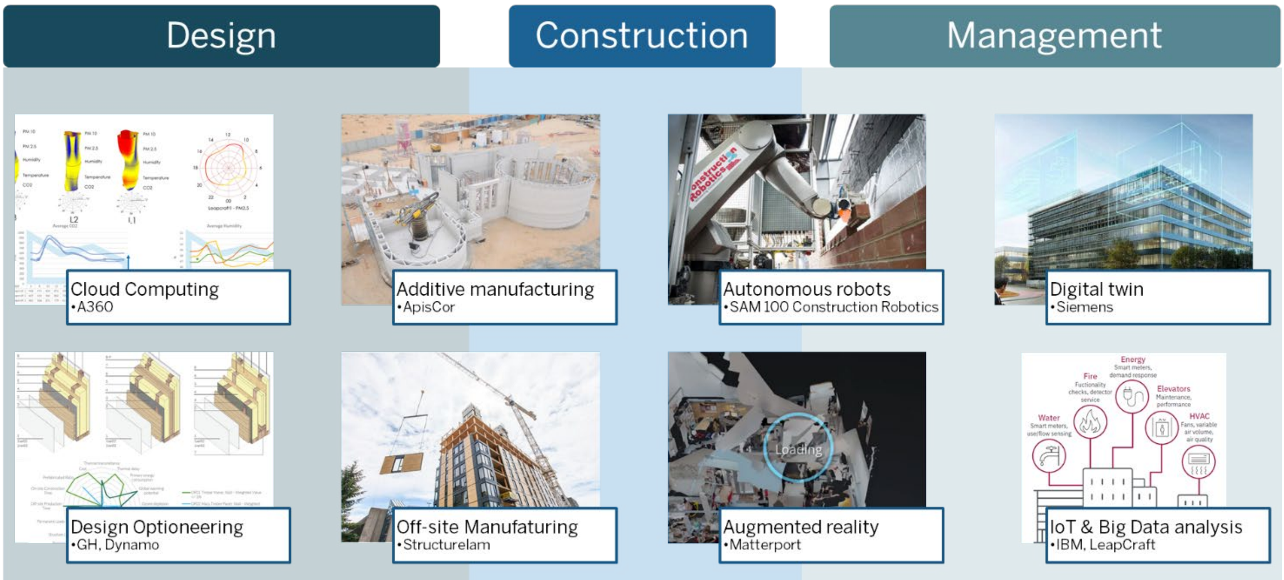


Figure 26: Industry 4.0 in the building sector

To explore this topic, the keywords selected to investigate the scientific background were: *Industry 4.0 and Buildings/Construction, Modern Methods of Construction/Industrialized Building System/Design for Manufacture and Assembly*, for the first step. Apart from some literature reviews about construction 4.0, most papers are generic and have few contemporaneous data. This is why the research was moved to grey literature, finding a lot of reports and studies about these topics. When the investigation field of the action on existing buildings was defined, the second round of scientific literature review was provided. The keywords added were *Offsite facade panel* and *Lean Construction*, finding more results especially in the last few years, as evidence of the growing interest in this prefab refurbishment approach.

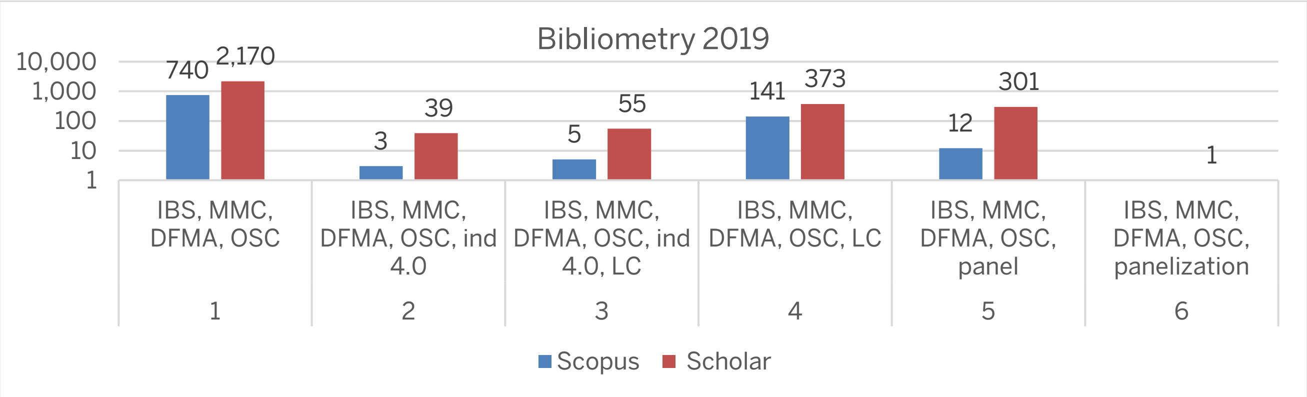
Figure 27: Some of the consulted reports [11], [14], [22], [55]–[67].[2], [13], [14], [21], [25], [58], [4], [69] –[70]
The complete list is provided in Bibliography (Chapter 11)

3.1.1 Bibliometric Queries

The graph in Figure 21: Bibliometry summarizes results obtained in 2019 in the Scopus and Google Scholar databases with different combinations of words. The queries used are:

1. "industrialized building system" OR "modern methods of construction" OR "offsite" OR "off-site" AND "IBS" OR "MMC" OR "DfMA"
2. "industrialized building system" OR "modern methods of construction" OR "offsite construction" OR "off-site construction" AND "IBS" OR "MMC" OR "DfMA" OR "OSC" AND "industry 4.0"
3. "industrialized building system" OR "modern methods of construction" OR "offsite construction" OR "off-site construction" AND "ibs" OR "mmc" OR "dfma" OR "osc" AND facade AND panel AND "lean construction"
4. "industrialized building system" OR "modern methods of construction" OR "offsite construction" OR "off-site construction" AND "ibs" OR "mmc" OR "dfma" OR "osc" AND "lean construction"
5. "industrialized building system" OR "modern methods of construction" OR "offsite construction" OR "off-site construction" AND "ibs" OR "mmc" OR "dfma" OR "osc" AND panel AND facade
6. "industrialized building system" OR "modern methods of construction" OR "offsite construction" OR "off-site construction" AND "ibs" OR "mmc" OR "dfma" OR "osc" AND "panelization"

The first research produced many results since 1974 (just one), trying to adopt prefab solutions born from the Second World War. The second rise of the topic was in 2005 when the MMC concept was introduced in the UK. However, due to the financial crisis of 2012, England started to consider offsite as a solid solution for the home shortage. The trend became more and more relevant but only related to new construction due to the lower maturity of digital instruments to adapt panels to the complexity of an existing building. As yet described, the scientific papers discussing the façade panels topic of recladding existing buildings were few (ID.5 and ID.6), especially in quantitative data to describe the topic. This is why the preferred research field was grey literature and reports that concerned 54 reports.



ID	*Name*	*Scopus*	*Scholar*	*tot*	*2019-2022*
1	IBS, MMC, DFMA, OSC	1374	7480	**8854**	304%
2	IBS, MMC, DFMA, OSC, ind40	65	261	**326**	776%
3	IBS, MMC, DFMA, OSC, ind 4.0, LC	15	118	**133**	222%
4	IBS, MMC, DFMA, OSC, LC	274	720	**994**	193%
5	IBS, MMC, DFMA, OSC, panel	37	520	**557**	178%
6	IBS, MMC, DFMA, OSC, panelization	4	15	**19**	1900%
	Tot 2022	**1769**	**9114**	**10883**	**283%**

Figure 28: Bibliometry and interest growth from 2019 to 2022

However, as confirmed by the government intervention (EU Green Deal), several European Research Projects are funded on this topic and scientific papers were published (+283% for all the ID. 6 queries) from 2019 to 2022, testifying the growth in the centrality of these topics. The word Industry 4.0 started to be associated with the AEC sector more frequently and the adoption of panel solutions for refurbishment became more and more investigated. This trend is also confirmed by market analysis (§ 3.3).

Figure 29: The Corner, Atelier(s) Alfonso Femia AF517, 2019, Milan, Italy

3.2 Construction 4.0 Tech Taxonomy

Themes concerning Construction 4.0 are many and technology is the starting point for organizing them into a coherent **taxonomy** (Figure 20). According to MGI's digitization index [1], construction is one of the least digitized sectors in the world (it is the last one in Europe), even thou is plenty of software and tools. Interoperability must be solved firstly inside the four main areas (**information, digital transformation, product optimization and automation**) but also among them [23] (Chapter 3, § C. Information Models). The four main areas can be collected into two Smart classes: **production** and **manufacturing**, but both are connected to the **Smart Factory** [71] idea that moves construction closer to the industry world. Besides Smart Factory and Smart Supply Chain, enrolled in the production and manufacturing phases, building introduced a new element in the Smart objective compared to the industrial world. **Lifecycle** is particularly relevant for buildings and deals with **Smart Use** [72]: the easy interaction of users with tools and the link between different communication layers.

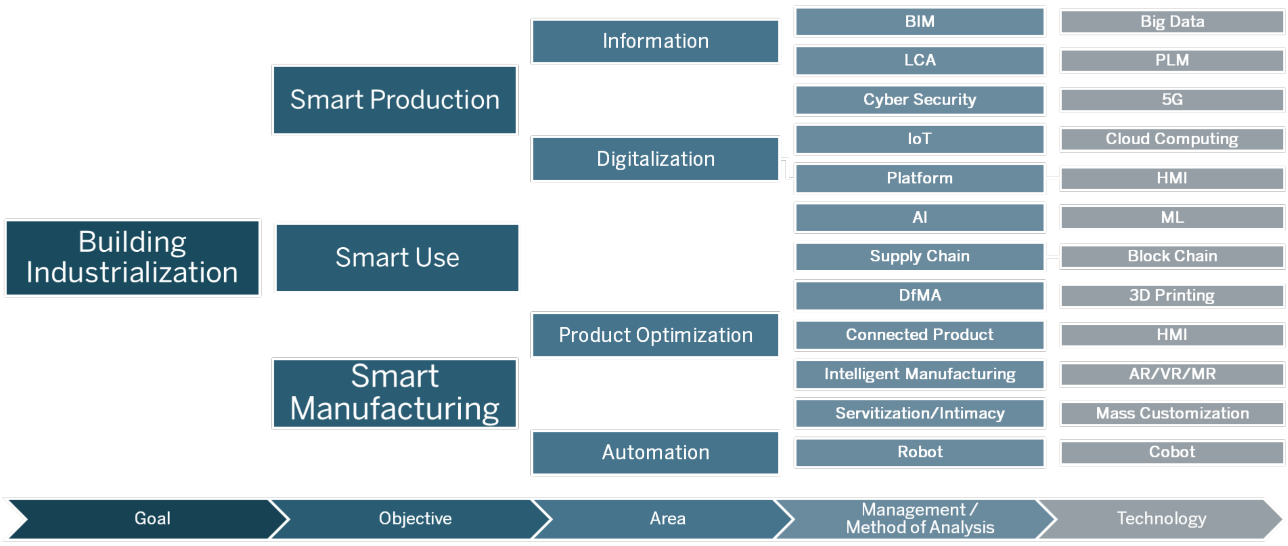


Figure 30: Industry 4.0 and Construction, a taxonomy of technologies, Management methods, areas, themes and key concepts

The technology trends are collected by their **management tools or analysis methods** and related to the four main areas. The second taxonomy categorization (management analysis) is the critical point of the process. Here the need to act is more relevant because data should be accessible and shared between different areas. The goal of building industrialization passes through the application of a smart approach, from the small product (and so factory and manufacturing) to home, building, grid and city (Figure 31).

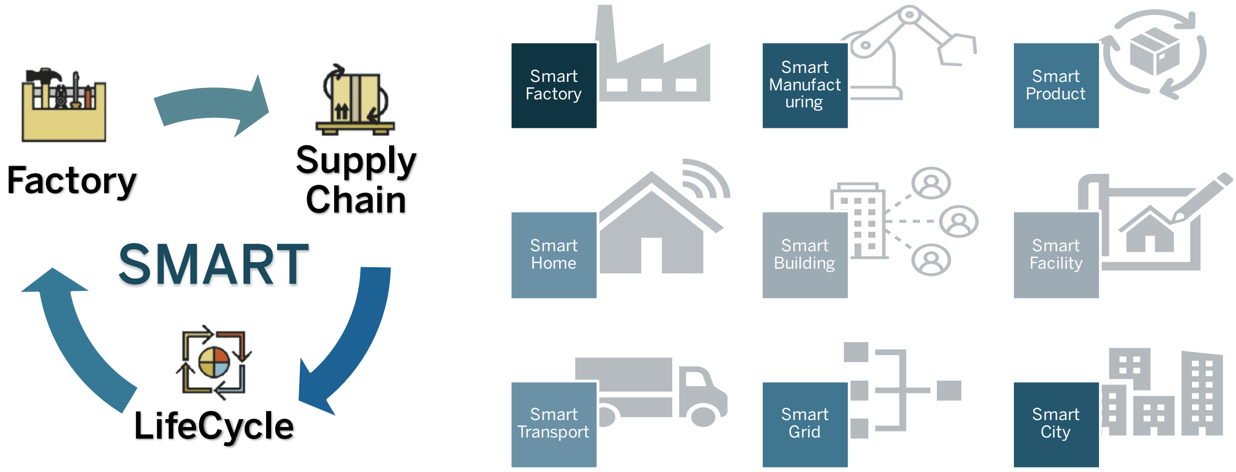


Figure 31: Smartness level and fields in 4.0 buildings

Literature is plenty of technologies definitions applied to the AEC sector. To avoid repetitions, the research focuses only on some of the most relevant technologies for the topics treated. For every Area, the key topics for this research are described, including Management Methods and Technologies.

Figure 32: Digital Tools for Construction 4.0: Mixed Reality Oculus and LiDar 3D Scanning

3.2.1 A. Digitalization and Digital Transformation

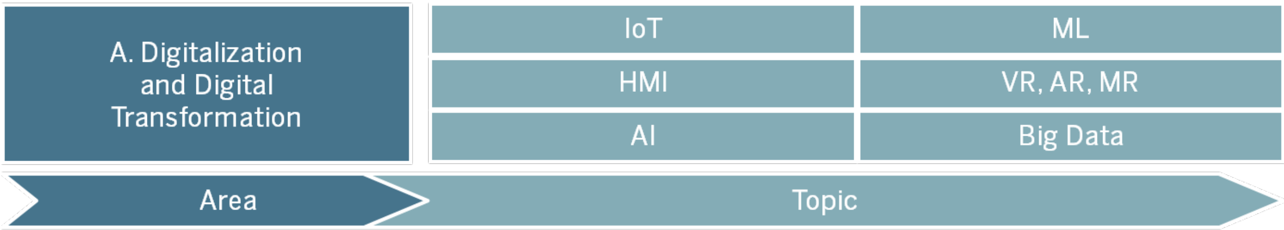


Figure 33: Digitalization and Digital Transformation Area with associated topics in Construction Tech Taxonomy

The digitalization and digital transformation area (whose definition is given in § 2.3.2) concerns the application of digital information management and business transformation to service by making data manageable by nor-high tech humans (3.2.1.5 Immersive Technologies and 3.2.1.2 Human-Machine Interaction (HMI)) or increasing introducing thinking machines (3.2.1.4 Machine Learning (ML), 3.2.1.3 Artificial Intelligence). These digital interactions are possible thanks to their mutual connection flowing data from single objects to a more articulated system: the Internet of Things (§ 3.2.1.1).

3.2.1.1 Internet of Things (IoT)

IoT is the idea that all the devices having a chip could be interconnected in some way: by Bluetooth, Wi-Fi, radio, internet, etc. Because of their connection, these instruments can share data in real-time. All the products can be chipped: projections show that the number of IoT devices will exceed 75 billion by 2025. That is roughly 10 IoT devices for every person on the planet [73].

The application of IoT in production is called IoT System or Industrial IoT. It consists of **Industrial Wireless Networks (IWN) and Internet of Things (IoT),** including design (*Internet of Brains*) machines and equipment, networks, the cloud and terminals (*Internet of processes/services*). It can offer specific and personalized products that users can modify via web pages (*Internet of Business*). Data are receipted by the cloud and then automatically start the design and production process with a dynamic self-optimization [29].

The strategic roadmap explains the complexity of themes and actors involved in the 4.0 Industry and how the Internet puts them into a relationship. The idea is that the Product is not a sale-end element because its interaction with production does not finish. The design team creates a product using digital instruments such as *augmented reality* and *simulations*. Once the optimization is completed, a product starts to be manufactured in the *smart factory* through digital machines like *robots, 3D printers and Smart lines*. Smart factory has real-time production flow monitoring and **real-time equipment management** that organize the workflow. Equipment coming from *suppliers* is available thanks to **supply chain management**. After production, the product is transported in a *smart warehouse* controlled by **logistic management** and then into the market. The new concept of the smart product is based on giving information to the smart factory during the **customer experience**. All the information collected by Internet of Things (IoT) is **Big Data**. Customers' feedback and real-time integration allow the factory to optimize design, production and manufacturing, logistics and market. The idea is that edge data and materials make a product; consequently, the strategic production plan becomes 3D **Data Driven Decision-based**. [50][51]

3.2.1.2 Human-Machine Interaction (HMI)

HMI, or Human-Computer Interaction studies the interaction between people and computers. Thanks to computer-based technologies such as Artificial Intelligence and Machine Learning, it is possible to improve the interaction between users and computers, having a more usable and receptive to user's needs [74].

3.2.1.3 Artificial Intelligence (AI)

Artificial intelligence (AI) develops and creates "thinking machines" capable of mimicking, learning and replacing human intelligence [53]. Since the late 1970s, AI potentiality has promised a consistent improvement in human decision-making processes, impacting the productivity of various business endeavors due to its ability to recognize business patterns, learn business phenomena, seek information and analyze data intelligently. Despite its prevalent acceptance as a decision-aid tool, AI has limited supply chain management applications (SCM).

AI develops "Thinking machines" to mimic, learn and replace human behavior. Born in the 1970s, it improves the human decision-making process and increases productivity by recognizing business patterns, learning business phenomena, seeking information and analyzing data intelligently [75].

The AI's ability to predict the market future allows factories to prevent production peaks or sales drops.

3.2.1.4 Machine Learning (ML)

Thanks to its own algorithm, ML is a machine's ability to read, analyze and interpret data without human interaction (no code to write). It is the way for the machine to learn, the AI instruments to "think" [72].

Supervised and unsupervised learning are two algorithms machines use to improve their knowledge. The first is based on human-compiling data and the machine is looking for a rule to connect them; the second produces an output based on all the data that humans can collect end internet world.

3.2.1.5 Augmented/Virtual/Mixed Reality (AR/VR/MR)

Also defined as **extended/hybrid reality** or **immersive technologies**, mixed reality merges real and virtual worlds. Through a visor, physical and digital coexist, interacting with each other in real-time [2].

The application in industry 4.0 is in the design phase and the assembly line (Smart Line), where the machine can help and check the worker to his task.

3.2.1.6 Big Data

Thanks to the 4.0 preview ability, the crucial purpose of Supply Chain Management (SCM) is to control and predict the market trend because there is more attention to clients than products nowadays [47].

Product is no longer referred to a single company but a system of companies with different interactions. Creating a collaborative model and processing know-how is fundamental to growing the business. Process mapping, highlighting fluxes and measuring performances are the main activities to optimize and complete cost control: the so-called **Process Intelligence** based on **Big Data**. In these fields, AI can make a significant contribution to revolutionizing the supply chain [47]:

- Reduce operations costs and inventory
- Respond to clients quicker
- Enhance SCM productivity
- Analyze product data
- Market demand Forecast
- Supplier relationship management
- Customer experience
- Production planning and factory scheduling

3.2.2 B. Optimization and Customization of Production

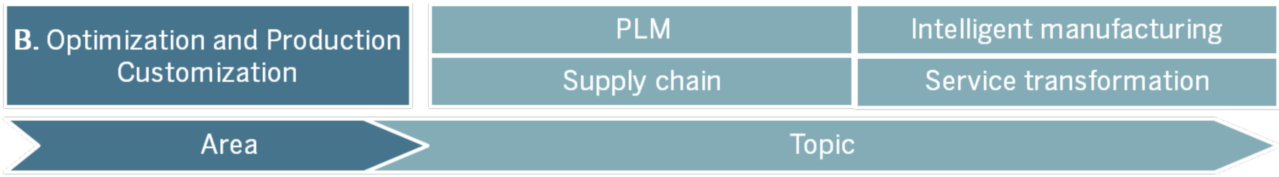


Figure 34: Optimization and Customization of Production Area with associated topics in Construction Tech Taxonomy

The never-ending process to optimize products is particularly true for the AEC sector, where every building can be intended as a unique product (or prototype) that can be associated with Product Lifecycle Management (§ 3.2.2.1). PLM starts from the production phase optimization to manage better the long and complex Supply Chain (§ 3.2.2.2), the use of Intelligent Manufacturing (§ 3.2.2.3) – factory located, more than on construction site – saving unskilled workforce. Data coming from production can help shift from simple product to Service business transformation (§ 3.2.2.4).

3.2.2.1 Product Lifecycle Management (PLM)

In Cambridge's production dictionary [76], *manufactured or grown to be sold, usually in large quantities*". Product can be material or immaterial, differently from manufacture, which refers only to physical objects.

The complete management of a product from concept to the end of its life is called PLM. In the previous industrial revolutions (from 1.0 to 3.0), the exchange of data and information between a product and its producer ended with the sale to the customer. The new 4.0 concept extends this network until the end of the lifecycle.

PLM improves **Enterprise resource planning (ERP)** to plan energy and resource consumption, **Customer Relationship Management (CRM) and Supply Chain Management (SCM)** [77].

It requires together:

- **Project Management**: time-cost analysis and planning (GANTT)
    - **Asset Management**
    - Process optimization using a **Bill of Materials (BOM)**: hierarchical list (father-son relations) of elements that are part of a product
- **Design** (CAD - Computer Aided Design, CAE - Computer Aided Engineering, CAM - Computer Aided Manufacturing) [78]
    - **Quality management**

- **Health & Safety**

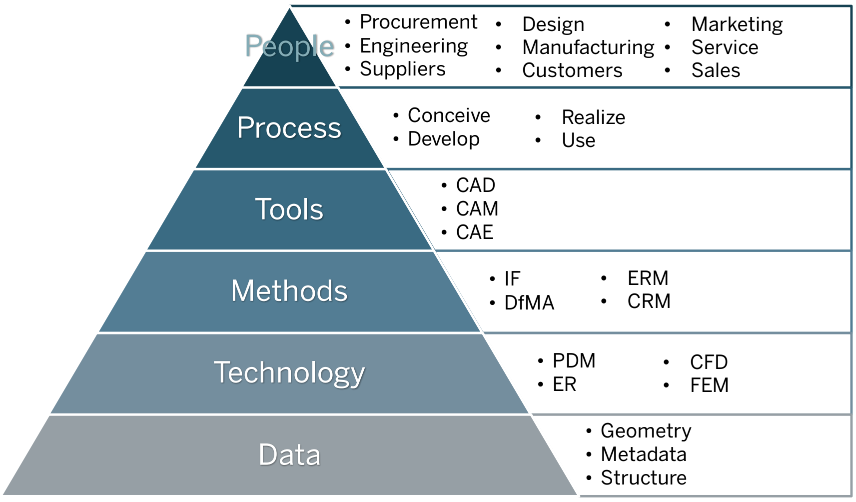


Figure 35: Product Lifecycle Management (PLM) diagram

The main advantages of a complete planning production allow to:

- Reduce waste
- limit storage
- document all the phases (both internal and external, by suppliers)
- direct/indirect cost control[79]
- Possibility to have a Business Process Reengineering (BPR) with a focused action (efficient). Measuring the maturity level of processes and certifying them (ISO 9001), it is possible to check automatic and manual or documental control level
- becoming a supplier for some activities or externalizing some processes (outsourcing)

One of the master companies in PLM optimization is *Toyota*. It splits the process into two base concepts:

- Automation: how to have an automatic process using an informatics production system
- Autonomation: from the Japanese word "*Jidoka*" how to find anomalies and waste the defective product

Thanks to this strategy, Toyota became the master of product management, conquering the market thanks to a faster factory line.

3.2.2.2 Supply chain

An important 4.0 concept is optimizing **Supply Chain Management (SCM)** [79]. It concerns logistics and production to increase efficiency and product categorization, coordinating all the actors involved in the production process.

Due to the various disciplines it concerns, SCM is defined as:

- Logistic integration
- Vertical integration between different companies
- Management process
- Management philosophy to create value for the client

A possible global definition is*: strategic and systematic management of the company's functions and strategies inside the company before and then outside*. The digital instrument allows digitalizing and integrates the entire value chain, from product design to service. The purpose is to improve long-term performances for single suppliers and all the chains [79].

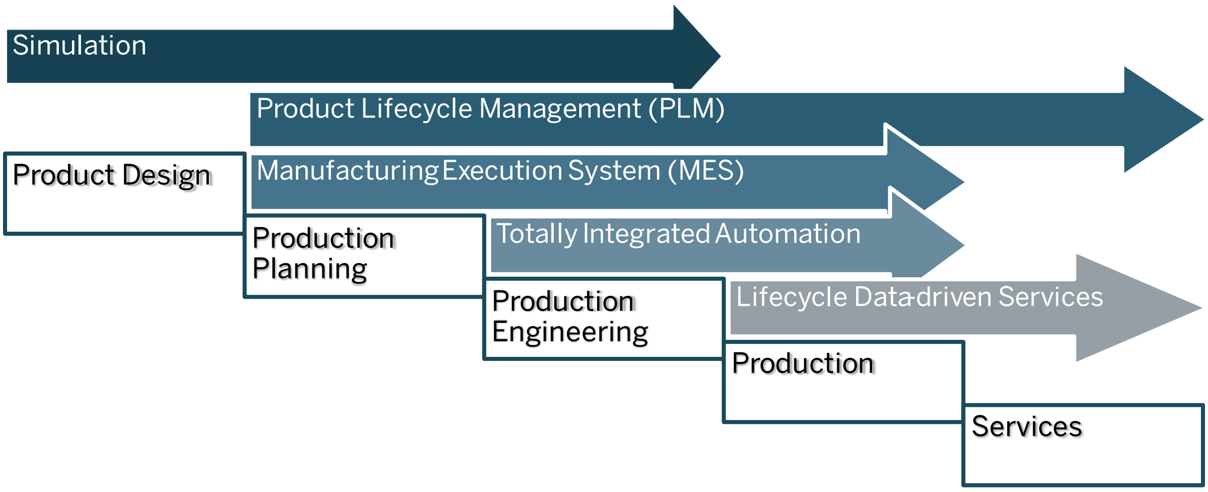


Figure 36: Value chain digitalization: from design to service [80]

3.2.2.3 Intelligent Manufacturing

The challenge to move from 3.0 to 4.0 is based on the early design process for **Information Technology (IT)** and **Operational Technology (OT)** [47]. In 3.0 OT, production and logistics are based on Computer Aided Design (CAD) or Computer Aided Manufacturing (CAM) and engineering instruments of analysis such as Computational Fluid Dynamics (CFD) and Finite Elements Method (FEM). Product Data Management (PDM) and Product Lifecycle Management (PLM) implement these instruments, having a much more integrated approach from a 4.0 perspective. On the IT side, the Enterprise Resource Management (ERM) and Customer Resource Management (CRM) - 3.0 concepts - were supported by Information Security (IF), compliance and Risk Management (RM) through the innovative approach of simulations (AI, VR, MI).

Thanks to technological innovations, the 4.0 industry completely revolutionizes the old concept of product in five steps growing up goods together with connections through AI and IoT [81]:

1. Product
2. Smart Product
3. Smart Connected Product
4. Smart System
5. System of Systems

3.2.2.4 Service Transformation

The new marketing (In-Thing Purchase) approach is based on the high customization of the purchasing experience through *as-a-service* and *pay-per-use* modes [31]. It starts from the **Service Transformation** or **Servitization** [81], where virtualization and representation of products as data transform the business model from product-sale to service-sale, changing companies' value proposition from product to Product-Service Systems. Servitization transform product by use-value and service-value instead of the possession culture. **Life Cycle** is changed because services, instead of products, are still producer responsibility all over their life. Product-service performance has to be stable during the time by they could be moved-up by extra functions or services through **In-Things Purchase**.

Four are the models of Service Transformation to refer to:

1. Product sale with additional services such as assistance, management and other functions
2. Product sale with strategical services which optimize processes before and after the sale
3. No product sale but only services: monthly fee to use the product and its services
4. No product sale but pay-per-use services: consuming paying logic

To better understand the relevance of this business model transformation, it is necessary to define some terms associated with the industrial production logic according to literature [82]:

- **Industrialization**: the industrial revolution of 1848 marked a change in the economy and society by the machine advent that is still pervasive in this decade.
- **Standardization**: the industrialized society generates standard products. This was most prevalent in developing standards related to military production.
- **Mechanization**: it moves standardization to greater economies of scale by introducing additional mechanized processes developed during the war years, but furthered by virtue of more advanced mechanical machinery, thus reducing human labor.
- **Mass production**: Thriving on the economies of scale, this concept is to produce as much of the same thing to bring down the cost of a single item. It has grown concurrently with consumer demand.
- **Automation**: The digitally informed manufacturing machinery development via computer numerical control and CAD/CAM software.
- **Mass customization**: This concept combines mass production and automation to deliver an economy of scope. Mass customization maximizes the benefits of mechanization and automation production methods, reducing labor costs, but works to preserve the benefits of variability and customization in the output.

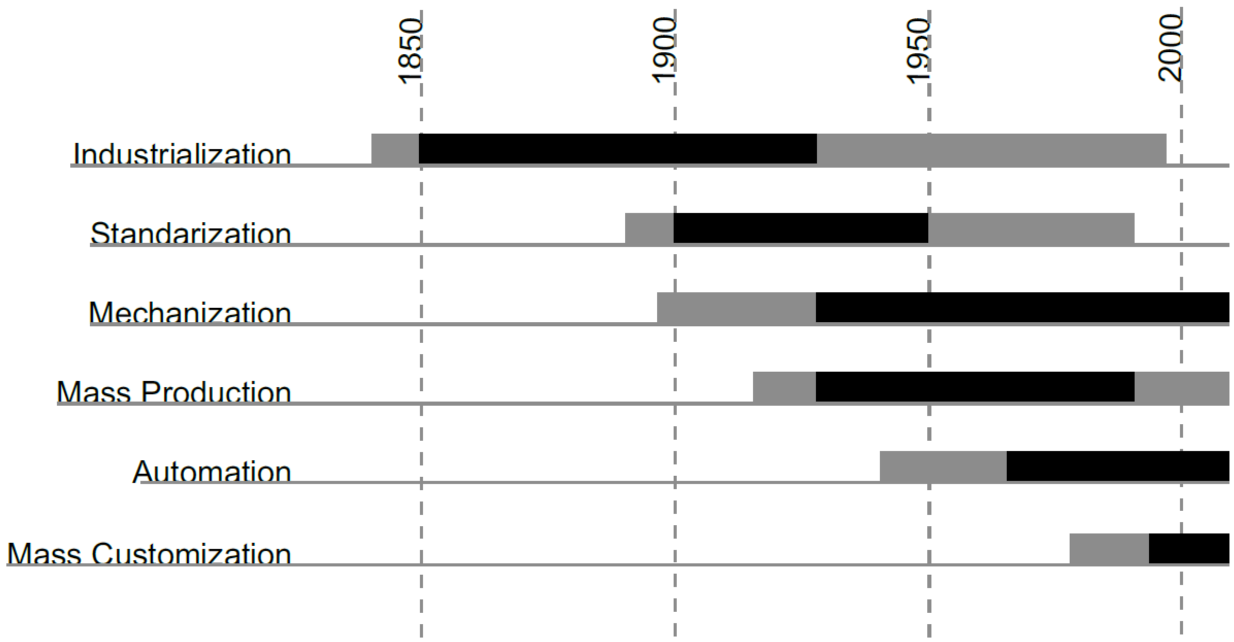


Figure 37: Industrialization of the building sector's main concepts throughout history. Black highlights the periods in which topics are more relevant [82]

The biggest challenge for 4.0 revolutions is **Mass Customization** and **Flexibility** is the main character necessary to fulfill this purpose thanks to Computer Aided Manufacturing (CAM) technologies [83]. From an industrial perspective, the technology evolution allows moving from a Fordist Mass Production logic, based on repetition, that is able to reduce the single unit cost thanks to the economy of scale (right graph of Figure 38) to have an acceptable margin of charge due to the variability of product.

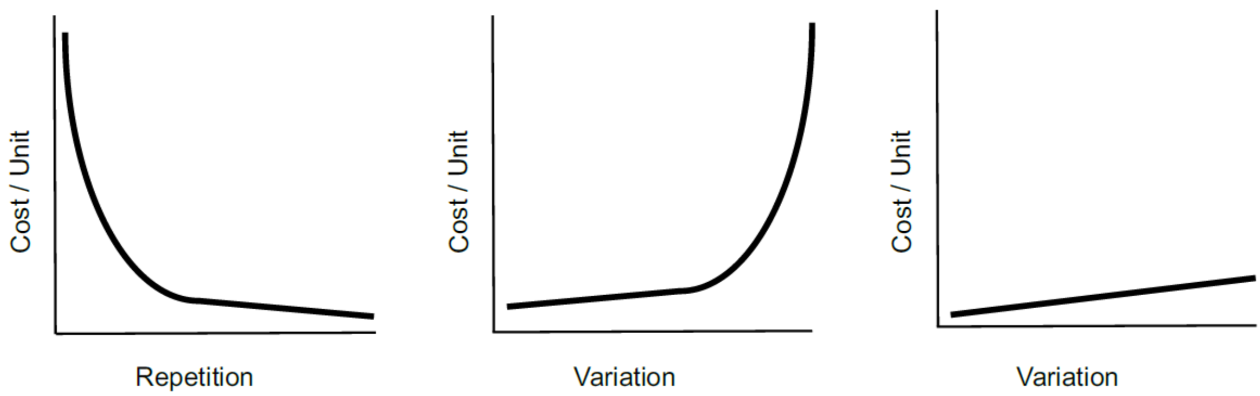


Figure 38: Cost per unit according to repetition and variation of a product in a Fordist (left), Custom (center) and Mass Customization (right) logic [82]

The literature describes four kinds of customization [84]:

- **collaborative customization**: the company and the client together define the product
- **adaptive customization**: standard products can be customized by the client
- **transparent customization**: the company produces customized products to clients' requests
- **cosmetic customization**: standard product with customized sale

The client and company must have a common language and clear communication to have solid customization, avoiding the **mass confusion** risk due to the enormous market.

This kind of production is typical for a vertical market with a high specialization of the company in a single sector or product. **Intimacy** explains the deep knowledge of customers and the company's market [81].

3.2.3 C. Information Models

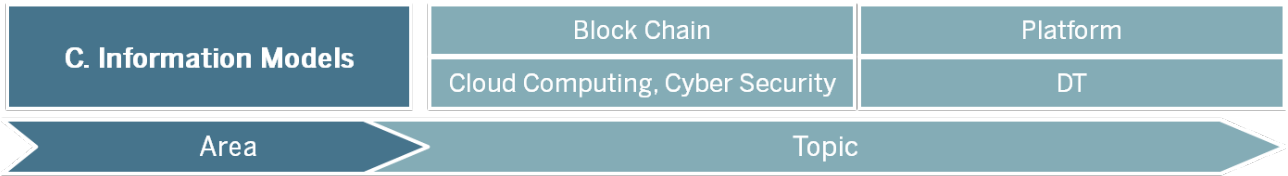


Figure 39: Information Models Area with associated topics in Construction Tech Taxonomy

The most relevant trend topics on Information Models (Figure 39) are **Errore. L'origine riferimento non è stata trovata.** (§ **Errore. L'origine riferimento non è stata trovata.**) – as disruptive information transmission -, which is related to Cloud Computing and Cybersecurity (§ 3.2.3.2) as a matter of security - and the Platform approach (§ 3.2.3.3) as a key concept to collect and valorize data creating a Digital Twin of a physical object to manage them (§ 3.2.3.4).

All these topics are related to the Information area and its language. Due to the complex network, a common language between all these elements is necessary to make the connection possible. This concept is called **Interoperability** [15]. It will synthesize software components, application solutions, business processes and context throughout the diversified, heterogeneous, autonomous procedure.

There are four levels of interoperability [29]:

1. operational: organization level regarding concepts, standards, languages, relationships
2. systematical: applicable
3. technical
4. semantic

In particular, the challenge is about the universal **standards** required to process CPS and CPPS across different levels. The purpose is to have a reliable and scalable process where **Information Technologies (IT)** and **Operation Technologies (OT)** work together [29].

The Architecture and Components Model must be implemented to properly develop the new 4.0 production process. Practically **Cyber Physical Systems (CPS) and Cyber Physical Production Systems (CPPS)** (*Production side*) must interact with technological systems (*digital side*), changing the **Interoperability** architecture of industries [29].

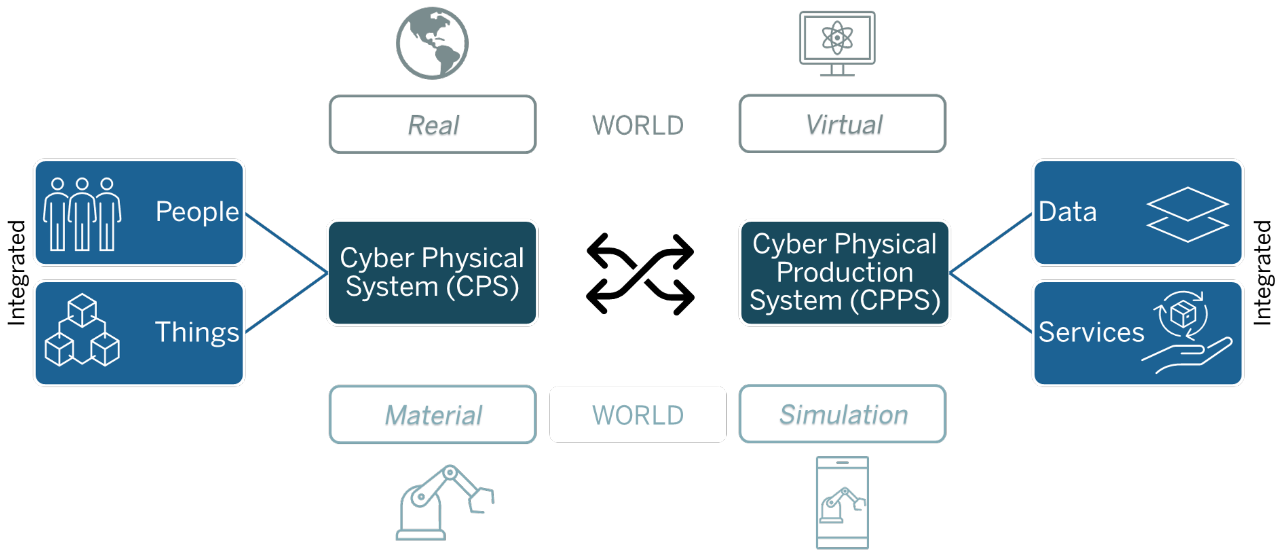


Figure 40: Cyber-Physical System and Cyber-Physical Production System

Cyber Physical System (CPS) applies **human-machine interaction (HMI)** to industry connecting physical reality with computing and communication infrastructures (*automation side*). CPS is enforced by developing computational entities, data-related procedures, manufacturing automation and technology and **Information And Communication Technologies (ICT)** [71].

The addition of machines to the human world required the development of a higher level of interoperability that is still based on the same **Principles** (flexibility, efficiency, language and security, from the most important one to the lower). Many interoperability **Typologies** are based on the **semantical** aspects, which is the common *language* to develop a **technical i**nteraction with *coherence*. The purpose is to retrieve a **system** *applicability* able to drive the **operation** phase inside and across *organizations* [71].

3.2.3.1 Blockchain

Blockchain will be the next big technological revolution. The data architecture is no more centralized or decentralized but **distributed** without a clear hierarchy. This technology is famous for cryptocurrency, but its applications are many: the system is born to collect and exchange data risking fewer thanks to the structure. Data storage is divided into blocks, chronologically ordered and put all the devices connected in that network. Once blocks are data written is impossible to change them without invalidating all the structure. It makes data extremely fragmented and difficult to collect without the cryptonym common to them [85].

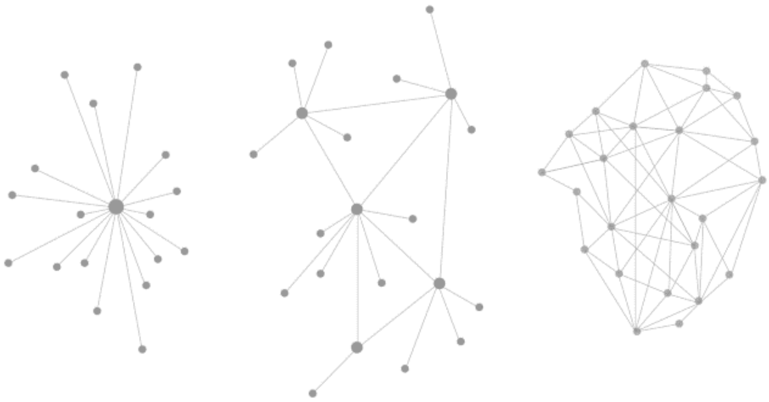


Figure 41: Blockchain Data architecture: from centralized to distributed [86]

There are many advantages to this technology [85]:

- **Scalability**: the structure is potentially infinite and its dimension depends on the number of devices connected.
- **Velocity**: data transactions are fragmented, but many devices are connected; the more connected, the faster the transactions are.
- **Security**: high fragmentation allows data storage to minimize the risk of theft.

3.2.3.2 Cloud Computing and Cybersecurity

Instead of Blockchain, industries currently use Big Data to collect information from internal sources (factory and logistics) and external ones (market and customers). The storage is usually in the cloud to control processes everywhere in real-time. Due to this cloud storage, the central theme becomes data security to protect the enterprise's know-how.

3.2.3.3 Digital Twin

To have a complete market preview, AI creates a full copy called Digital Twin, which can simulate all the strategies and products. It allows a comprehensive 4.0 **Product Lifecycle Management (PLM)** where both design (and simulation) and production are digitalized [80].

Two models are interacting together:

- **Physical Model**: a total **Computer Aided Design (CAD)** modeling with all the parts and their dynamic movement
    - **Computer Numerical Control Machine (CNC)** to have a **Computer Aided Manufacturing (CAM)**
    - Static, dynamic, fluid dynamic and thermal analysis to have a **Computer Aided Engineering (CAE)**
    - **Virtual Commissioning**: how to automation react to external interactions
        - E.g. **PLC (Programmable Logic Controller), Motion Control, CNC (Computer Numerical Control) and HMI (Human Machine Interface)** control all the clash detection during the design stage and before the final test.
- **Virtual Model**: single element test based on BIM model simplified for every engineering and predictive analysis
    - **process simulate** to value logic, functionality and efficiency process
    - **plant simulation** to value logic, functionality and efficiency facilities

- **rule stream** rules to standardize a process based on input and output (**know-how**)

An extreme application of Smart manufactory is the Autonomous Factory or Light-out Factory: a place working 24/7 without any humans involved [87].

3.2.3.4 Platform

"*A rules-based approach to design that uses standardized components and processes to maximize use across different assets, resulting in efficiencies*" [88]. A platform design approach provides crucial control elements within efficient and cost-effective build options.

To obtain such a comprehensive building approach, integration is key to merging design aspects with management, business with operations, logistics with construction and design with production. Two are the integrations typologies: **Vertical** - inside the different company's areas, such as design, management, production and logistics - and **Horizontal** - among different companies in the same supply chain, as producers, delivers and general contractors -. The sharing regards not only data or information but also processes and strategies using digital instruments.

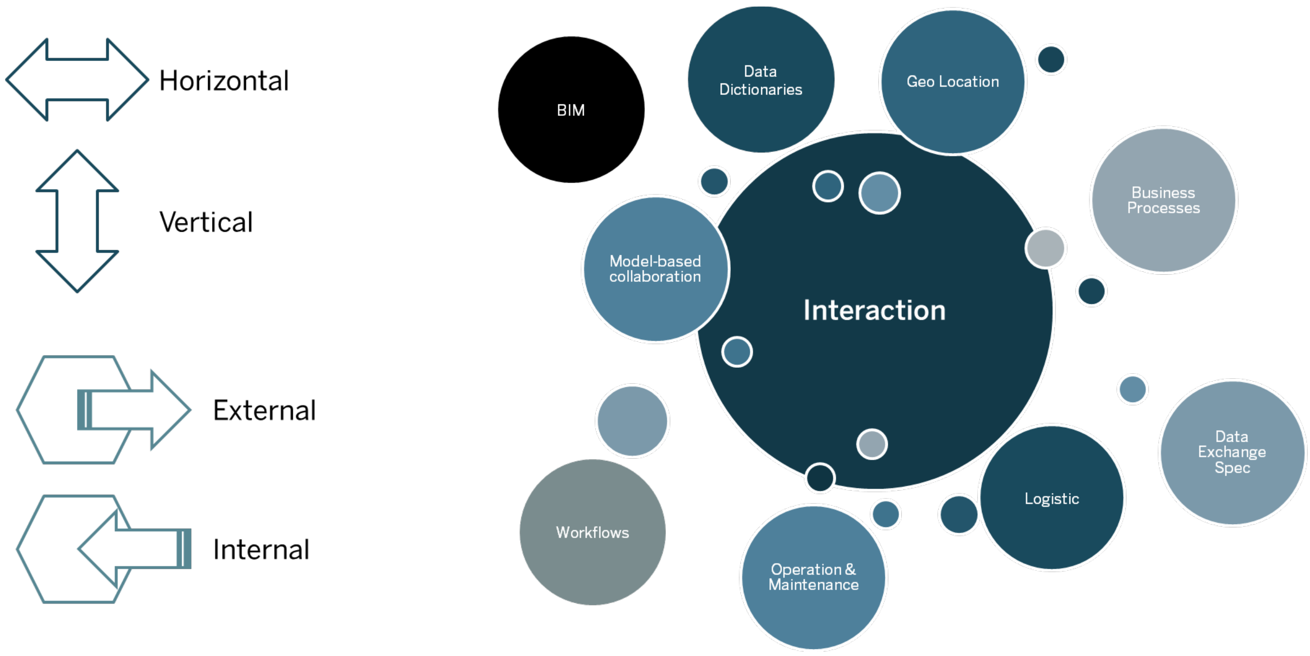


Figure 42: Horizontal and Vertical Interoperability, beyond the simple Interaction of different phases

3.2.4 D. Automation

"Automation is the technology by which a process or a procedure is performed with minimal human assistance" [56]. Control systems of machines check the completion of a task awarded by a human. In the industry world, the concept is strictly related to the robot.

3.2.4.1 Robot

A general explanation valid all over every field of robot application is that the robot is an automatic system able to do a job by itself. The industrial robot has a more specific definition:

- **Easy**: the robot is a special intelligent connection between perception and action [72]

- **Robotic Institute of America (RIA)**: the robot is a reprogrammable multi-function instrument that moves, adds and removes objects as material, parts and tools through scheduled movements [89].
- **ISO 8373**: the robot is a system with automatic control, reprogrammable, multi-function, mobile or not, with three axes suitable for industrial automation operations [90].

Physically, a robot is composed of cinematic chains: the robot bracket making of rigid elements (links) connected by **Joints**. At the end of the bracket is an **End Effector**: a **Grippier** or something else (generic **Tool**) [72].

The architecture of the robot is based on a connected structure with sub-structures. It will modify and improve its efficiency thanks to artificial intelligence (AI) based on Machine Learning (ML) through data. The "intelligence" level defines three different types of the robot based on their ability to "think" [78]:

1. **First level**: an accurate robot able to complete a task by parameters input (velocity, directions, distance, acceleration)
2. **Second level**: a flexible system adapting to external conditions (e.g., artificial view). It plans a trajectory based on object dimensions.
3. **Third level**: a robot with a neuronal network (AI) can make decisions automatically. It is the future.

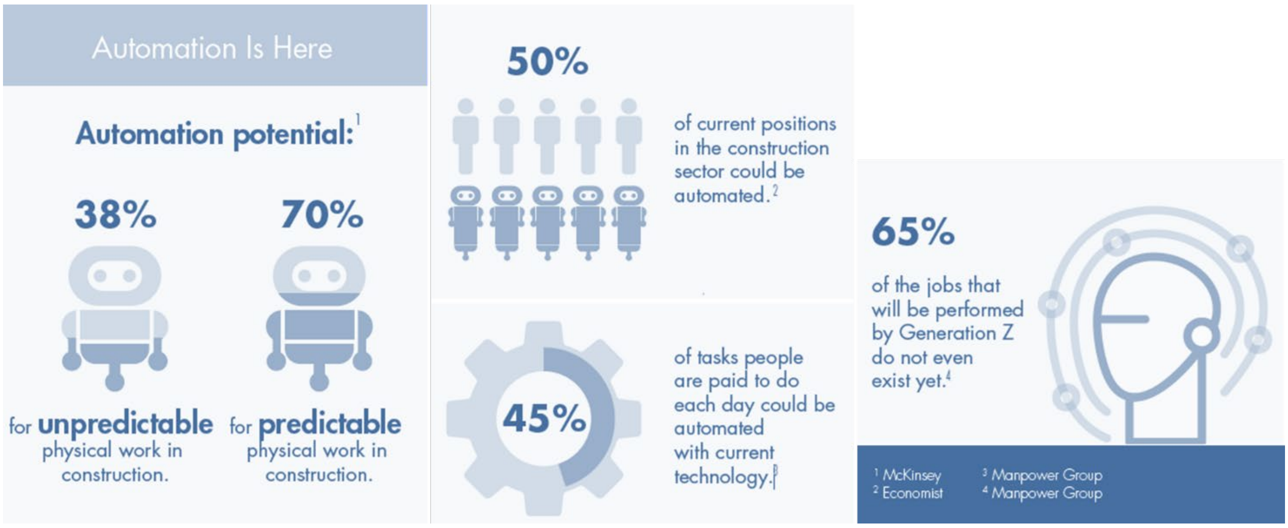


Figure 43: Automation potential in construction [91]

50% of the current position in the AEC sector could be automated because 45% of repetitive tasks can already be mechanized [91]. The main barrier to automation diffusion is high initial investment cost and robots' low flexibility. The automation potential in construction is limited compared to other industries because of the high unpredictability of physical work, to which robots have a low capacity to answer (only 38% of adjunctive productivity). On the other side, where labor is more predictable, efficiency grows to 70% [91].

Human-Machine Interaction (HMI) is in the early stage of 2022, but it is the future of robots: the third-level robots are called *cobots*, able to cooperate and interact with humans participating in a decision. They will reduce lost time and interact with humans to choose the optimum path for a task. The passage is from **Industrial automation** to **cognitive automation**

through **collaborative automation** [50]. Cobots are the most versatile typology of Robots; this is why their application in the construction industry is suggested, although their cost is ten times higher than the first level of Robots. The repetition of activities, typical of robots, is more adapted for serial production, while the more complex the task, the more is necessary to have flexibility, especially for onsite activities, where the machine should be able to adapt itself to obstacles, non-flat ground and inputs overload.

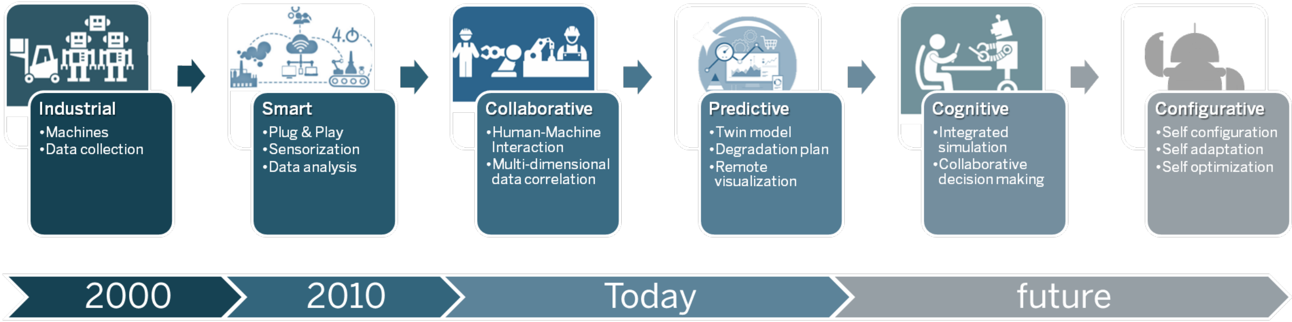


Figure 44: from industrial to cognitive automation

The common thought about industrialization and adopting automation is the loss of jobs substituting men with machines. A Bryden Wood research [92]demonstrates that every industrial revolution coincided with a growing number of employees with better work conditions. According to this trend, 65% of jobs that Gen Z will perform are not yet exist, witnessing the need to reskill the actual workforce with new competences.

Figure 45: Reinforncement Steel Mesh Carpets

3.3 Market

The industry 4.0 market is projected to grow from USD 64.9 billion in 2021 to 165.5 by 2026 with a CAGR of 20.6% driven by IoT, AI, ML, Cloud services and 5G [93]. The value of this market in Italy in 2020 was 4,1 billion €, with 8% growth and the 2022 plan is to double this rise driven by Industrial IoT (2,4 million €, the 60% share) and then Cloud Manufacturing (390 million, 8%), Consultancy and training services (275 million, 7%), Advanced Automation (215 million, 5%), Additive Manufacturing (92 million, 2%) e Advanced Human Machine Interface (57 million, 1%) [94].

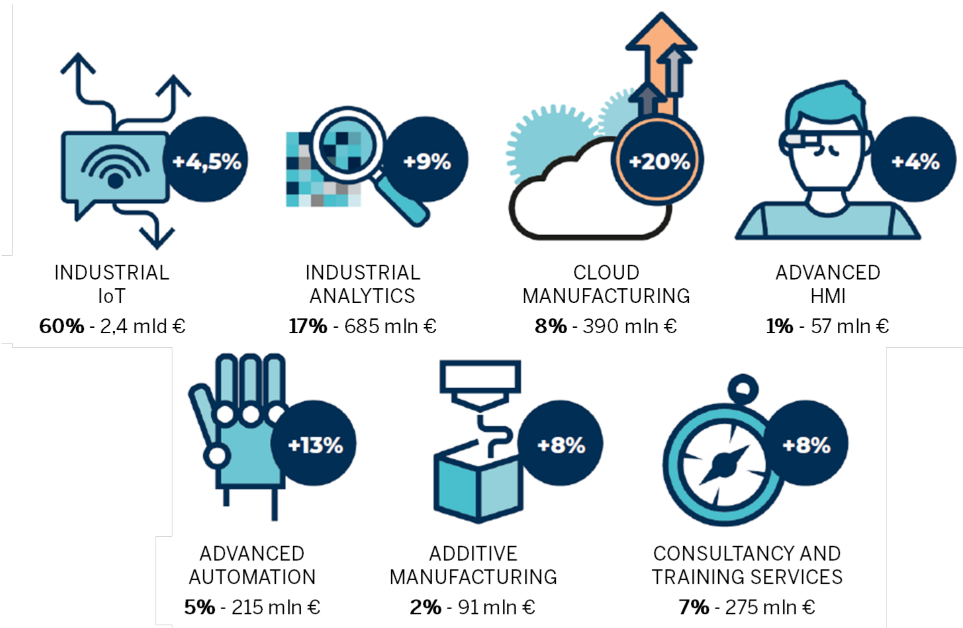


Figure 46: 2020 Industry 4.0 Market in Italy. The blue bubble shows the increment to 2019; the percentage in the below text is the Industry 4.0 market slice for each technology [94]

In Italy, the Transition Plan 4.0 (Piano Transitioned 4.0) [7], launched in 2020, provides a tax credit at variable rates (up to 20%) repayable in three years for large companies or in a single year for small and medium-sized enterprises. The European Investment Bank (EIB) finances projects related to tangible and intangible assets 4.0, research and development, technological innovation, green and blue[3] innovation, new product design and staff training 4.0. However, these projects are still more the preserve of large companies than of the SMEs regarding knowledge (97% against 39%) and diffusion (54% against 13%) because of the lack of skills (56%), integration difficulties (46%) and poor understanding of the value of solutions (44%) [50].

Despite these gaps and the health crisis just crossed by the industry, the Italian 4.0 Observatory estimates that by 2025 the Smart Factory will triple [94], thanks to investment in infrastructure (e.g. 5G), which is currently a major structural constraint that creates a territorial imbalance in Italy. Apart from the global 4.0 market, the research focuses on Construction 4.0; to understand its peculiarities, it is necessary to analyze the market from the global scale to the local one.

[3] Sustainable and Digital Innovations

3.3.1 Global Market

The construction 4.0 market, sized 11.88 billion $ in 2021, is projected to reach 30.54 billion $ by 2027 with a CAGR of 16,8 % in 6 years due also to infrastructure investment planned by rising and third-world countries such as Brazil and India [5]. Due to the large investment required at the beginning of new technology adoption, the 4.0 market was stopped in 2020, but its recovery is planned for 2022 with a focus on IoT, while AI and robots follow as secondary markets [93].

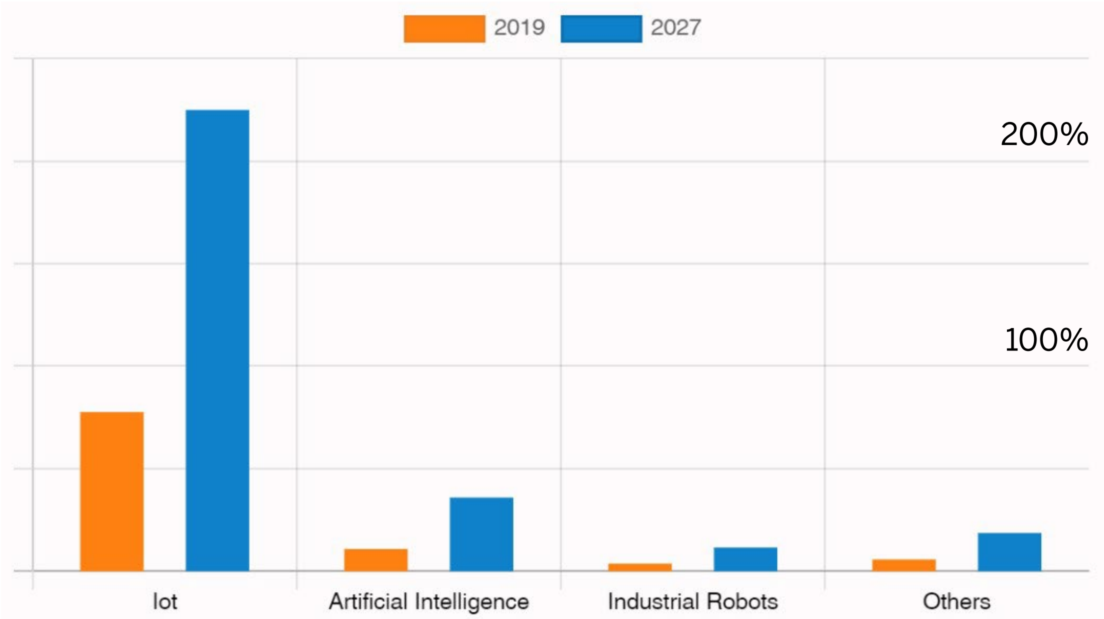


Figure 47: Construction 4.0 Market 2019-2027 [5]

Sensors and IoT drove the 4.0 sector growth by tripling its value in the next seven years (from 80.62 billion USD in 2022 to 328.62 billion USD in 2029). The reason why Construction 4.0 is focusing on IoT stays in the world trend of globalization that takes people to the city, leaving the countryside every year (1% of the world population: 76 million people). This data is growing yearly: in 2018, 4,2 billion people lived in the city (55%), but they will be 2/3 of the world population in 2025. It will cause a new home necessity for 30 billion people in the next 20 years [59], including people living in slums (100 million) and homeless (1/3 of the city people) [95].

3.3.2 Productivity question

Construction is a relevant sector for the world economy, concerning 13% of the World's Gross Domestic Product (GDP), but it has a slow growth of its production[4] rate (1%) per year (from 1997 to 2017). The comparison to other sectors (manufacturing increased by 3.6%) and the global economy (2.8%) explains why there is an improvement in the gap between construction and other markets (Figure 48) [4]. Increasing it means producing fewer resources or better quality with lower costs for owners, higher profitability for contractors and higher salaries for workers.

[4] The labour productivity is defined as the value added by construction workers (output in terms of structures created minus purchased materials) per hour of work, adjusted for inflation.

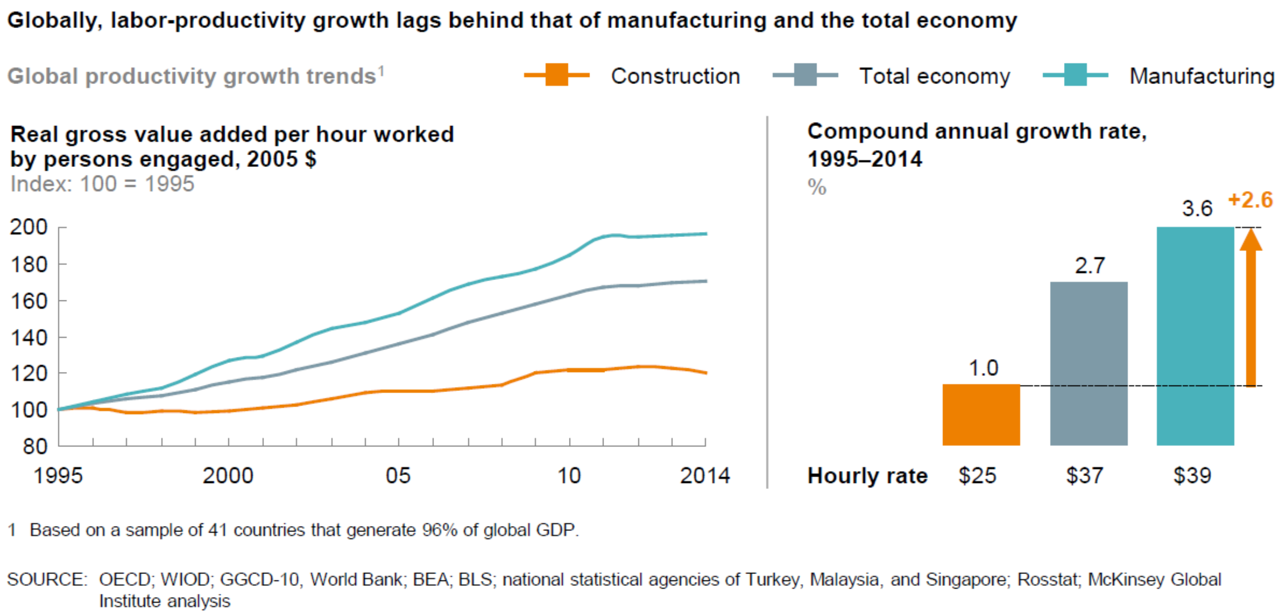


Figure 48: Productivity in manufacturing doubled the construction one in 10 years [4]

Analyzing the causes of the productivity gap, the most relevant is the enormous necessity of human employees during the on-site phase, representing the leading cost voice (40% of the total construction cost). Furthermore, employers cannot build for 29% of the on-site time because of the waiting for approval, permits, shipments and equipment due to slow paper trail or human error [96]. In Italy, this percentage is higher: workers must stop their job 65% of the time resulting in a lag compared to the total economy of about -1,2% from 1995 to 2015 [3]. The last comparison data between different countries shows that Italy is in the middle between the Declining Leaders and Laggards, with around 25$ per hour worked, which is the world averaged value, but far away from the 35$ developed countries (Figure 49). Furthermore, the labor-productivity growth is 1% behind the annual growth in real gross value added per hour worked due to the few sector investments. This trend and the amount of money dedicated to the AEC in 2022 is different (compared to 2015 data) due to some events like the European Green Deal and PNRR (Piano Nazionale di Ripresa e Resilienza) [5] investment in the country, better explained later in chapter 3.3.4 Synthesis of the Construction environment.

[5] The PNRR (which is the Italian acronym for National Recovery and Resilience Plan) is the document that Italy prepared to access the funds of the Next Generation EU (NGEU), the tool introduced by the European Union for post-pandemic Covid-19 recovery with the goal of relaunching the Member States' economy. It has 191,5 billion € value divided into six core missions: Digitalization, Innovation, Competitiveness, Culture and Tourism (49 billion €); Green Revolution and Ecological Transition (68,6 billion €, included built environment); Infrastructures for sustainable mobility (31,5 billion €); Education and Research (31,9 billion €); Inclusion and Cohesion (31,9 billion €), Health (18,5 billion €)

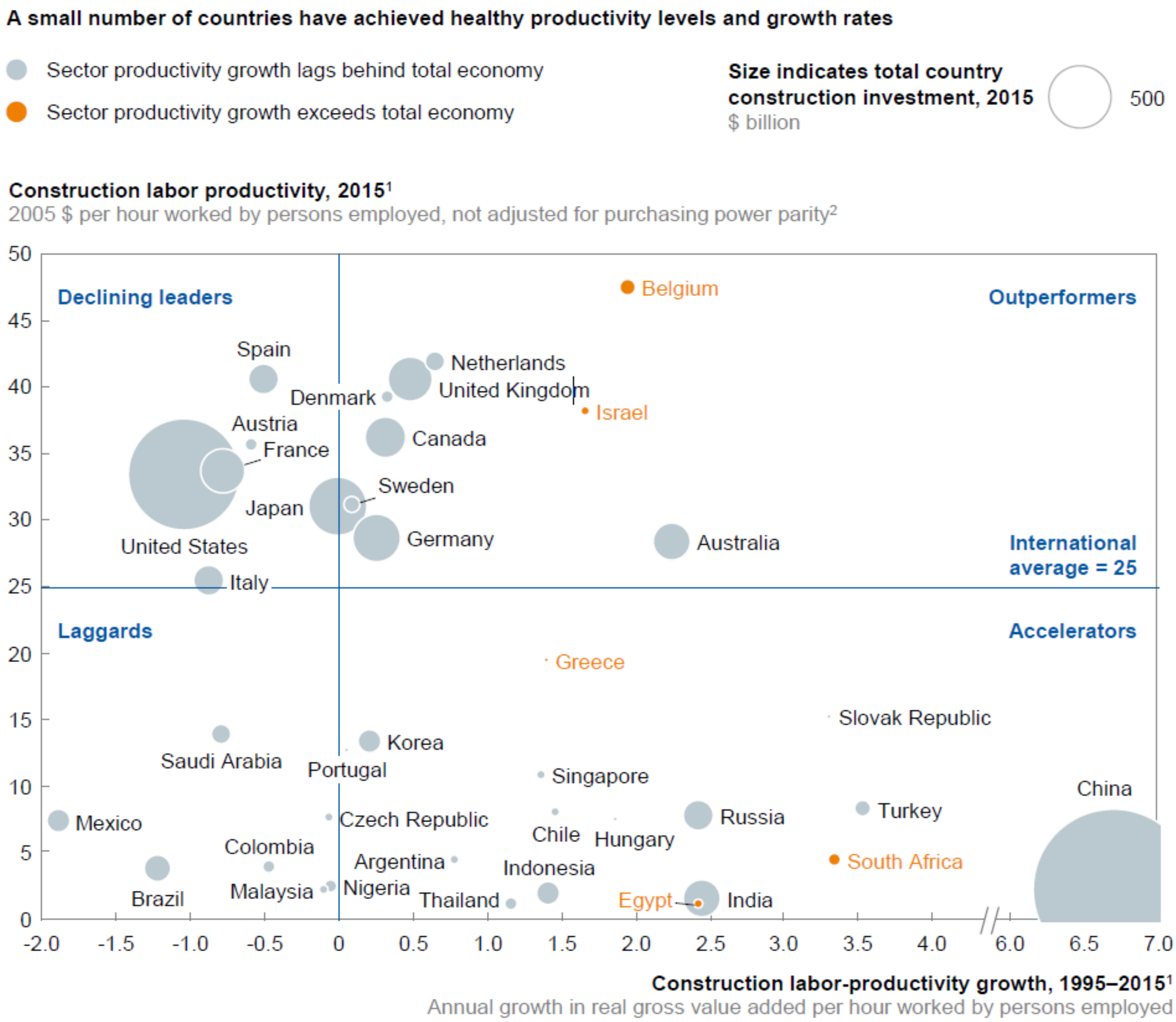
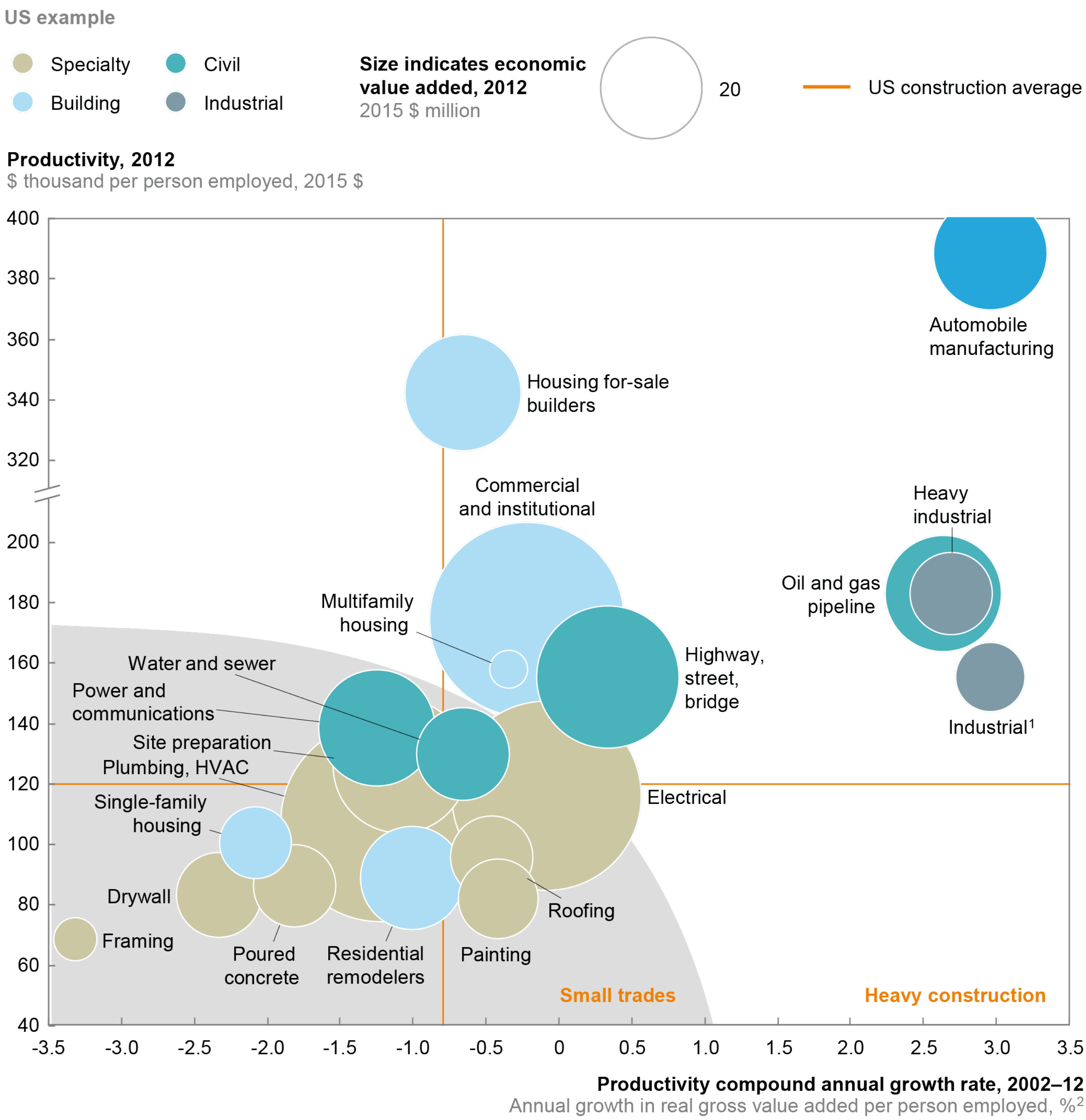


Figure 49: Construction labor-productivity worldwide [4]

The productivity performance is not uniform worldwide due to the specification of every single market, but a common element is the market split due to the company size. There are few Large-scale players engaged in giant constructions (civil, industrial and housing) and many SMEs working on smaller projects (such as the refurbishment of single-family housing) or as subcontractors for the big ones in specialized small trades (Figure 50). The first one has a 20% to 40% higher productivity than the smaller one [4]. However, the economic value added (the size of the bullet) highlights that most small trades have a relevant market influence that can greatly benefit from adopting an industrialized approach and increasing their productivity rate. This paradigm shift from a traditional to an innovative mindset is hard to get mainly due to the lower possibility of investment in research and development (R&D), especially at the beginning of this journey: DfMA requires a significant initial investment, difficult to be sustained by SMEs [4].



1 Manufacturing plants and warehouses.
2 All subsectors deflated with overall construction sector deflators, not subsector-specific prices.

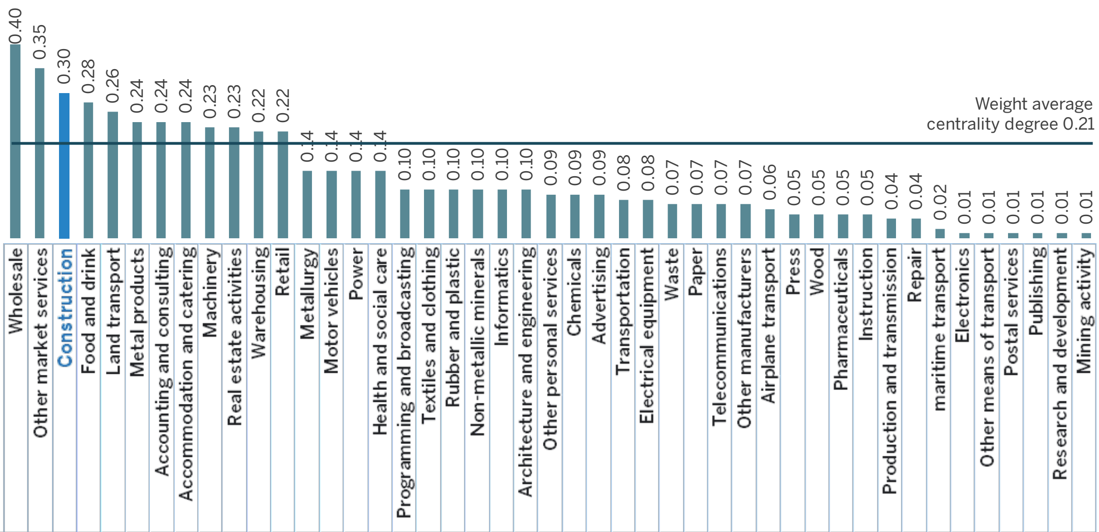
SOURCE: US Economic Census; McKinsey Global Institute analysis

Figure 50: Small trades and heavy construction productivity in the US market [4]

3.3.3 Italian Market

To understand the concrete application of construction 4.0 in Italy is necessary to focus on its market. The building market is traditional and slowly receptive, as confirmed by the ISTAT research [3]. Its low innovation inclination in product, process and digitalization is due to the few operating capital and capitalization. Architecture and engineering, the specialized services for buildings, have low economic profitability compared to the centrality of the construction sector in the world financial system (Figure 51). The last Innovation Report (years 2018-2020) [7] showed the AEC sector as the last in innovation activities, but with a +3,3% compared to

2016-2018 against the trend of the others (-5%) and a higher investment success rate (+6%) compared to other sectors. The product development is around half the process innovation, but with a big step ahead, mainly thanks to air treatment and sanitization due to the pandemic diffusion. These new products are developed mostly inside the company; indeed, only 8,5% of enterprises are collaborating with external firms, due also to their small sizes: SMEs' investment in innovations are affected by 66,7% from the Covid-19 crisis, 16,5% more than Corporates, resulting in a SMEs cut of R&D internal activities of 63,6% with only one-third of them still involved in it, half number of bigger enterprises (64,8%) [3].



	Product innovation	Process innovation	Digitization level
Wholesale	1	1	3
Other market services			
Construction	1	1	1
Food and drink	2	3	1
Land transport			
Metal products	4	3	1
Accounting and consulting	1	1	3
Accommodation and catering			
Machinery	4	4	3
Real estate activities			
Warehousing	1	2	2
Retail			
Metallurgy	1	4	2
Motor vehicles	4	4	3
Power			
Health and social care			
Programming and broadcasting	1	3	3
Textiles and clothing	3	3	1
Rubber and plastic	3	4	2
Non-metallic minerals	2	3	1
Informatics	4	2	4
Architecture and engineering	1	1	4
Other personal services			
Chemicals	2	4	3
Advertising	1	1	4
Transportation	1	1	1
Electrical equipment	4	4	2
Waste			
Paper	3	3	2
Telecommunications	4	2	4
Other manufacturers			
Airplane transport			
Press	3	2	2
Wood	2	2	1
Pharmaceuticals	3	4	4
Instruction			
Production and transmission			
Repair	3	2	2
maritime transport			
Electronics	4	4	4
Other means of transport	4	3	3
Postal services	2	1	1
Publishing	1	2	4
Research and development	4	2	4
Mining activity			

Figure 51: Construction, architecture and engineering innovation inclination and centrality level [Author's elaboration on [3]]

The central role of the construction sector in the Italian market (4.9% in 2021) is testified by the number of employees (6.6% of the total Italian workers) and by a consistent growth of the national Gross World Product (GWP) (+6.5%) - beyond expectations and more than any other EU country, except France [9]. At least one-third of the construction sector was driven by investment growth (+16.4% in 2021) which is 9% better than the pre-covid 2019 figures. Considering construction sector turnover, 90% of the economic sectors are tangled, with an overall influence on 22% of the GWP for the activities involved (2016 data) and a reasonable probability that the widespread influence is currently higher given the flourishing moment of the sector. Beyond this, the production of +24.3% and increasing employment of 11.8% show a growth of 26.7% in working hours, noting a lack of systematic productivity and a greater workforce employed [3]. The urgency of work and the co-existence of lockdown only partially justify the increase in time intended for work and underline a structural deficit in the sector, which appears, as mentioned above, not surprisingly to have annual production growth rates significantly lower than the other sectors.

The Italian construction sector is not only one of the nine sectors with a higher-than-average centrality index, but it is also characterized by a very high number of incoming relationships, appraised by the transmission speed of the received inputs [3]. It is no coincidence that the sector is demarcated as one among those with "widespread transmission", namely with a large and dense ego-network (or social network) regardless of its ability to mediate. Therefore, this reactivity has made it a powerful economic driver on which it has strategically focused during and after the pandemic crisis at the European and National levels. The nodes (the size of which is proportional to the added value) and transactions graph (outlined by arcs, the thickness of which is proportional to the value of trade) show that, unlike 60% of the other sectors, the building sector has been less impacted thanks to the multitude of good relationships (grey) that allow it to overcome the crisis (Figure 52).

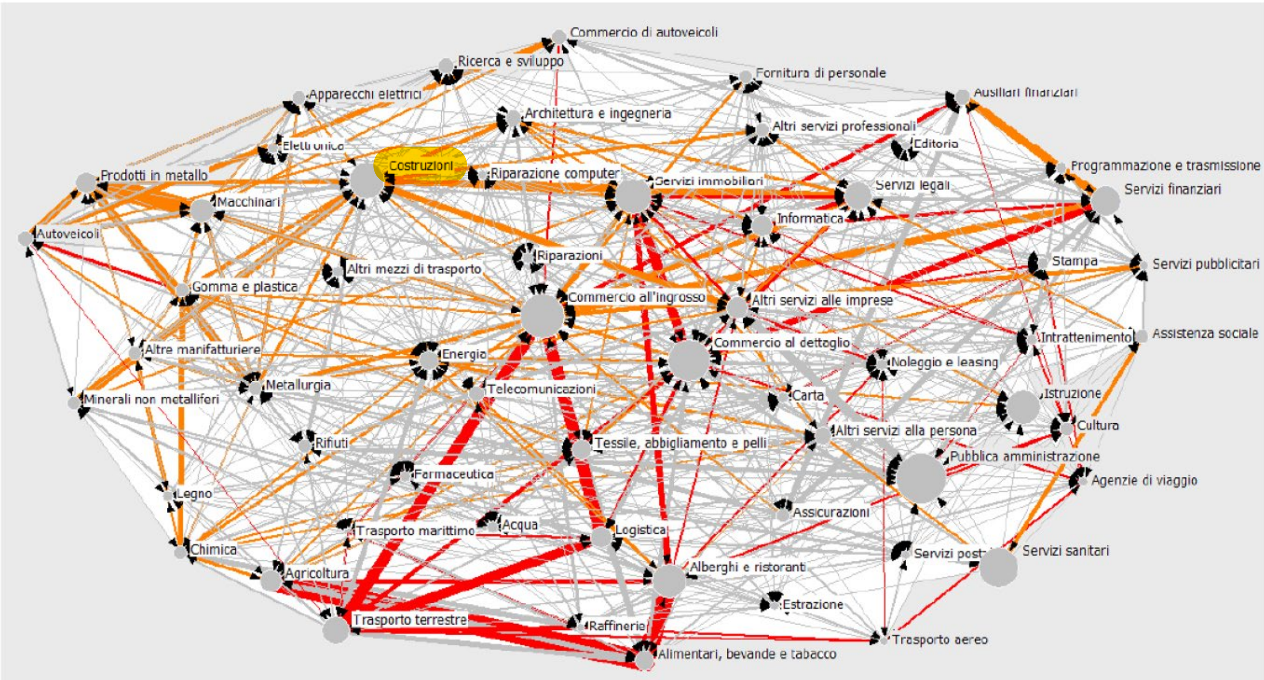


Figure 52: Inter-sector relation across the Italian production system [3]

Regarding investment orientation, the tax deductions (e.g., Superbonus 110%, etc.) generated by the Green Deal boosted the existing residential buildings revamping 25% more than in 2019 for a total of 55 billion euros driving the construction market. The extraordinary maintenance of dwellings affected 37.5% of the market in light of 10.8% of new dwellings and 51.6% of not residential buildings [3].

Construction Investments *				
	Value	Percentage change in quantity		
	2021 Mln €	2020	2021	2022
BUILDINGS	**147.869**	**-6,2%**	**16,4%**	**0,5%**
RESIDENTIAL	**71.546**	**-7,7%**	**21,8%**	**-5,6%**
New	16.078	-9,7%	12,0%	4,5%
Extraordinary maintenance	55.468	-7,0%	25,0%	-8,5%
NON RESIDENTIAL	**76.323**	**-4,9%**	**11,6%**	**6,4%**
Private	46.094	-9,1%	9,5%	5,0%
Public	30.229	2,6%	15,0%	8,5%

(*) Net of transfer costs

Ance processing and estimation on Istat data

Figure 53 Italian Construction Investments 2020-2022 [3]

Figure 53 Italian Construction Investments 2020-2022 shows that growth in 2022 is expected to slow (+0,5%), especially for revamping context (-8,5%), due to some co-factors, increased (o connected) to structural problems for the sector:

- High materials cost: due to materials scarcity, the lack of adjustment of the price lists on which the public tenders are based and the assessment of the interventions financed by the country;
- Workforce shortage: 40% of employees, even unskilled, are challenging to find due to the increase in demand;
- Long process schedule: related both to the ability of the public administration to process the procedures because of the Superbonus close deadline (2023) and to construction site timing;
- Skepticism concerning the sector: a stop to credit transfers by credit institutions caused by the lack of certainty about the work of the public administration, impoverished by years of investment losses and turnover blocking;
- Delay in the funding release: regarding credit transfer and post-pandemic structural support for the SMEs Guarantee Fund.

The moratorium extension and the companies' debt restructuring directly with banks are possible solutions to limit economic damages. Bypassing the bureaucratic delays of the state and having cash flow - although with less revenue - the double bullwhip effect, where the demand is overestimated in correspondence to a shortage of available assets caused by the lack of confidence in the financial markets (increased risk loans) can be bounced.

3.3.3.1 Digitalization level

Italy ranks 20th in the 2021 edition of the Digital Economy and Society Index (DESI Index 2021[6]) [7] with low levels of public services and especially human capital (Figure 54). This is particularly evident in the construction sector, where individuals aged 55-64 are currently 20% of the workforce, with growth prospects of 30% by 2030, with one of the highest aging rates in Europe.

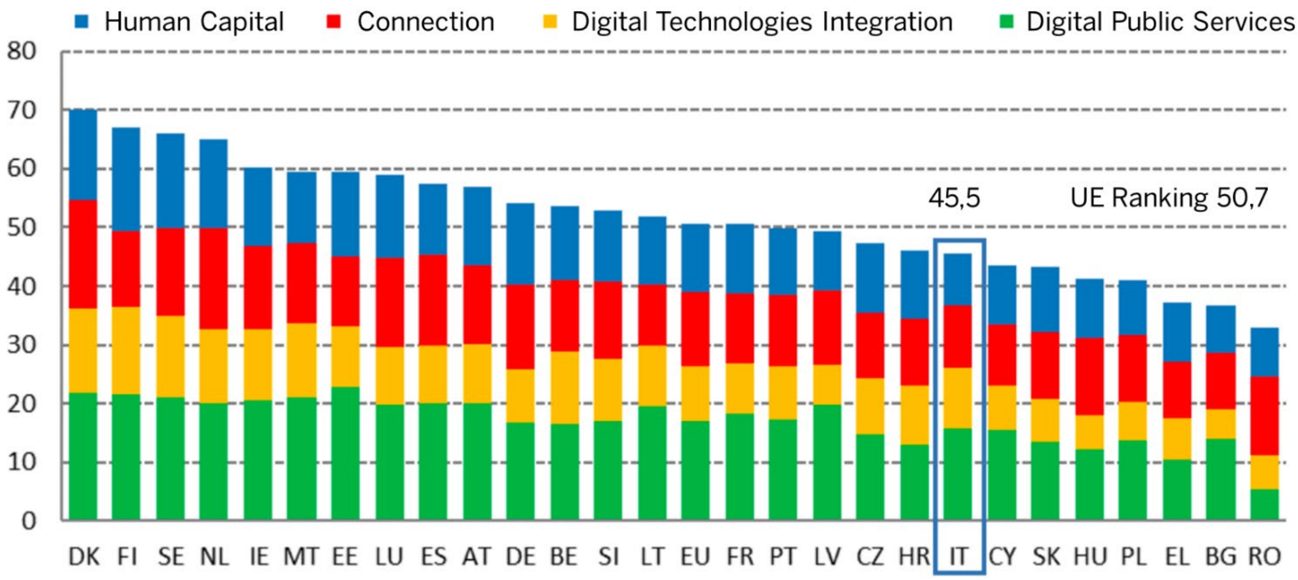


Figure 54: Digitalization of Economy and Society Index (DESI), 2021 [7]

The following elements prove that Industry 4.0 in Italy is not a fleeting phenomenon. Despite the post-pandemic crisis, the sector's market value is stable at around 4,5 billion euros. Market

[6] DESI ranking (Digital Economy and Society Index) would inform choice, design and implementation of projects to achieve that goal. The DESI index is a measure of the progress of EU member states in digitalizing their economy and society. DESI analyzes five areas: connectivity, human capital and digital skills, use of the internet by citizens, integration of digital technology, digital public services.

investigations show the simplest initiative, such as digitization – namely the dematerialization with a view to paperless - as consolidated projects, while product development and automated decision-making are at the beginning stages. In fact, the digital transformation objective concerns a deeper and multi-technological revolution, supported by instruments to be reinforced yet, such as Artificial Intelligence (AI), 5G network and big data cloud computing. It is no coincidence that the SMEs' story in Italy is characterized by high-quality execution, but very low capitalization of the monitoring and control phases during production and after-sales due to a low diffusion of technologies. Indeed, the small-micro size of enterprises makes it very difficult from a structure point of view to invest in innovations of Process (production and quality control) and Product (engineering and Smart Product) [97].

Innovation delay is particularly true when talking about the construction sector, where generally the in-use phase is overlooked because those who design and create the building itself are not involved in the management and maintenance of the same, losing interest in the economic assessment during the building life cycle. Nowadays, a higher energy and resource consumption sensitivity is changing the situation. In addition, from a future perspective, an increased diffusion of Information Technologies (IT) - communication technologies that focus on collecting, retrieval, transmission, manipulation and data protection), which account for 85% of business spending – and Operation Technology (OP) - computer system for monitoring devices and adapting processes to external inputs, which account for 15%, but growing, of business spending – intensify the changing perspective [50].

Although the construction sector is the lowest in the adoption of the digital revolution, the PNRR resources (108 billion €) are pushing the adoption of sustainable practice (39%) and the digitalization level (6%) to achieve much more competitiveness and innovation. These resources are equally distributed between north and south, with a lower concentration in Middle Italy, but Lombardy (11%), Sicily (10%) and Veneto (9%) are receiving more funds due to their centrality in the revenue production [9].

According to interviews, AEC companies believe in the sector's digital revolution and 60% are satisfied with their money tracking and data storage readiness. This first level of digitalization is interiorized for a single user, but there is no sector's vision due to the gap between the office work and the onsite one. Although 45% confirm the centrality of BIM, only 8% adopt it as a process, remarking a gap in the cultural value of digitalization as a working instrument, but it is perceived as a management tool only [7], [94]. The scenario of a 4.0 factory with a robot, AR, 3D printing and ML is far away due to the time shortness – perceived as the main obstacle – and the economic barrier. In this perspective, the adoption of Digital Innovation Hub at the national and regional level (e.g. MADE in Lombardy, IPFG in Friuli-Venezia-Giulia), the European hub for digital innovation in the AEC sector (DIHCUBE) [98]. The purpose is to activate a virtuous process that led the public administration to adopt the driver role of creating a national platform for construction (*Piattaforma Nazionale delle Costruzioni*) as an instrument to push digitalization at all the levels, starting from the e-procurement, to remove the red tape barrier.

3.3.3.2 By use

In Italy, 48,4% of constructions are residential, but only 10,9% are new buildings and 37,5% are special maintenance or refurbishment, confirming the refurbishment market trend developed in the last years (Figure 55) [9]. **Lombardy** is the market leader for new construction and refurbishment (28,9%) [56] and one of the fastest regions to react to the GWP growth thanks to the higher ratio of enterprises and population.

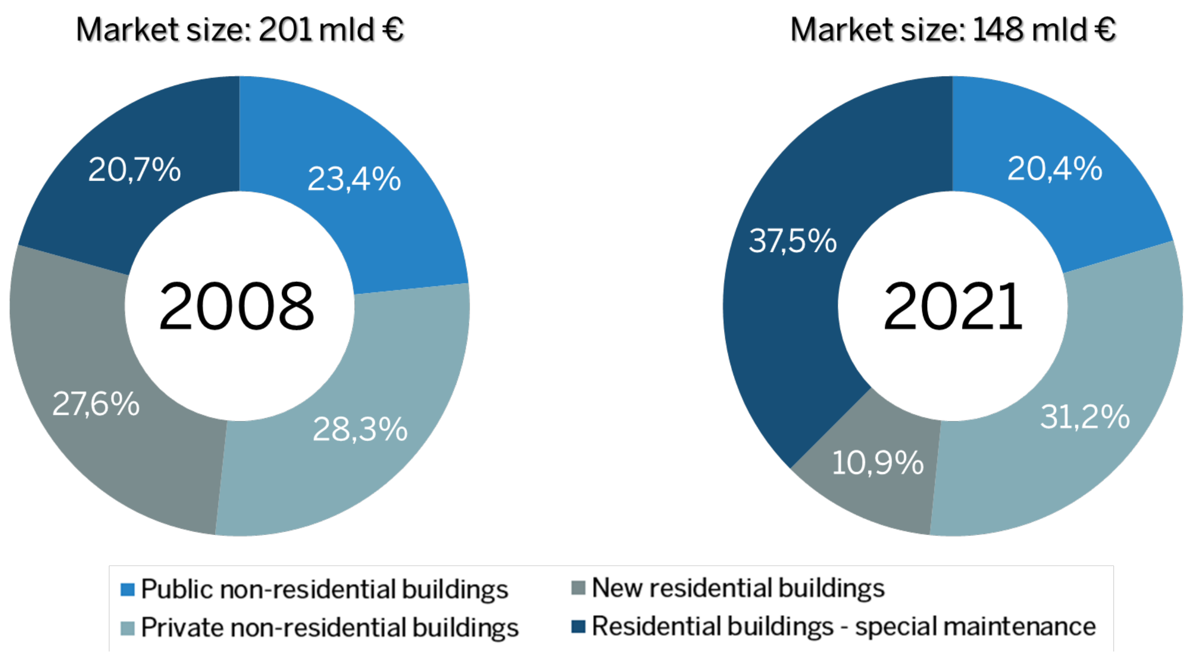


Figure 55: Italian Construction Investment by Sector in 2008 and 2021 [9]

The main problem with the residential market in Italy is the **high cost of houses**: 4,9 million families (19,5% of the total) are unable to buy, so most of them are obliged to rent (1,7 million), living the default risk [99]. After a short period of decreasing prices, the higher cost of materials and the grow-up of requests pushed up the market, obliging the country to control the primary material cost. Since 2012 the government has allowed investment (1,5 billion €) in **social housing** to solve this problem, particularly nearby the edge of the cities. It helps families that cannot access public housing – because their salary is not low enough - but, at the same time, they cannot buy their own apartments. The number of families in the "absolute poverty line" grew by about 1 million from 2019 to 2020 and the increasing energy cost of 2022 will worsen the problem [19].

Furthermore, the available residences are **old** (54% built before 1970 and only 10% from 2000) and many are abandoned (3 million empty residences, plus 2 million public non-residential buildings)[10]. According to 2019 data [99], 17% of Italian emissions are caused by construction (28% by Construction-Demolition CD materials, 72% of energy for heating, cooling and lighting). Renovating existing buildings instead of building new homes in Europe would cut CO_2 emissions by 15% because of the **low environmental performances** (in Italy, 56% in G class, only 7% in A-B class). Looking at the 2050 European strategic plan, Italy has to refurbish 1500 houses daily to reduce energy consumption (25% of them consume more than 160 kWh/m^2 per year[19].

The concomitance with the residential building investments has generated an overbooking of demand against a narrow offer of market solutions. This has led to numerous frauds (more than € 4 billion) and increased employees (the construction companies have increased their membership by 11.8%), often composed of unskilled workers [10].

3.3.3.3 By company size

The "analogic" business model cited before for the world market fits perfectly with the Italian one. There is a high intensity of human capital, low productivity and cyclic work tasks that avoid a long-term investment strategy [69].

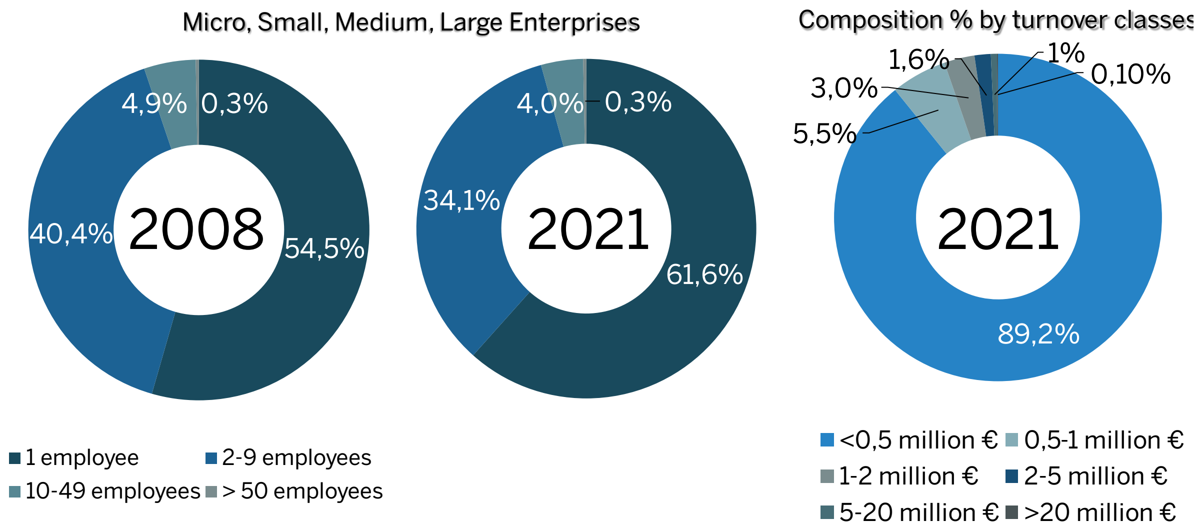


Figure 56: Building companies composition by number of employees [9]

In Italy, 96,7% of the construction companies are SMEs, with less than ten employees and 61,4% are single-person activities (micro-enterprises) (Figure 56) [9] and the trend in the last ten years has been going in the same direction. Most of the 4,4 million enterprises are involved in the services market (79,8%), while only 9,1% are industries and 11,1% are construction companies. The result is a highly fragmented selling compound with low investment capacity and an old managers and leaders class (95% over 65). According to the data, only 3,8% of the companies made some outlay from a 4.0 point of view, primarily acting on management or marketing aspects; only the big ones work on product/process innovation. Corporates particularly did **R&D** mainly on big data (5,7%), very few on 3D printing (1,9%) or robotic (2,2%), according to an off-site assembly approach to buildings more than an on-site one (Figure 57) [10]. Robots are not so diffused in the AEC sector because of the flexibility required to adapt to every building construction site and the high initial investment to acquire a collaborative robot (Cobot) - necessary to assemble small parts and trinkets – that is more than double a traditional Robot. The result of all these factors is the lower productivity of SMEs (130%) compared to Corporates (190%), generating lower added value per labor cost [97].

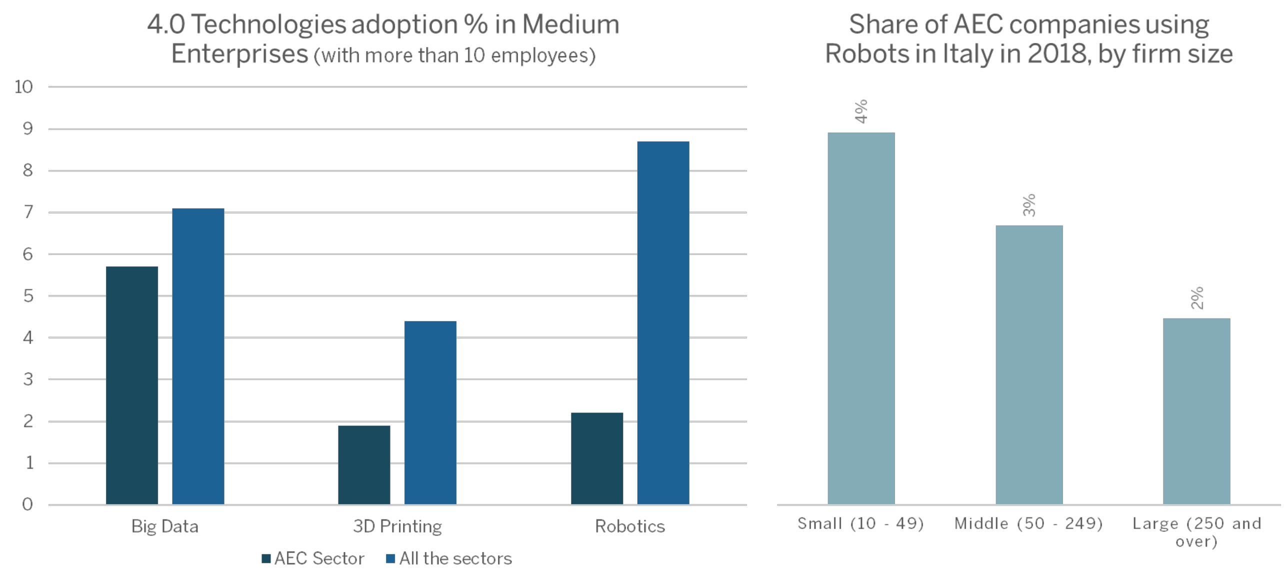


Figure 57: Tech trend comparison between construction and other sectors in Italy [10]

The comparison of the Italian construction sector to the European one shows the half income capacity of the companies compared to German and France, even though the number of companies is one of first (Figure 58). This is due to the lower specialization of companies that are general contractors only in the 10,3% and 7% of the total respectively in France and Germany, generating a higher adding value per capita. Italy also shows a lower number of Corporates with more than 50 employees and a lower average number of employees (2,7) per company (7 in Germany) [10].

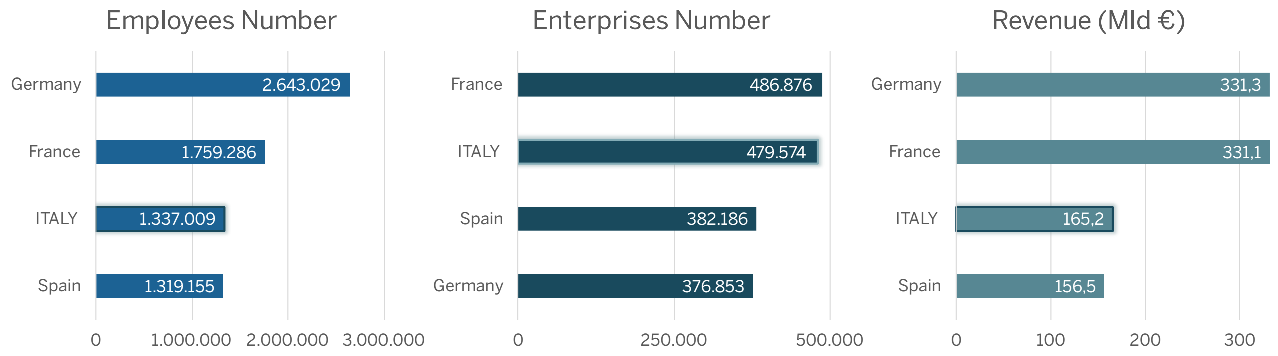


Figure 58: European Market Comparison per Employees and Enterprises Number and Revenue [9]

3.3.3.4 By material

The market analysis on the structural materials for 2018-2019 [9] outcomes that in Italy, complete **concrete** construction is the most used (41% for residential buildings, 23% for non-residential buildings), the mix of concrete and **steel** is the second (32% residential, 25% non-residential), with a low market share for **stone and masonry** (9% and 10%). Concrete prefabrication and full steel are mainly applied to non-residential buildings (24% and 8%), while only 14% and 1% are residences. The trend is still based on traditional methods, but the use of precast and ready-made solutions is increasing, also for timber construction that now finds a short application [10].

Another relevant factor in the material distribution is the price increment due to macroeconomic and microeconomic reasons. On one side, the lockdown period during the Covid-19 pandemic created a gap in semi-worked material production that is still to be recovered. On the other side, the energy cost caused the logistic and transport prices growth, which is most relevant in Italy because 86,5% of materials are road transported (+10% compared to UE average value) [6]. The result is a growth of the material cost of steel, wood and concrete by about 72%, 78% and 50% (April 2022 data) compared to 2019 pre-pandemic values [100]. Apart from the actual price, the trouble consists of the high volatility of costs, generating uncertainty and higher risks for enterprises, without the possibility to plan and manage the pipeline in a medium-long time perspective. Prices also went +350% for steel and aluminum and +315% for timber in 3 months during the 2021 summer, with a monthly variation obliging companies to the quick estimate [101] [102].

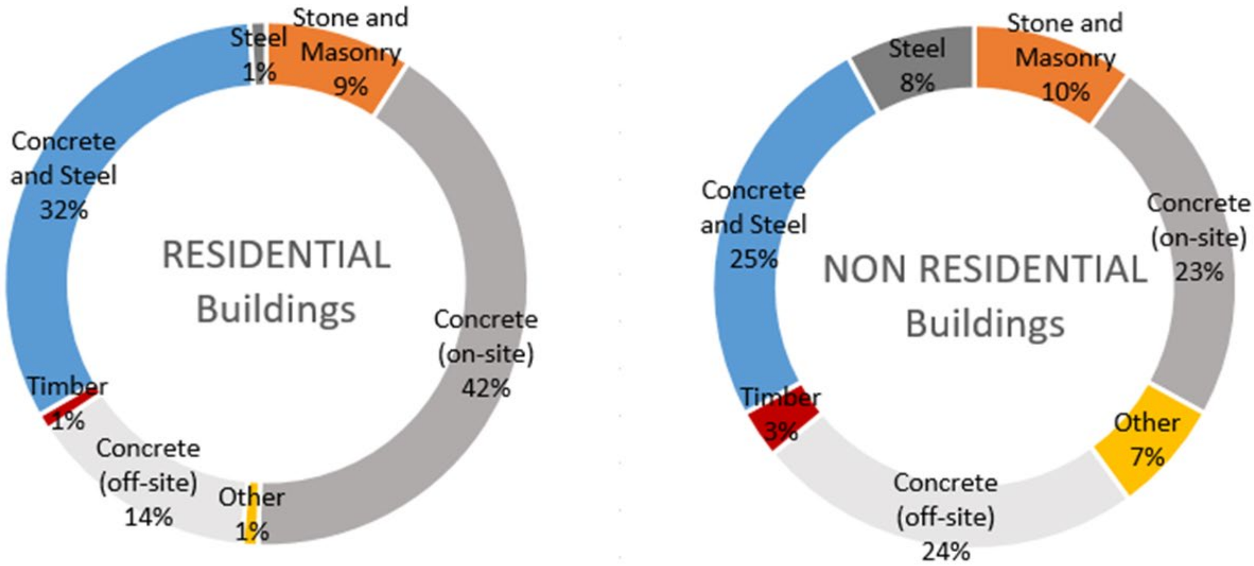


Figure 59: Structural frame of buildings by percentage materials in 2018-2019 [10] [103]

3.3.3.5 Timber market

The advantages of wood are many: good structural resistance, best thermal properties compared to all the other construction materials, lightness, adaptability and easiness to manage but most of all, its low environmental impact thanks to its capability to store carbon [104]–[107]. The traditional application of it is in small structures, but thanks to the engineering of the material and its **industrialization process** nowadays, it is also applicable to high-rise structures (such as the 40-storeys Earth Tower, Vancouver or via Cenni, Milano, residential buildings) [105]. This construction is a clear example of **Off-Site Manufacture (OSM),** intended as a factory-based production assembled on-site.

The timber building production volume of sales in Italy is growing by 5% yearly, becoming the **fourth producer in Europe** behind Germany, Sweden and UK, but with the first growth rate (+10%) in the continent market [108].

In Italy, timber buildings grow by 2,3% yearly and Lombardy has the highest producer number in the regional ranking (55 companies corresponding to 22%, more than Trentino Alto Adige, 17%). Lombardy also has the second volume of sales (13%) behind the Trentino region (51%), basically due to the lower forest surface [103].

Recognizing the high specialization of the timber producers, the new Italian "*Codice degli appalti*" [109] inserts them in the high specialistic works (OS32): companies that produce off-site and assembly on-site their products.

The main aspects of the OSM timber opportunity in Lombardy are the new regulation [110], the market expansion, the fully adaptable technology and the technical improvement of the 4.0 construction.

3.3.4 Synthesis of the Construction environment

"*Markets, institutions and technologies result from a collective creation process*" [111]. The quotes summarize that innovation and changes should involve all the different actors, with a multilevel approach that touches the economy, culture, technology and government. However, all these aspects have a common denominator: man.

3.3.4.1 Diagnosis

To sum up, it is possible to synthesize the diagnosis in 10 failure points, suggesting three root causes to have the paradigm shift of the Italian AEC sector to a 4.0 approach.

Failure points:

1. Low Productivity
2. Funding & Delivery Model
3. Low Predictability
4. Workforce skill & Demographics
5. Structural Fragmentation
6. Lack of Collaboration & Ancient Leadership
7. Traditional Culture
8. Low Margins, high volatility of Pricing
9. Poor Innovation Lack of R&D & Investment
10. Old business Models & Financial Fragility
11. Poor Industry Image

Root causes:

1. The complex environment in which it operates led the AEC industry to evolve in a “survivalist” shape. The sector’s market is characterized by high demand cyclicality and low levels of capitalization/investment.
2. Conventional procurement models and deep-seated cultural resistance to changes reinforce the industry's and clients' divergent interests.
3. No long-perspective strategy or implementation framework exists to overcome and initiate large-scale transformational change across the industry. This includes a lack of government policy or broader public client measures that more positively impact the shape of demand and how the industry responds to that demand. The demand variability, conservatism and lack of alignment/integration with clients highlighted in the first two causal statements above have become de facto accepted norms for the industry.

3.3.4.2 Opportunities

Building industrialization has excellent applications in the residential market, both for homes (single-family, new apartment buildings or refurbishment of them) and students, giving economic advantages to these constructions that have low added value (4%) [4]. Although the world population trend is growing, Italy has expected a depopulation of 12% in the next 50 years and 5.5% by 2050[112]. However, there will be an almost constant seal within the cities (-0.3%), characterized by the biggest cities' gentrification (+2,7% for Milan until 2030) and a downsizing of smaller ones [113]. The fast growth of Milan is another opportunity for OSM: the **Winter Olympics Games of Milano-Cortina 2026**, the refurbishment and new constructions expected for **Scali Ferroviari**, the new social housing projects (15 only in the urban area) and the student housing (Bocconi and Bicocca for example) projects are great opportunities for the sector.

Furthermore, the 55% greenhouse gas emissions cut by 2030[7] (Fit for 55) asked by the European Green Deal, is supported by 0,9 trillion € of Next Gen EU Recovery Plan's seven-year program. In Italy, it was applied on the old building stock by the government taxes deductions (*Superbonus 110%, Ecobonus, Sismabonus, Superammortamento*, etc.), allowing to refurbish

[7] Compared to 1990 levels

by using these offsite technologies, as the only change to renovate 16 million buildings in the next 16 million minutes from 2022 till 2050.

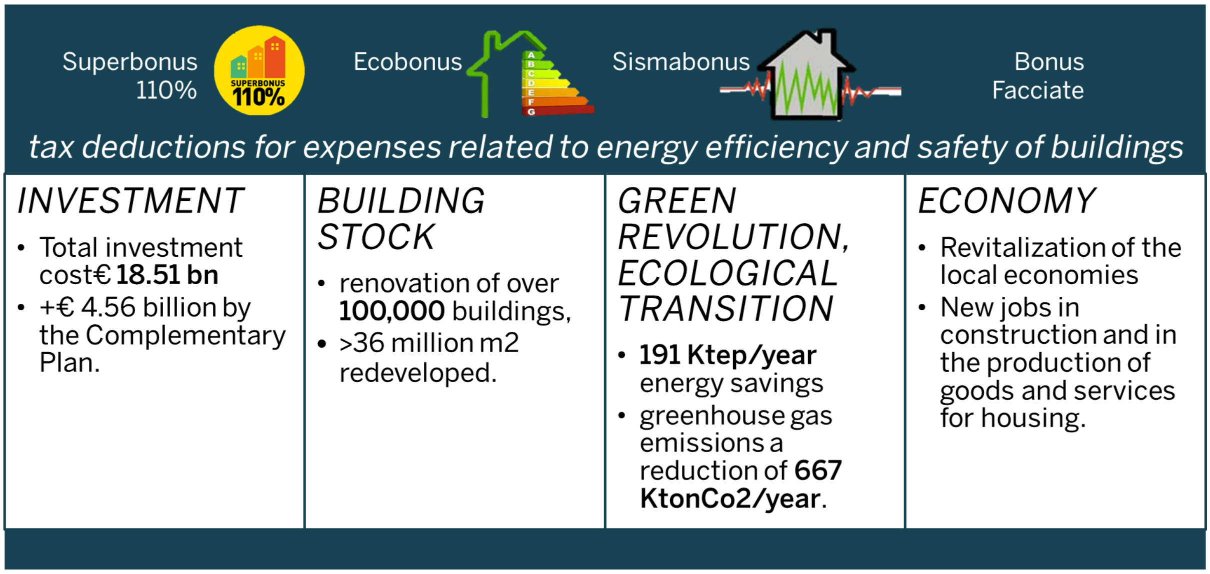


Figure 60: Italian government support to sustainable buildings

According to the Government estimates [114], construction is the sector that will benefit the most from the implementation of the Plan with a change in value added of 3.3%, along with 2.8% of investment activities, or the highest values among all economic sectors. The long-term objective of these monetary and fiscal policies should be to avert the risk of a downshift following the closure of the PNRR program in 2026. However, to respond promptly to the need for redevelopment both from the climate and from the economic point of view, It is necessary to speed up the renewal of individual buildings and this can only be achieved through a technological leap that will lead to the construction sector towards greater industrialization of the same. Creating an **Offsite Observatory**, tracking the Italian (and maybe also European) market, highlighting best practices and supporting the government in the transition to better performance and efficient constructions can accelerate this process.

3.4 Building Industrialization

3.4.1 Historical background

The relationship between industry and architecture develops almost simultaneously with the first industrial revolution and then learning about different phases during the last two centuries. The ARCHAIC PHASE of the end of '800 - where «the building are no more of the architects but of the engineers», characterized by philosophical-utopian views because of the backwardness of the production systems - is then transformed into a phase of CRITICAL REFLECTION enlightened by the Modern Movement, which is subject to the risk of subordination to productivity and the (economic) god of efficiency [115].

Starting from the second industrial revolution and mainly due to the acceleration of two world wars, the construction process became essential for military purposes and reconstruction. *Jean Prouvé* and *Buckminster Fuller* are two "fathers" of the **prefabrication** of buildings. The technological transfer from automotive and industrial production took buildings to a new era led by the **Modern Movement**. In fact, according to this movement, "*House is a machine for living in*" (*Le Corbusier* [116]). Thanks to the technology improvement, contemporary buildings are more an assembly of high-tech elements – like cars - than an on-site creation starting from raw material.

According to this building interpretation, the **Off-Site Manufacture (OSM)** (3.4.4.1), the most advanced version of the **Modern Methods of Construction (MMC)** (3.4.4), affirms that the industrialization of the building sector is the way to have more quality and lower costs [117]. This new concept adds quality and economic value to the ancient prefabrication technique, also recovering the holistic approach that the specialization of the industrialized society risks losing, as Gropius suggested. The **third industrial revolution** was characterized by **materialization** and **technicization** or **mechanization** as declinations of an excess of instrumentalism that diminishes man's role to an executor instead of the driver. The atomization of components and parts led to a drop in the **humancentric goal**, leading to the machine prioritization that generated cultural opposition to the Modern Movement [118]. It was also due to society's technological gap, compared to the digital era where we are and the too high of a request to satisfy.

The HYPE phase [115] perdures until the 50s in Italy, when the post-war rebuilding phase had been characterized by good quality, thanks to the traditional construction companies that applied prefab components with their deep expertise and long-term know-how.

Enhance, from the 60s, the quality decreased due to the territoriality unbalance generated by the convergence of resources in the north triangle (Milan-Turin-Geneve), which obliged the southern population to move to the country's north side. To quickly answer the market, the young Istituto di Case Popolari (Institute of Public Housing) imported French prefab systems (Coignet, Trecoba, Balancy) without enough know-how to install and with a lower quality compared to Italian products. The result was that – poor - building construction prevailed in architecture: buildings were similar and standardized due to the home needs and the economic boom that gave no time to develop architectural projects properly. This phase is known as CRITICAL STAGNATION, where technological limits to variations led to a technological massification that resulted in a social massification in which the economy prevailed over architecture. It marked the end of the Closed System Integral Prefabrication [115].

Stock Products born in the 70s, even though sometimes with low quality, marked a new phase characterized by an Open Prefab System driven by on-demand building components/systems provider industries [82]. This new PROPOSAL phase developed advanced concrete solutions and new steel systems (Light Steel Frame) with higher quality, typical for school applications. It was characterized by a higher industrialization level allowed by the introduction of CAD drawing tools and CAM machines, shifting the sector's focus from designer to manufacturer in a logic of centralization of the enterprise. The fewer workforce availability and the simultaneous higher cost of skilled workers led to moving them to factories, where productivity and cost were lower compared to onsite jobs. The increasing quality resulting from this shift generated the birth of certifications and quality control systems due to the increasingly complex **requirement system**, with the rising norms and bureaucracy as counterparts and making it impossible to return to simpler technologies.

This vision was then expanded in the 1990s to include a broader spectrum of aspects straddling design and production, summarized in the concept of Lean Construction [115]. The continuous development of prefab technologies opened the route to the structure/envelope construction systems based on dry assembly that embedded prefabrication in its nature. Thanks to its ductility, the fully customizable solution can fit technology to presentation with an on-demand design instead of a standard solution, solved by their integrability that can be modified and replaced during their life.

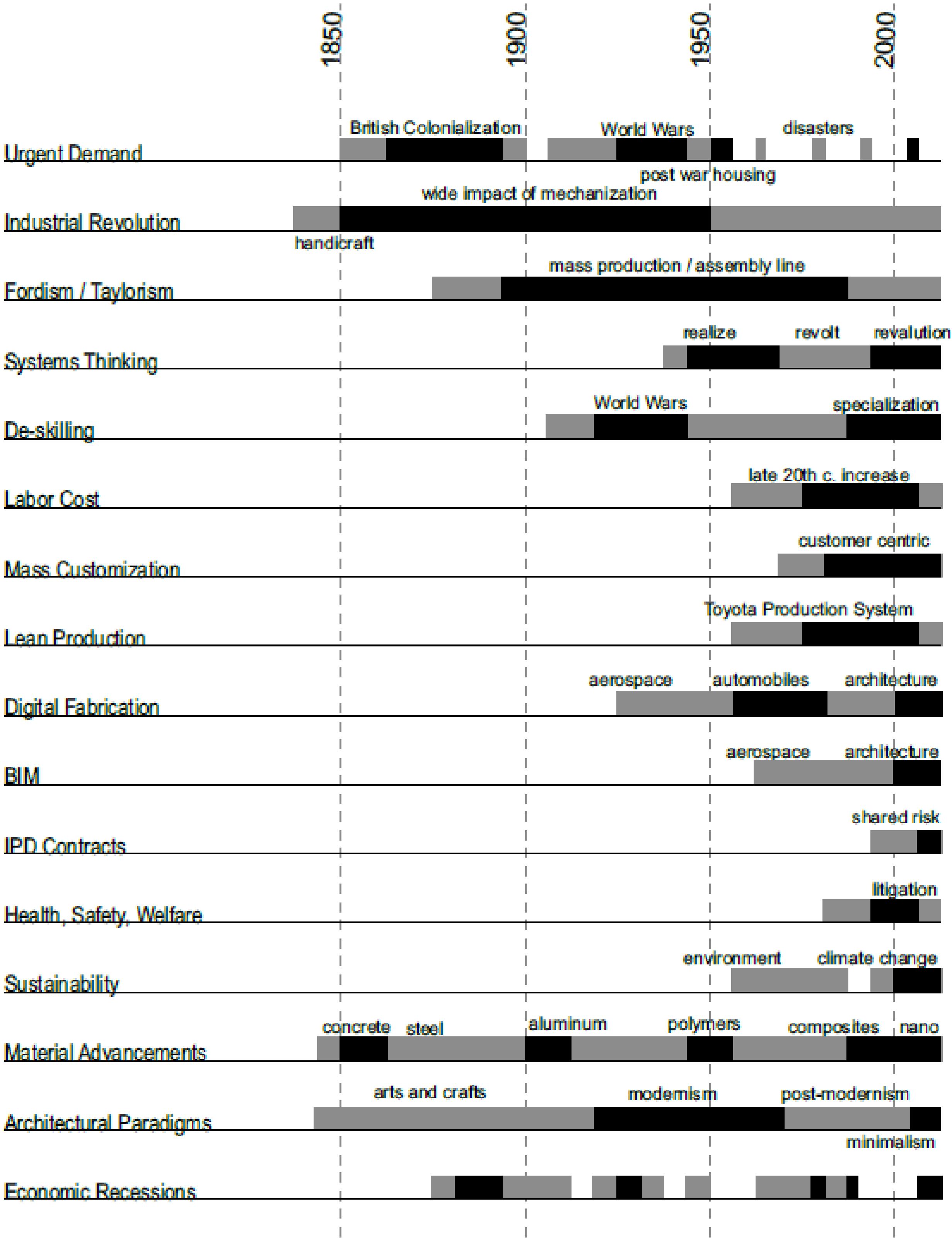


Figure 61: vocabulary and events across industrial history [82]

3.4.2 Lean Construction

The simultaneous optimization of design, construction, use, management, recovery, reuse, recycling and dismission phases in a holistic approach was introduced in 1993 by the **International Group for the Lean Construction** [119]. The purpose is to apply management to the building process, adapting lean manufacturing to this sector. The **guideline is the minimum cost for the maximum value by reducing spreading and focusing on the client's needs**. This approach contrasts the traditional one based on the late intervention on the on-site issue instead of preventing them. The problem is evident in construction site management, where tasks planned during the week were often completed at the end of the week in 50% of the cases. It causes the shift of planning or, at least, the impossibility of anticipating actions and recovering the lost time in other activities. The lean approach wants to highlight the impossibility of traditional construction management to respect deadlines and constraints. Three are the KPIs of this theory and they are all connected: **time-cost-quality** [120]. Once again, the industrial approach that optimized all three aspects was the future of buildings.

At the beginning of the new century, the **Toyota Production System** [121] was identified as the model for a new paradigm with three complementary elements: **transformation (T), flux (F) and value generation (V).** The results were new planning, execution and control methods specified for the building sector [122]. The system conceives the organization working on a building not as different actors involved in one project, linked only by contracts and documents but as one body empowering the single suppliers.

Lean construction and production have different applications - because the building product is a prototype, while the product is usually the same - but they have identical **principles**:

- System optimization by collaboration and systematic learning
- Continuous improving and tension to perfection
- Focus on the value delivered to owners, clients, final users
- Remove obstacles to value generation having a slim process
- Pull production (led by client)

These principles find application in the **best practices** for all the actors involved in the process:

- Maximum functionality of buildings for the end-users
- Users need satisfaction with the lower cost for the owners
- Workman and material waste/inefficiency deletion
- Constructor and supplier involvement in the early design process to improve constructability creating functional teams
- Design, production and construction link and coordination
- Check and verification advances with quantity and quality evaluation

However, the technological transfer of all these principles from aerospace, shipping and automotive industries suggested by Lean Construction is hard to achieve due to the SMEs' market features and the reverse approach to Product: mechanical sectors invented products manufactured by suppliers, while contractors adapt the design to the products created by suppliers.

Lean Construction determines the separation between Process and Product because of the increasing complexity of the market and the company. The emergence of new professions, the inclusion of different intermediaries in the process and the growing specialization required to make a centralizing/architect-centric process impossible, as it was until the XIX century. Still, it is necessary to have a multiplicity of specialized actors.

However, the analogy with the automotive sector is impossible because of some intrinsic differences in the sectors, such as:

- The non-randomness of the customer who has specific solid needs and is not willing to accept compromises;
- A completely customized product that cannot be limited to the variation of the standard through the only options and makes the building a unicum, a product directly at full scale and, for this reason, not replicable
- A prototype created virtually and not physically as it occurs for cars.

These observations are more evident in the Italian market, in which the historical culture, the passion for beauty and the visceral bond with the territory make accepting compromises by standardization impossible in contrast with the USA, Japan and Scandinavian countries.

The leading Italian architectural theorists of the time provocatively stated that if cars were produced as buildings, the costs would be 40 times higher (*Zanuso*, 1970). They pointed out an ideological opposition to the use of innovations in favor of a traditionalism linked to formalistic mannerisms (*Mario Botta* and *Aldo Rossi*) instead of opening up to experimentation embraced by the British and Americans (*Nicholas Grimshaw*, *Richard Rogers*, etc.) [123]. It is precisely from these designers that the solution to bridge the gap between the need to industrialize and the desire to customize, albeit with limited technical possibilities. Thus was born the modern concept of assembly, which can be translated as the hybridization of serial production and ad-hoc solution, perfectly synthesized in «do more with less» (Foster) as a synthesis of the principles of Lean Construction to be pursued: lightness, speed, Accuracy, multiplicity and visibility (Calvin, American Lessons [124]).

Figure 62: Lean Construction approach [Adobe Stock]

3.4.3 Industrialized Building System

Lean Construction aims to introduce an industrial approach in the building sector. In the last ten years, the idea was embraced by many institutions and researchers to reduce the productivity gap. The productivity growth will reduce the default risk of construction companies scaling up their profit margin. Like all the other sectors, Construction 4.0 should also invest in digital transformation by adopting AI and IoT from a factory production perspective

MMC, Off-Site Construction (OSC) and Industrialized Building Systems (IBS) are different names for the same concept. The main themes related to this idea are collected in the **Industrialization Mindset** of buildings by RIBA (Royal Institute of British Architects) [21]. It defines *objectives* (Innovation, Quality management, Marketing and business development, Cultural change), *instruments* (Project management, Supply chain, Smart product, Interoperability) and *methods* (DfMA, Off-site manufacture, On-site assembly, Logistic) as a path to industrialize the sector [82].

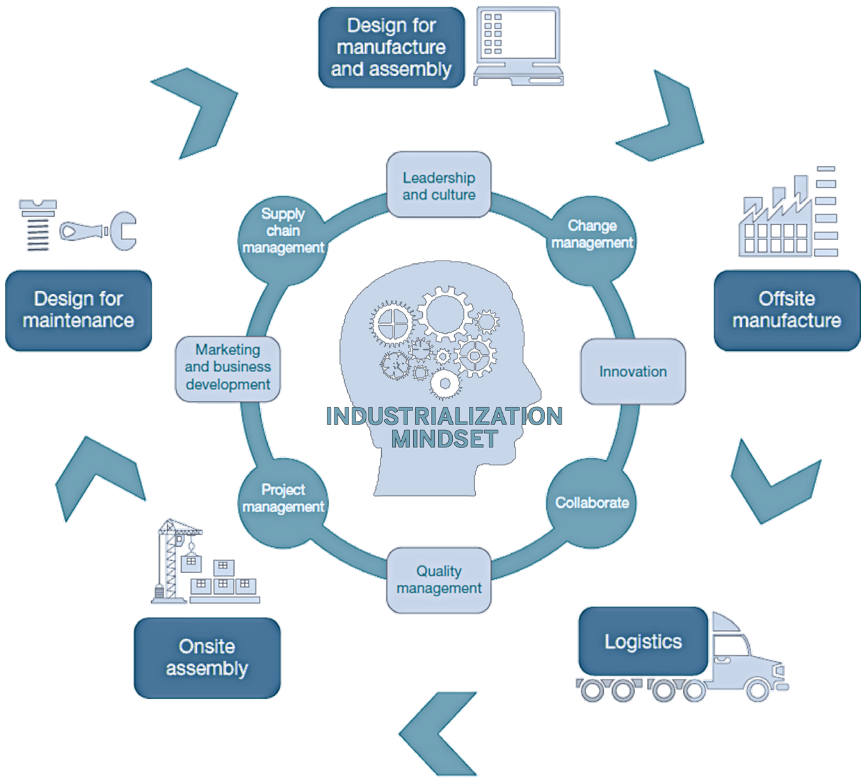


Figure 63: Building Industrialization Mindset [21]

This mindset synthesizes the different purposes of the two main actors involved in the sector: the construction company wants to achieve **Smart Production** by organizing manufacturing, transport and construction, while the design team aspires to an **integrated design**. The computational strategy of the first one seems to be opposite to the request of **mass customization** of the second one, but - thanks to the combination of **DfMA** and **BIM approach** - the purpose of satisfying both requirements can be achieved.

The new challenge of this industrial production concerns the digital and tech adoption inside the BIM and DfMA approach – quite - already achieved. The rules-based and generative design, the **nDimensional information modeling** (time, cost, sustainability and facility management from 4 to 7D) need to be integrated with the manufacturing workflow and **digital tools** such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT) and Digital Twins (DT).

Adopting these tech trends requires disrupting the traditional process, according to the scientific revolution path [40] and the new 2020 RIBA report [14].

3.4.4 Modern Methods of Construction (MMC)

In the early 2020s, after a *particellization* of components - due to the tectonic of building technology that privileges the small components (2D prefab systems) -, builders assist in a return of 3D and complex systems (hybrid and ready-made panels) thanks to the fill of the technological gap that allows having much more complex and ready-made solutions [59]. The simultaneous control of geometry and data allows a parametrical shape in a BIM environment, enabling free composition for architects and free data access for engineers, where digital tools can manage both the design phase and the production. The production customization became open to different process typologies: Subtraction (e.g., 5 axes, laser-cut, hydro jet), Shaping (e.g. matrix, shaping machines) and Additive (e.g. 3D printing, welding). These typologies are strictly connected to the manufacturing process and can be different according to the customization priority given to:

- Line: fully customizable thanks to the file 2 factory that should be engineered every time
- Product: it is possible to modify the production line to allow mass customization starting from a standard product
- Material: hybrid materials are applied thanks to the technological transfer from other sectors.

The spread of manufacturing and production process strategies generated multiple new approaches to construction that can be synthesized under the name of Modern Methods of Construction. On of the definitions given to these methods is:

"*A broad term to describe various innovative approaches used to construct buildings and infrastructure, resulting in increased efficiencies and improved productivity. All types of 'industrialization' are captured within the definition, from completely modular builds to the prefabrication of individual components and the use of robotics and digital technologies*." [87].

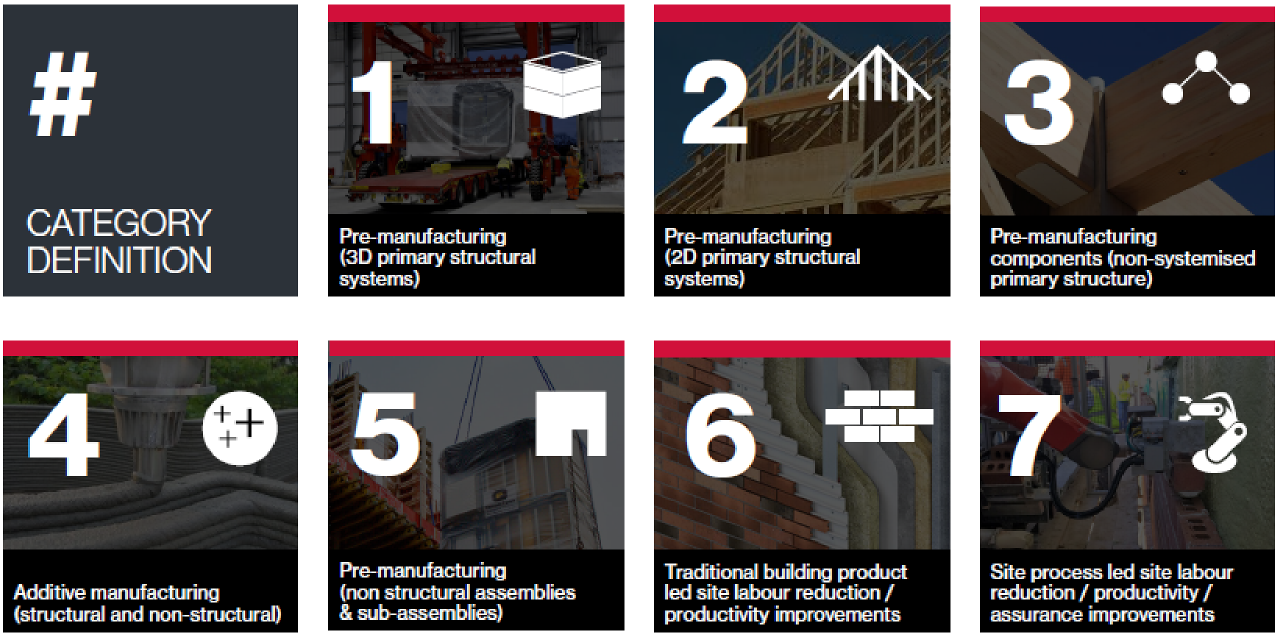


Figure 64: Modern Methods of Construction (MMC) categories [69]

MMC Category definitions [69]:

1. **3D primary structural Systems.** Volumetric units are produced in a controlled factory and brought to the site with various completeness percentages, from basic structure to complete internal and external finished with/without services.
2. **2D primary structural systems.** Flat panel components for floor, wall and roof structures, produced in a factory and assembled onsite to create a 3D structure. Closed panels can include lining materials, insulation, services, windows, doors, internal wall finishes and cladding.
3. **Non-systemized primary structure.** Framed or mass-engineered timber, cold rolled or hot rolled steel or precast concrete members, including load-bearing beams, columns, walls, staircases, core structures, slabs, ring beams, piles caps, driven and screw piles.
4. **Additive manufacturing.** The remote, site-based, or final workforce-based 3D printing of structural and non-structural components. The material depends on digital design and manufacturing techniques.
5. **Offsite and near-site pre-manufacturing.** Non-structural assemblies, walling systems, roof cassettes, non-load bearing kitchen, bathroom and utility pods, service packs, plug-and-play systems and energy production modules.
6. **Optimized Traditional building products.** Large format manufactured products, pre-cut configurations or easy jointing features to reduce site labor, E.g. roll-out reinforced flooring, brick slips and underfloor heating mats.
7. **Site labor tools.** Innovative site-based techniques including lean construction, physical and digital worker augmentation, robotics, wearables, drones, verification tools and technology-led plant.

The main difference among them is the level of prefabrication and their application: the last two solutions are extemporary onsite solutions that can support the construction phase but cannot be feasible to scale up the market. Instead, the first 5 are offsite strategies that anticipate and make the quality control procedure more effective, transforming the construction site into an assembly place instead of a creation spot, with higher precision and lower approximation.

From the housing perspective, the dwellings renovation rate requested by the Italian market (1 per minute from 2022 till 2030) is achievable only by boosting productivity[8] by about 1,8%. MMC efficiency is 1,3%, more than double the traditional one (0,5%): a great improvement but still not enough to get the target. It is possible to increment the ratio by working on efficiency (h/m2) through digital tools, as previously mentioned and scaling up the market.

The initial investment is a barrier to entering and scaling the SME market (Figure 65). The 1000 units required to show relevant advantages in terms of productivity limits the diffusion of MMC because the higher the automation, the bigger the cost [4]. On the other hand, the advantage is that the critical mass to start is the same per every automation level while scaling up the impact on labor volume increase.

[8] Measured as value of goods and services produced/input man hours

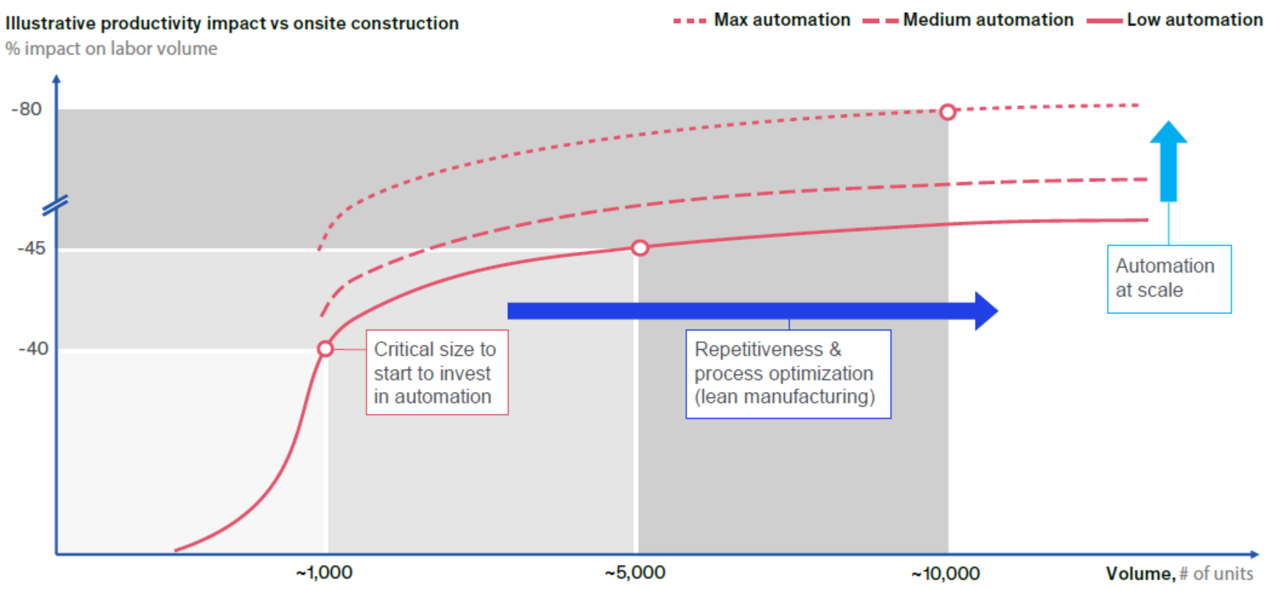


Figure 65: Automation scale-up barrier [4]

It is possible to highlight 10 Key aspects to expand the MMC adoption into the housing market [22]:

1. **Innovate**: run from "That is the way it has always been done" and do things (e.g., procure, design, pay, manage) differently from state-of-the-art to get benefits.
2. **Specialize**: specialist designers or consultants optimize the project and avoid costly mistakes.
3. **Go straight**: Plan and design for MMC instead of converting a traditional project.
4. **Find your way**: there are MMC solutions for almost every type of project and several different procurement routes to get there.
5. **Cluster**: Clients can gain efficiency by working together to standardize home designs and aggregate demand.
6. **Design**: Standard designs do not have to equate to aesthetic uniformity and beauty.
7. **Team early engagement:** design team, manufacturer and delivery partner participation are essential from the beginning of the project.
8. **Scale up**: financial benefits for organizations are unlocked by working on multiple schemes and significant commitment up front on design and planning to get quicker deployment and delivery.
9. **Start**: MMC market is growing and many examples of organizations are making it work.
10. **Modularize**: the efficiency of the 3D module is higher for MMC solutions.

3.4.4.1 Offsite construction

Among the MMC solutions, the most efficient is the offsite construction because of its higher level of prefabrication. Offsite Manufacture (OSM) or Offsite Construction (OSC) can be defined as "*an approach to process in which the construction value added onsite is less than 40% of the final construction value at completion*" [69]. Part of the construction process is carried away from the building site. This can be in a factory or sometimes in specially created temporary production facilities close to the construction site (or field factories). This has the benefits of reducing labor demands on-site, improving quality and safety and reducing the environmental impacts compared to traditional construction.

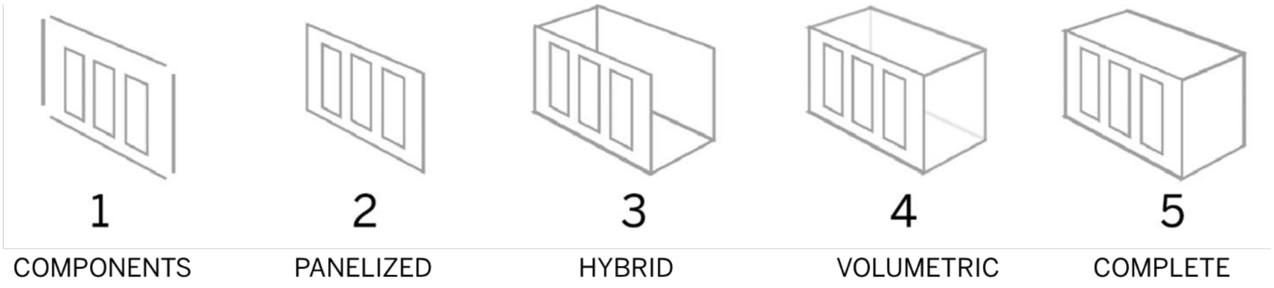


Figure 66: Prefabrication level of Offsite Manufacturing

The level prefabrication level [82] can be different according to the typology of the solution adopted:

1. **Components**: single mono-dimensional elements like roofs, glazing, beams, etc.
2. **Panels**: 2D elements around 60% prefinished
3. **Hybrid**: mixing solutions 2 and 4 in volumetric solutions not fully enclosed
4. **Volumetric**: 3D modules completed around 80-90%
5. **Complete**: full offsite modules including internal and external finishings 90-90% completed

The biggest advantages of offsite solutions are quality and time-cost efficiency: 94% of OSM respects the budget, while traditional solutions are over costing 49% of the time. Similarly, only 63% of the traditional construction site are delivered on time, while the percentage for offsite technologies is consistently higher (96%) [125]. The precision of planning can be higher thanks to the lower labor requested onsite and the extra effort in design required in advance. Furthermore, factory production allows a faster and more precise production phase overlapping some onsite activities such as foundations and infrastructure (categorized as preparation works), shortening the construction phase in situ (Figure 67). A shorter onsite activity above ground balances the more expensive design phase due to anticipating the production process during the foundation and underground works. Infrastructure and foundations time usually remain the same because they applied traditional building techniques (cast-in-place).

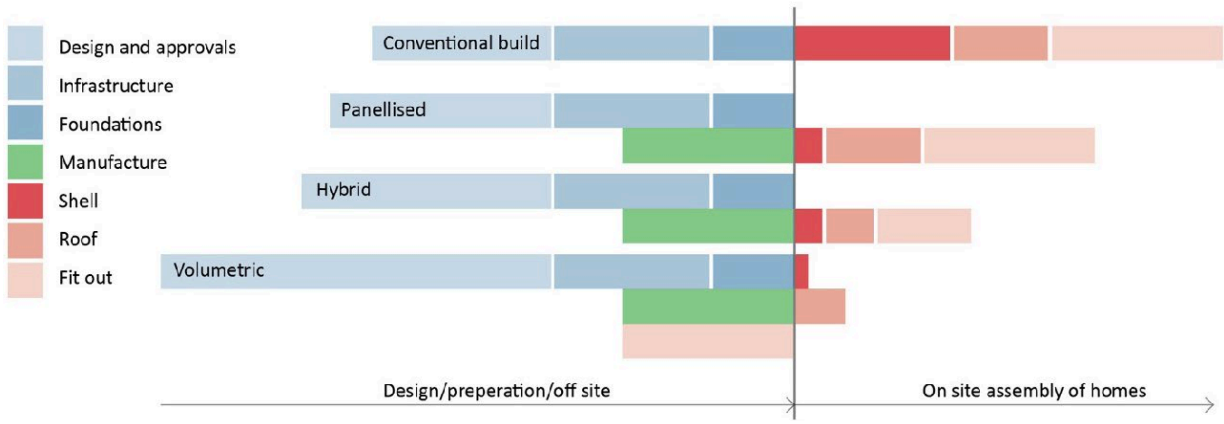


Figure 67: Offsite Manufacturing advantages in delivery time compared to traditional buildings [126]

To summarize, the advantages of the Offsite adoption are mainly about the increase of **quality** (+30%) and **security** of workers (+80%) together with a reduction of **costs** (-20%), **time** (20-50%) and **energy consumption** (-30%) due to better management of resources in **offsite** activities instead of the onsite ones (-70%) [21], [22], [57], [61], [67], [117], [127]–[129] (Figure 68).

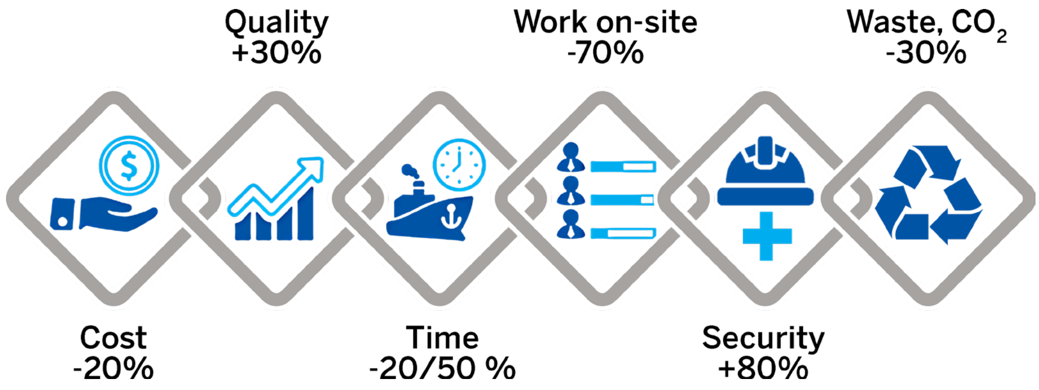


Figure 68: Offsite Manufacturing's main advantages

This is why MMC is the faster answer to the **need for new homes and** they are growing by 5-15% by year, partially recovering market slices from traditional buildings. In 2019 they were 5-7% of the new buildings' total, constantly increasing [63]. Volumetric and Panelized solutions are the most diffused in the UK market (adopted by 61% of developers), while only 28% applied hybrid systems. However, 39% of companies used onsite MMC technologies in 2018 [63], [130], [131].

3.4.4.2 Pre-manufacturing value

The term "pre-manufacturing" encompasses processes executed away from the final workforce, including in remote factories, near-site, or onsite "pop-up" factories. The passing test applies a manufactured led fabrication of consolidation process in controlled conditions before final assembly/install.

Pre-Manufactured Value (PMV) [63][132] is the value created from completing work away from the site. It is calculated by taking the gross capital cost of the project and deducting the prelims and the site labor costs. This result is then divided by the capital cost and is reflected as a percentage.

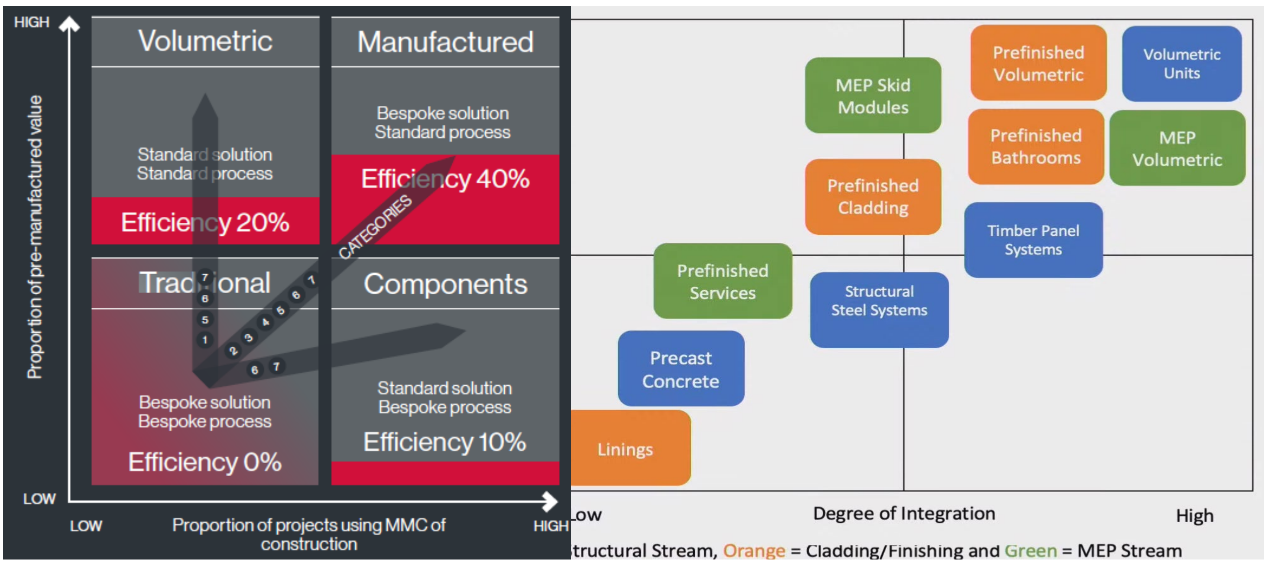


Figure 69: Pre-Manufactured Value (PMV) of MMC [132] and Components Integration Level [107]

According to NBC research [108], the number of projects adopting volumetric solutions in the whole market is lower than the manufactured elements because of the flexibility required from offices and public spaces compared to the possible standardization of solutions and the housing process. Conversely, the PMV of 3D solutions is higher because of their full integration of finishings and services. This analysis also matches the level of prefab per degree of integration of different technical elements: the more complex the system, the more efficient the offsite solution is. This is why volumetric construction and MEP boxes require a high level of integration in the project.

3.4.5 Barriers to Construction 4.0 adoption

Analyzing the building lifecycle allows for understanding the application of industrial concepts to construction. Supply chain, design and production processes, technology and cultural maturity underline some structural problems to 4.0 concepts application to buildings [49][24][133]

- Uncertainty:
  - **Each project is different**: prefabricated products must be adapted to the construction project because climatic conditions, urban restrictions, geotechnical aspects, architectural value, end-user requirements, etc., are different
  - **Dynamic working environment**: "product mobility approach" is not possible because of the static position of the product (building or infrastructure). Thus is used the "team mobility" approach where the team moves from one building site to another
  - **Uncontrollable working environment**: the same construction site has different conditions because the space is large and dynamic with possible decoupled work teams
  - **Missing Early Engagement of Suppliers**: it is crucial to engage the supply chain from the beginning of the project to optimize the design phase. The uncertainty of projects and the absence of contract preserving their effort and valorizing their risk in the next building process phases is a barrier that the government can overcome.
- Complexity:
  - **High fragmented value chain**: 93% of Small-Medium Enterprises (SMEs) have less than ten employees, while buildings are big and workers must be next to the construction site. It follows that creating a standard process among many stakeholders is challenging.
  - **Material optimization**: due to the high specialization required, all the supply chains have different problems, actors and requirements based on material properties (wood, steel, concrete, bricks, windows, etc.).
  - **Increase of Skilled workers**: unlike traditional buildings, prefabrication needs a highly specialized workforce due to specific and complex activities on workshops and construction sites.
  - **High logistic management required**: traditional buildings solve most of the problems on-site; prefabricated ones need to plan and design everything before.
- Digital revolution:
  - **Low digitalization**: The construction sector is the economic sector with the lowest digital intensity index in Europe. According to this, there is a huge potential to increase productivity because digitalization is connected to the size of the company and most of them (92%) are SMEs at the first level (lower) of digital transformation (business as usual).

    - **Different levels of technologies' maturity**: not all the 4.0 technologies involved in this sector are at the same level: BIM, Cloud computing and Mobile computing are currently available; additive manufacturing and augmented/virtual/mixed reality are not.
    - **Young Digital design support**: modular design tools are unripe instead of traditional ones that can be driven be the ancient workforce with the worst results.
- **Short-term thinking:** individual projects without a system and connection
    - **Higher initial cost**: the manufacturing cost of MMC is higher compared to the traditional price, but the advantage is evident from a medium-long-term perspective, thanks to a shorter construction time and a faster ROI. However, the production and manufacturing costs will decrease by activating the market scale-up.
      A similar discussion regards digital tools for SMEs. If it is valid from the automation point of view, on the other hand, the acquisition of simpler devices such as RFID to track and automatically provide reports is supposed to have a small initial investment and low digital competence.
    - **Long product lifetime**: buildings have a longer life than industrial products, with shorter production time and faster development.
    - **Uncommon language of information**: there is a gap between BIM and Product Information Management (PIM): a lack of information or an excess between general contractors and suppliers in the construction industry.
    - **Small data valorization**: the extra effort to produce and manage data is not evident for SMEs that prefer to focus on shorter cash flow balances instead of investing in valorizing data during the use and EoL phases to increase revenue.
    - **Inability to catch opportunities**: the difficulties in getting productivity boost thanks to government funds handout changing the future perspective of the sector.
- **Cultural opposition**:
    - Strong resistance to changes in a sector governed by old managers' class, unable to follow the fast-changing technology world.
    - No political instrument to help this sector (although the industrial one has).
    - Law support: there is a lack of regulations for prefab components procurement.

The uncertainty of a dynamic working environment, the high fragmented supply chain of Small-Medium Enterprises, the need for skilled workers, the low digitalization, the short-term thinking and political/management cultural opposition are the **main barriers** to the MMC adoption. In contrast, horizontal integration of networks, End-to-end digital integration, Vertical integration and networked manufacturing systems are the three **keys** to implementing industry 4.0 in buildings.

3.4.6 Keys for 4.0 buildings implementation

The market trend previewed the increase of Off-site buildings because of their ability to satisfy the customer's and building companies' requests. *T. Oesterreich* and *F. Teuteberg* sustain that there are three key elements to introduce 4.0 concepts in the building sector [49]:

1. **Horizontal integration of networks**: IT systems, processes and data have to flow between different companies
2. **End-to-end digital integration** (using CPS) of engineering across the entire value chain, facilitating highly customized products and reducing the internal operating cost
3. **Vertical integration and networked manufacturing systems**: Integration of IT systems, processes and data flows within the company from Product Development to Manufacturing, Logistics and Sales for cross-functional collaboration, resulting in an intelligent manufacturing environment.

Dividing the AEC sector into different compounds, it is possible to identify a *cascade effect* that starts from the regulation as an external enabler force and moves to the industrial approach till the firm-level operational factor:

- **Regulation**: transparency is a key factor for the efficiency of the norms and laws, but a common strategic policy is also needed to lead the system to best practices adoption in terms of green (sustainable) and blue (innovation) investments. Adding social value in the remuneration counting can be a solution to push the innovative approach with short time benefits form SMEs and longtime benefits for society.
- **Collaboration and contracting**: based no more on cost but on the value and performances of products in a more open-innovation environment that is required for new challenges shared between competitors acting in the same field of expertise. The intro of quality evaluation with Energy Performance Contracts (EPC) that guarantee a long-term performance standard can be a game changer for the whole process.
- **Long-term business strategy**: Waiting for new procurement contracts for the suppliers' early engagement, adding assurance against the failure of offsite manufacturers, can preserve the risk that SMEs should assume. On the other side, adding a logistic, transport and use warranty scheme can enhance the Present Net Value in cash-flow business analysis, a first step to move to the Total Cost of Ownership investment evaluation.
- **Design and engineering**: DfMA approach allowed by BIM instruments can push the adding value of this phase beyond the on-site phase, acting on the production process (factory making), the management and the disposal phase (DfMD).
- **Procurement and supply chain management**: digitalization of the connection between technical offices and suppliers can have a significant impact thanks to the digitization of the activities and, beyond, adopting digitalization (block chain) and autonomous management of the orders (Artificial Intelligence) exploiting all the adding value of the chain.
- **Onsite execution**: the phase with the higher benefit coming from industrialization is the construction phase, where three main steps can boost efficiency:
    - **Smart Production**: faster and more reliable relations between owners, contractors and manufacturers, better monitored by KPIs and KERs.
    - **Digital Design**: a more retriable design approach thanks to mass customization opportunity given by parametrical and design optioneering instruments, but also much more control for the production phase of sub-assembly and prefab components before the onsite construction.
    - **Smart Construction**: having clear and precise planning, now allowed by the technology control system for risk and management (e.g. Last Planner Systems)

- **Technology**: new technologies, materials and approaches step through the digital revolution for enabler and secondary technologies across all the building process (BIM approach) from design (Digital Design), production (robot), construction (Extended reality, IoT) and management (Artificial Intelligence and Big Data).
- **Building Capability**: reskilling the workforce is necessary due to upcoming technological challenges and to avoid the risk of reducing the employment number but increasing their value. The sector cannot use the same technology as 30 years ago and to unlock the 4.0 potential, it is necessary to plan a continuous learning path for labors.

Many of these aspects are related to the exchange of data and the possibility of quickly overseeing building interaction, analyses and management. For this reason, **interoperability** [23] must be solved vertically (inside the four main areas: information, digital transformation, product optimization and automation) and horizontally, in a future perspective. Ideally, companies will have considerable advantages from the open-source data, realizing the data valorization that Big Data promises without achieving. Looking at the entire production process, three Smart classes (**production**, **manufacturing and use** – the Objectives) collect the four main areas. They are connected to the Smart Factory idea, which moves construction closer to the industrial world according to Building Industrialization (§ 3.4), as required by the market analysis (§ 3.3).

To summarize, buildings will move to the 4.0 era solving the productivity problem of the production and construction phase thanks to these strategies. **Productivity can be boosted by 50-60%,** plus a **cost saving of around 27-38%,** according to 2017 data [24], by the intervention in regulation, contract, design, supply chain management and improving onsite execution by technology innovations and reskilling workers. Unfortunately, in the early 2020s, value chains ready to apply these concepts are few.

3.4.6.1 Modern Supply Chain features

Due to the closest location to the market opportunities of timber manufacturers, the largest part of the value chains is involved in the wood chain. Summarizing the positive elements in the wood chain [82]:

- **The short supply chain**: fewer suppliers from forest to user than the metal chain.
- **Turnkey approach**: companies usually give a complete product to final customers,
- **DfMA ready**: the high prefabrication of elements, most of the work inside the factory and the possibility to transport the most extensive completed parts suggest the 4.0 quick introductions in this chain.
- **Boost productivity** thanks to off-sit fabrication:
  - **lighter** than other materials
  - large **2D/3D modular systems** could be transported and handled on-site
  - **improve safety and quality construction site**
- **High flexibility**: balloon frames, big panels and beam-column are some of the construction principles applicable to wood.
- **Sustainability**: it is a natural material because it is **renewable, carbon-neutral and** timber stores CO_2, contributing to footprint **reduction**

However, supporting one technology compared to another is not the best approach to push the offsite solution approach in the market. Every material has positive and negative aspects and every designer should choose according to the project requirements. To have a summary of the pros and cons [82]:

	Steel	Concrete	Timber
+	• CFS (Cold Frame Steel) widely diffused • Light and easily craned (1-3,2mm thickness galvanized steel strip) • Most recycled material without downgraded	• Robustness, durability (weather resistant) • Strength (Heavy cladding finishings) • Sound insulation (mass-damping qualities) • Fire resistance (A0 class)	• Industrialized process (closed loop from processing to manufacture, assembly and installation) • low embodied energy (carbon storage) • Natural and renewable material • Engineered material (CLT, GLT, etc.) • Standardized design
−	• Water protection (raised off the ground, flashings and overhangs) • Fire protection (plasterboard capsule, fire barriers required between modules) • Highly conductive (cold bridges risk) • Durability for claddings (high maintenance required)	• Weakness of Joint (design and construction critical) • Non-readily altered (cast-in-situ or precast) • High conductive (cold bridges risk) • High embodied energy (due to manufacturing emissions of clinker) • Mass-heavy transport	• Fire protection • Strength (limitation for tall buildings) • Vulnerability to weather (protection and ventilation) • Live material (dimensionally variable for shrinkage and differential movement, except from CLT)

Figure 70: Materials pros and cons for OSM applications [82]

Figure 71: second skin façade hybrid Panel (CLT+Concrete) [WoodBeton]

Figure 72: Unitized facade, PwC Tower, Daniel Libeskind, 2019, Milan, Italy

4. Lean Construction 4.0

"It is not the strongest or the most intelligent who will survive, but those who can best manage change."

CHARLES DARWIN

Scope:

The first result of this research is exploiting the new **Lean Construction 4.0** paradigm [Obj 1] that applies the 3P revolution: **Process, Project and Product** [*RQ 4*]. New information management connects all these three aspects.

The **BIM nD approach** is the baseline for the **Platformization** that facilitates the transition from products to services defining a new Process. The application of **Digital Design** to the Project deals with data valorization through **Design Optioneering** (parametrical design) and **Design for Manufacture and Assembly (DfMA).** It leads Products to a new era based on the supply chain's early inclusion [*RQ 3*], mass customization by autonomation and a more sustainable approach thanks to the circular economy.

4.0 Process Mapping, 4.0 Radar and Phygital figures – such as **PhygitArk** [RQ 2.1 and Obj 1.3], **Phygital Coach** [Obj 1.2] and Producer - are the proposed solutions to apply and check the new paradigm.

This ontology suggests a new **Information Management** by mixing experience with a more data-driven process, as the Knowledge-Based Engineering (KBE) approach suggested. Two different instruments (LC 4.0 Assessment and Panelization Design Tool) are proposed as examples of this **new Value Proposition** that increases the intrinsic value of products.

Contents:

Expected results:

- Lean Construction 4.0 ontology description
- 3Performances: Process, Project, Product description
- Identification of the Information gap

- BIM nDimension explanation
- Digital Design opportunities outline
- DfMA comprehension
- Definition of Phygital World and figures competencies list
- Knowledge-Based Engineering description
- New Value Proposition

Keywords:

3P Paradigm; Project; Process; Product; Phygital Coach; PhygitArk; Phygital producer; Design for Manufacture and Assembly (DfMA); BIM approach; Knowledge-Based Engineering (KBE); Data valorization

The 4.0 suffix to the already existing **Lean Construction (LC)** [119] highlights how the digital revolution allows adopting LC principles to optimize all the building Process. Digital transformation dominates the whole society, but it will enable the passage from the rationalism of the archaic phase to the standardization of the post-war years, to 2020's optimization, helped by the second digital revolution, finally able to customize the standard solutions according to user requests.

The **theory's guideline is the minimum cost for the maximum value by reducing spreading and focusing on the client's needs.** The Toyota Production System maximized it**,** the model for a new paradigm with three complementary elements: **Transformation (T) – the Offsite approach to construction (**Offsite construction **§ 3.4.4.1) -, Flux (F) – interpreted as (Information Management § 4.3) - and Value Generation (V) – in a new** Value proposition **(§ 4.4) (**Figure 73**)** [122].

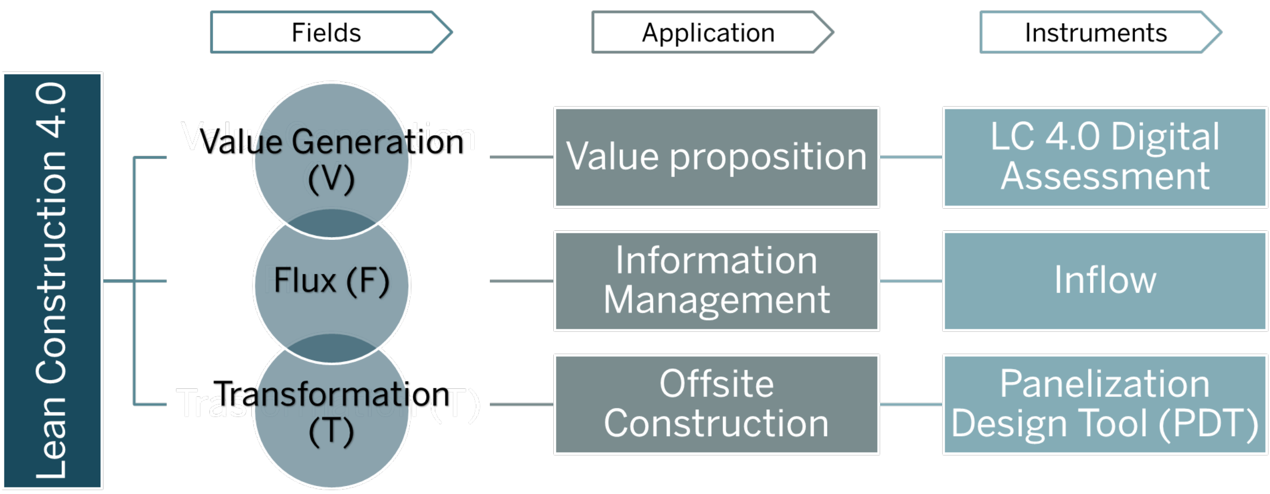


Figure 73: LC4.0 Fields, Applications and Instruments

The paradigm aims to achieve the industrial goal of Smart Factory by analyzing its four main areas defined by the **tech trend taxonomy.** Among them are identified **11 enabling technologies** useful to accomplish the **functions** defined by the **LC 4.0 Paradigm**, which aims to improve **performances** of the **3P: Process, Project and Product** (Figure 74**).** The framework defines Function as an assigned task to achieve a Performance by using instruments (Enabling Technologies) and tools (Secondary Technologies).

INDUSTRY 4.0

GOAL
1. Smart production
2. Smart Manufacturing
3. Smart Use

AREA
1. Information
2. Digitalization
3. Product Optimization
4. Automation

TECHNOLOGIES

ENABLING TECHNOLOGIES
1. IoT
2. H-V Integration
3. Cyber Security
4. Cloud Services
5. Additive Manufacturing
6. Extended Reality
7. Big Data
8. Digital Twin
9. Robot
10. Artificial Intelligence
11. 5G

FUNCTIONS

10 POINTS PARADIGM
1. BIM nD Approach
2. Platform Approach
3. Servitization
4. Computational Revolution
5. DfMA/DfMD
6. Data Valorization;
7. Supply Chain
8. Circular Economy
9. Mass Customization
10. Automation

PERFORMANCES

3P
1. Process
2. Project
3. Product

Figure 74: from Industry 4.0 to Lean Construction 4.0

Figure 75: Revitalization into a smart, safe, sustainable, energy and carbon positive high school building.ENVILOP, wooden facade developed at CTU, 2022, Prague

4.1 The new 4.0 Paradigm

The **Lean Construction 4.0** holistic approach (Figure 76) involves all three aspects of architectural objects: Process, Project and Product. The defined theoretical framework is a development of the **S/E (Structure/Envelope)** one, where construction started to be a dry assembly of components instead of a wet construction based on gravity and starting from raw materials [115].

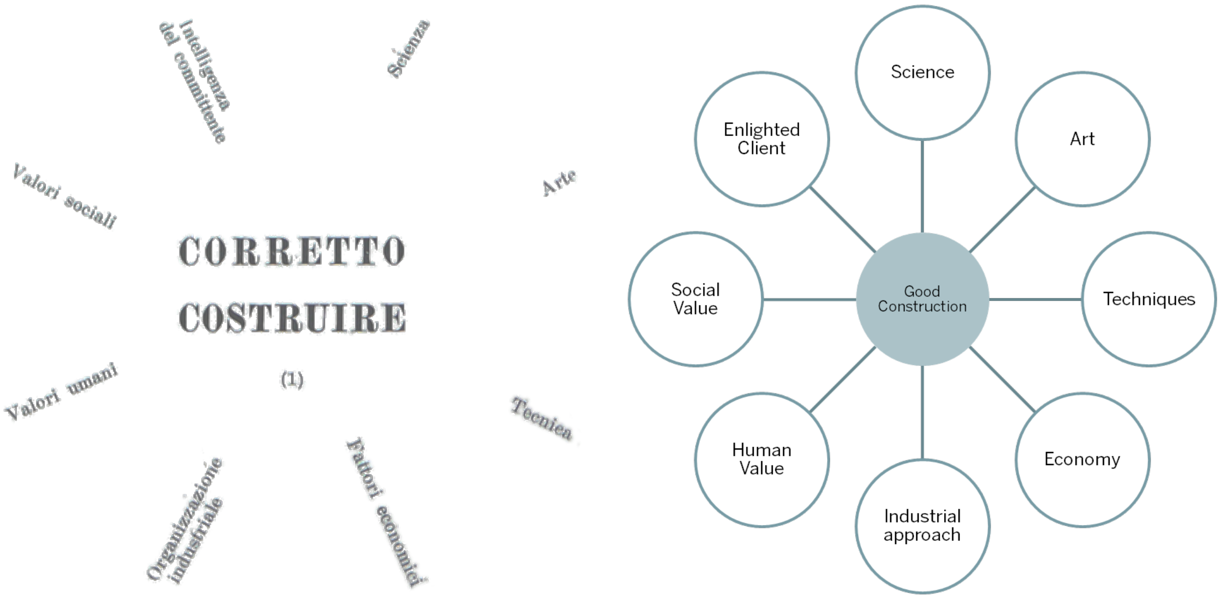


Figure 76: Holistic Construction Approach [134]

Sustainable Development Goals (SDGs) [135] - at a global level - and **Building Back Better (BBB)** [136] - at the local one - marked out the route for a sustainable future. The purpose is to achieve a **New Bauhaus** where architecture will be led by the "*Voxel*" (a 3D pixel) concept, defined by *Mario Carpo*[9] [137]. Parametric Design [32] is essential in this vision to discretize an object into small parts that can be assembled. From the 2010s, the common interpretation of Parametric Design is given by *Patrik Schumacher* [10] that comes from *Greg Lynn*[11]'s definition of "*blob*" as a digital aerodynamic. In architecture, it concerns drawing smooth and morphological geometries based on complex curves: NURBS [15]. This interpretation of Parametric Design is embodied by **Formalism** led by *Zaha Hadid* and *Frank Gehry*, defined as "digital streamline" by *M.Carpo*.

In contrast, the opposite approach to the digital revolution in construction is *Kengo Kuma*'s **Particellization** [123] (Figure 77). The so-called "Digital Neo-brutalism" concerns the industrialization of construction, where "*computational design is revitalizing old-fashioned building methods with the new calculation speed*" (*K. Kuma*) [16]. The craftmanship shall be returned to the production phase, as Covid-19 shows.

[9] architectural historian and critic, Reyner Banham Professor of Architectural History and Theory at the Bartlett School of Architecture, University College London and Professor of Architectural Theory at the Institute of Architecture of the University of Applied Arts Vienna.
[10] architect and architectural theorist, principal of Zaha Hadid Architects, launcher of Parametricism Manifesto.
[11] founder and owner of the Greg Lynn FORM office, University Professor in the Institute of Architecture at the University of Applied Arts Vienna and UCLA School of the Arts and Architecture. He is CEO and co-founder of the Boston based robotics company Piaggio Fast Forward.

During the pandemic, SMEs continued to live and thrive thanks to their flexibility, allowed by the world wide web and the workman value, while large factories suspended their activity [16]. The pandemic accelerates deregulation, leading to a new human-centric period: the digital renaissance. The new modern era's architectural consequence is a shift from Formalism to humble architecture, which helps and supports human life without being invasive [15]. Formalism can be an aesthetic added value for the iconic architecture, but it is not appliable to ordinary buildings, where the only chance to have better quality is in specialization and factory making of single parts. Digital revolution became the instrument to realize the *Gropius* utopia of "*unity into diversity*", creating beauty for everyone starting from the past as a value, where we learn from tradition merging aesthetic with functionality, as Japanese culture teaches. The centrality of the Project consists of the need to describe Architect who can manage hyper-specialized technicians with an interdisciplinary background, realizing its etymology. In fact, Arché denotes superiority of whom detents technique and realizes it as an artisan (*ték-ton,* from Greek) able to merge the different project areas from both the useful and the intellectual aspects: the link between the modern perspective of Nordic culture (designer as manager and technical expert) and the classical one of Italy, where the old construction systems prevail and the role of stakeholders (designer, producer, manufacturer, builder) are often confused and overlapped. The need to have multiple souls in one figure led Architect to become a representative of *multiple cultures of the project* [45]: intellectual (conceiving the project), engineering (applying techniques to solve troubles), making (realizing products to change the society), management (organizing and driving figures to create the object).

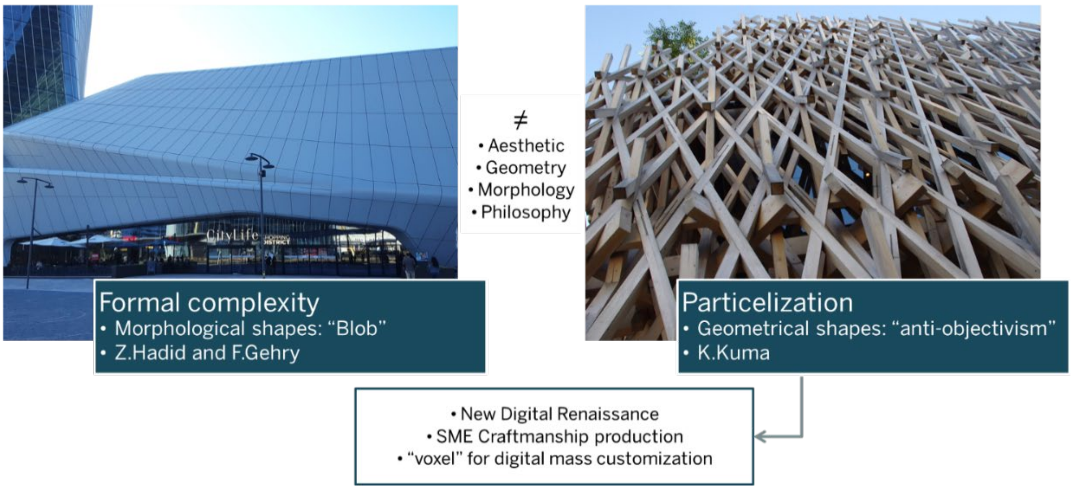


Figure 77: Digital revolution in architecture

This **sprawl** of competences also reflects the need to fragment the **functions** inside neighborhoods and, at the same time, inside large buildings. The **tower** can also be interpreted as a vertical neighborhood: multiple functions will lead to a better quality of life in high-quality construction, reducing the gross floor consumption and returning land to green and nature, especially in the city center. Simultaneously, **suburbs** will be transformed thanks to the single/multiple families' refurbishments through recladding and external exoskeleton. It can be interpreted as an "*airbag*" giving structural, energy and aesthetical quality to ordinary buildings [138].

MMC is an excellent opportunity in this contest, particularly in Italy, covering all the construction requirements, from new buildings to renovating the existing ones. To better classify these technologies, provided with an **Industrialization Level Classification**. The three prefabrication levels of single components, industrialized systems, or building industry match three product models: **made to stock**, **assembled** or **engineered to order** (Figure 78) [82].

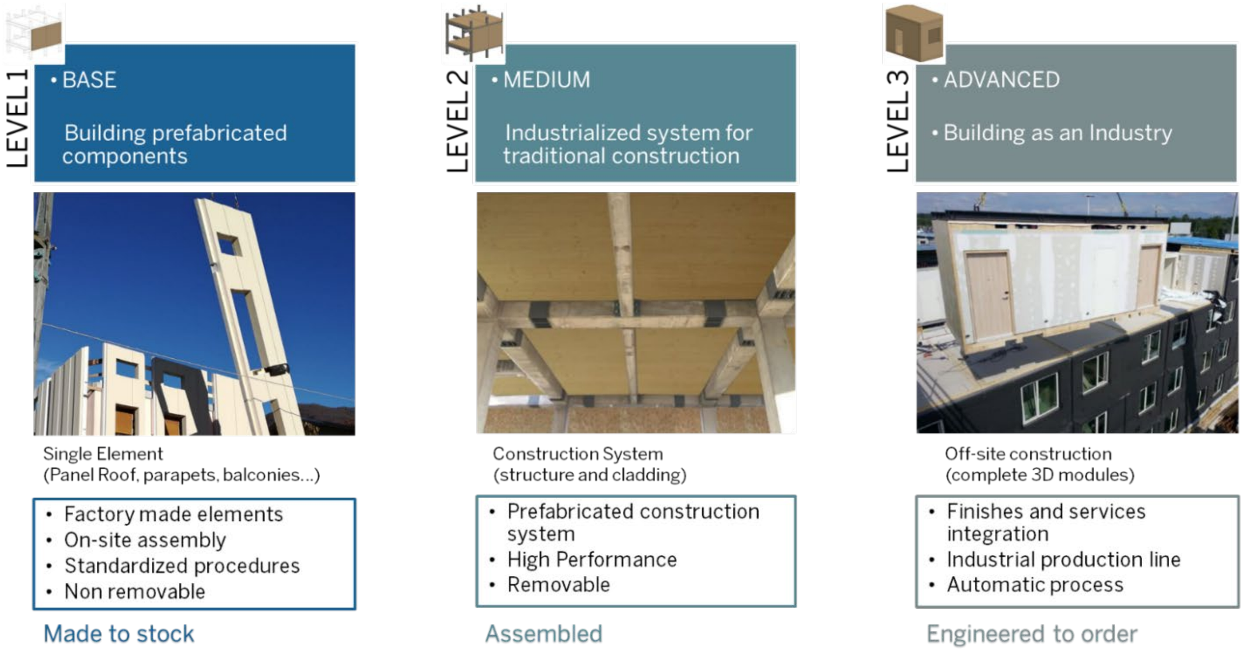


Figure 78: Product Industrialization Level

Using parallelism, in the tailoring world, the difference between made-to-measure and bespoke consists of the garments' unicity. The creation from a standard model and the customization to fit each customer represents the mass-production, while the bespoke is fashioned from scratch, based on the customers' request to match their desire perfectly.

Unfortunately, architecture requires a "*tailor's approach*" to each element without starting from scratch but customizing standard solutions according to the client's needs. Italy's different approach to offsite solutions is due to cultural and practical aspects. On one side, the Italian perception of prefabrication is affected by the low-quality products coming from the second world war; simultaneously, the logistic limitations due to narrow roads avoid the possibility of adopting volumetric constructions (3D). The longer lifetime, the higher quality and the unique design request led to adopting a bidimensional element approach to buildings. Thus, the theory behind this concept is closer to the **Anti-objectivism** (object breakdown in simple elements creating a unique shape) from *Kuma*, than the standardized solution suggested by *Taylorism* [139]. This fits the complexity of multifunctional neighborhoods instead of a more efficient zoning distribution where residences are concentrated in one place (Figure 79).

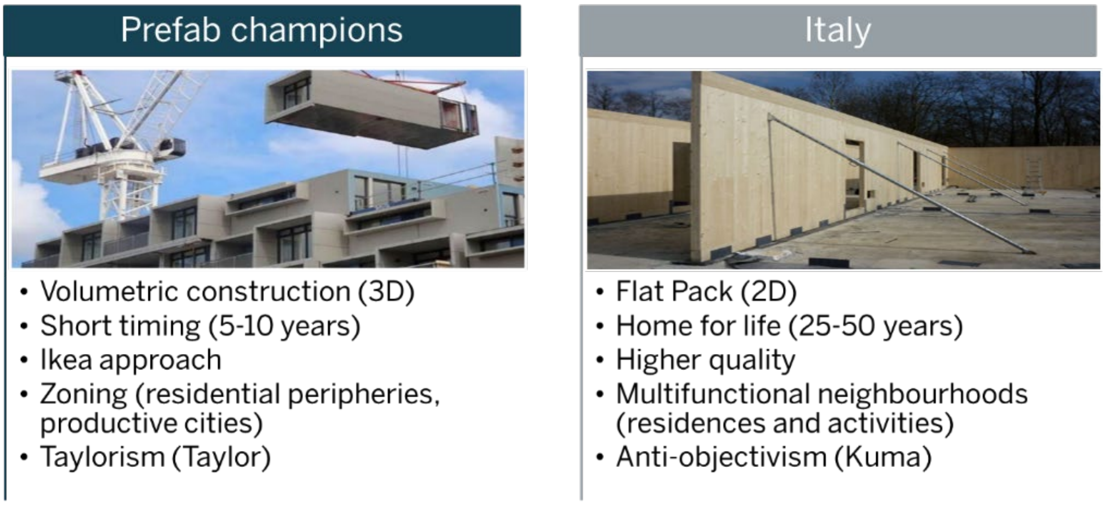


Figure 79: Prefab champions and Italy's approach to offsite

To summarize, the LC4.0 pushes construction to adopt a new paradigm where designers, manufacturers, builders and owners can be more integrated into an interoperable and more informed environment thanks to digital instruments wisely driven by men: the Phygital World.

Figure 80: 3D Housing Module truck carrying

4.2 Process-Project-Product (3P) revolution

The new paradigm concerns the three critical aspects of construction, called 3P: Process, Project and Product [140]. The decalogue of the paradigm is resumed in Figure 81.

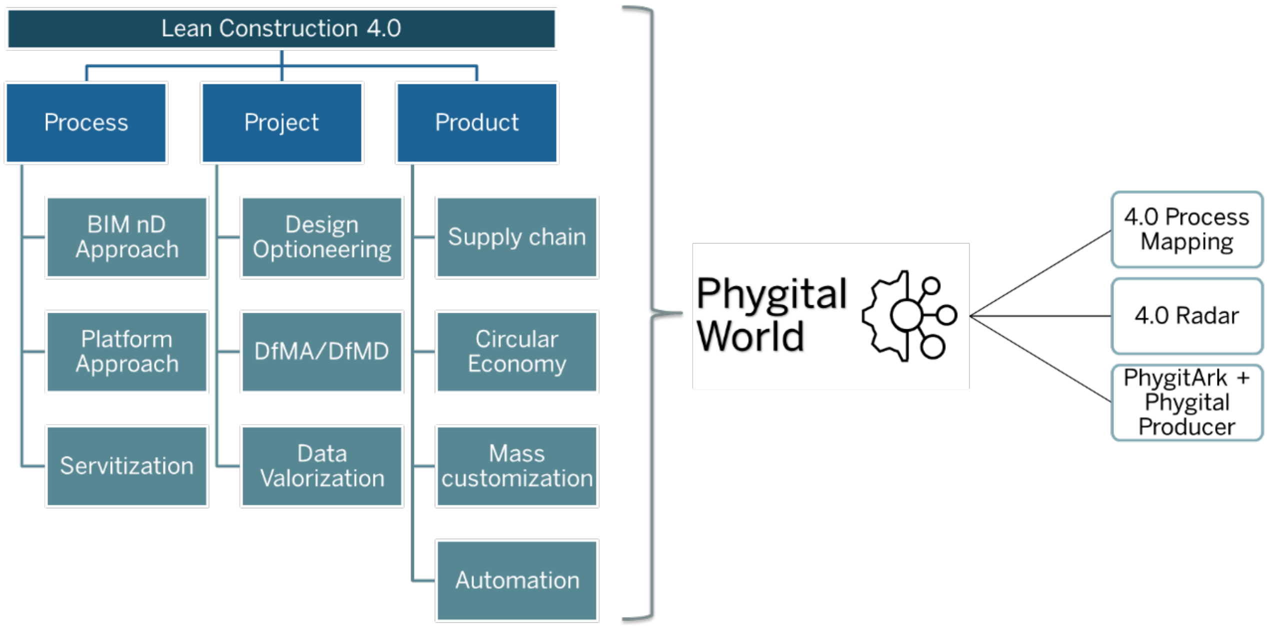


Figure 81: the 3P revolution in Lean Construction 4.0

The **LC 3P Radar** or LC4.0 Radar (Figure 82) measures the 4.0 performances of companies in a gamification way, as better explained in Chapter 5, Companies Assessment. The single score will outcome from the tech adoption of the single paradigm points, according to the i3P technological mapping in the construction industry [141].

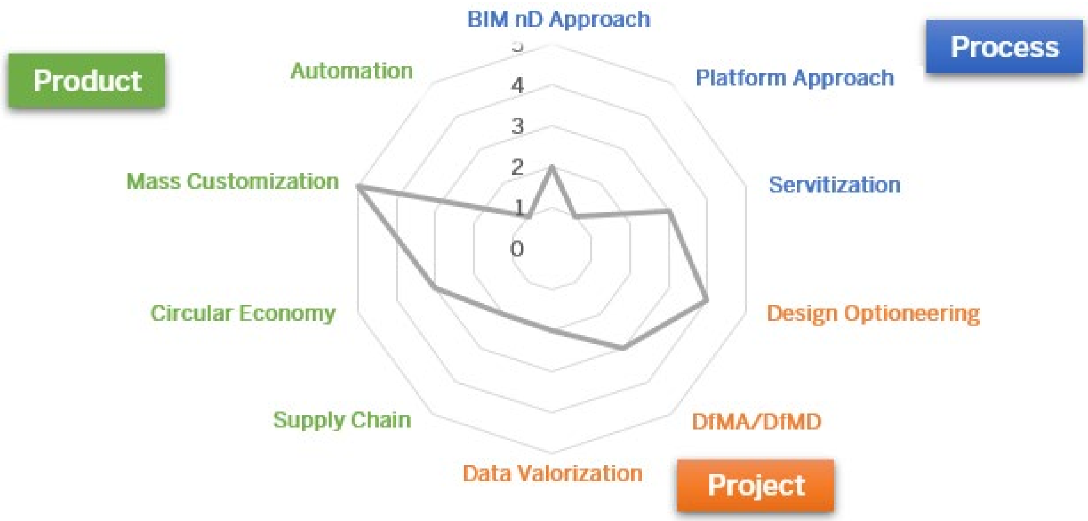


Figure 82: Lean Construction 3P Radar - Process, Project, Product scores

4.2.1 Process

The Process should be based on the **nDimensions of BIM,** with a **Platform**-data exchange inside and between organizations [142]. Changing the design, production, construction and management approach will move from the product market to the **service market.** In this view, designers, suppliers, builders and all the actors involved in the process are no longer a producer of goods but service providers that manage the building from the conceiving to the end of life in a **circular economy** approach. **Automation** is the technological enabler for product **mass customization**, where the project is conceived as a unique, optimized prototype – as all the buildings are. This research's first deliverable is the **4.0 Process Mapping (**Figure 84**)**, describing the whole process compared to the traditional one (Figure 83) [143] [144].

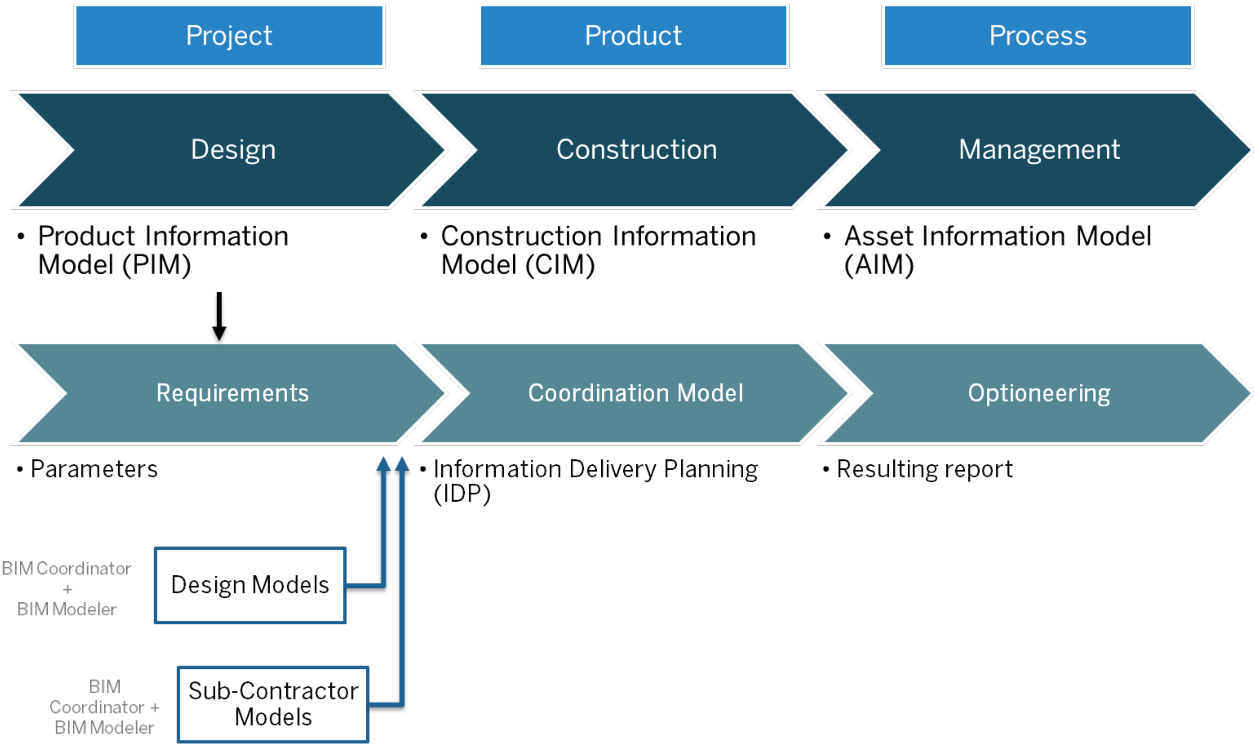


Figure 83: traditional process mapping (author's elaboration on [143] [144])

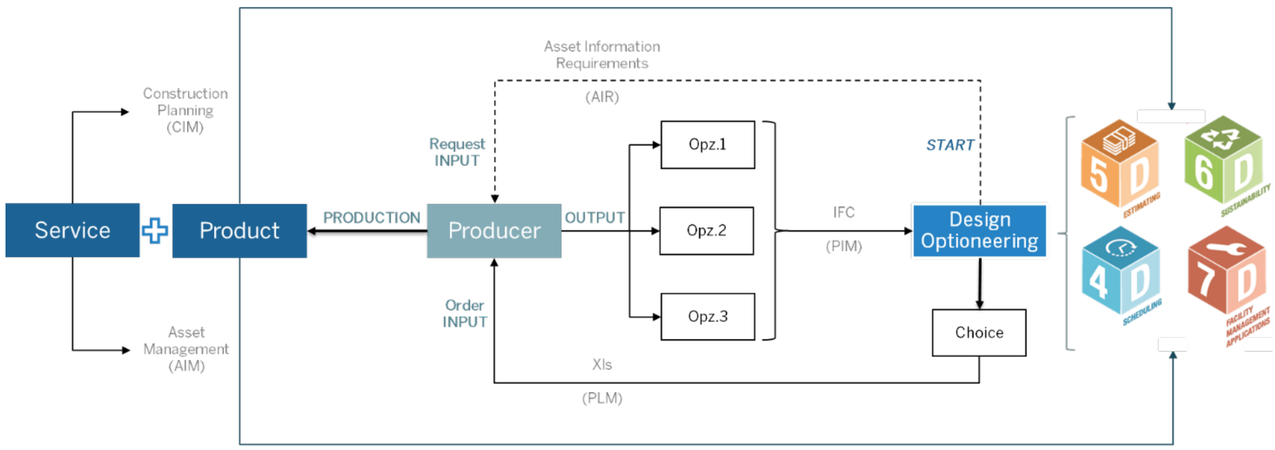


Figure 84: Lean Construction Process Mapping

4.2.1.1 BIM approach definition

The management of such a complex process is allowed by a BIM approach to OSM. It starts from the early design and goes to the EoL stage, holistically taking care of the scheduling, design, production and management phases. **Visualization (3D), schedule and site management (4D), cost management (5D), sustainability (6D) and facility management (7D)** are collected in a Building Information Model, where information is the real value of the approach [145]. The full adoption of BIM can lead to a reduction of time in **design** (50%), **construction** (33%) and **operations** (20%) [73], [145], [146]. However, this perspective is far from the Italian market state of the art: the BIM level of adoption is around 2 for medium size projects and lower for smaller ones. The level of dialogue between stakeholders is at the compatibility level instead of interoperability because files have a common format and share point but are not ready to facilitate a smart dialogue among technicians. The IFC format with a 4-5D analysis is quite diffused where general contractors should monitor multiple suppliers, but the adoption of CoBie, 6D and 7D (Level 3) is far away. Only Bigger Companies are wholly involved in BIM adoption and monitor their investment results. PWC Italy provided a report [142] for the Italian market to exploit the advantages of the early adoption of informed models: **1€** invested in **design** generates **20€** in the **assembly phase** and **60€** during **operation**, leading **to saving 1,5-3% of the entire investment cost** compared to traditional management.

Furthermore, **document management time decreased by about 50%**, **saving 30% of errors** due to the paper translation of information into Digital World, which s**hrank 60% for the management cost (7D)** [78]. A new market trend for Corporates consists of the building management offer during the operational phase. The advantage of being the builder is consistent in the Servitization business, saving time and information from the handover between different companies. The new trend is also allowed from integrating BIM into SAP software and a Geographic Information System (GIS) service to localize and monitor the failures and track the reparation and maintenance operations.

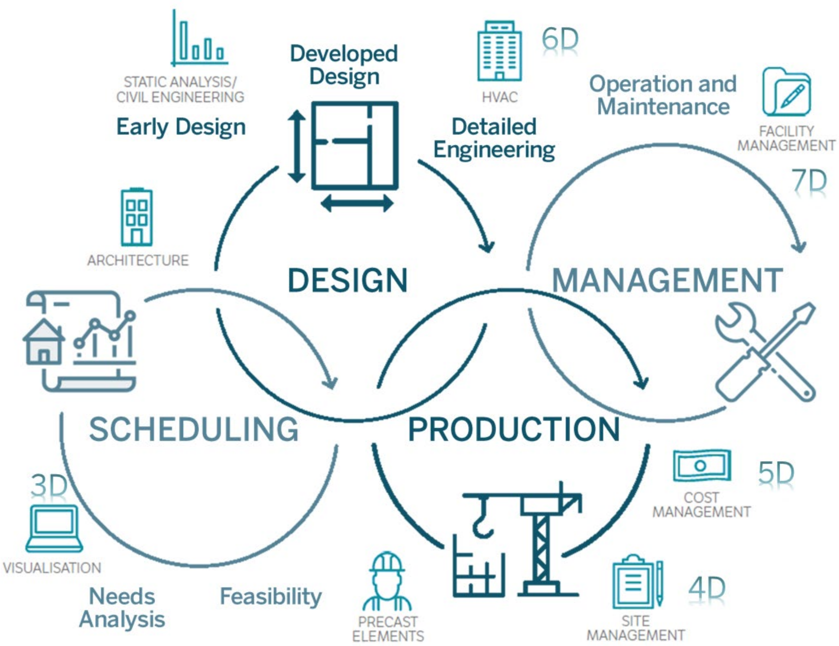


Figure 85: BIM nD themes, tasks and concepts

4.2.1.2 Platform

The adoption of a Platform approach consists of developing a standardized construction system, as the mass-production logic suggests, that can adapt itself to customization as an imperative logic for modern constructions.

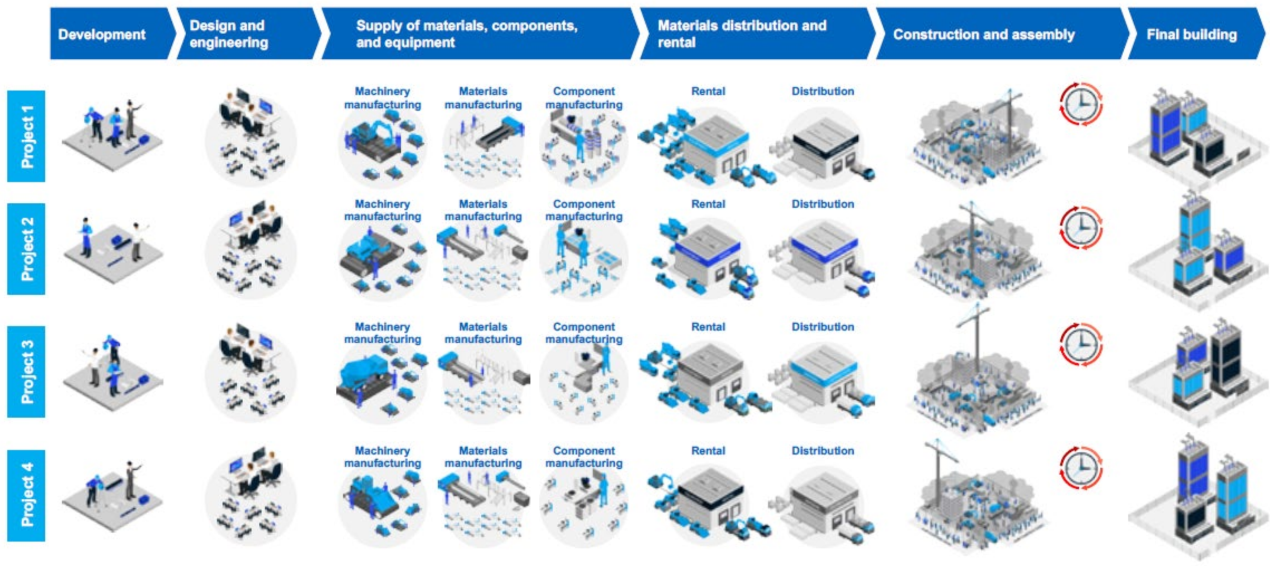


Figure 86: Traditional Building Construction Process [147]

As explained in the previous chapters, **today's construction ecosystem** is highly *complex*, fragmented and *project-based*, developed from *unique customer* specifications and *designed/* planned *from scratch* (Figure 86). Due to the *local* and highly *fragmented* horizontal and vertical *supply chain*, the single-use model has **zero repeatability**. The result is a hostile onsite construction site, where an additional manual workforce solves the lack of communication with limited use of end-to-end digital tools. The result is **low productivity and a short profit margin** for all the stakeholders involved in the process.

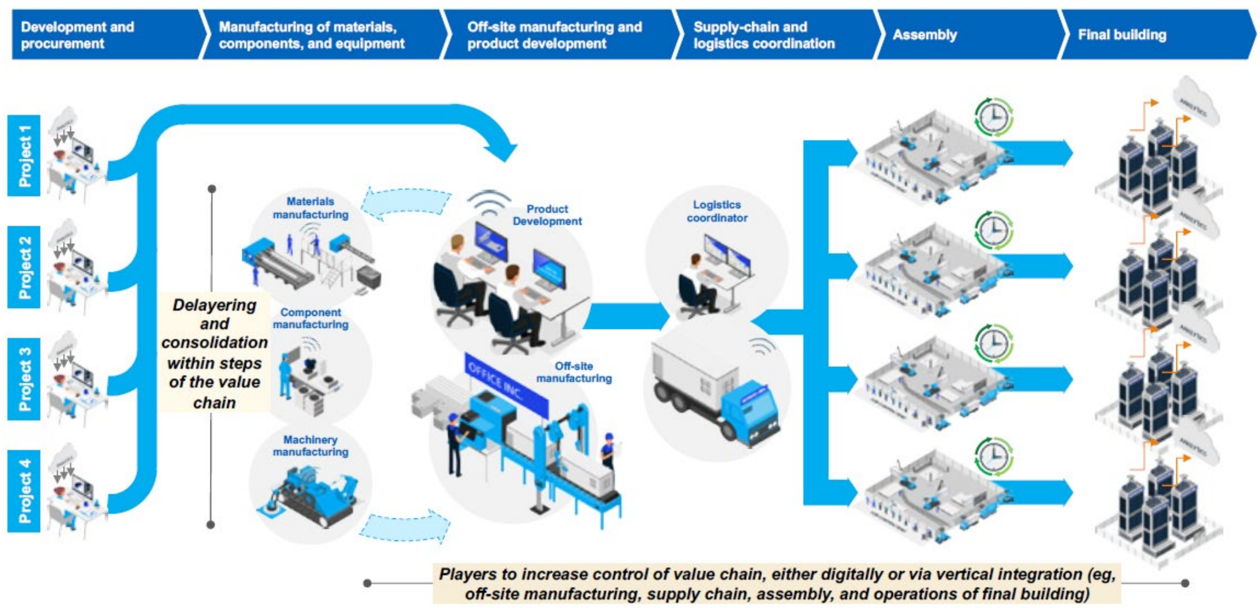


Figure 87: Platform approach to Industrialized Building Systems (IBS) [147]

The new ecosystem (Figure 87) is centered on standardizing an integrated construction process based on offsite manufactured products. The single-product project can be developed and optimized by every single supplier. It creates a more efficient offsite procurement model, managed by the product development office interacting with the design team. The Platform consists of a sort of chassis, a place that collects and assembles many different components from different suppliers, realizing the **one-stop-shop** [148] business model, able to optimize both from the production and the design point of view the value chain (Investigate deeply in chapter 4.4 Value proposition). This led to a product catalog from where the designer can select the options according to client requests in full mass customization perspective and lean management thanks to the disintermediation of digital marketplace. The result is the consolidation of the value chain vertically – by delayering the materials, components and machinery manufacturing – and horizontally – by also involving new national and international suppliers time by time.

However, this approach differs from the housing catalog, thanks to the capability to adapt single components to – quite – every purpose, interpreting prefabrication as a 2D elements sum, eventually leading to a full 3D volumetric construction.

The Platform approach concerns every single step of the process:

1. **Design:** with **parametrical design** options generation and **design optioneering** processing to evaluate multiple solutions.
2. **Procurement**: including risk assurance, quality and adding the *social value* of **MMC** in new contracts.
3. **Manufacturing**: adopting an **offsite production** process allowed by **DfMA**.
4. **Construction**: accelerating the process thanks to **prefabrication**, reducing the time by planning certainty and monitoring the onsite execution by **digital tools** with KPIs to assess the efficiency.
5. **Use**: live monitoring data caught by **sensors** can be monetized to control the value of the good. This transformed the business approach from product to service, allowing the shift to a *Total Cost of Ownership* business model.
6. **End of Life**: the **Design for Disassembly (DfD)** implementation can add value to offsite components in a circular approach.

LC Platform can be defined as the framework helping stakeholders achieve their purpose by making the right decision using interconnected Decision Support Systems. The challenging goal is to develop *one product* according to *one project* for *one client*, a complete reversion of the automotive perspective, where the clients are many for the same product and project. The sustainability – intended in its broader interpretation - of the project remains the key driver to accepting and selecting projects, translating into reality this high concept. Constructability score can be an analytical instrument to make a practical choice based on previous knowledge acquired instead of only to personal feelings of managers according to their experience. To achieve this purpose and make the production process efficient, it is necessary to implement the digital instrument's level to support workers in their activities due to the non-standardized operations they must do for every project. This is why the necessary level of automation is closer to Cobots, instead of the Robots used in the automotive compound, because of the weight (10 times heavier than the cars [92]) of the elements and sub-system the building assembler has to move.

Finally, the Platform approach should help into:

- **Digitize**: allowing the digital transformation and introducing digital instruments to the traditional and manual workflow of the AEC sector.
- **Integrate**: actors and phases involving suppliers, SMEs, construction companies, owners and government across the life cycle.

- **Optimize**: data flux is described and monitored to generate value and increase efficiency

4.2.2 Project

Digital tools have already modified the design phase thanks to parametrical and computational design (**Design Optioneering**). The enormous energy impact of the sector [149] requires to have a more sustainable design taking into consideration also the disassembly and disposal phases together with assembly (**DfMA** and **DfMD**) [13]. A step ahead should be taken in **Big Data management**: the information lake is not already traduced in economic value because of the production market approach. Moving to Servitization, data enhancement will be easier for owners and investors to understand.

4.2.2.1 Digital Design

The digital design was described as "*a more retriable design approach thanks to mass customization opportunity given by parametrical and design optioneering instruments; but also much more control for the production phase of sub-assembly and prefab components, before the onsite construction*" in chapter 3.4.6 Keys for 4.0 buildings implementation. In the LC4.0 approach, this concept is defined as the next step of design regarding the whole Platform and not only one of the strictly intended design. The BIM approach can help in this goal according to its precise data structure and the possibility to integrate side design instruments, such as the previous parametrical design and Digital Twin later. In this perspective, Geometry, Production and Metadata are mixed through the Digital Design instruments to adopt a DfMA approach for the production process and a BIM nD one across the building lifecycle.

The improvement of the **nD BIM approach** led to support of the **Internet of the decision-making progress** [150]: a support and a **Common Data Environment (CDE** – according to ISO 19650-1) [151] to manage the information able to validate different scenario in real-time, using the Computational Design or, better, the **Design Optioneering** concepts [152].

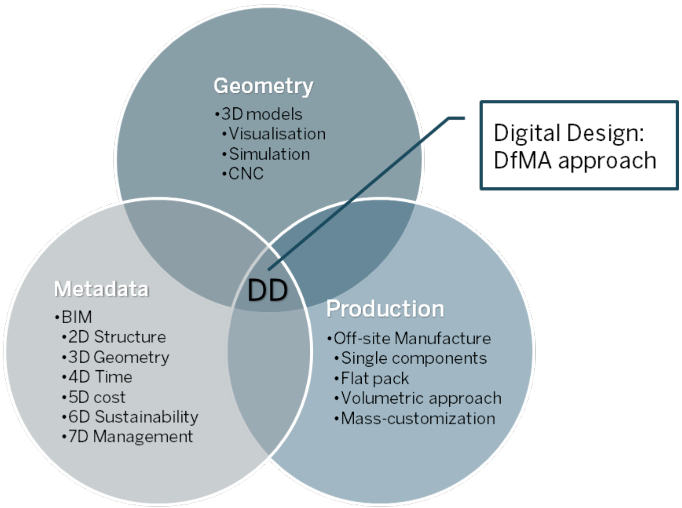


Figure 88: DfMA envelope in Digital Design

4.2.2.1.1 Design Optioneering

Design Optioneering (DO) consists of applying **Parametrical Design (PD)** as a creative instrument to define different options to evaluate according to the settled parameters [138]. The input and output parameters are defined as constraints and results in the first step (Setup) during the problem definition phase. PD generates different solutions according to the constraints, creating various possible choices that are evaluated (automatically by ML or manually by users) to select one solution (Figure 89). This is why this instrument can be seen as a **Decision Support System (DSS)** for **Decision-Makers** to have a much more precise tool to evaluate solutions based on analytical values instead of only experience, as better described later in chapter 4.3.1 Knowledge-Based Engineering. The evaluation is usually done through a system ranking score grab from video games, in a sort of **gamification** of the process that is common to many digital instruments applied nowadays. The more accessible and user-friendly approach makes the lean, faster and more transparent complex results at the first impact, allowing the user to go deeper inside the single analytical value. The DO instrument creates multiple solutions, which are hard to evaluate due to the number of parameters that generate complexity. DSSs' purpose is to avoid complexification by simplifying without depleting the results.

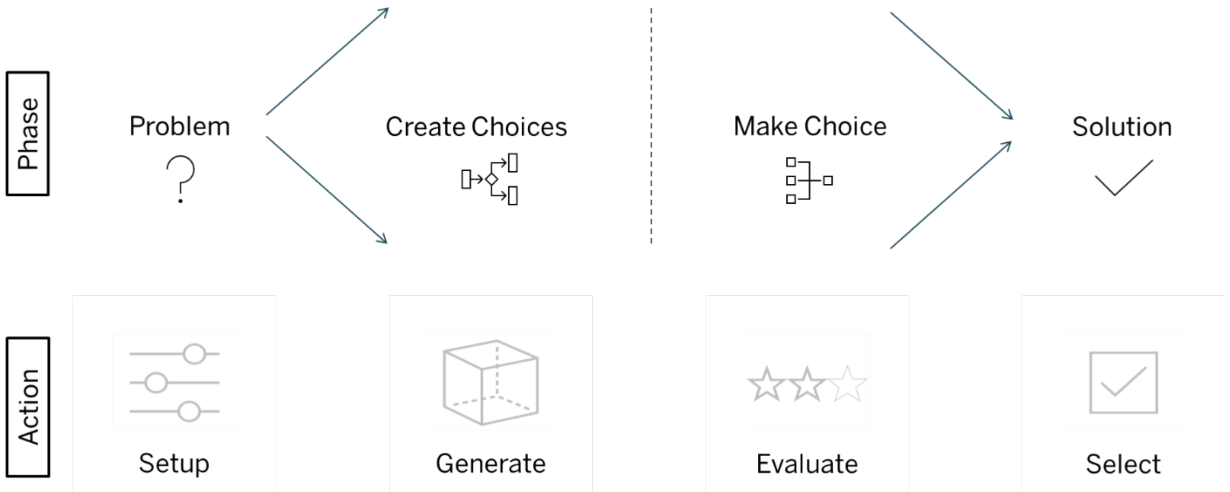


Figure 89: Design Optioneering Process and Actions

4.2.2.2 Industrialized building design

The design effort for IBS solutions is considerably greater than the Building As Usual (BAU) one [82]. Due to the lower adaptability of prefabrication to the onsite foreseen, the design team should operate extra activities to precisely define the elements and components' defragmentation (Figure 90). The OSM concerns the discretization of architectural shape for the spatial design according to manufacturing feasibility (in the factory and about logistics, which is the more significant constraint usually), tolerances of production and onsite assembly [11]. Finally, DO select one of the multiple design options for design feasibility for systems and components. The key element to design in prefab elements is the joint because it is the geometrical part able to absorb incongruences and tolerances during the onsite assembly. However, the extra effort required for these systems design is amply rewarded by the advantages of timing – thanks to the partial overlapping of OSM and onsite activities (land works and foundations) – and efficiency – as shorter and more accurate construction site delivery time. All these aspects can be resumed in the DfMA approach.

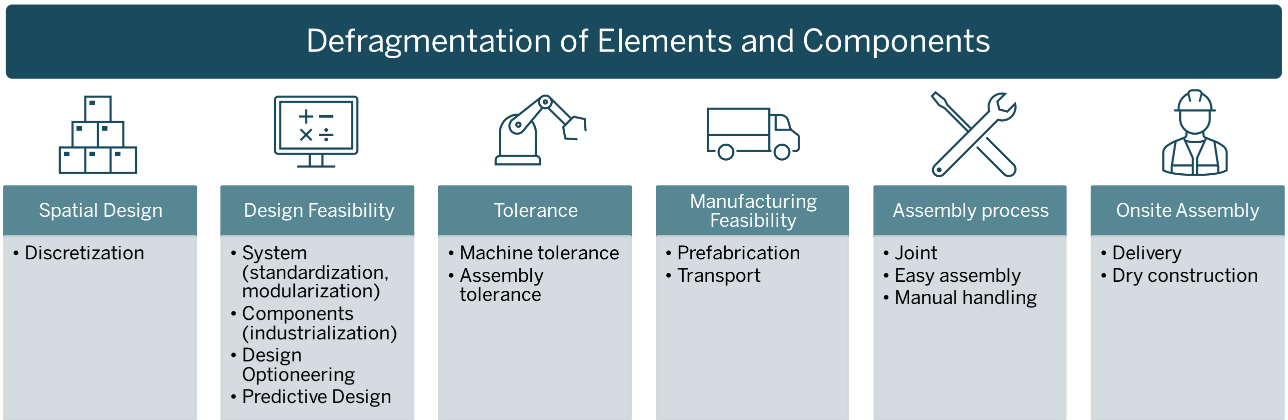


Figure 90: Defragmentation of Elements and Components in IBS [25]

4.2.2.3 Design for Manufacture and Assembly (DfMA)

The necessity of large quantities of some good (volume deal) provokes the optimization of the product – first – and then the process, starting from the design. The old industrial concept divides **Design for Assembly (DfA)** and **Design for Manufacturing (DfM)**. They are about material, overhead and labor but focus on different processes. The first is the optimization of the part/system assembly (easy assembly); the second is the method design for ease manufacturing the collection of parts that will form the product after assembly (optimization of the manufacturing process). The difference concerns the reduction of cost [153]:

- DfA is about assembly cost:
  - Minimizing the number of assembly operations
  - Single parts have a more complex design
- DfM is about overall part production cost:
  - Manufacturing operations are easier
  - Use common datum features and primary axes

The split between DfA and DfM in the early 2020s was overcome by the concept of DfMA, where assembly and manufacturing are analyzed together. DfMA aims to reduce costs, improve quality and have speed time to market. Starting from the '90s, product end-life became important; this is why DfMA is declined in Design for Environment (DfE), Design for Disassembly (DfD) and Design for Service (DfS) [153].

DfMA advantages also allow the deconstruction phase, planning the end-of-life (EoL) to re-use, re-cycle or landfill in a **circular-economy approach** for sustainable construction [61]. The 5R approach to construction presumes to have a Reuse, Reduce, Recycle and Repair before Refusing [138]. The offsite production process based on DfMA allows an efficient disassembly phase, thanks to the plug-and-play connections beyond the standard dry construction (structure-envelope) approach, where components are demolished and replaced. DfD introduces the concept of the *building as a material bank* [154]: constructions can be seen as a temporary store of materials collected in products and components that can be disassembled and reused at EoL to construct new ones. On the other side, DfD highlights the actual industrial paradox: pushing too far the optimization of norms and laws, logistics, urbanism, production, time and cost consists in the resources consumption at EoL phase, which overcomes every single optimization provided.

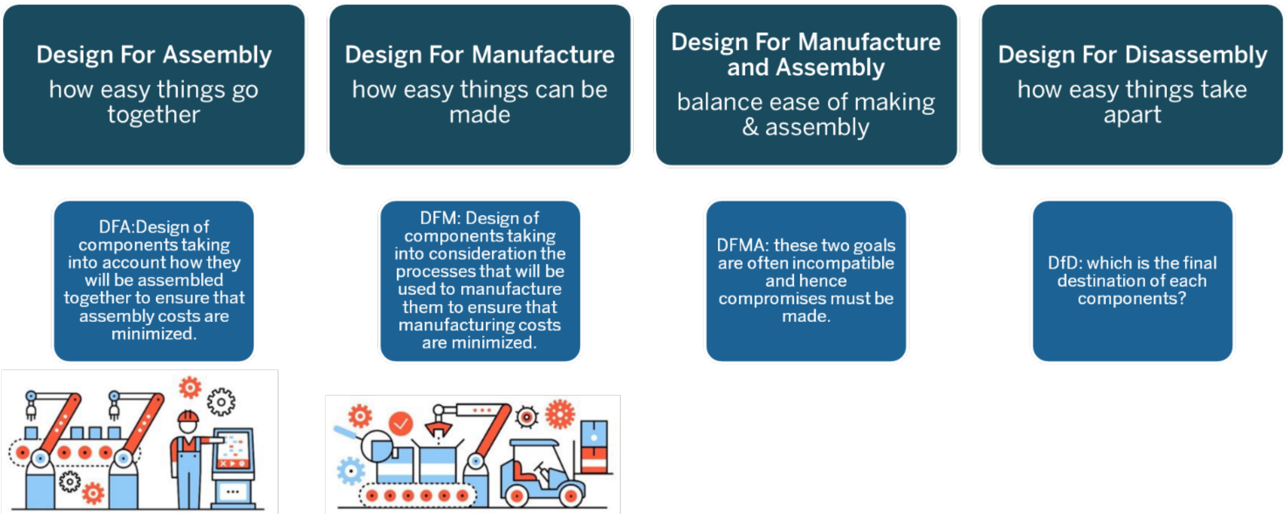


Figure 91: DfA, DfM, DfMA, DfD approach [13]

Design for Manufacture and Assembly is defined as the route to transition towards faster and more effective ways of making buildings (**assembly**) and - by contractors - as a way to lower the costs of delivery and reduce risks (**production**) [14]. This industrial concept fills a lack in building process optimization: the usual methodology is focused on the design and planning phase, but it does not take into consideration the production and construction phase [61][155]–[157]. Thanks to eliminating any activity that does not add value to the client, designer or supply chain, the DfMA approach works on time, cost and quality [107] through to the early engagement of contractors, suppliers, sub-contractors and other specialist engineers. It merges inputs and requirements of downstream players with those upstream in an information pull strategy [158]. UK government, the most advanced country in MMC, called **P-DfMA**: a platform approach to the product where the use of a set of digitally designed components across multiple types of built asset minimize the re-design of them for different use [159]. Applying a standard process to a customized solution gives value to the product [132] thanks to the new technology adoption in a full (vertical and horizontal) integration of networks.

4.2.2.4 Data Valorization

LC 4.0 purpose is to valorize data in the AEC sector by their transformation into wisdom. The process to get this starts from raw **data** (e.g. 23), which insert into a context to create **information** (23°C), adding meaning to a number.

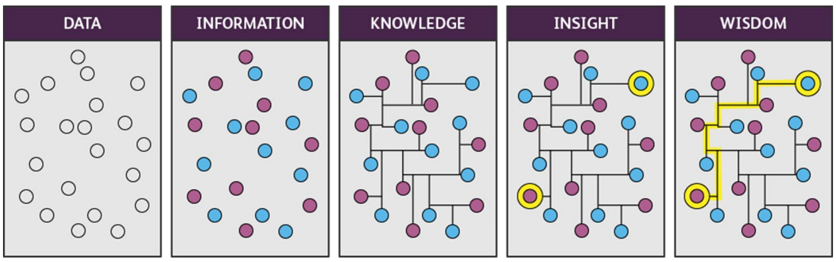


Figure 92: from Data to Wisdom [two-panel version by Hugh McLeod]

The knowledge from this information spreads from the combination of different information (23°C is the room temperature) and allows to synthesize results as **insight** (23°C is a comfort temperature). The final step of the journey is the **wisdom** facilitating decision (air conditioning is not needed in June). The effectiveness of learning gained depends on the **accuracy** (positioning of data and their centrality to the topic), **precision** (homogeneity of data to analyze) and **provenance** (quality and reliability of data). These three aspects strongly affect processes that do not start from scratch but base their analysis on existing databases [160].

Therefore, especially for initial design stages and fields with few available and consistent data, such as the AEC sector, **experience** and acquired knowledge are crucial to defining whether data reliability is enough to generate a relevant and steady result. The lack of Big Data creates a gap in informing Deep Learning algorithms of Machine Learning and Artificial Intelligence is applied to specific tasks such as failure recognition by images or onsite productivity control - even if they are the future and a growing market - while Decision Support System are always completely managed by men in building-construction.

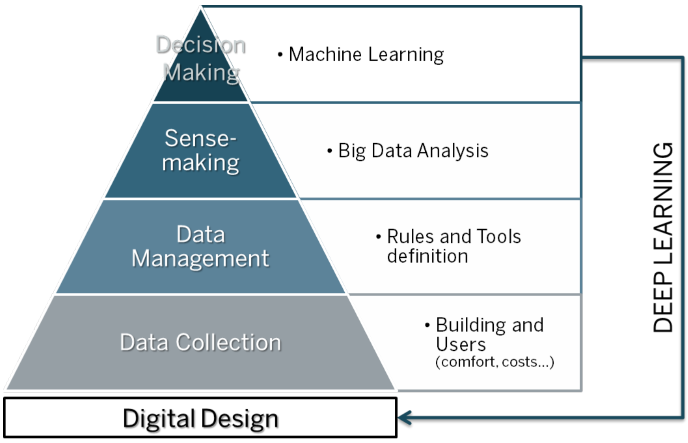


Figure 93: Digital Design and Machine Learning path

4.2.3 Product

Production is the turning point of this revolution. The advantages of digitalization for clients (more quality and less time) and contractors (few costs and risks) are evident, but what about the traditional/SME that leads the Italian market? Product manufacturers have excellent know-how and handling but low digital competencies [16]. The costs of learning and acquiring tech competencies are unsustainable because these craftsmen's principal value is handling work. From a future perspective, the research supposes that new manufacturers will have skills in the digital field (**Phygital Producer**), but it is a utopia nowadays. LC 4.0 paradigm suggests introducing a **PhygitArk** to fill the informative gap. PhygitArk is a technician with physical and digital competencies. It will be an expert in a particular technical element (e.g. Windows), working with all the suppliers involved in the chain (glassmakers, fitters, steel producers, plastic molders, etc.) and giving back to producers and design team digital models. The main task of PhygitArk is to provide the models for each stage: one for the production, one for the optioneering choice in the first phase and the as-built digital prototype. The **Phygital Loop** describes the continuous interaction between the physical and the digital world, applying the CPPS concept to the architectural world (Figure 94).

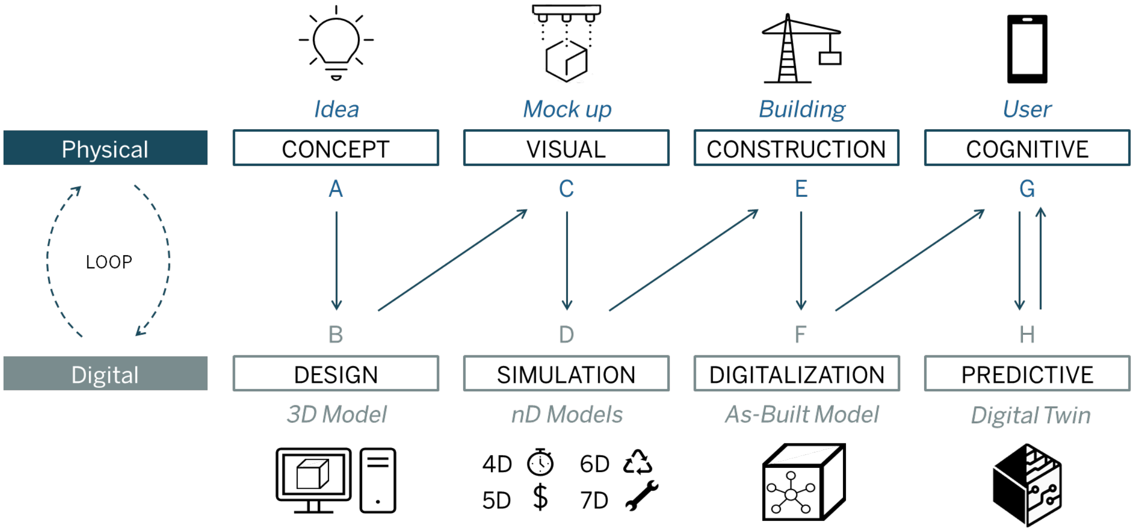


Figure 94: Phygital Loop

4.2.3.1 PhygitArk and Phygital Producer

The research suggests the introduction of two figures to overcome the information gap between design and industrial production for the AEC sector. PhygitArk's capability to manage the digital machines for production and design phases is the added value that fills the information gap between production and design. This figure shall have the competencies of geometric, Architectural, technological, structural, physical, thermal, sustainable, management and digital modeling. It is more than an engineer; the Ark suffix to Phygital calls back the Architect's ancient conception as the universal figure, collecting all the design competencies in one person. Nowadays, due to the hyper-specialization of competencies, the Architect-Manufacturer, able to hand-make drawing ideas, disappears. Often producers are obliged to re-design the object coming from the design team that should recreate the as-built model because it does not fit the design tools (Figure 96). Big construction companies/producers will have this figure as an internal one, while SMEs will use one external freelancer shared with other suppliers involved in the same chain, avoiding the risk of uncontrolled know-how flow between competitors through PhygitArk.

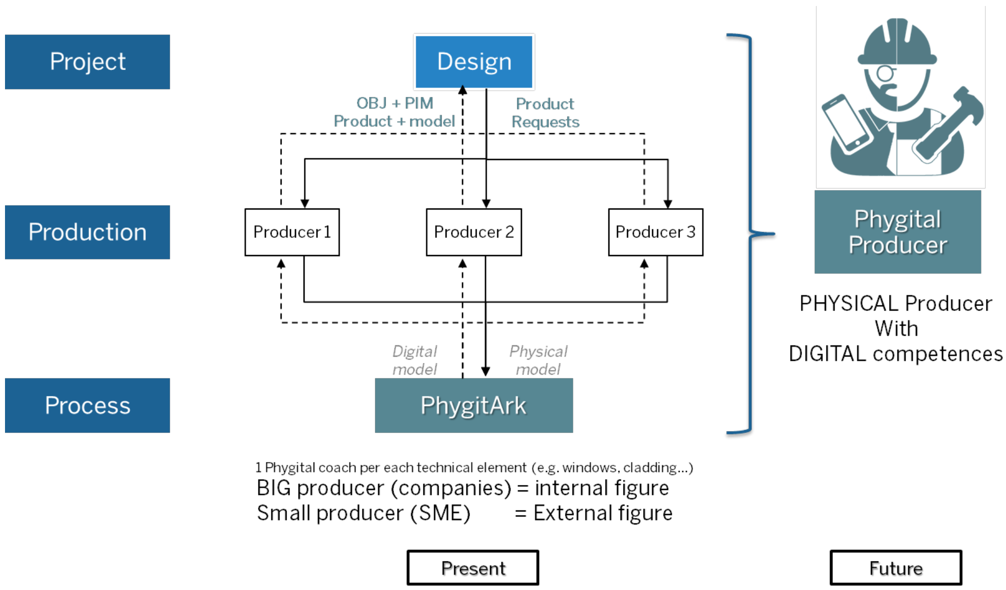


Figure 95: Phygital Producer

4.2.3.2 Phygital Coach

Another figure introduced by LC4.0 that can be useful in the transition from the actual industrial approach to the construction 4.0 one is the **Phygital Coach** (Figure 96). It works at a higher level than Ark: it is not specialized in the design and manufacturing phase but is an industrial-process expert. It is a digital enabler that optimizes the digitalization of the production process and the digital transformation of the company's business. It supports the transition to the 4.0 revolution, facilitating access to government and public funds and certifying the company's process and products.

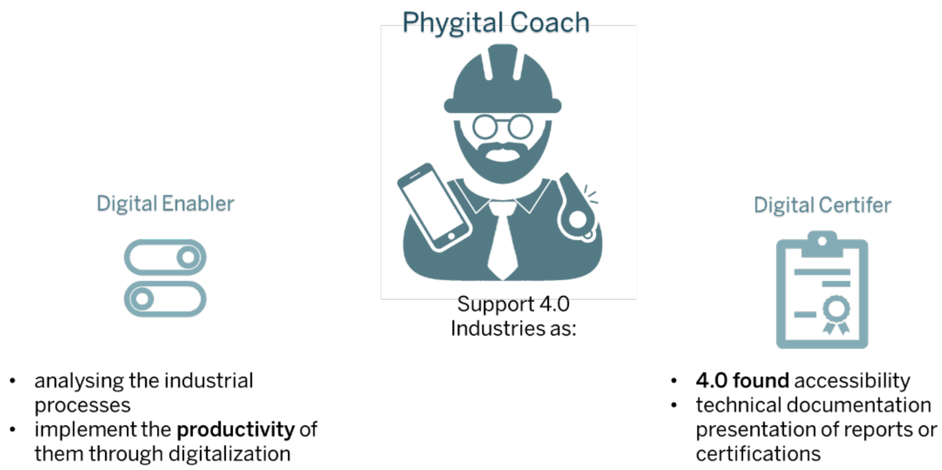


Figure 96: Phygital Coach tasks

Summarizing Phygital Coach tasks, it supports companies in the 4.0 adoption as a:

1. **Digital Enabler**: analyzing the industrial processes to implement their productivity of them through digitalization

2. **Digital Certifier**: identifying the possibility of accessing the 4.0 found according to requirements and technical documentation presentation of reports or certifications

Figure 97: Precast bearing wall system façade, NY, 2015

4.3 Information Management

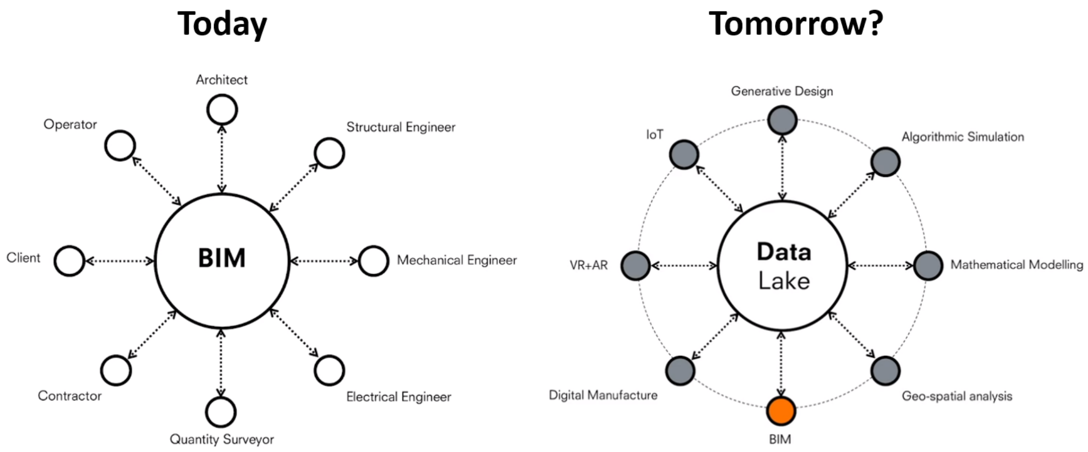


Figure 98: from today to tomorrow Information Management [160]

PhygitArk (PGA) will lead the information flow from today's centrification in a BIM approach to a circular one, where data flows freely between different tools. Thanks to interoperability and real-time synchronization, it is possible to allow the nine enabling technologies adoption (IoT, Generative Design, Algorithmic Simulation, Mathematical Modelling, Geo-spatial analysis, Virtual Reality) and many others in a **Platform approach** [92] (§ 4.2.1.2 Platform).

The **information flow gap** is between the BIM environment-based design and the Enterprise Resource Planning (ERP) production software. The Asset Information Requirements (AIR) and the Product Information Model (PIM) use different languages from the Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM) machines. The information translation causes a loss or excess of data that will be regulated by the PGA, creating a smart process defined by the Information Delivery Planning (IDP).

The UK government, the most advanced country in MMC, defines **P-DfMA** as a platform approach to the product where the use of a set of digitally designed components across multiple types of built asset minimize the re-design of them for different use [92]. Applying a standard process to a customized solution gives value to the product. Thanks to the new technology adoption in a full (vertical and horizontal) integration of networks, it is possible. An incremental approach to digital models is possible in the progressive development of these instruments, as tested by Arup Italy for medium size projects: a raw model is shared with suppliers where they can easily insert and check the feasibility of their product with the basic information required, instead of the federated BIM model that is more challenging to manage. A designer inside the design team (**PhygitArk**) supervises the suppliers in this process and connects this model with the BIM one, avoiding the risk of errors due to the lack of experience of SMEs in the application of the digital instrument.

LC 4.0 Platformization leads the **Digital Design** approach from a model-based process to a data-driven one, where the information added to transform the model from the Design Model (M0) to an informative one (M1) able to communicate with the Physical Construction (Cp) through Sensors (S). Inside the platform, Digital Manufacturing, Digital Production, Digital Twin and Digital Site can receive, manage and return data thanks to their layering and avoiding the information desert, typical of the movement from one phase to another. In this perspective, Information Management assumes a key role and it has to be declined in different aspects: Digital Communication (DC), Digital Cognitive (DG), Digital Interaction (DI) and Digital Learning

(DL) (Figure 99). It makes possible the interaction of the Phygital world between the digital sphere insight by analytics and drives physical actuators (machines) to create products able to communicate back to the virtual dimension, where data are aggregated, creating a Digital Twin that can inform, simulate, commission, calculate, learn and so predicted the expected status of the physical object. Computer Aided Engineering (CAE) is added to the CAD and CAM dimensions to integrate the double dimensions of simulation and real-world also during the engineering phase from the product design, the manufacturing process, the engineering and commissioning, the operation and (were planned) the recipe service, feedstock quality, plant and site maintenance and security by applying the cloud platform and data analytics. CAE acts at the product level and concerns all industries, but the AEC sector has a higher level of design management required from the huge amount of products involved in building construction. The instrument to realize this integration is called Digital Design, acting from concept to end of life of a building.

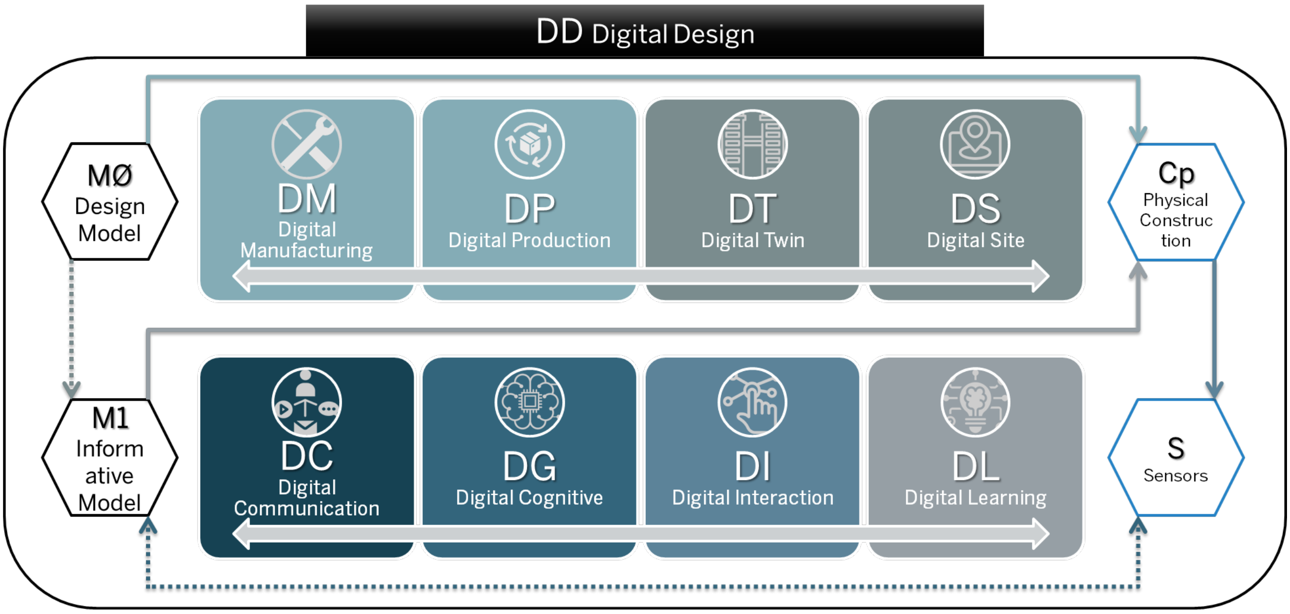


Figure 99: Informative Lean Construction 4.0 process

The instrument to merge and make effective Information Management in a BIM environment is the **Digital Execution Plan (DEP)** [12]. It consists of an evolution of the BIM Execution Plan and a competition of the Information Delivery Plan (IDP), describing how the design team will use digital tools on a project, demonstrating its experience, skills, software and hardware to produce the Information Requirements and the workflow shared with other stakeholders across the building life cycle [2].

4.3.1 Knowledge-Based Engineering

Knowledge-Based Engineering (KBE)[17], [161] is a multidisciplinary design approach that supports the different actors across project development by applying *decision-making tools from the early concept stages*. Its goal is to exploit the cognitive processes and *designers' experience* that are difficult to *translate into quantitative and sensitive analysis* to be able to enhance and automate the processes by simplifying the choosing phases and opening them

[12] "A document (also commonly called the BIM execution plan) that sets out how the design team will deliver the Information Requirements for the project, considering the tools to be used at each stage. The construction team might prepare a separate DEP to confirm how the Asset Information and Verified Construction Information will be produced." [159]

also to designers with less experience. The Knowledge Process starts with **Data Gathering** from three different sources:

1. **Indirect**: from the Engineer (designer) to the Expert (manufacturers)
2. **Direct**: from digital tools of management/design to Expert
3. **Automatic**: from Data gathered to Tool

The Engineer's ability to mix information, manage and integrate Data to food the BIM models from which extracting information to generate the knowledge necessary to make Decisions achieving **Wisdom**. The peculiarity of this process is the never-ending learning coming from experience and knowledge acquisition in a Deep Learning path, similar to AI, as original suggested by the parallelism represented in Figure 100.

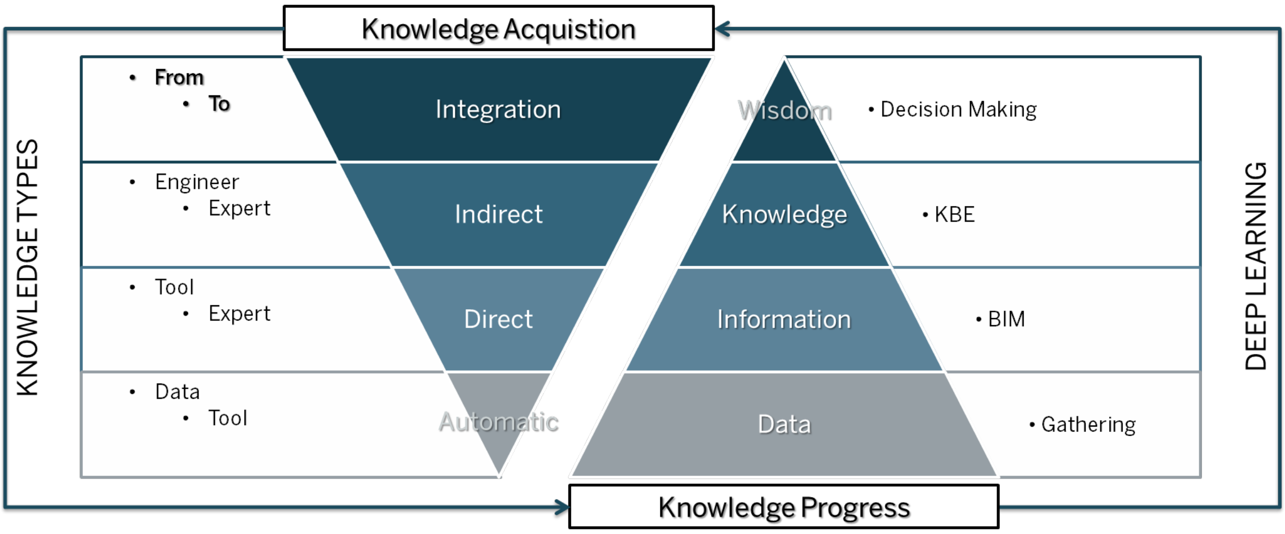


Figure 100: Knowledge-Based Engineering Process

This approach was developed in a particular way for façade design because they have technical and technological aspects to analyze that require a synthesis often based on *intuitive choices by the designers rather than data analytics*. They include several aspects that concern product models, an iterative process of project control and the involvement of producers from the early stages as proper holders of the necessary know-how for the realization and translation into a product of what was thought by the designer. This tool aims to bridge the gap between design manufacturability and the integration of design disciplines due to the lack of manufacturing knowledge of those who carry out the specialized design and the narrowness of design options available from manufacturers. The spread of digital tools and approaches to design, such as the advent of BIM, has not allowed for reducing the gap due to the *lack of flexibility and high complexity* of management of early design stages tools from the *façade design* side and the *lack of instrumental skills* from that of *producers*.

The need to easily manipulate geometric and physical attributes according to *rules and limits* on the part of the designer is not reflected in informed models, from which it is not easy to recover and insert quickly. The technological boundary of **interoperability** between the different teams involved in this process makes it difficult to transmit and compare information even when using open formats such as IFC, governed in any case by BIM-authoring software for the design phase.

The *contrast* between the **KBE** - which concerns **non-quantifiable aspects of know-how** - and the **KPIs** - which examine the overall **quantitative coefficients** - is crucial for process efficiency. In this scenario, the figure that manages the different actors involved (client, architectural designer, facade engineering, manufacturer and general contractor) is precisely the **PhygitArk**, as a facilitator and collector of the requirements and demands of the various stakeholders, as well as the one ensuring the achievement of technical, economical and qualitative advantages for the entire supply chain.

The goal of **façade engineering** is to create less energy-intensive buildings by acting on the *envelopes*, as **responsible for 57% of the buildings' energy losses**, aiming to improve the performance of the cases through more efficient solutions, with a lower environmental impact and - possibly - with guaranteed performance, as the only guarantee of achieving the global **decarbonization objectives** by **lowering 22,8% of GWP** [12]. The envelope efficiency is even more fundamental for the redevelopment of existing buildings. This necessarily passes through the adoption of **Industrialized Deep Renovation (IDR)** as the only way to reach the largest number of buildings ensuring overall quality for the entire population and not only for iconic architecture. This approach is multi-actor and multi-criteria in BIM nDimensions. It systematizes aspects of energy, architectural quality, structural-seismic, acoustic, production and Building Process Management (DfMA), sustainability, operation/maintenance and economics, looking at the entire life cycle of the object. Early 2020's view of DfD consists in replacing the façade or its parts by increasing the performance of the building envelope. For these reasons, *adopting off-site prefabricated solutions guarantees higher value and more ability to customize and produce a quality product with larger complexity in the design phase* [126].

Due to the complexity mentioned, producing multiple design options is the only solution to find the optimal point along the multicriterial Pareto curve. Adopting a Design Optioneering approach based on parametric programs is therefore successful, thanks to the ability of these tools to retrieve data from a Common Data Environment (CDE). It looks at **Digital Design** and the **Open Platform** as an added value, which shall be web-based to ensure everyone has access to it since several users in this supply chain base their business on non-digital tools and therefore do not have the required parametric skills to manage it yet. In this scenario, **PhygitArk** is proposed by the research as the key figure to enable the transition to **Phygital Producer**, as the actor can incorporate all the design side information into manufacturing. Therefore, **PhygitArk** can retrieve data, grounding, generate and extract value from the KBE on the façades by applying it to a **Decision Support System (DSS)**.

In this perspective, the research developed a DSS focused on the Early Design Stage to demonstrate the applicability of a BIM approach without setting the entire design. Hence, the **Panelization Design Tool (PDT)** - later described in chapter 0 - is a tool that PhygitArk manages to compare different technological solutions for recladding existing façades. Recladding is a topic of great attention, as evidenced by the numerous European projects, the increase in the number of scientific articles dealing with the topic and the first steps of the market in this direction. The challenges to which the instrument answers are:

- **interlocked process**, whereas all the choices have repercussions on many different aspects;
- **Design-Build approach** in which the Bid phase is usually skipped due to the need to embed the manufacturability information in an early supplier involvement;

- enormous early **Design Stage influence,** committing 80% of costs;
- the low added value of design because 80% of regular design activity consists of repetitive tasks and only 20% is spent on **innovation and improvement**;
- absence/lack of **multi-objective optimization instrument** with little applications of computational design on the various engineering disciplines involved in façade design, while the parametrical (shaping) design is widely applied;
- avoid the **redesign risk**: usually, the engineering design is not compliant with the factory design;
- The **end-of-life phase** is missing because the **DfD** approach is generally ignored.

The unlocking of the façade design value passes through the adoption of KBE approach in the process, concerning the use of *scores, radars and tools* to simplify the complex results as in **gaming**, but without making it superficial.

4.4 Value proposition

The triple application of the Digital Revolution concerns the approach to virtual information as value to stream to improve the performance from the **efficiency** (faster thanks to the paperless transmission) and the **effectiveness** (more direct, targeted) perspective. The critical change is led by identifying value across the whole process stages and inside them. The Danish Design Ladder [162], extended by prof. Bucolo [163] (Figure 101) explains the steps that companies have to take to make the transition from the traditional design (step 1: non-design) to an innovation process (step 3) and then a **business strategy** (step 4). This last step is the boundary between inside a company and outside: steps 5 and 6 concern the grouping of enterprises into **communities** and organizations involved in the same field and then a **national strategy**. The building industrialization goal matches this approach suggesting the creation of a system where the cooperation of building construction companies or manufacturers (e.g. offsite façade manufacturers) can be enhanced by creating a community - at the private level - and a national strategy to transform the entire sector.

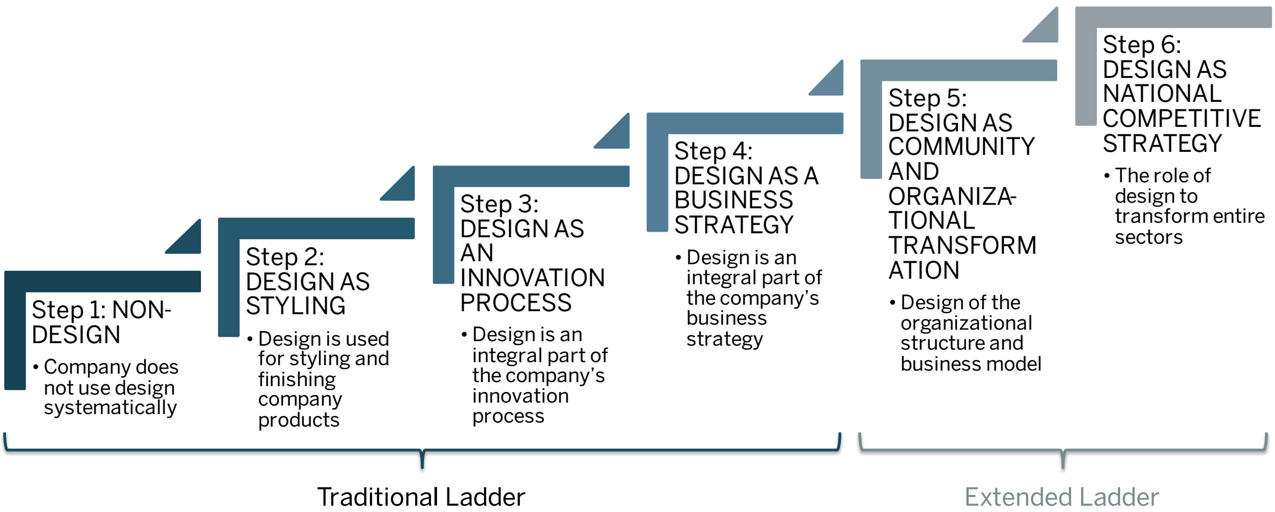


Figure 101: (Extended) Danish Design Ladder [Danish Design Center, [163]]

Identifying the ladder step of every company/enterprise is the first step to understanding where to act to improve their performance. The reason to adopt this approach inside the AEC sector is in its intrinsic characteristics: the need to design or adapt technologies to every single project push-up the value of the Design phase inside the business model, requiring specific actions and focus to this step.

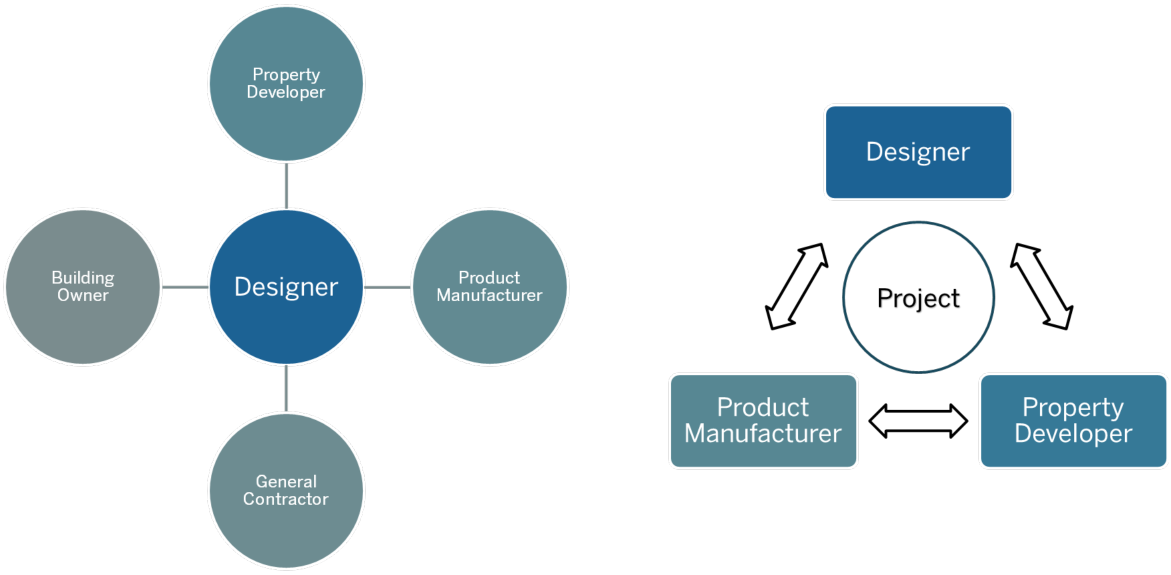


Figure 102: from Designers Centralization to Project Platformization [Author's elaboration]

In this perspective, adopting a Platformization approach moves from the centralization of the Designer as a key role in the process [49] to **Project centralization** (Figure 102). It also helps move from a traditional value chain (Figure 50) to a more complex value system involving the building sector's complexity. According to **Porter's Value Chain** [164], the margin of products is higher than the sum of different primary activities (inbound/outbound Logistics, Operation, Sales, Services). It arises from their interaction with the supporting activities (Procurement, Technology Development, Human Resource Management, Firm Infrastructure), multiplying the product value at every step. *This model is hard to apply to the AEC sector because it is strictly focused on an internal framework, excluding external ones* (the Five Forces [165]: Power of Buyers, Power of Suppliers, Threat of Substitutes, Threat of New Entrants, Competitive Rivalry). Building production's long and complex value chain requires changes in the traditional business model.

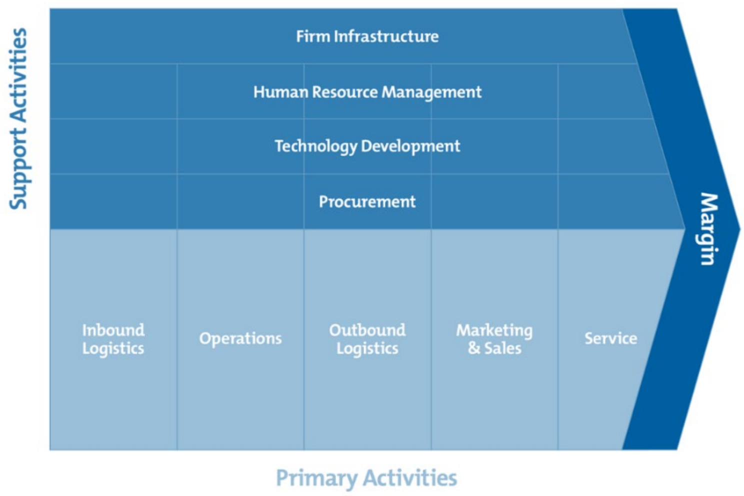


Figure 103: Porter's Value Chain [165]

The monocles industrial point of view needs to be extended to other stakeholders involved in the construction of a building as a product (production phase). The **Value System Mapping for the AEC Sector** (Figure 104) proposed by the research includes the perspective of Manufacturers, Developers and Designers in the evaluation, highlighting their different perceptions of value.

- The **Property Developers**' (building owner or investor) purpose is to optimize production to make the product (the whole building or a single component) *more accessible*. Its target is to make effective decisions based much more on analytical values than sensitivity analysis based on experience. Creating a **Data-Driven Workflow** can be a practical solution to achieve this goal.
- The **Product Manufacturers** (General Contractors or specialized companies) aim for a faster and more precise production phase. Because of the mass-production inapplicability to buildings from one side and the need to optimize the production costs, it is necessary to adopt **mass-customization** as a driven approach to every project. The adaptation of a single product to customer needs requires the capability to have slight changes in the production process, avoiding the risk of resetting the machine at every step. This ready-made adaptation is provided by the *flexibility of software that manages the machine (hardware)*.
- **Designers** must identify clients' requests and create a **tailor-made solution**. This process can be time-consuming, causing limitations in creativity investment due to the scarcity of available time. Hosting a personal **design hub** from which to select the technical solution closer to the client's brief led the designer to have much more efficiency in the repetitive tasks, focusing on the creative part (the product unicity).

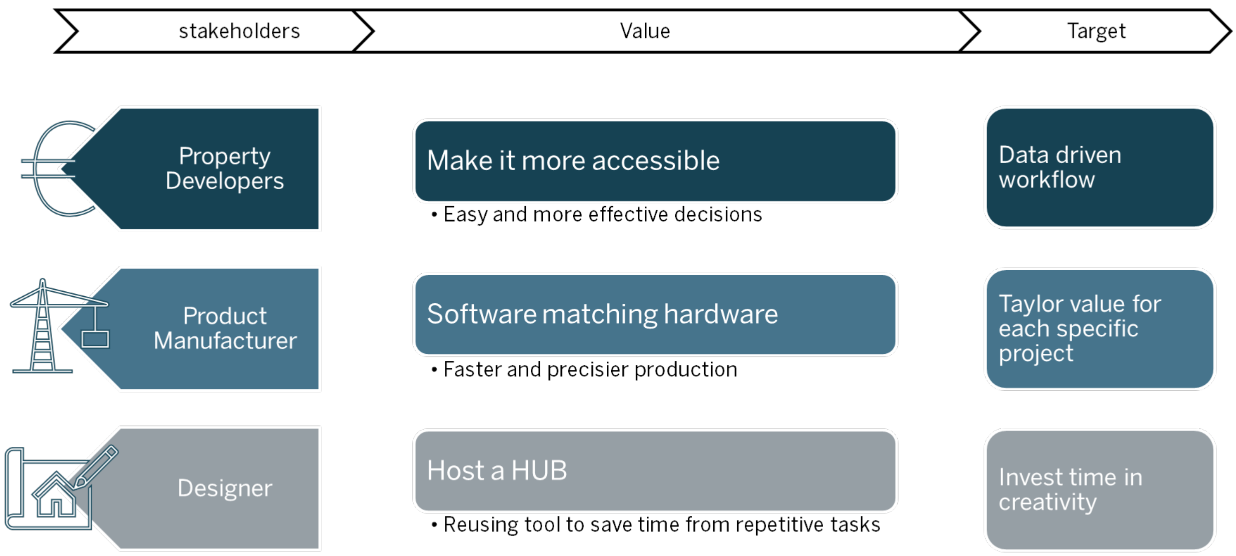


Figure 104: Value System Mapping for the AEC sector

The leitmotif connecting and preserving all three targets is the application of digital tools and instruments to optimize the process at different levels. On one side, *the digital readiness of manufacturers should be adequate for the complexity level of products* [166]. The technological improvement of machines (hardware) is adequate to fulfill the purpose, while the management of the information flows across the different divisions (horizontal integration) and beyond the company (vertical integration) – described in § 2.3 – is still to improve. At the same time, the Developers' and Designers' value is shared because the choosing phase of the investor depends on the options the designer can propose. This is why the optioneering phase should be based on analytical data and taken in the early design stages instead of downstream to save designers time by avoiding starting from scratch for every project.

To pull up the value of buildings is necessary to act on the product itself, as the most valuable thing in the process (51,3%) [160] that can enhance thanks to the **PMV (Pre-Manufacturing Value)** value, but also to other phases that can get adding profit margin. According to KBE [58], an example can be:

- **Development**: + 10% by adopting more productized solutions
- **Design & Engineering**: + 5-10% by adopting design libraries and skipping repetitive tasks
- **Manufacturing**: + 3-10% by adopting BIM and DfMA offsite factory production
- **General Contractors**: + 2-4% by BIM nD models adoption
- **Logistic**: + 3-5% by or modular solutions
- **Operation and Maintenance**: + 2-3% by adopting cognitive/predictive life cycle models

Furthermore, a *breakdown of costs for a steel-frame multistorey commercial building* reveals that *30-40% of the building value is in raw material, 30-40% in fabrication, 10-15% in construction, 1% in transport, 2% in engineering and 10-15% in fire protection*. These budget caps vary according to the building size and typology, but from façade KBE, a common value dedicated to the *façade is 20% of the overall investment*. Translating these results in a **Present Net Value (NPV) Cash flow analysis** across the building lifetime makes it possible to represent *the adding value of Offsite solutions compared to traditional ones*. The qualitative graph shows that the *initial investment* in the design phase generated a *shift in the fabrication phase* (that overlapped with the construction in prefab technologies) and *a shorter delivery time (-50%)*, resulting in *cost savings* that can also be *about 20%*. The faster start of investment recovery generates an *earlier return of investment (ROI), about 50%*, thanks to the higher quality of the building and the lower consumptions, allowing higher rent [59], [60], [70], [148]. During the use phase, the DfMA and BIM nD approach allow easier maintenance and replacement, maintaining the value of the building over time. Finally, according to a few data available on the *EoL phase, DfD generates an extra value of 20%* compared to traditional constructions going to landfills [145].

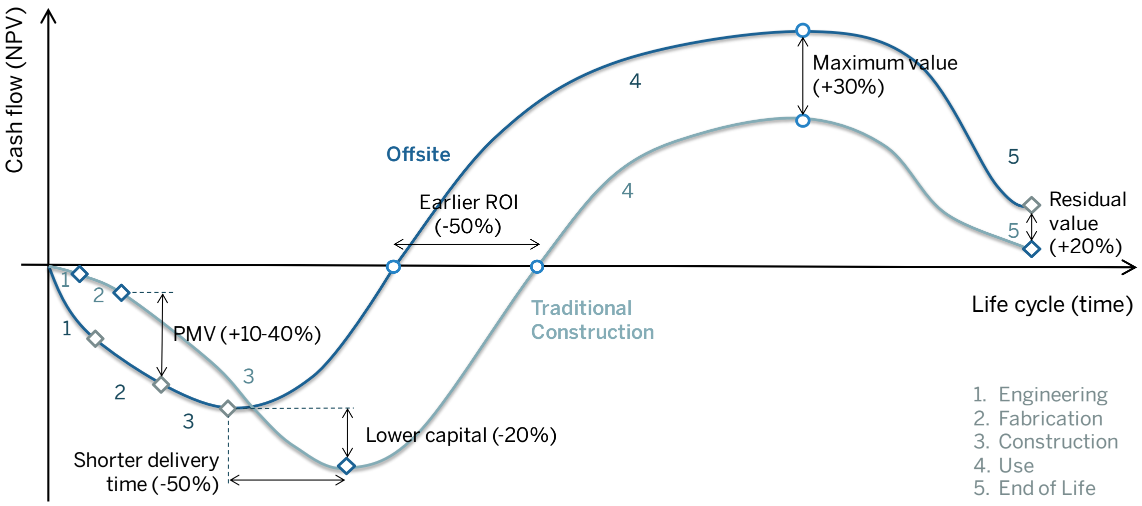


Figure 105: Value comparison of Offsite and traditional buildings intervention

The result is a relevant budget reduction of ROI growth using a simplified Life Cycle Cost (LCC) approach instead of an NPV. Still, the economic advantage of the offsite system can be eroded by introducing multiple stakeholders into the business model. *A SMEs based market generates a spread of financial resources because of the multiplication of profits required by every single company* instead of having a single **one-stop-shop** enterprise that can manufacture, assemble, install and maintain the offsite product (e.g. a panel).

A further development in the research can be the introduction of a **Total Cost of Ownership (TCO)** investment analysis taking into account also of indirect benefits coming from the Industrialized Deep Renovation (IDR), as well as circularity (disposal), carbon neutral approach (not only LCA but also lower traffic and a polite environment) and better life quality (health and safety) [126].

Another aspect that increases the manufacturing value is the shift **from products to services**. With this different business strategy, there is the chance for companies to add value to the product, having a non-stop rent that pushed them also to have a *better quality* in the production phase because of the *higher cost (5 times) of maintenance related to the construction phase*. The economic advantage of EDS actions is demonstrated by the growth of investment across the process in Italy [167]: *0,15€ invested in design corresponded to 1€ during construction, 5% at operation and maintenance and 200€ during the use phase*. The overall *business outcome is about 2500€*, a huge return on the investment compared to the extra effort required from the Design teams to adopt offsite solutions.

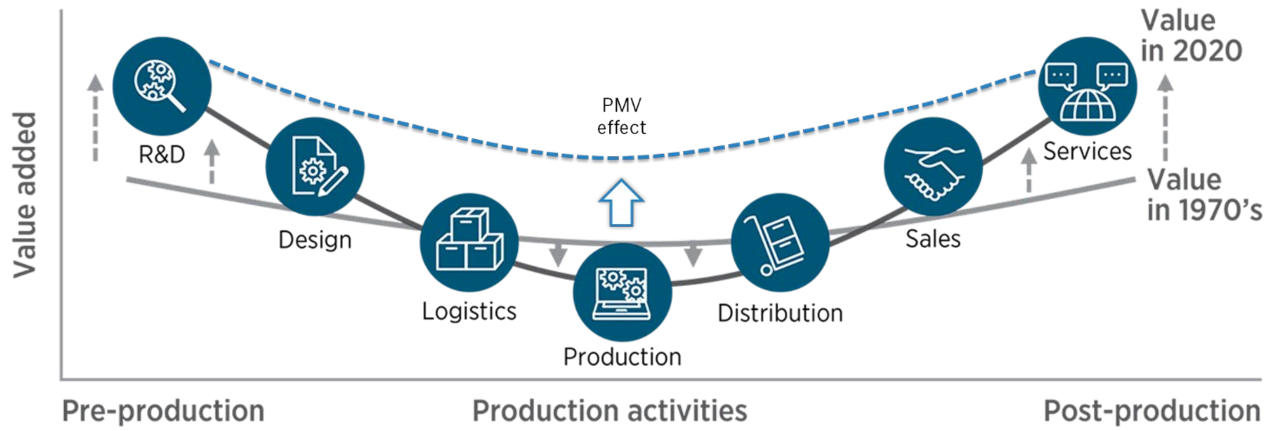


Figure 106: Added value per phase during years and PMV effect
[Author's elaboration on [2]]

The added value generated by *R&D and Service investments* shows that the service approach is the most advantageous business model, generating a lower value for the production phase in the other sectors. In contrast, the *built environment has the most valuable stage in production*, resulting in the necessity to valorize the production phase by adopting offsite solutions with higher PMV value and in a Present Net Value (NPV) and product business model based on the cash flow analysis. This is particularly true *in the built environment*, where the *Servitization approach is challenging to implement because the traditional leadership of producers and builders who prefer to skip the operational phase risk recovering the (low) margin as soon as possible*. A one-stop-shop approach can be a solution to manage this shift, managing construction as a big production plant instead of the automotive industry. In a bigger site, the multitude of activities and actors is similar to the building site and the management controls the timeline with respect to analytical data about efficiency and every other aspect. This is not applied to the AEC sector, except for BIM models required in the biggest procurement in Italy, because the supply chain leader usually does not recognize the value of data. Generating added value from data increases companies' margins with a short investment when the tertial services profit more than the secondary sector products and the payback accelerates. *Distributing* the **added value** can be a solution to reverse the oppositive approach of the chain in two directions:

- **To the top**: designers are not stimulated by clients to optimize because their profits remain the same;
- **To the bottom**: suppliers host general contractors dictating time, but with no power on costs due to large competitors' pool.

To get the adding value is necessary to change also three habits:

- Go **paperless** and save time by avoiding the risk of redesigning or wrong select drawings during the production/construction phase,
- **Eliminate redundancy**: the three Italian design phases (Preliminary, Definitive and Executive) do not generate bid projects, but another phase that is not recognized by procurement is necessary. Developing *ready-to-built projects* is essential to accelerate the sector transition
- **Separate competencies**: dividing figures in charge of *managing time (70%) should decrease in favor of built time (30%)* to increase productivity.

Sensorization becomes a pivotal step to monitor all 3Ps and create ratings (**KPIs**) common to different companies and projects. The design of a whole process certification label can effectively valorize data from a very interoperable perspective. An example of this holistic approach to construction and management was provided from the Dedalo platform, where many different web-based platforms control project and process quality by sensors on the machine (pouring concrete) and the construction site (workforce) across every single realization step.

4.5 Proposed Instruments

The LC 4.0 paradigm described the theoretical framework as the possible future development of the sector to adopt the digital revolution. In this perspective, the research proposed two different instruments to achieve this purpose by acting at multiple levels:

1. A 3Performance and Digital Readiness Assessment of companies and enterprises (**Lean Construction 4.0 Assessment**, chapter 0) starts from the secondary technologies adoption analysis and defines the digital transformation adoption across the different stages of the building life cycle.
2. A design tool (**Panelization Design Tool** - **PDT**) to support the adoption of MMC, especially the Offsite solutions for building construction (Chapter 0). It is a tool helping designers create their offsite panels Hub and provides holistic results for decision-makers acting as a decision support system for choosing one technology instead of the other.

Figure 108: Timber Frame façade Panel Factory, [Bluefactory]

Figure 107: Cold Frame Steel (CFS) panel structure to fill with insulation

5. Companies Assessment

"There is one rule for the industrialist: make the best quality goods possible at the lowest cost possible, paying the highest wages possible."

HENRY FORDHENRY FORD

Scope:

Evaluating the 4.0 adoption level of companies and enterprises in the AEC sector led to the development of an assessment method called **Lean Construction 4.0 Assessment**, a scoring tool specifically developed for this sector [RQ 1.1, Obj 1.1]. The instrument process starts with the **Secondary Technologies** score assigned by the **Phygital Coach** through interviews and company factory visits. The scores assigned to every single building stage (RQ 3.1.2, according to EN 15643-3:2021) produce **Enabling Technologies** [RQ 3.1.1] rankings that are collected in different ways, generating the **Smartness** (efficiency across the process) and **Digitalness** (technology level) results. Furthermore, by grouping Enabling Technologies in Functions, the **LC4.0 Radar** [RQ 3.1.3] is created to evaluate the 10 points of the paradigm, identifying areas where companies must act to accelerate their digital transition. **Digitization** (to go paperless), **Digitalization** (interoperability of the process) and **Digital Transformation** (changing the business model to service) level complete the results that are tested in a case study application. The chapter ends with the LC4.0 Assessment test for a large company and the discussion about the **tool's effectiveness** thanks to the scores obtained by its application to nine case studies [RQ 3.1.4].

Contents:

Expected results:

- LC4.0 Assessment definition
- Scores and parameter definition from the LC4.0 radar
- Phygital Coach role explanation
- 9 interviews results
- Sensitivity analysis
- Changes over time: Radar effectiveness

Keywords:

LC4.0 Assessment, Phygital Coach, LC4.0 Radar, Smartness, Digitalness, Digitization, Digitalization, Digital Transformation, Sensitivity Analysis

The first output of the research is the LC 4.0 Assessment, which evaluates the digital level of enterprises. Many companies are researching this field, providing instruments to quantify the adoption of 4.0 inside their processes. The most advanced are developed for industrial purposes, focusing on single activities monitoring different compartments: administration, production and delivery. The result is a process mapping of every activity identifying bottlenecks and suggesting implementation strategies (a road map, seminaries and teaching activities) to increase productivity by 10-15% [2] and decrease labor costs. These advanced instruments, however, are generically dedicated to every industry market without a specific focus on the AEC sector. According to the peculiarities of the construction synthesized in chapters 3.4.5 and 3.4.6, the various activities on and off-site required a more flexible instrument that involves many different phases, from design to disposal. Existing tools (§ 5.1) are more qualitative than quantitative and provide little information about where to act to implement a company's digital strategy. This is why the LC4.0 can be proposed as an innovative instrument that can still be implemented by the open platform configuration, able to adapt itself to new digital tools implementation and availability on the market.

5.1 Existing tools

The following list (updated to November 2022) describes features of existing tools, with their release data, main features, purposes, pros and cons to understand why a different instrument was designed as an output of this research.

5.1.1 Digitalization of Construction SMEs - Maturity scan

- First release: September 2022, link
- Features:
    - Double scan level
        - 1: quick scan, with basic questions
        - 2: in-depth, with advanced ones
- Purpose:
    - Cover specific technologies (e.g. BIM) but also non-technological topics
    - Technical dissemination for managers by Interactive Handbook about strategy, process, ecosystem and culture, enabling technologies and best practices both for design, construction and management phases
    - provide SMEs introductive training sessions about opportunities in 4.0 and various technologies (e.g. Drones, Sensors, IoT)
- Pros:
    - Free online tool
    - Double scan level allows having a fast overview and then a more precise one
- Cons:
    - Stand-alone online tool
    - User has little information about how to compile the form
    - Progressive selective responses, which exclude other options
    - Not possible to go deeper into technologies and processes

5.1.2 Force Technology – Digital Factory Mapping

- First release: November 2020, link
- Features:
    - Industrial process analysis and implementation strategy with test and validation of the solution adopted

- Purpose:
  - Analyze a single process step by step from administrative to production and delivery
  - Time and precision tracking with sensors and live monitoring
- Pros:
  - Digital manager presence to compile data and decide strategy together with the client
  - Effectiveness measurement by data monitoring pre/post activities activation
- Cons:
  - Focused only on the production processes
  - Construction sector non-specific consultancy
  - Designed for medium-big companies, non-related to SMEs

5.1.3 Kearney IMP³rove - Digital Scan for Construction SMEs

- First release: October 2022, link
- Features:
  - Global digital assessment by online form with qualitative report
- Purpose:
  - Analyze digital transformation strategy by an overview of processes, company culture, BIM and other technologies
- Pros:
  - Designed for SMEs with different businesses (construction of buildings, civil engineering, specialized construction activities)
  - Semi-quantitative (5 levels) report based on benchmark generated by other assessments done by companies in the same segment
- Cons:
  - Progressive selective responses, which exclude other options
  - Non-detailed analysis of processes and technologies
  - Selective business areas: not possible to cover different segments (design + production + construction)

5.1.4 Punto Impresa Digitale – Selfie4.0

- First release: Selfie4.0 September 2020
- Features:
  - Detailed digital assessment by online form with scores developed by the Italian Chamber of Commerce together with universities also creating a qualitative description of the as-is scenario with suggestions on where to implement the strategy
- Purpose:
  - Self-assessment to understand the strength and weaknesses of the company according to its size
  - Move to the Zoom4.0 consultancy instrument with a Digital Promoter
- Pros:
  - Designed for all Italian companies' sizes for all the economic sectors
  - Score assigned in different fields: economy and decision processes, clients and markets, technologies, human resources, purchases, logistics, product/service
  - Semi-quantitative (5 levels) report
- Cons:
  - Progressive selective responses, which exclude other options

- Non-detailed analysis of processes and technologies
- Selective business areas: not possible to cover different segments (design + production + construction)

5.1.5 Digital Assessment – Supply Chain Sustainability School

- First release: Digital Assessment September 2022
- Features:
  - Generic survey about many different aspects from business to strategy, innovation, collaboration, people (employees, customers and suppliers) and technologies across different phases
- Purpose:
  - Self-assessment to understand the strength and weaknesses of the company according to its size
  - Move to consultancy instrument for Digital Adoption
- Pros:
  - Designed for construction companies
  - Qualitative answers are pretty detailed
  - Stages assessment
  - Multiple areas analysis
  - Semi-quantitative (5 levels) scores
- Cons:
  - Non-detailed analysis of processes and technologies
  - Selective business areas: not possible to cover different segments (design + production + construction)
- Plus: the Supply Chain Sustainability School web platform – developed by Construction Innovation Hub and UK HM Government – also offers a toolkit and assessment for other related topics such as Value Toolkit, Offsite and Sustainability assessment instruments. The Offsite knowledge rate analyses Management, DfMA, Offsite Manufacture, Logistic, Assembly and In use/maintenance topics, according to the LC 4.0 paradigm and the PDT tool.

5.1.6 Resume and comments

The existing tools' analysis shows as there are few instruments (2) specially designed for the construction sector and both of them provided qualitative data without a figure who drove through the assessment process – at least in the first phase. Furthermore, only one instrument is specific to the Italian market, with its characteristics, as described in chapter 3.3.3, really peculiar compared to other countries. Finally, all tools were released after the research began and many arrived closer to the delivery (2022), certifying the global interest in this topic. Many engineering societies offer similar tools and instruments to assess the digital level of AEC sector companies, but they are not available online and the author has no chance to test them; for this reason, they are not included in the existing tool description. For all these reasons, creating a tool adaptable to different companies' sizes and able to cover all the building phases, from early design to construction, management and disposal phase, can be a step ahead in the sector's digitalization. Furthermore, the possibility to implement the tool with new technologies and the capability to analyze different areas of the companies from the business perspective and the performances are key aspects that make the tool unique.

5.2 Methodology

Defining the LC4.0 Assessment tool starts with the development phase, which transforms the Construction 4.0 Tech Taxonomy (§ 0) as a synthesis of the digital tools and approaches for the AEC sector into a label to define the digital level of a company. The instrument covers all the life cycle of buildings according to EN 15643:3-2021 [168] and defines various scores according to a matrix by the secondary technologies mark. Results regard the Digital Readiness (the company strategy about data), the Performances (as defined in the Lean Construction 4.0 Paradigm (§ 4.1)), the Digitness for every primary tech and the Smartness across the process. All these results are collected by the Phygital Coach together with an Innovation or Digital Manager from the company.

This instrument was designed and modified during its test with companies of different sizes and businesses: from design to manufacturing and construction. Unfortunately, only a few of them (2) works on the End of Life stage because, at the moment of the research development, this stage is out of economic advantage for them. The threads between these companies are:

- the focus on the envelope, working on both opaque and transparent skin;
- the DfMA approach, looking at MMC and offsite as adding value for the sector;
- the various business sector with a B2C focus concerning both the product and the service market;
- SMEs companies.

After the interview and sometimes the factory visit (when it was possible, due to the Covid-19 pandemic period), the LC4.0 Assessment was compiled and double-checked with companies to verify the consistency of scores, as described in § 5.3. Collecting all the tests allows for discussion results and a sensitivity analysis (§ 5.5.1) describing the instrument's effectiveness. Finally, a test with a bigger company gives a chance to test the tool's robustness by testing a variation of some scores and demonstrating how the final results are modified.

5.3 LC4.0 Assessment Tool – Process Description

The first step for creating the tool is the evaluation of secondary technologies according to the **Construction 4.0 Tech Taxonomy** developed by the author according to the literature review (chapter 0). The **Phygital Coach** compiles the score of every single technology according to the interview provided to the **Innovation Manager, the Digital Manager and/or the BIM Manager** of the company. It is suggested to interview different figures within the company to have multiple and non-biased points of view, while the presence of the Phygital Coach ensures the coherence of the judgment, acting as an aleatory mediator thanks to its experience. The results stream out from:

- the tech score given to every single **Secondary Technology** in each phase of the building process (EN 15643-3:2021, [168]),
- the answer given to standard **questions,**
- the **visit of factory** done by the Phygital Coach

The double level of the interview led to two results: the Lean Construction 4.0 Radar and the definition of the Information Flow (11.2) to understand the phases in which the company is involved and how it acts to streamline the process.

From the **Secondary Technologies** score, the tool can calculate the analytical value of **Enabling Technologies** by compiling the **Digital Smartness Matrix**, assessing the **Digital Revolution**

Level branched into the **3Digit Readiness** (*Digitization, Digitalization, Digital Transformation*, already described in 2.3) and the **3P*erformances*** according to the **10 Functions** defined into the LC 4.0 Paradigm. A synthesis of the process is figured out in Figure 109.

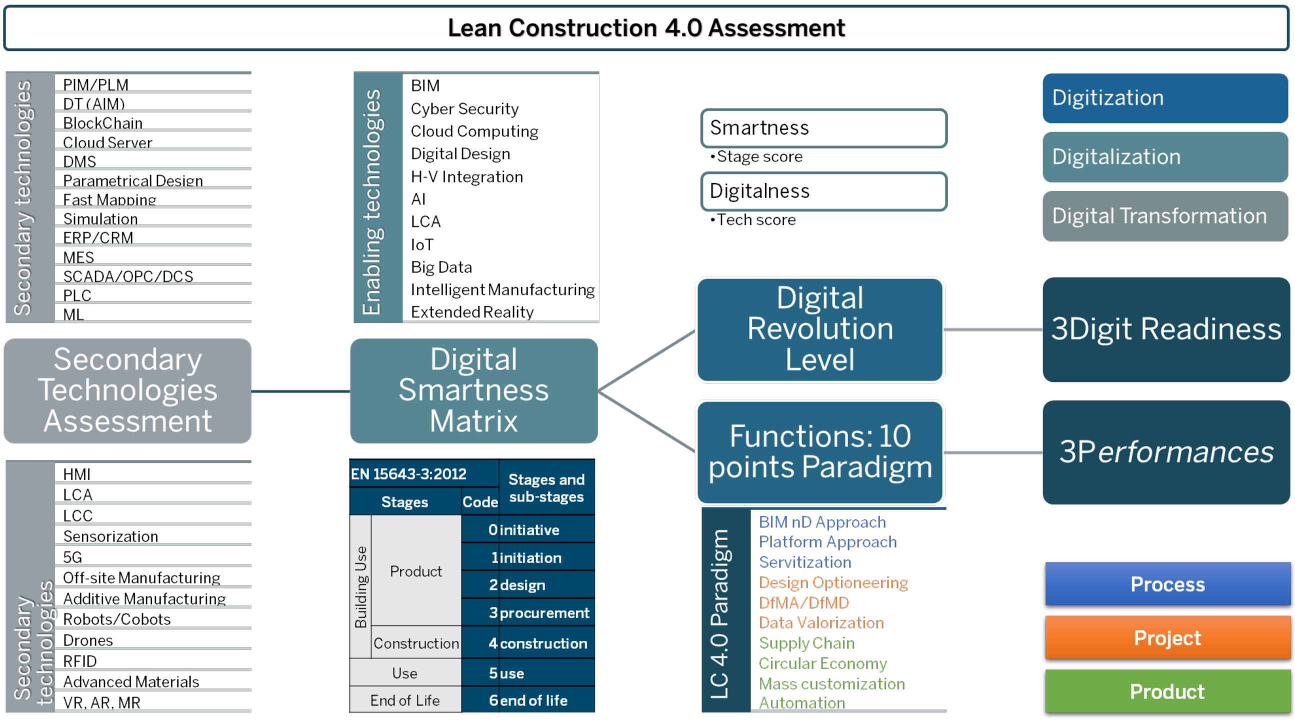


Figure 109: LC4.0 Assessment Process

The Enabling Technologies and the 10 Functions relations are described in Figure 110, highlighting the complexity of their interaction with the final Performances related to the 3P paradigm. The graph shows that the number of relations of a single Function of the 3Paradigm is 4 on average, with a lower value of 2 for Circular Economy (related to the Life Cycle Sustainability Analysis and the Intelligent Manufacturing) and a higher value for the BIM nD Approach, Data Valorization, Supply Chain and Automation. These last 4 Performances are identified as the main drivers of change, as confirmed by all the tech trends represented by stakeholders involved in the sector and confirming the two pillars (BIM nD Approach and P-DfMA) of the LC4.0 paradigm. Furthermore, the assessment map shows by colors that all 25 Secondary Technologies are involved in each of 3 Paradigm points, highlighting the assessment process complexity due to the high interaction and interconnection of single technologies to the various Performances.

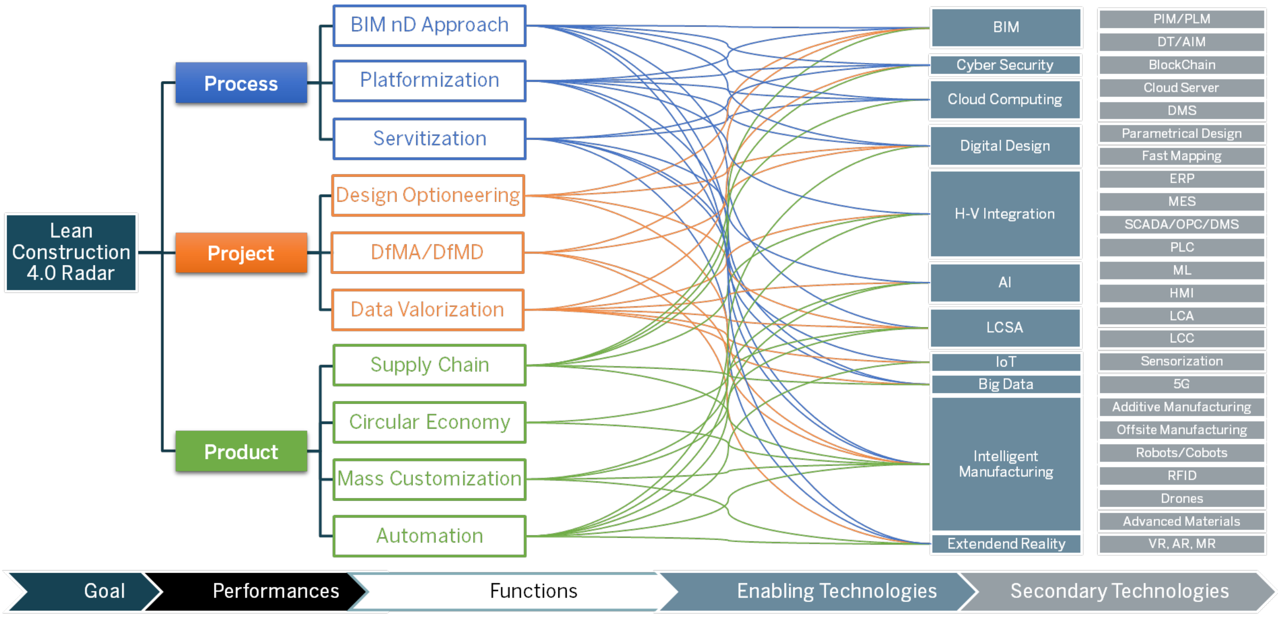


Figure 110: LC4.0 Assessment, map of secondary and enabling technologies to functions and performances

A second level of the methodology analysis consists of counting the Enabling Technologies related to the 10 Functions. The graph (Figure 111) shows that Data Valorization and Mass Customization involve the largest number of Enabling Technologies, followed by Platformization, Servitization, Circular Economy and BIM nD Approach, DfMA/DfMD.

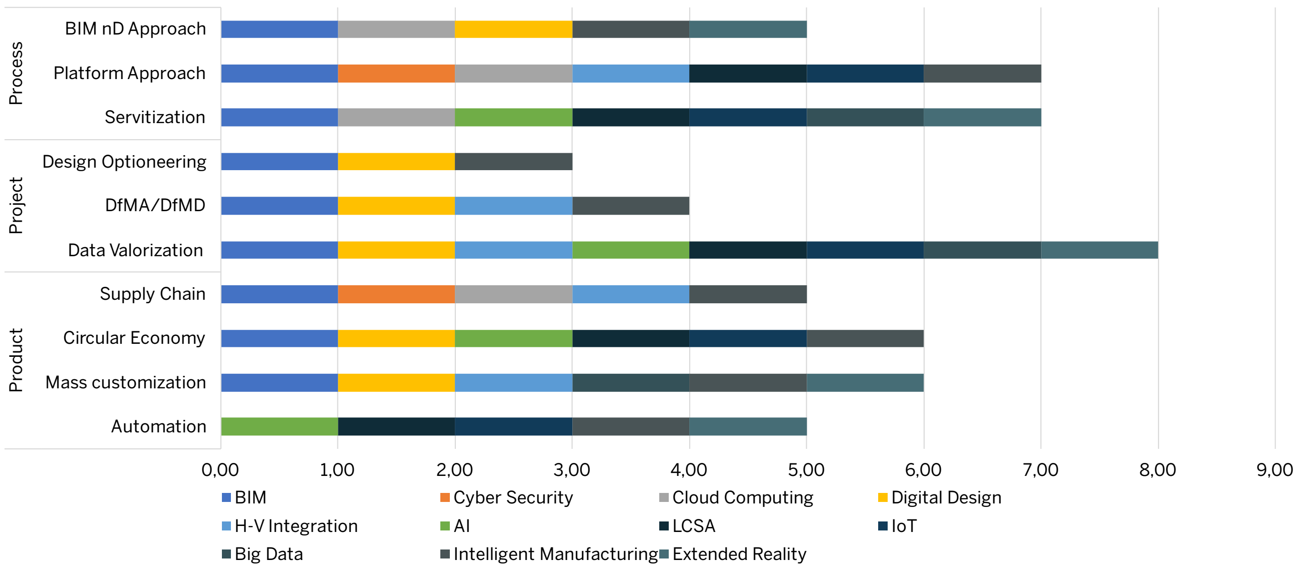


Figure 111: Enabling Technologies' influence on the 10 Paradigm Performances

Matching the Secondary Technologies with the 10 Performances and then the 3Paradigm results in a lower influence of tech on Servitization and Design Optioneering (11), followed by Automation (12). While Platformization (18), Mass Customization (17) and then Circular Economy plus Data Valorization involved the largest number of technologies due to their transversality across different disciplines. The overall tech number for Process and Project is close – respectively 43 and 42 -, while Product is affected by 60 different technologies because it involves 4 Performances instead of 3 as the other 2P. This gives an overview of Secondary Technologies' influence on the final assessment, even though all the 25 techs are involved in the

3 Performances. This analysis may be engaging in a possible further development of the assessment, where ST can be differently evaluated for each Performance by a weighted score.

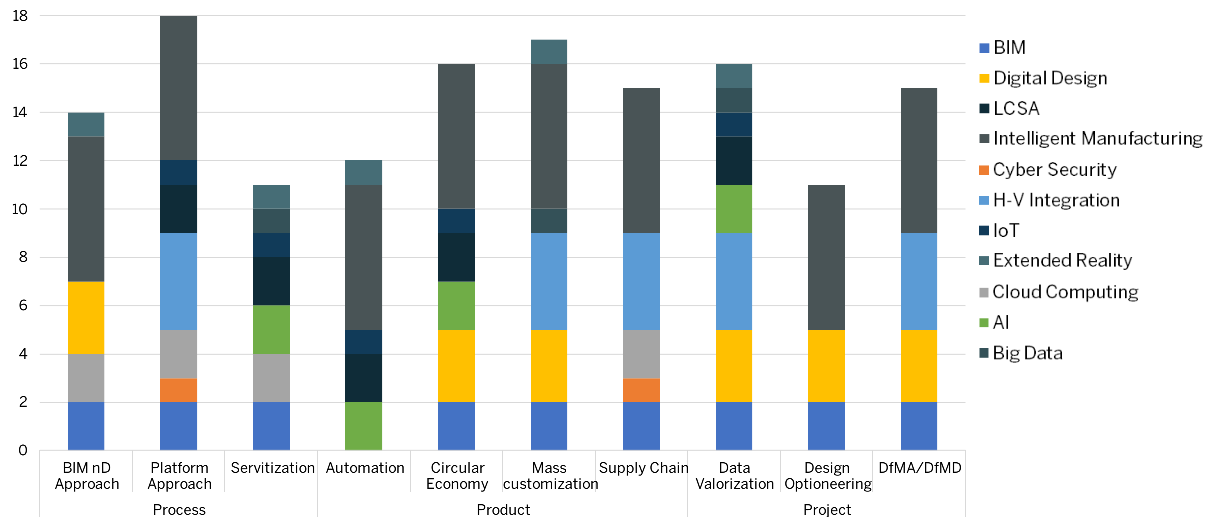


Figure 112: Number of Secondary Technologies involved in the 10 Performances and the 3 Paradigm points

The second assessment is the 3Digit Readiness concerning the three digital levels of the Digital Revolution (Figure 113). All the secondary technologies described are related to the Digitization level, moving data from paper-based transfer to the virtual world. The second level – Digitalization – evaluates information management in a digital environment. Nine secondary technologies are not directly involved at this level because they only relate to virtual data reporting. The final level – the Digital Transformation one – supports the business transformation, using Digital Revolution as a game-changer for the sector. Only 8 Secondary Technologies are directly involved in this Digital readiness assessment.

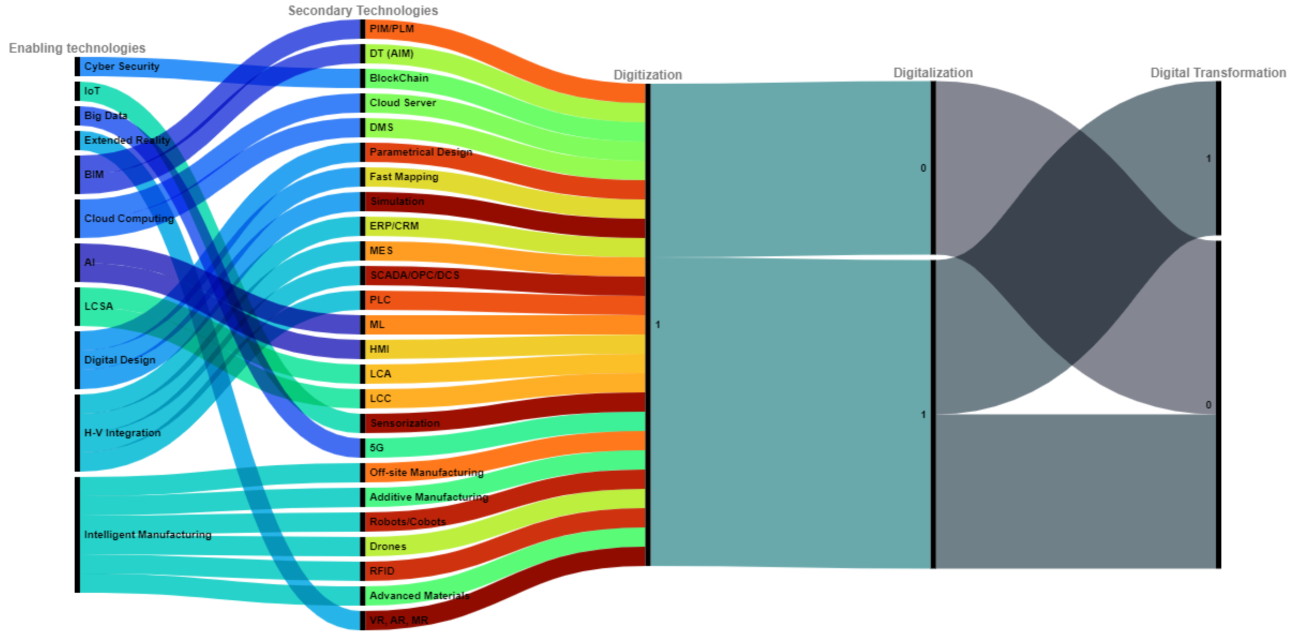


Figure 113: Relation of Secondary Technologies to Digital Readiness branched into Digitization, Digitalization and Digital Transformation

5.4 Results

The tool consists of a calculator starting from the label reported in the example (Figure 116). The compilation of Secondary Technologies scores per each stage of the building process led to multiple results:

- Digitalness measures the digital readiness of all the enabling and Secondary Technologies, calculated as the average of the EN 15643-3:2021 stages. The overall Digitalness score comes from the average of only the Enabling Technologies
- Smartness measures the digital readiness for every stage of the building process and gives the overall scores by their average.
- Digital Revolution is calculated as the average of Digitization, Digitalization and Digital Transformation, described in § 2.3 Digital world.

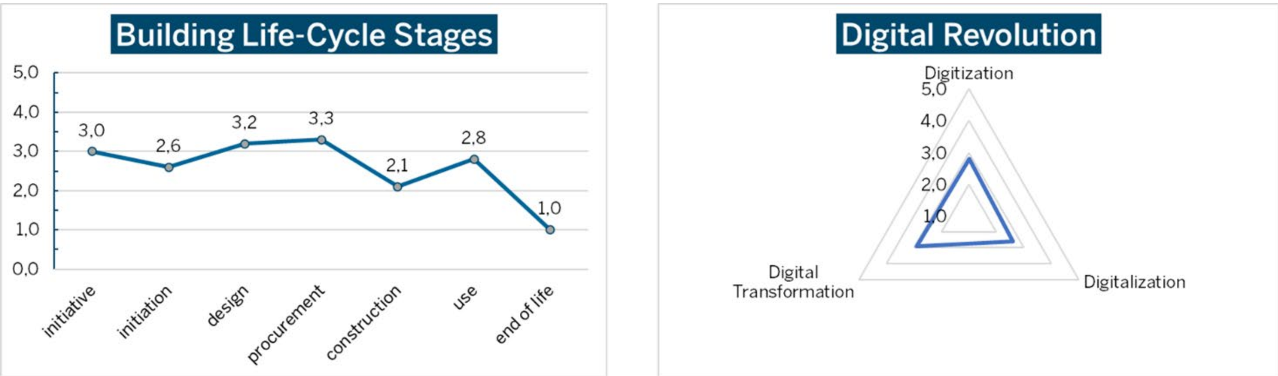


Figure 114: Smartness across the Building Life-Cycle Stages (EN 15643) and Digital Revolution Level

The Smartness graph shows results for each stage to better explain the digital level across the building life cycle. On the other side, the Digital Revolution level is assessed by another radar that exploits three aspects resumed in Figure 115:

- Digitization concerns all the secondary technologies without a prioritization
- Digitalization analyzes the information path across the actors and the companies' compound
- Digital Transformation refers to the Servitization business model

Tech Assessment		Digital Revolution		
		Digitization	Digitalization	Digital Transformation
Enabling technologies	Secondary Technologies			
BIM				
	PIM/PLM	1	1	
	DT (AIM)	1	1	1
Cyber Security				
	BlockChain	1	1	
Cloud Computing				
	Cloud Server	1		
	DMS	1	1	
Digital Design				
	Parametric Design	1	1	
	Fast Mapping	1		
	Simulation	1	1	1
H-V Integration				
	ERP/CRM	1	1	1
	MES	1	1	
	SCADA/OPC/DCS	1		
	PLC	1		
AI				
	ML	1	1	1
	HMI	1	1	
LCSA				
	LCA	1	1	1
	LCC	1	1	1
IoT				
	Sensorization	1	1	1
Big Data				
	5G	1		
Intelligent Manufacturing				
	Off-site Manufacturing	1	1	1
	Additive Manufacturing	1	1	
	Robots/Cobots	1	1	
	Drones	1		
	RFID	1		
	Advanced Materials	1		
Extended Reality				
	VR, AR, MR	1		
Smartness	3,0	2,8	2,6	2,9

Figure 115: Digital Revolution Score

Tech Assessment		Macro-Stages (EN 15643-3:2012)	Building					Use	End of Life	Digitalness
			Production				Construction			
		Stages	initiative	initiation	design	procurement	construction	use	end of life	2
Enabling technologies	Secondary Technologies	Description	0	1	2	3	4	5	6	Tech Score
BIM			-	3	5	5	-	-	-	**4**
	PIM/PLM	Product Life Management / Product Information Model	-	3	5	5	-	-	-	4
	DT (AIM)	Digital Twin (Asset Information Management)	-	-	-	-	2	2	1	2
Cyber Security			-	-	-	1	1	-	-	**1**
	BlockChain	for communication, contracts, etc	-	-	-	1	1	-	-	1
Cloud Computing			5	5	5	5	5	-	-	**5**
	Cloud Server	Online data storage	5	5	5	5	5	-	-	5
	DMS	Database Management System	-	1	4	5	2	1	-	3
Digital Design			-	1	2	2	1	-	-	**2**
	Parametrical Design	e.g. Grasshopper, Dynamo...	-	1	2	2	1	-	-	1
	Fast Mapping	e.g. Lasera Scanning, LIDAR	-	1	1	-	1	-	-	1
	Simulation	CAE (Computer Aided Engineering) level: from manual to FEM (Finite Element Analysis)	-	-	5	-	-	-	-	5
H-V Integration			-	5	5	5	5	5	-	**5**
	ERP/CRM	Enterprise Resource Planning / Customer Relationship Management (Business)	-	5	5	5	5	5	-	5
	MES	Manufacturing Execution System (Operation)	-	-	-	5	-	-	-	5
	SCADA/OPC/DCS	Supervisory Control & Data Acquisition / Open Platform Communication / Distributed Control System (Production)	-	-	-	4	-	-	-	4
	PLC	Programmable Logic Controller (Control)	-	-	-	5	-	-	-	5
AI			-	1	1	1	-	-	1	**1**
	ML	Machine Learning (Predictive buildings)	-	1	1	1	-	-	1	1
	HMI	Human-Machine Interaction	-	1	1	1	-	-	1	1
LCSA			-	5	5	5	1	1	1	**3**
	LCA	Life Cycle Assessment	-	5	5	5	1	1	1	3
	LCC	Life Cycle Cost	-	5	5	5	5	5	1	4
IoT			-	-	-	1	1	5	1	**2**
	Sensorization	Cognitive buildings	-	-	-	1	1	5	1	2
Big Data			-	-	-	1	1	1	1	**1**
	5G	fast data transmission	-	-	-	1	1	1	1	1
Intelligent Manufacturing			-	-	1	1	1	-	-	**1**
	Off-site Manufacturing	CAM (Computer Aided Manufacturing) e.g. CNC (Computerized Numerical Control)	-	-	1	1	1	-	-	1
	Additive Manufacturing	3D printing	-	-	1	2	1	-	-	1
	Robots/Cobots	unhuman workers/exoscheleton	-	-	-	3	1	-	-	2
	Drones	unhuman flying site survey	-	1	-	-	1	-	-	1
	RFID	product unique code tracking	-	-	5	5	5	3	-	5
	Advanced Materials	innovation in new materials adoption	-	-	5	5	2	-	-	4
Extended Reality			-	-	1	3	2	2	-	**2**
	VR, AR, MR	Virtual/Advanced/Mixed Reality	-	-	1	3	2	2	-	2
Smartness	3	**Stages score**	**5**	**3**	**3**	**3**	**2**	**3**	**1**	

Figure 116: LC 4.0 Tech Assessment Label

The first results are evident directly from the label: the Smartness level is marked at the bottom of the label, with the overall total calculated as the average of every building process step.

Similarly, the Digitalness is represented in the last column as the average per ST and the average splitted by ET. The average of all the ET led to overall value.

The choice to make evident the partial score of Smartness and Digitalness for each technology and stage clarifies the single intervention area where companies can improve their scores before having the overall results.

Likewise, the final 3 Paradigm points are represented in the single radars (Figure 117) with the single Performances and the complete LC 4.0 radar (Figure 118). Different colors help in reading the various Performances.

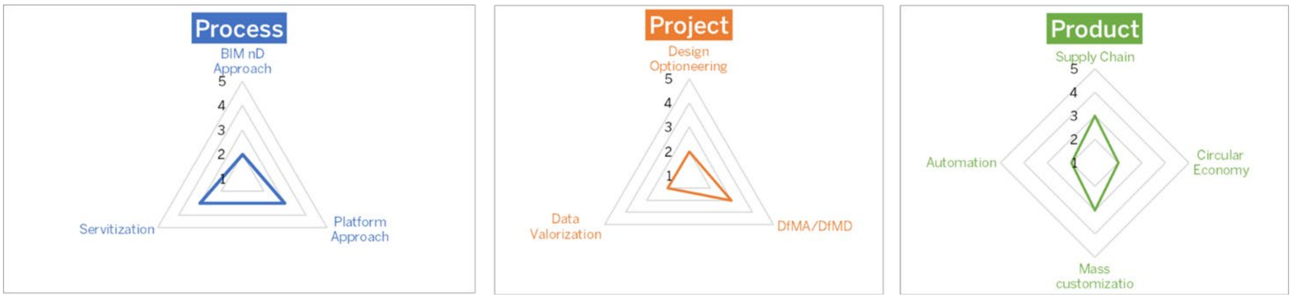


Figure 117: 3Performances Radars, the detailed results in each paradigm point

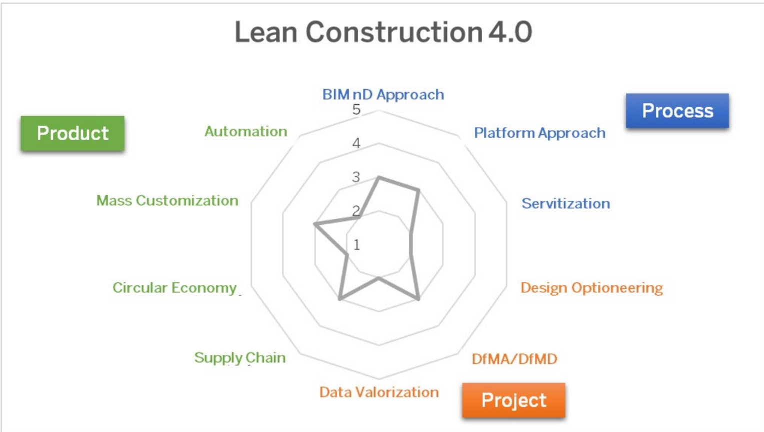


Figure 118: LC 4.0 Radar

5.5 Discussion

The LC 4.0 Assessment is validated in its efficiency and effectiveness by the application to 9 companies through an interview with internal figures working on digital innovation topics. Due to the Covid 19 pandemic for only a few of them (5), it was possible to visit the factories, compile the radar with the Phygital Coach and check the results.

The features of the selected companies were resumed in REF 5.2, but some details can be added:

- Interviews were taken between October 2019 and March 2022 with one or two staff members, usually who is in charge of the digital/BIM/innovation department;
- All nine companies are SMEs, as well as 89% of the construction companies in Italy (§ 3.3.3.3). Their average employees' number is 14.3;

- All nine companies' business is focused on the Production and Construction stages. Only two of them followed the client during the Use phase and none at EoL, even if they all started to analyze their product behavior close to the disposal phase. The Initiative phase is quite non-relevant, while Initiation involves all of them but a few technologies because of the as-is site analysis necessary before starting the design.

Velux is the only deviation from SMEs because of its location (the test was realized at Velux Global, sited in Denmark), size (Big Enterprise) and business. It was same selected because it provided the opportunity to go deeper into its digital processes, with the chance to see from the inside how employees work and where bottlenecks are. Furthermore, Velux enterprise can be seen as a cluster of smaller companies, each with a size not too far from an SME and with an articulated structure of products and services. Inside each of these divisions, the organization is similar to an SME. The results coming from the assessment certify the possibility of applying the tool to various companies sizes because the results are not so far from average due to the shared gap that all the sector shows in digital transformation.

The five levels of scores led to concentrating results to the median value (3) because of the mindset of interviewees, as explained by Zavadskas et al. [169]. However, the support of the Phygital Coach in the assessment process positively affects the evaluation's precision, thanks to its impartiality.

A possible implementation of this method is the application of a weighted score of every Secondary and Enabling Technology to each performance and different building process steps according to their influence and/or the economic effect on the whole result.

5.5.1 Sensitivity Analysis

The subchapter evaluates the instrument's effectiveness in having a varied output per each company, appreciating the diversity of each assessment according to the company's key features.

Figure 119: LC 4.0 Performances sensitivity analysis

The graph shows the nine companies' assessment results with their label diffusion and the average value get. The result is a similar distribution of scores in all the 10 Performances, with a relevant number closer to the medium value and few data over them. The reason for this distribution consists of the companies' similar size (SMEs), market and business, with few exceptions (darker are Corporates or Big Enterprises) confirmed by the aggregate result of the 3 Performances.

The following label synthesizes[13] the sensitivity analysis of the instruments:

Score	Average	Variation	Variation %
3 Performances	2,48	0,57	23%
10 Paradigm points	2,53	0,35	14%
Digitalness (primary technologies)	2,44	0,37	15%
Secondary technologies	2,71	0,71	28%
Smartness (building process stages)	2,44	0,34	14%
Single Stages	2,44	0,43	17%
Digital Revolution (Digitization, Digitalization, Digital Transformation)	2,81	0,38	15%

According to expectations, the more disaggregated the result, the more variation the score has due to the average method of aggregating results. Secondary technologies show a 28% variation on the medium value, while their Digitalness score has 15% because of the double average done by primary technology and the final score. However, the 3P score, which should be the more aggregated results, has a good variety of 23%, demonstrating the instrument's responsivity to the input given by the user and the Phygital Coach during the assessment compilation.

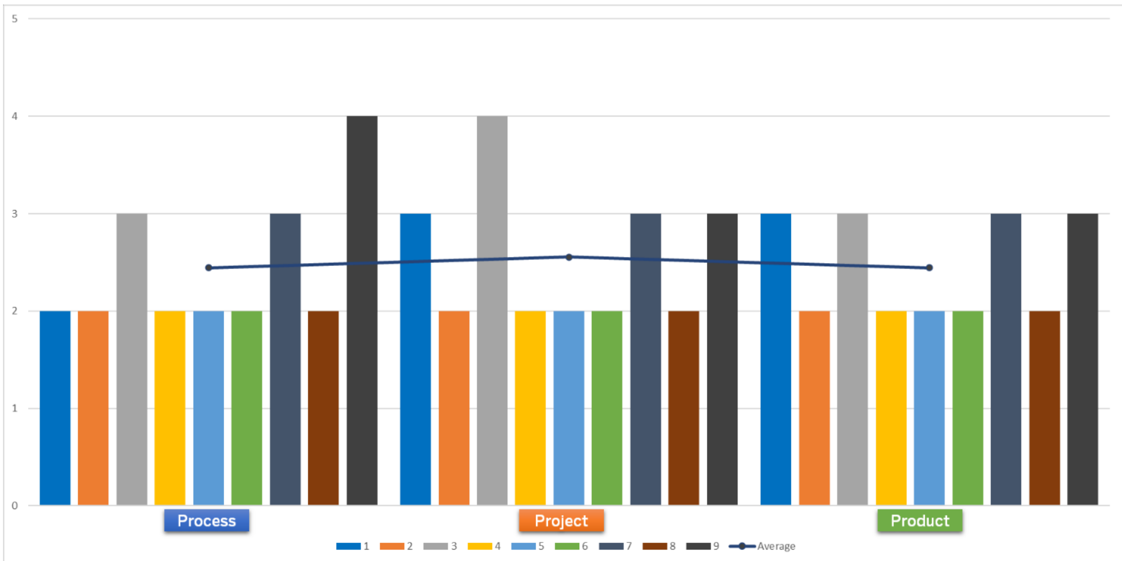


Figure 120: 10 Points Paradigm scores per each company

[13] The full labels of assessments and their score variation according to sensitivity analysis is attached as appendix

5.6 Case study: Product development and radar effectiveness

The application of the LC 4.0 paradigm was tested in its effectiveness during the abroad research period in Copenhagen (August-December 2021), where the relation with Velux got closer thanks to work done inside the Urban Tech accelerator program. The instrument application to a big enterprise like Velux allows the researcher to monitor the process inside the company step by step and treat different projects and topics like clusters. Corporates can be seen as a collection of SMEs, where project managers are small unit leaders trying to improve business in their specific field. To scale down the results for smaller companies, it is possible to assume that these units are B2B (Business to Business) suppliers for the Corporates, as well as the accelerator program suggested for the start-ups involved.

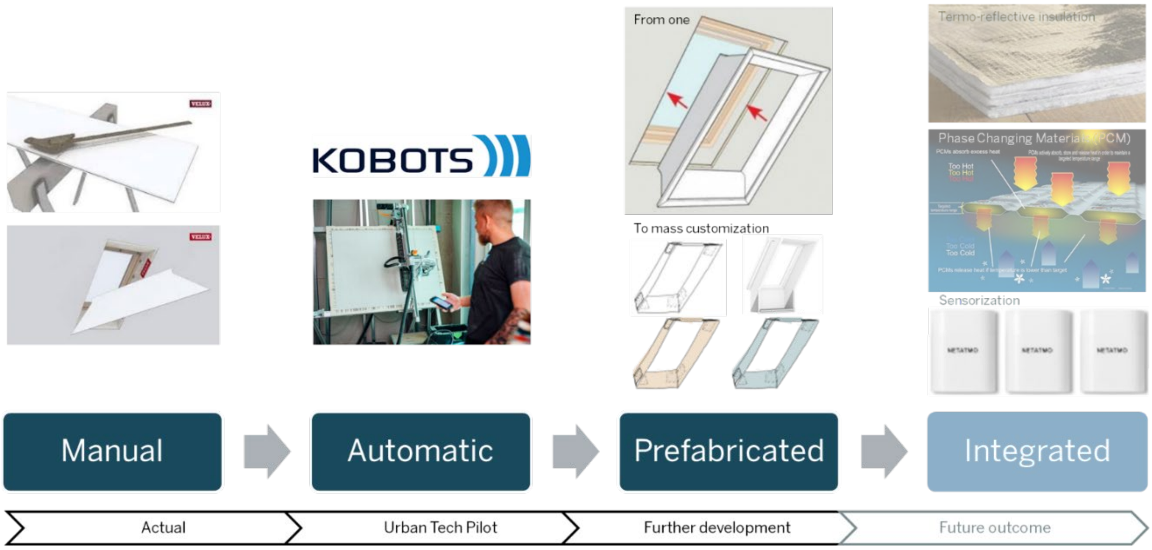


Figure 121: actual, implemented and possible further development for the Kobots application in the lining construction

The result was the application of an automatic cutting tool called Kobots (Figure 121), which acts on the paradigm's three aspects, acting on Product, Process and Project performances.

The extended project description is included in the Appendix chapter: Kobots tool § described as an automatic board-cutting machine that can help carpenters realize the lining. Optimization of the geometrical and finishing lining design to reduce the time consumption of the activity having much more flexibility in geometry and finishing, as well as more healthy for workers by reducing dust coming from the cutting process. This instrument involves manufacturing aspects and digitalization, thanks to using a simple smartphone app to design the boards' shapes. Including Kobots start-up in the Velux business allows the introduction of robots, digital design and prefabrication in the cutting process.

Apart from the quantification of advantages, the interest of this chapter is to exploit the effectiveness of the LC4.0 Assessment instrument after this tool's adoption (Figure 123). The Parametric Design, Offsite Manufacturing and Robots/Cobots scores of 2 points on average, generate a modification of the primary technologies (Digital Design and Intelligent Manufacturing) of 2 punches, that change 1 point in Design Optioneering and DfMA/DfMD for Project Performance and Supply Chain plus Automation for Product (Figure 122). Parallelly, the Design and Procurement stages change by a unit, resulting in no variation for Smartness, while Digitalness changed from 2 to 3 (Figure 124).

This responsiveness of the scores certifies the instrument's effectiveness during the time, thanks to the input change.

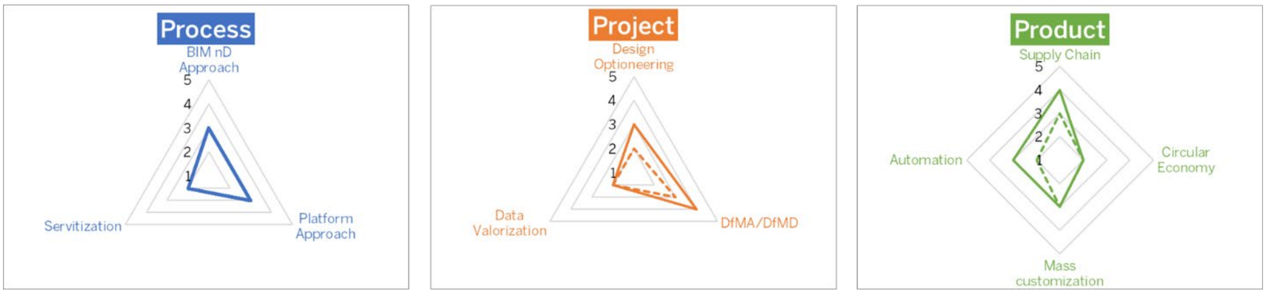


Figure 122: 3P radar implementation after the cutting robot application (dot lines are the previous score)

Figure 123: LC 4.0 Radar comparison before and after the case study product implementation

While the as-is scenario was built and controlled by the company, unfortunately, it was impossible to verify the score after the implementation because the cutting-line project in the Velux process was under discussion at the business negotiation level. The researcher assigned the new marks according to the measured time, cost and health benefits.

Tech Assessment		Macro-Stages (EN 15643-3:2012)	Building					Use	End of Life	Digitalness	
			Production				Construction				
		Stages	initiative	initiation	design	procurement	construction	use	end of life	3	
Enabling technologies	Secondary Technologies	Description	0	1	2	3	4	5	6	Tech Score	
BIM			-	3	5	5	-	-	-	4	
	PIM/PLM	Product Life Management / Product Information Model	-	3	5	5	-	-	-	4	
	DT (AIM)	Digital Twin (Asset Information Management)	-	-	-	-	2	2	1	2	
Cyber Security			-	-	-	1	1	-	-	1	
	BlockChain	for communication, contracts, etc	-	-	-	1	1	-	-	1	
Cloud Computing			5	5	5	5	5	-	-	5	
	Cloud Server	Online data storage	5	5	5	5	5	-	-	5	
	DMS	Database Management System	-	1	4	5	2	1	-	3	
Digital Design			-	-	4 +2	4 +2	3 +2	-	-	4	+2
	Parametrical Design	e.g. Grasshopper, Dynamo...	-		+2 4	+2 4	+2 3	-	-	4	+2
	Fast Mapping	e.g. Lasera Scanning, LIDAR	-	1	1	-	1	-	-	1	
	Simulation	CAE (Computer Aided Engineering) level: from manual to FEM (Finite Element Analysis)	-	-	5	-	-	-	-	5	
H-V Integration			-	5	5	5	5	5	-	5	
	ERP/CRM	Enterprise Resource Planning / Customer Relationship Management (Business)	-	5	5	5	5	5	-	5	
	MES	Manufacturing Execution System (Operation)	-	-	-	5	-	-	-	5	
	SCADA/OPC/DCS	Supervisory Control & Data Acquisition / Open Platform Communication / Distributed Control System (Production)	-	-	-	4	-	-	-	4	
	PLC	Programmable Logic Controller (Control)	-	-	-	5	-	-	-	5	
AI			-	1	1	1	-	-	1	1	
	ML	Machine Learning (Predictive buildings)	-	1	1	1	-	-	1	1	
	HMI	Human-Machine Interaction	-	1	1	1	1	-	1	1	
LCSA			-	5	5	5	1	1	1	3	
	LCA	Life Cycle Assessment	-	5	5	5	1	1	1	3	
	LCC	Life Cycle Cost	-	5	5	5	5	5	1	4	
IoT			-	-	-	1	1	5	1	2	
	Sensorization	Cognitive buildings	-	-	-	1	1	5	1	2	
Big Data			-	-	-	1	1	1	1	1	
	5G	fast data transmission	-	-	-	1	1	1	1	1	
Intelligent Manufacturing			-	-	3 +2	3 +2	4 +2	-	-	3	+2
	Off-site Manufacturing	CAM (Computer Aided Manufacturing) e.g. CNC (Computerized Numerical Control)	-	-	+2 3	+2 3	+3 4	-	-	3	+2
	Additive Manufacturing	3D printing	-	-	1	2	1	-	-	1	
	Robots/Cobots	unhuman workers/exoscheleton	-	-	-	+1 3	+3 4	-	-	4	+2
	Drones	unhuman flying site survey	-	1	-	-	1	-	-	1	
	RFID	product unique code tracking	-	-	5	5	5	3	-	5	
	Advanced Materials	innovation in new materials adoption	-	-	5	5	2	-	-	4	
Extended Reality			-	-	1	3	2	2	-	2	
	VR, AR, MR	Virtual/Advanced/Mixed Reality	-	-	1	3	2	2	-	2	
Smartness	3	Stages score	5	3	4	4	2	3	1		

Figure 124: LC 4.0 Assessment application after the implementation

Figure 125: Existing Building Refurbishment by Panelization, Corte Franca (BS), Italy [Edera]

6. Panelization Design Tool

"Complicating is easy, simplifying is difficult. To complicate, just add all you want [...]. Everyone can complicate. Few are able to simplify. To simplify, you need to [...] know what to remove, [...] recognize the essence of things and communicate them in their essentiality. [...] Simplification is the sign of intelligence [...]: "what you cannot say in a few words cannot be said even in many" (Chinese proverb)."

B. MUNARI

Scope:

The need to refurbish the older existing building stock and the market opportunities (tax deductions from Fit for 55 [170]) can push the recladding of existing buildings through the application of façade panels [Obj 2.1, RQ 4.1.1]. A decision support system is developed to facilitate the decision-makers choice of one solution among different technologies and materials [RQ 4.1.2, RQ 4.1.3] in the Early Design Stage.

The theoretical information flow is tested in the tool to overcome the recognized information gap and the lack of interoperability between different actors across the different phases. All the tool steps are described according to the n BIM dimensions, while results are shown in different shapes and solutions.

The Panelization Design Tool consists of a parametric script able to scan the existing IFC (BIM open source file format) and create a second (or new) cladding according to geometrical constraints given by different stakeholders (e.g. architect, panel manufactures, logistics, general contractor). The tool compares lightweight concrete and timber frame panels against a traditional insulation system (ETICS) by checking the energy performance (U-Thermal transmittance and H't-Global average heat exchange coefficient), structural resistance (panel deflection, anchoring typology, position and number), geometry (size and panels number, corner solutions), time and cost, plus sustainability (LCA). All these results are collected and compared by multiparameter radar and graphs (Analytical Spidergram) with scores (Marked diagram) and grouped by categories (BIM nDiagram), plus a web-based viewer. These outputs are intended as facilitators to support non-technicians in effective decision-making by better understanding different technologies' differences and performances through complex digital tools [RQ 4.1.4].

Contents:

Expected results:

- State of the Art of existing tools and identification of their gaps
- PDT Scope & Goals explanation
- Main actors' identification
- In-Flow definition by phases, data flow and data sets
- Tool steps definition
- Relevant parameters choice
- Case study test
- Results representation
- Effectiveness of the technological comparison

Keywords:

Design Optioneering; Panelization Design Tool; BIM nD; Recladding; Refurbishment

The fourth P, added to the 3P evolution, is the "**Palinsesto**", intended as the necessity to act on the existing building stock, instead of investing in new constructions. The research trend of European projects, the interest in advanced manufacturing and the opportunity coming from the Italian government fund push the interest in applying MMC and DfMA to refurbish existing buildings (Figure 126). The strategy is to add a layer to the existing envelope, giving them much more quality and performance (e.g. thermal, structural, acoustic). The activity of applying prefab panels to recladding the building is called Panelization. It is based on producing 2D offsite elements carried to the construction site and installed without scaffoldings. The dry-assembled system is loaded by crane and anchored to the existing building structure (beams and slabs more frequently than loading walls), having a faster, cleaner and much more efficient construction phase. Thus, the high technological complexity of these elements requires a precise and detailed design because all the elements are factory produced and their onsite adaptability is demanded only for joint and anchor positioning. For this reason, Digital Design support is particularly relevant for them. A decision support system for owners, designers, or developers can be a strategic instrument to avoid redesigning the elements due to technological, material, production and manufacturing problems.

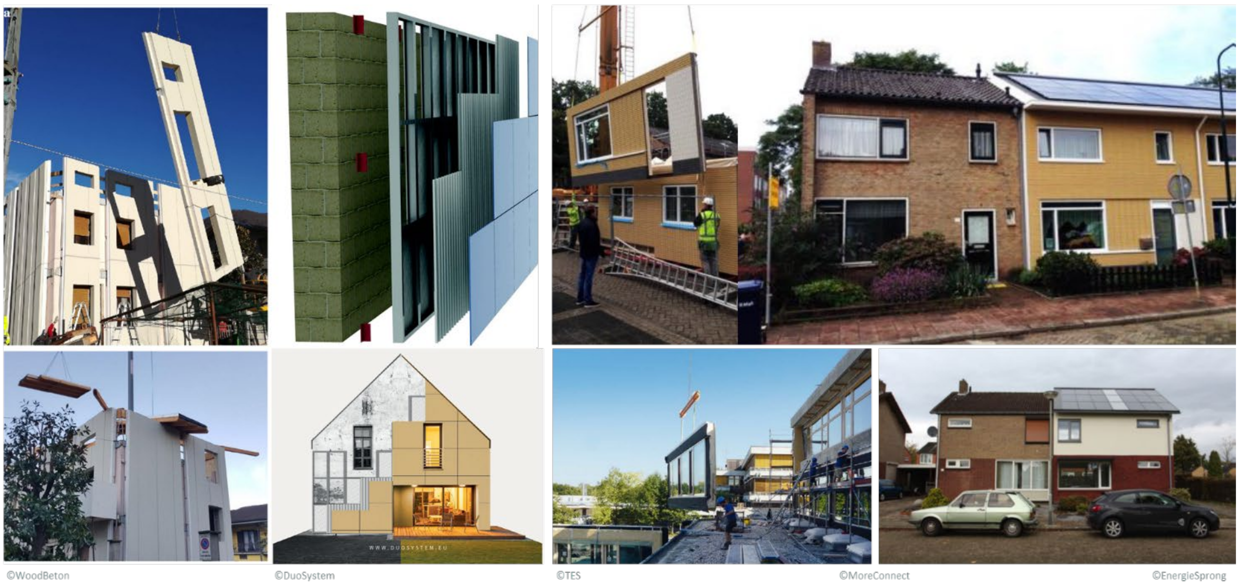


Figure 126: MMC & DfMA for retrofit. Panelization application to existing buildings examples

6.1 a Decision Support System for offsite façades

Panelization Design Tool is a multi-software (Excel, Revit, Grasshopper) tool created to test the LC4.0 theoretical framework defined in a specific Secondary Technology with great potential for the future. This original instrument aims to apply a holistic design approach to recladding through the Design Optioneering (DO) method on meta-technological façade options. It is a Decision Support System (DSS) to provide a more informative decision process that applies the DfMA and BIM nDimensions approach to offsite solutions (Figure 128). It unlocks the value of Knowledge-Based Engineering in façade design by linking data and proposing results in an easier and based on gamification way that follows the simplification approach against the complexity of *Munari*[14].[171]

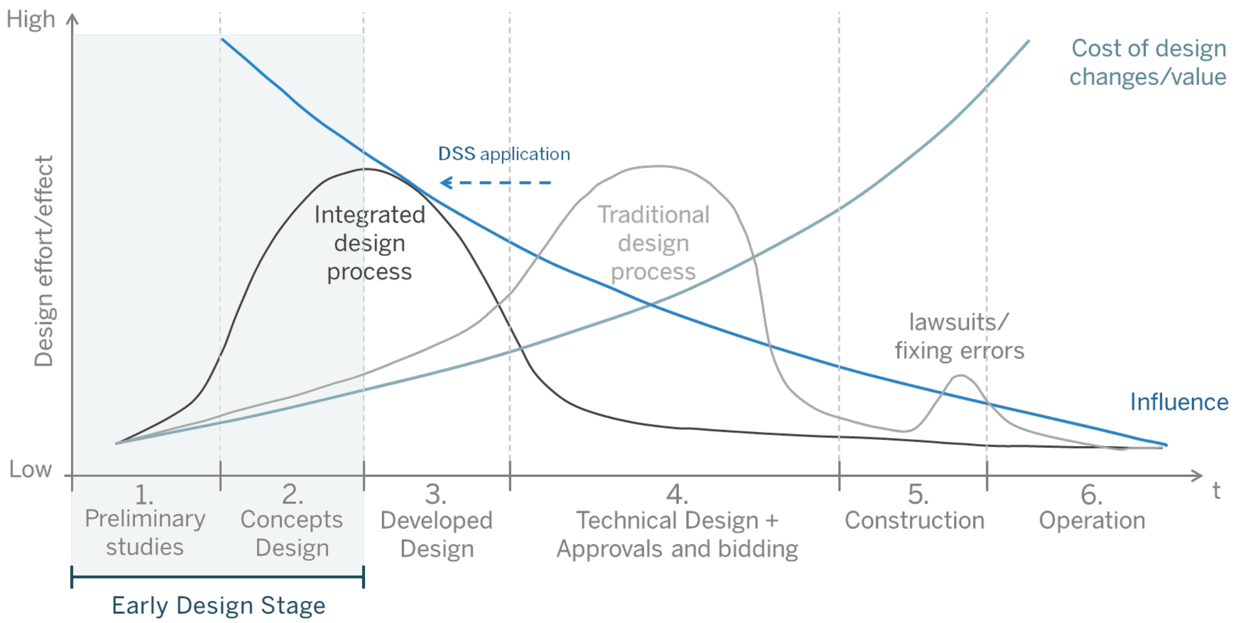


Figure 127: Decision Support System for the Early Design Stage

Moving choices to the Early Design Stage, it is possible to save effort and time, valorizing data to make an informed decision. This instrument collects key parameters for different actors (designer, manufacturer, owner, architect and constructor) to compare other technological panel solutions. 2D panels are defined as meta-technological products characterized mainly by material and technology (timber frame or concrete, e.g.), figuring a rough geometrical solution that can exploit KPIs to make an effective decision.

[14] Bruno Munari (1907-1998), one of the most influencer artist, designer and writer of '900.

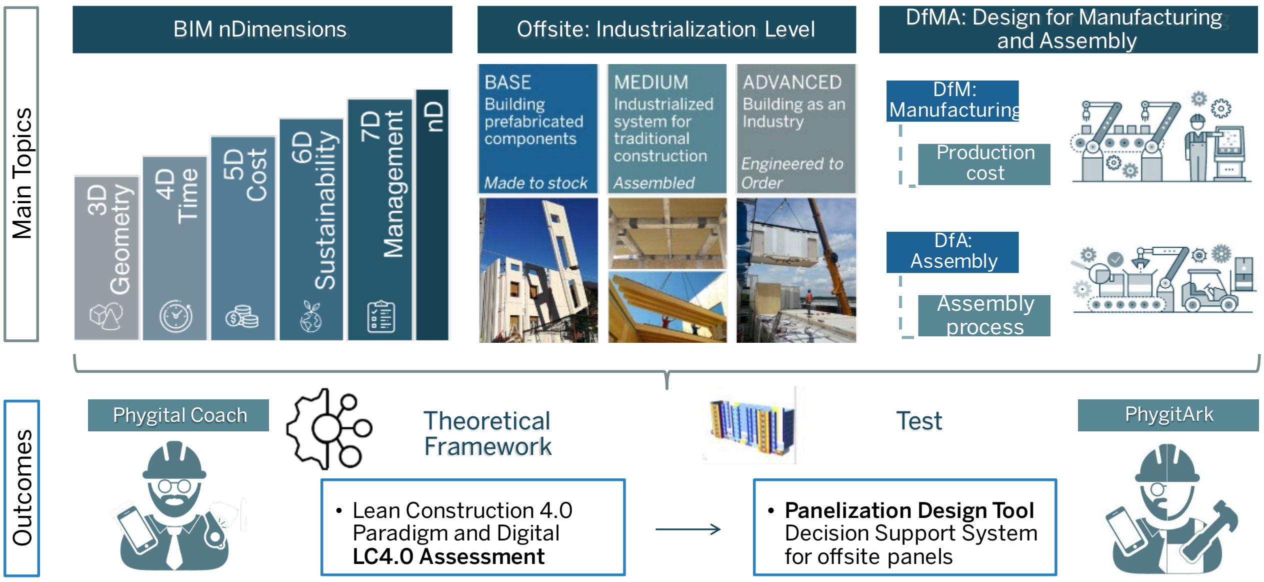


Figure 128: Lean Construction 4.0 Ontology

The tool is tested on an existing residential building in Milan suburbs to validate MMC solutions' advantage in the retrofit. “Via della Birona” building is the BIM4EEB case study for applying the **Building Information Model Management System (BIMMS)**: all the platform tools will be tested for intelligent, open-source data management [172]. The residential building of the 1960s period is nine floors and 65 apartments, with a post and beam concrete structure and it was retrofitted with a simple ETICS system in the H2020 project (Figure 135). Task 7.5 provides for *BIM-enabled design for prefabricated thermal insulation components,* providing conceptual guidelines without applying them to a real case study. However, as an original outcome of this research, the tool is created to test the Common Data Environment and the LC4.0 information flow during the whole lifecycle [173].

Figure 129: “Via della Birona” Case Study, Cinisello Balsamo, Milan [Google Earth]

6.2 Methodology

The tool aims to have a **multi-criteria optimization across the nD dimensions of BIM** (geometry, energy, structure, time, cost, sustainability and facility management from 2 to 7D), allowing the choice between different technological solutions (concrete, timber and steel). Geometry is solved according to the existing model, starting from architectural, structural, manufacturing, logistical and energetical **constraints** that different actors (e.g. architect, engineer, norms, façade designer, manufacturer, owner, general contractor) provide. The tool is optimized for the Industry Foundation Class (IFC), the open-source BIM file format, for a solid, informed decision process.

The geometrical model is built starting from the existing building, while the architect generates the BIM model by adding information to the 3D shape. The script read geometry and data stored in the model generating multiple panelization solutions that fit the manufacturers' technology as BIM Library. At the end of the process, various solutions are shown to the decision-makers categorized by the n BIM dimensions.

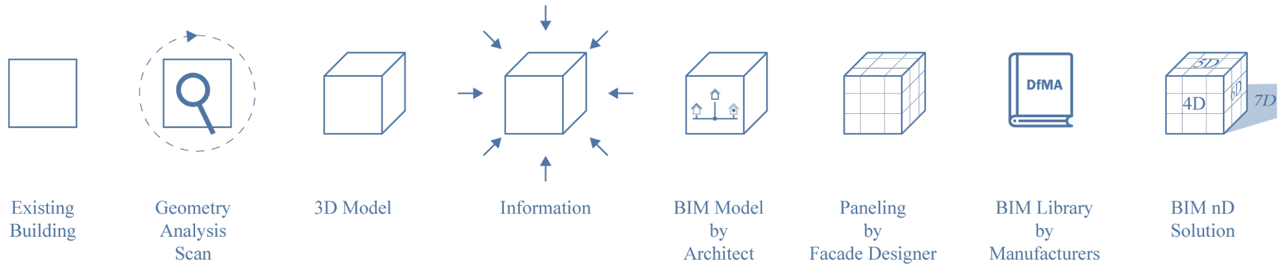


Figure 130: Panelization Design Tool steps

Comparing this tool to the existing ones, it gives:

- A multi-objective informed design process can provide for the requirements coming from all the actors involved in the process;
- A progressive information addition in the whole design process across all stages, starting from Analysis until the End of Life;
- Manufacturing optimization and compatible design with shop drawings production prevent the multiple iteration process between design and production;
- A double sensitivity and analytical analysis of different parameters covering all the BIM n Dimensions. nD approach is beneficial in simplifying multiple data thanks to a neutral perspective for all the stakeholders (e.g. architects, facade designers, sustainability managers, manufacturers, façade construction specialists, general contractors, building asset managers and owners) involved in the process with their different points of view.

The Tool's process and architecture are based on dismantling the process in stages, as described in Figure 130. The method to compare meta-technological solutions is to identify KPIs per each field, from geometry to building physics, structure, time and cost and resource consumption. The instrument's effectiveness is tested on a real building case study by comparing and analyzing results by showing them to technicians (façade designers and manufacturers).

The existing tools can be divided into two main categories:

- Technology-focused tools for recladding: instruments created from façade design and manufacturing European Research Projects or producer (e.g. design, construction, cost), but without material and technology flexibility. Many of them are not open source or available to test.
    - E.g. Renozeb, Legnattivo, 4RinEu,Impress, Universe façade solution

- Generic tools for new buildings: they are created by engineering consultants (not open access) covering some specific aspects or a cluster of them (e.g. generative design and energy/sustainability), but all of them together.
    - E.g. Arup Inform and CRISP, Buro Happold Bespoke, Parametric Design

The relevance of the EDS topic and the need for instruments to make more informed data-driven decisions are confirmed by the investment of many engineering offices in instruments like these. The closer one to the functionality described before is *Inform*, where a multicriteria analysis is provided and synthetized by a spider gram. However, this tool was released in November 2022 and did not involve time/cost analysis and carbon assessment features (CRISP tool). Its focus, as well as Parametric Design, is to create a range of building shape options according to efficiencies in terms of square meters, apartments number, etc. They are designed to create or replace existing buildings merging the developers' purpose with sustainability aspects.

Compared to existing tools, PDT fully integrates all the phases of the building life cycle, even thou in an early design stage evaluation. Like the Horizon2020 projects, it is focused on recladding, with the possibility to apply it also to strip out and recladding or new building construction very easily. Apart from the simultaneous or later development and release to PDT, it can merge many different topics and the flexibility of technologies compared to other research projects. Furthermore, the open platform allows implementing and increasing the LOD/LOI level according to the purpose, also adding new layers of analysis inside the existing one (5D can include a ROI with NPV and risk evaluation or a TOC business model) or other dimensions of BIM (8D security).

The tool was developed on a simple box-shaped building without any complexity (out-of-squares facades, balconies, etc.) and then tested on a more complex building nearby Milan (Figure 129). A second step test is provided by changing the shape of this building to verify the tool's capability to adapt to different geometries. Many other case studies are in progress, together with the development of various adding features, thanks to the open platform design.

PDT was shown and described to different façade designers and technical offices from manufacturers involved in the LC4.0 Assessment in single interviews. Their feedback was positive even thou they had no chance to test the tool because many have few competences in parametrical design and the front-hand part is not yet implemented. Designers were selected among engineering consultants that work on façade design and production from relevant offices (Arup, Bollinger & Grohman, Eckersley O'Callaghan, Deerns). Both designers and manufacturers highlight some possible implementations that are under development. All the results discussion and further developments are better described in § 6.5.

6.3 PDT Process description

Starting from the Inflow and the Panelization Dataset, the PDT focuses on the Early Design stage (Concept and Preliminary Design), where decisions are taken with a more considerable influence on the overall result (Figure 131) [174].

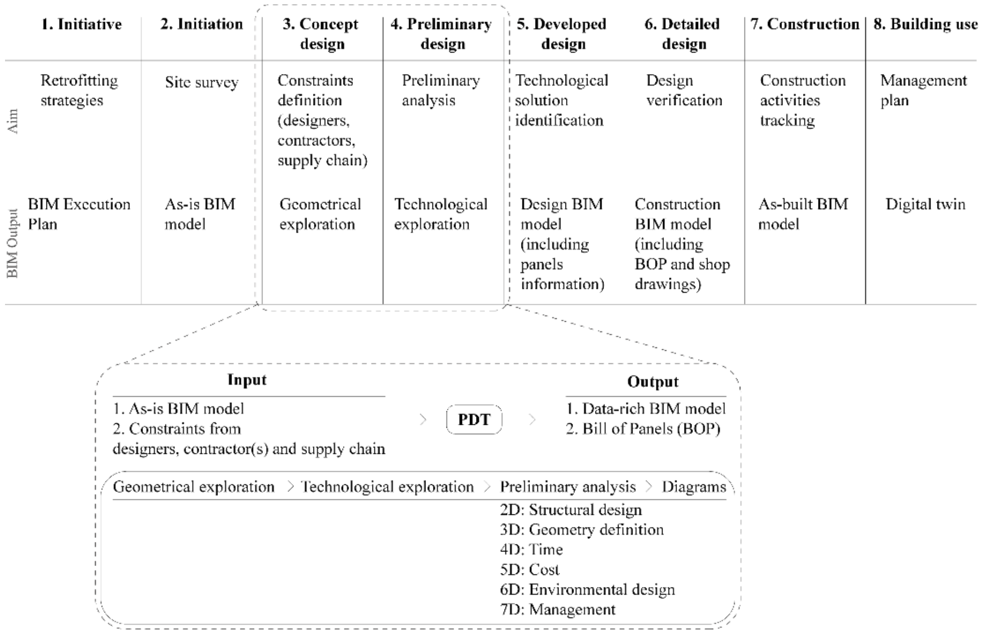


Figure 131: The PDT application in the building stages

This Decision Support System (DSS) evaluates data that concern all the processes according to the BIM nDimensional approach but provides information for the Design (De), Production (du) and Construction (action) phases. Unlike the Inflow, the Deduction Flow (Figure 107) did not include the installation, maintenance and dismantling instruction because of the meta-technological level where it acts. These aspects can be a further implementation of the next steps. Deduction Flow purposes explain what kind of data the tool provides for each step across the process.

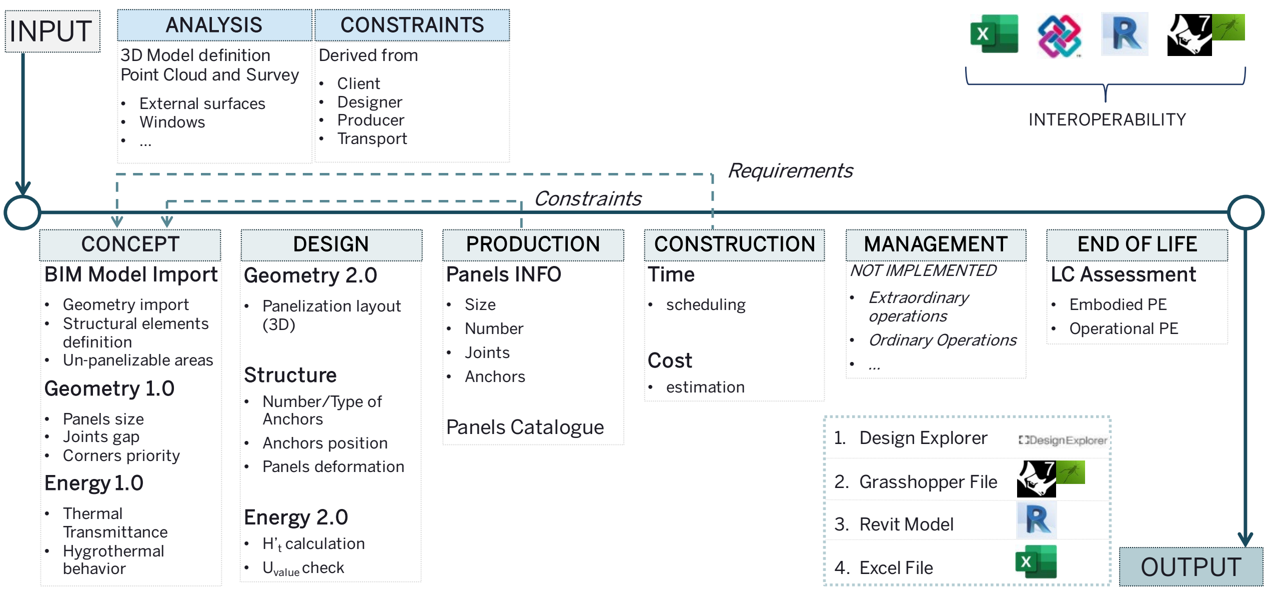


Figure 132: Deduction Flow for Panelization Design Tool showing data and information provided at each step for every stage of the process.

The script processes these two input typologies to define a geometrical solution providing the required performances according to the technological solution. The tool is planned to work at a meta-technological level, different from the a-technological one. The test offers two diverse panel sub-structure and layer compositions starting from existing BIM families, simulating a realistic – but not strict – technological solution (Figure 133). They are not referred to as a specific product but a concept product [175] where the façade designer project can implement and modify the technological solution. However, they are both based on two technologies already applied in the market and developed inside European Research Projects: EASEE [176] for the Lightweight Concrete Panel and TES [177] for the Timber Frame Panel.

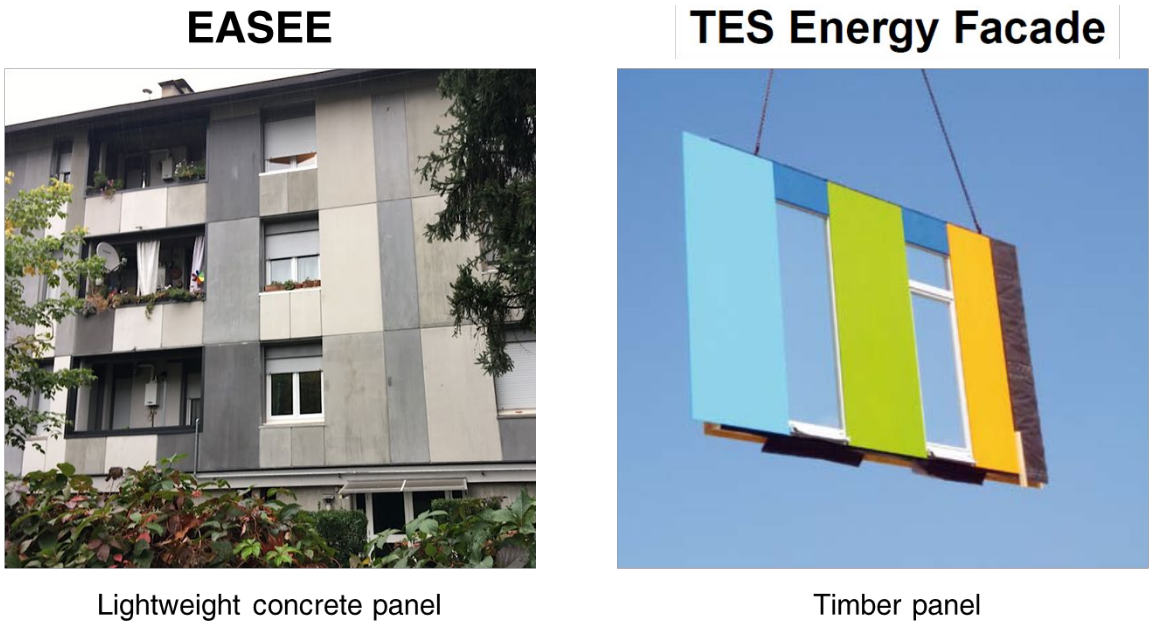


Figure 133: two technological choices for PDT

The iterative process finds different solutions, including all parameters and their acceptable ranges according to regulation and experience collected in the nD of BIM [174]:

- 2D Structure:
    - Anchoring positioning, typology and number
        - Number of anchors / m2 (n°/m^2) [0-2];
    - Panel deflection
- 3D Geometry:
    - Sizes
        - Number of total panels / Total cladding surface (n°/m^2) [0-1];
    - Corner solution
    - Bill of Panels
        - Number of different panel types / Number of total panels (-) [0-1];
- 4D Time:
    - Scheduling
        - Installation time (h/m^2) [0.02-0.27]
- 5D Cost:
    - Cost
        - Total cost (€/m^2) [80-250]
- 6D Sustainability:

- Building Physics:
  - Thermal transmittance U (W/m^{2}K) [0.13-0.26];
  - Global average heat exchange coefficient H't (W/m^{2}K) [0.3-0.75];
- 7D Management:
  - Life Cycle Assessment
    - LCA (PEren/PEtot) [0-1]

6.3.1 In-flow

A specific dataset is provided for the offsite panels (product) application. It is defined as the entire process of linking the information to a single task to the data requirements.

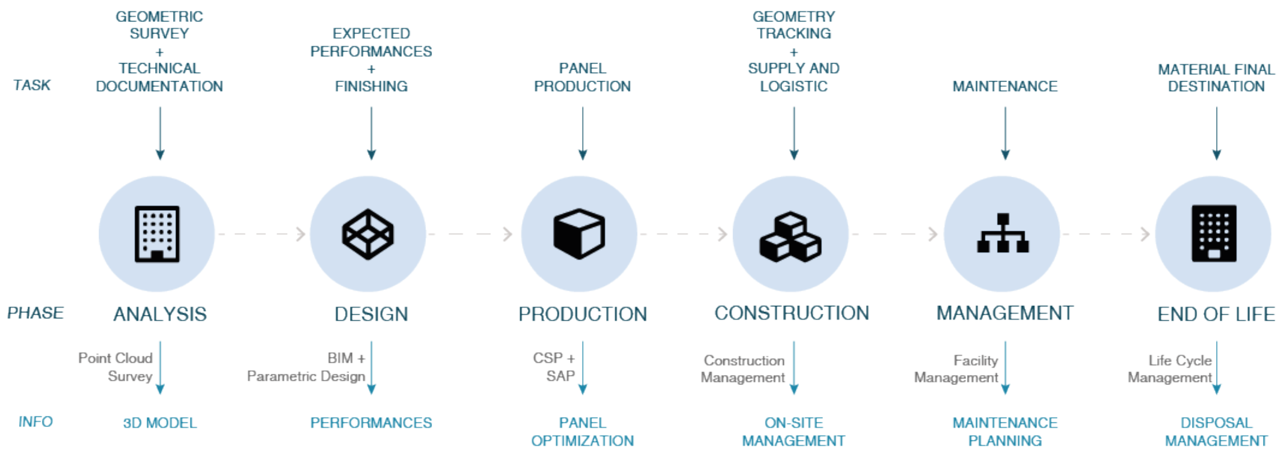


Figure 134: In-flow process divided by phases, information, tasks, data and software

The information flow (In-flow) allows for defining the data path across distinct actors in the various phases. Data input will come from the IFC as-built model (geometrical data and building features) and an accessible exchange format (CSV or XLS) for the single stakeholders' constraints. Shape, sizes and thermal/structural resistances are boundary conditions from the logistic, manufacturing, architectural and engineering figures [178].

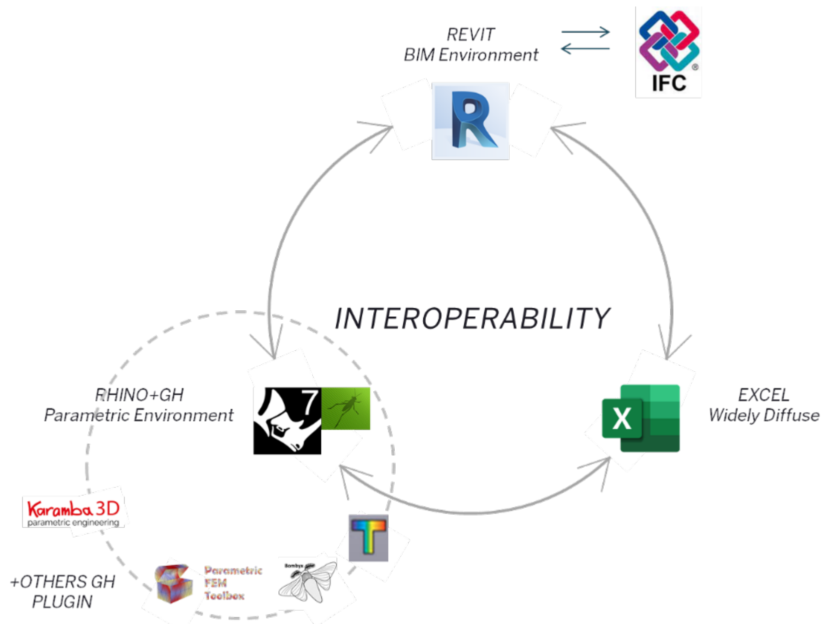


Figure 135: Interoperability of PDT

The tool is based on interoperability between different instruments (Figure 135). The hyper-specialized digital environment required multiple approaches defining other instruments specifically for various tasks. The open-source BIM format is read by the most diffused BIM program (Autodesk Revit), which can now be live-managed by a parametric tool like *Rhino Inside Revit*[15], a Grasshopper (GH) plugin. The decision to use GH instead of the integrated parametrical program inside Revit (Dynamo) exploits the more extensive development of the first one thanks to a longer lifetime and the number of available tools.

At the same time, the purpose of having a lean information process, open to everyone and not only to technicians (computational designers), led to choosing a simple excel file as the input source. Reading the constraints from the XLS file and activating all the tools involved inside GH (e.g. Therm, Parametric FEM Toolbox, Bombyx, Karamba 3D) and outside (Dlubal, a Finite Elements Mesh structural program), the system can solve the geometrical question.

The generated information is stored in the BIM model and mapped from source to end-user (Figure 136).

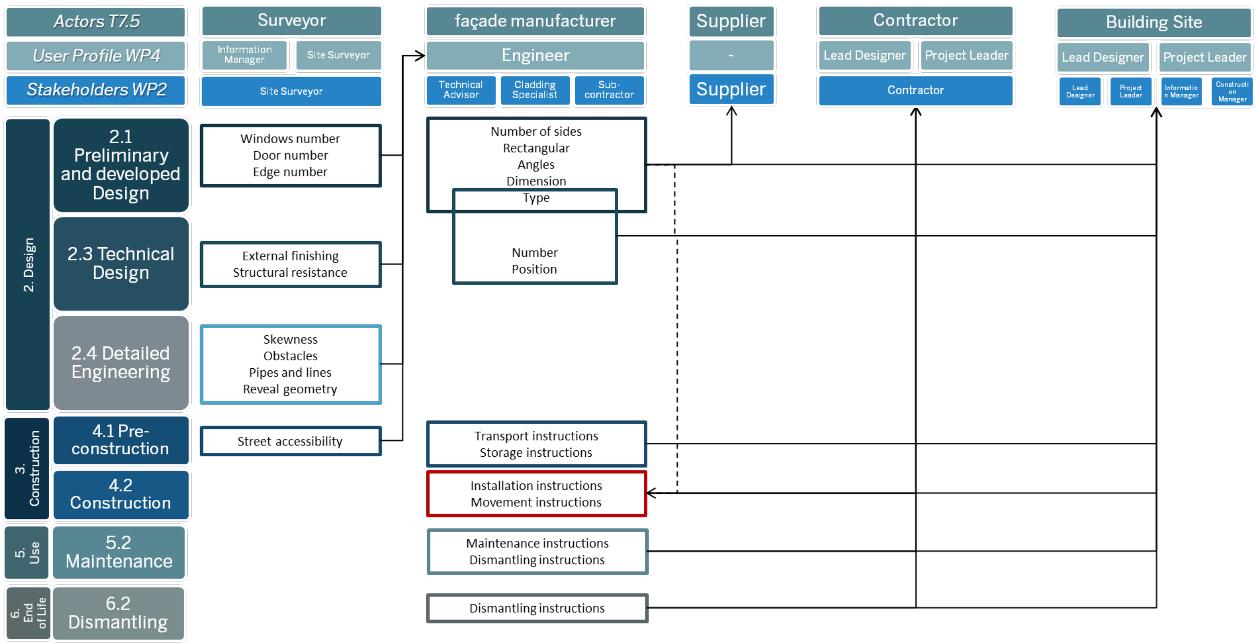


Figure 136: Panelization Dataset and data exchange between various actors in all the building stages

6.3.2 Steps

Steps start from the double Input of a BIM Model (6.3.2.1 BIM Model import) of the existing building and Geometrical constraints (6.3.2.2 Geometrical Constraints). The following steps regard the geometrical definitions of joints, anchors and corners (6.3.2.3 Geometry 1.0) to exploit the first environmental performances (6.3.2.4 Energy 1.0) from which thermal transmittance and hygrothermal behavior are verified and compared to norm and law. Once the regulations are respected, the 3D model of panels is created (6.3.2.5 Geometry 2.0) and the second level of analysis begins. Here the verification of anchors' position, their types and number, plus the deflection of panels, is checked into from the structural point of view (6.3.2.6 Structure). At the same time, the second environmental analysis concerns the thermal bridges

[15] "It is an addon for Autodesk Revit® that allows Rhino 7 to be loaded into the memory of Revit just like other Revit add-ons. Rhino.Inside.Revit brings the power of Rhino 7 and Grasshopper to the Autodesk Revit® environment." [Robert McNeel & Associates]

to exploit the global envelope performance (6.3.2.7 Energy 2.0). Completed the simplified Design phase, it is possible to export the Bill of Panels (BOP) for the Production phase (6.3.2.8 Production), the Bill of Quantities (BOQ) together with time and cost for the Construction phase (6.3.2.9) also assessing the Life Cycle Analysis (6.3.2.10 End of Life). Finally, Results are exported as CSV files, the BIM Panel model and an Excel sheet (6.4 Results) to have different reading levels according to various users: technician and non-technician.

All these aspects are collected in an Excel file composed of 16 sheets. It makes simple to implement the tool by adding new sheets for further dimensions of analysis or other technological solutions. The list of sheets is composed by:

1. Constraints Timber: definition of the geometrical constraints of timber frame panel
2. Constraints Concrete: characterization of the geometrical constraints of lightweight concrete panel
3. Layers: description of material layers for all the technological solutions and the as-is wall
4. Weight-U comparison: thermal transmittance value technologies comparison
5. Layer's properties comparison
6. Thermohydrometric: Glazer and vapor saturation trend superficial and internal
7. Wind-load: quantification of wind pressure applied to the façade
8. Building: volume/surface analysis of existing building
9. Thermal Bridges: quantification of losses due to linear thermal bridges
10. HD: Direct Heat Transfer coefficient definition
11. HG: Ground Heat Transfer coefficient definition
12. ETICS BOQ: Traditional insulation solution Bill of Quantities
13. CLS BOQ: Lightweight Concrete panel solution Bill of Quantities
14. Timber Frame panel BOQ
15. Comparison BOQ
16. Windows

The detailed steps, the chosen parameters and the applicability range are described below.

6.3.2.1 BIM Model Import

The As-is BIM Model uploaded can be IFC or RVT file. It can be a single or federated model (splitted into Architectural, Structural and MEP). The goal is to define the external shape of recladding, openings (windows and doors) and key levels (finished and structural floors) and identify the structural families to whom the prefabricated solution should be anchored. For this purpose, walls, families and structural BIM families must be identified manually by PhygitArk, selecting the *Element Type* for each *Model Category* as geometrical elements to import. This implies some troubles as:

- the elements imported in Rhinoceros lose all their non-physical information;
- it is necessary to know the Type name of the element to import precisely: it is not possible to automatically import all the envelopes' parts;
- often there is no uniformity in 3D geometry: each designer has its own standard to draw (e.g. wall position about structure, jointed elements) with personal families.
- Therefore, a deeper knowledge of the instrument and a strict correlation with the as-is BIM model designer can be required.
- Importing external walls causes holes and gaps due to the 2D line associated with the parametrical family: corners priority is not considered.

The purpose of this first step is to define the geometry intervention by identifying the horizontal perimeter (floors) and their position (levels), the vertical surfaces (external walls: as-is envelope) and structural elements (beams and columns). This is why the process is defined on the reverse; it is possible to create the 3D envelope to reclad starting from the inner perimeter.

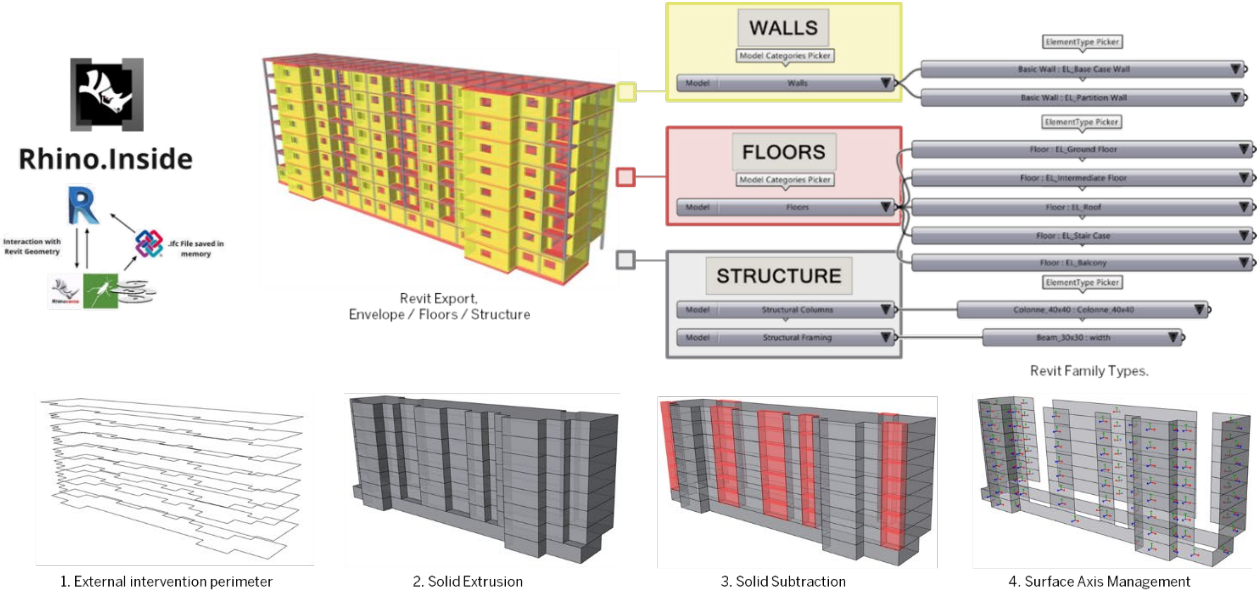
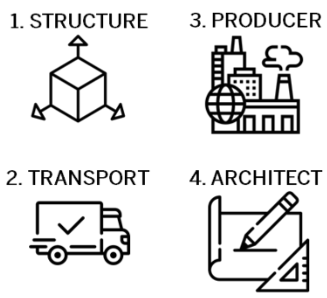


Figure 137: 3D Model Import and identification of structural BIM families

Once the 3D volume of the building is created, starting from 2D floors, a subtraction operation is planned to remove the non-penalizable sectors (loggias and balconies). The last check is the surface axis orientation to correctly locate the panels on their internal and external sides once they are created (Figure 137).

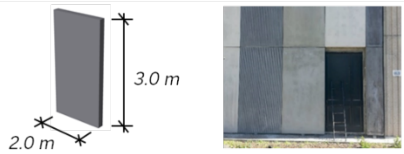
6.3.2.2 Geometrical Constraints

Dimensional constraints provided are collected in an Excel sheet to be compiled by different actors such as clients, architects, engineers, manufacturers, transporters, etc. (Figure 138). The size constraints come from the shape desired (L/H ratio: close to 0 for vertical panels, close to 1 for squared), the transport truck availability in the location and according to the street path between the factory and the construction site and, overall, the production limits of the machines and the manufacturer. The number of constraints and stakeholders is variable because the tool can read any number of rows. In this phase, selecting one material according to the client's or architect's preferences is also possible.



Light-weight Concrete panel

CONSTRAINTS	max WIDTH [m]	max HEIGTH [m]	Ratio
L/H RATIO	/	/	0.1
TRANSPORT	2.30	12.00	/
PRODUCER	2.00	6.00	/
ARCHITECT	2.00	3.00	/



Timber Frame panel

CONSTRAINTS	max WIDTH [m]	min Width [m]	Ratio
L/H RATIO	/	/	/
TRANSPORT	12.00	2.30	/
PRODUCER	18.00	5.00	/
ARCHITECT	25.00	1.00	/

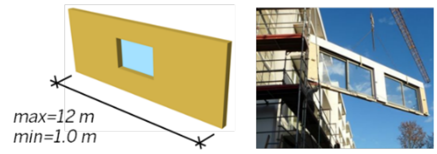


Figure 138: Different dimensional constraints for PDT according to technologies

6.3.2.3 Geometry 1.0

The tool generates different possible two-dimensional (2D) panels layout according to the constraints defined in the previous two steps. Here it is possible to identify the main subdivision of panels (vertical joints position) and the lower/upper window panel for concrete technology with a live check of panels that are not respecting the constraints. A rough calculation of different panel numbers and the total number of panels is also provided, excluding further geometrical details.

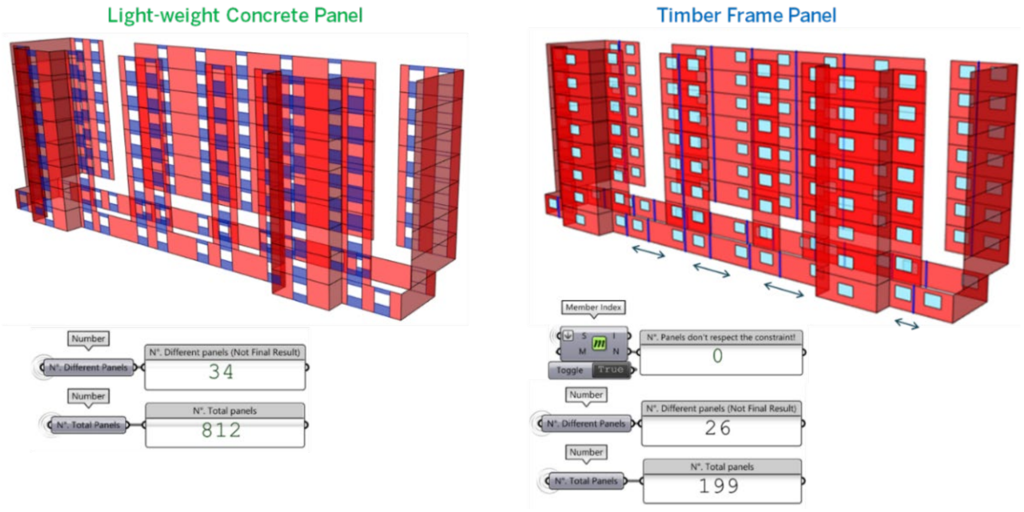


Figure 139: First geometrical exploration of panels layout, with total panels' number and different panels' number

6.3.2.4 Energy 1.0

Different technological solutions are defined by the layers list. Starting from the existing wall, the performances in terms of thermal transmittance (U [W/m^{2}K]) and hygrothermal behavior Z_{TOT} [Pa*s*m^2/kg] are checked according to the norm and law limits (Figure 140).

The parameters required for this step are:

- Thickness (mm)
- Thermal conductivity λ [W/mK]
- Gross density [kg/m^3]
- Specific heat capacity C [J/KgK]
- Coefficient of resistance to water vapor diffusion [-]

While the outputs automatically generated are:

- Weight [Kg/m^2]
- Heat transfer coefficient [W/m^{2}K]
- Thermal resistance [m^{2}K/W]
- Resistance to vapor permeation [Pa*s*m^2/Kg]

If law limits are not respected, adding insulation or radically modifying technologies is necessary.

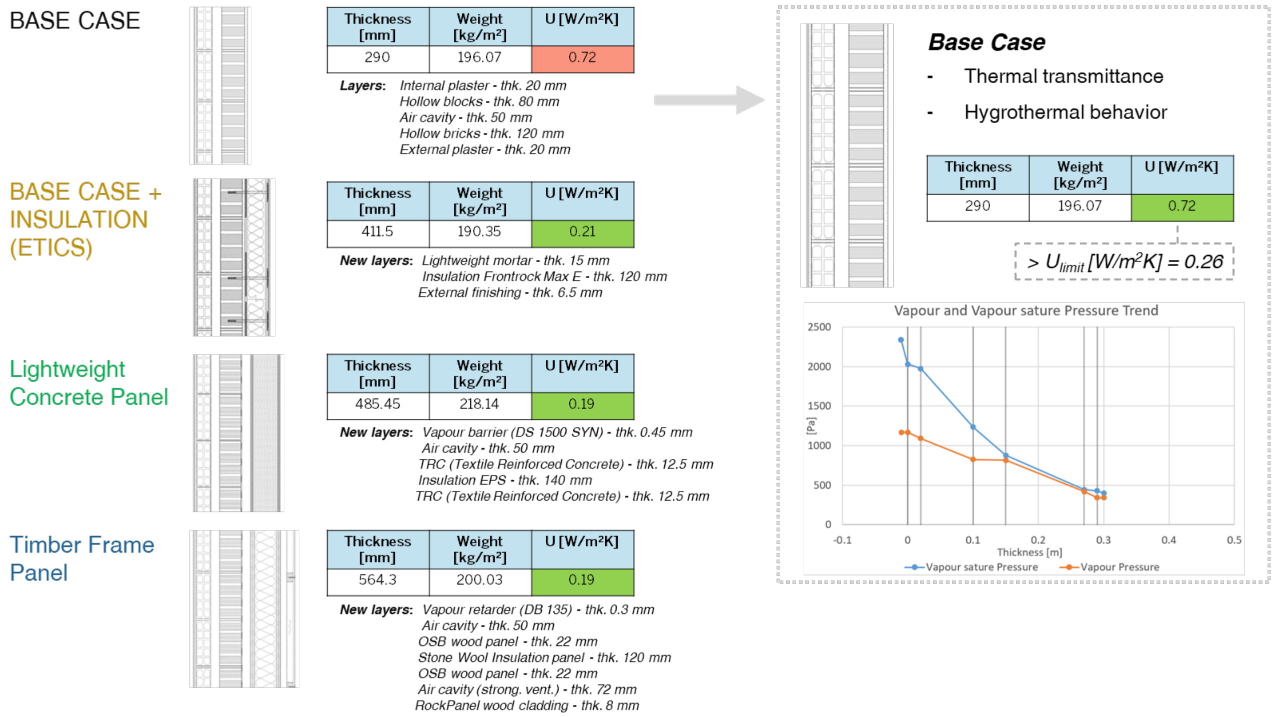


Figure 140: First technological exploration by thermal transmittance (U_D) and hygrothermal behavior (Z_{TOT}) compared to norm and law

6.3.2.5 Geometry 2.0

The second level of geometry design concerns the definition of corners, the width of joints and the anchors' position on the existing façade.

- Corners' priority can be defined locally at every position according to architectural preferences. Due to the panel's structure and technology, the 45° cutting is available only for Concrete solutions.
- Joints of lightweight panels are completed by curtain cord polyethylene coupled with an acrylic silicone sealant sizing 2 cm, while the timber technology has no joint to plan because the silicon between them is pressed.
- Anchors localization on the façade allows verifying positioning aligned with the structural elements (beams and slabs). It is possible to manually move the object modifying the panel typology according to it. A linked output is the plotting on the façade of the mutual distance between anchors and fixed elements (e.g. façade edges and windows), useful for the installation phase.

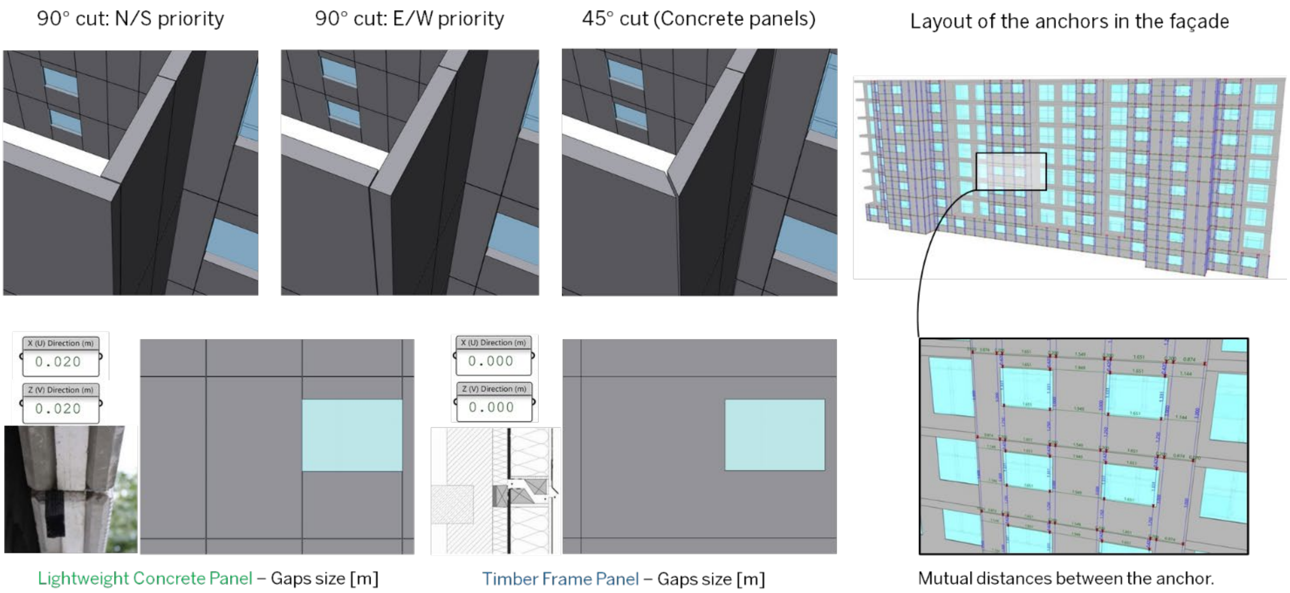


Figure 141: Joints and Anchors positioning

6.3.2.6 Structure

Anchoring type and size are checked according to the panels' weight (kg/m^2) and the panels' material: Halfen connections are provided for the concrete panels, while dowels and plugs are chosen for timber technology (Figure 142).

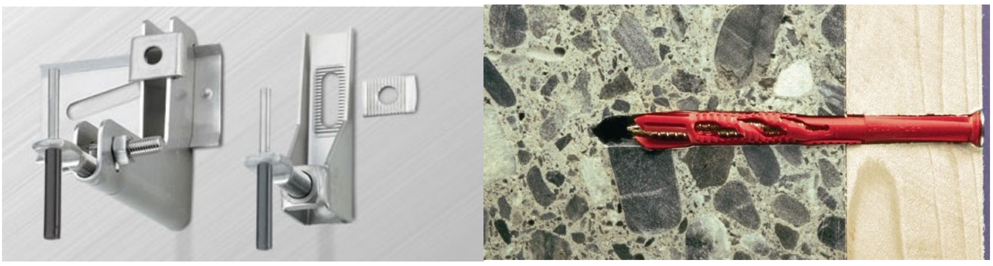


Figure 142: Anchoring type for Lightweight Concrete Panels (left) and Timber Frame Panels (right)

The second sub-step of structural analysis concerns the deflection of panels according to the anchors' number and their link to the building. This feature is available only for timber frame structures with or without windows (Figure 143). It provides changes in the mullions wheelbase (60 cm in the picture), plus the number of screws fixing the external cladding to the substructure (30 cm).

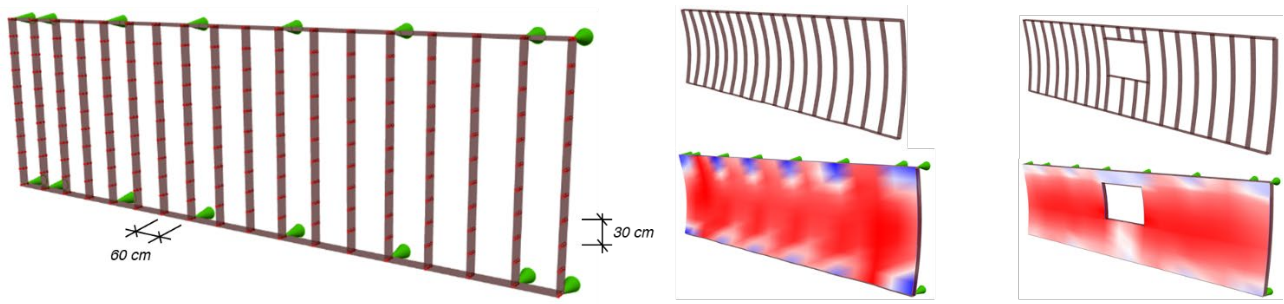


Figure 143: Timber Frame structural analysis with and without window

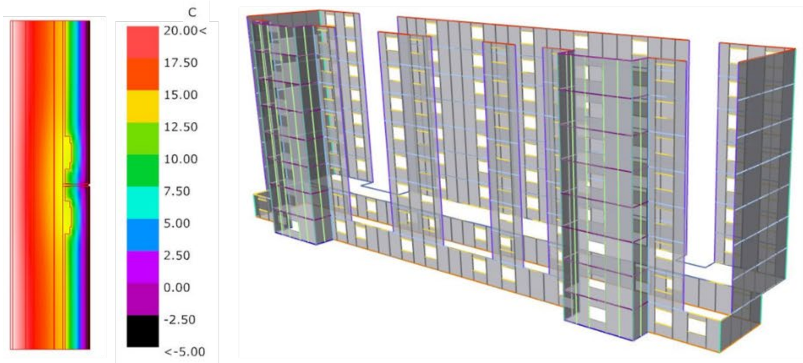
Further development of the structural analysis consists of the possibility to live export and import the 3D panel model to a Finite Element Method (FEM) software, as the Dlubal GH plugin can do. It opens to wider studies, such as seismic analysis, using the panel as an external skeleton to add to the existing envelope.

6.3.2.7 Energy 2.0

The last technical analysis is the global envelope performance: H't value collects the thermal transmittance of opaque and transparent surfaces plus the linear thermal bridges between the panels. The dispersions are parametrical calculated, collected according to their thermal performance through a GH plugin (THERM) and multiplied by length. The tool highlights them on the panels with different colors (Figure 144). This calculation is based on UNI EN 13789:2008 and UNI EN ISO 13370, excluding the heat exchange to other buildings and hypnotizing that all the rooms are air-conditioned and there are no punctual thermal bridges as simplification. The thermal bridge types considered are roof, perimetral walls, windows, non-panelizable horizontal and vertical surfaces (loggias and balconies are treated with the ETICS system) and French doors according to their exposition length. According to the typology assigned to every single thermal bridge, the tool can read thermal transmittance (Ui) values on the excel file. The results collected from the tool are:

- The total area of each side (m^2);
- Total A*U of each side (W/K);
- $U_{average}$ of each side (W/m^2K);
- Total area of each element (m^2);
- Total A*U of each element (W/K)

These results automatically come back to the excel file, where, selecting the boundary conditions, it is possible to exploit results. It is essential to highlight that there is no more profound analysis of transparent surfaces in this process, but they play a crucial role in the global envelope performance. This is why the excel file includes the possibility of substituting them, but in the case study, the as-is situation regards a double-glazed wooden frame (4 mm thick each) with an air cavity of 15 mm that is not replaced in this intervention.



	Base Case	Base Case + Insulation	Lightweight Concrete Panel	Timber Frame Panel
Thickness [mm]	290	411,5	485,5	564,3
Weight [kg/m²]	196,07	190,35	218,14	200,03
U [W/m²K]	0,72	0,21	0,19	0,19
H'_T [W/m²K]	-	0.53 < 0.75	0.55 < 0.75	0.53 < 0.75
Total dispersion [W/K]	-	3057.37	3209.22	3093.09

Figure 144: Thermal Bridges parametrical analysis to assess the global heat exchange coefficient (H't)

The final result shows the better thermal transmittance performance of offsite solutions. The overall envelope performance is the same for the ETICS system and the Timber Frame because of the heating resistance of wood. Concrete has a lower performance due to its conductivity: the bigger joints and the larger number (wooden panels have wider size) cause a more significant thermal performance decay, as visible by the total dispersion count.

6.3.2.8 Production

During the previous steps, it is possible to go back to the design gate changing technology and performances of materials. Once the regulations are respected, finalizing the BOP and extracting essential data for production is possible. The total panel number and the number of different panels (Figure 145) are key parameters for realistic output regarding production costs and construction efficiency.

Figure 145: 3D Panels layouts output generating two parameters: the total number of panels and the final estimation of different panels number

The tool can also assign different names to every panel according to the chosen rules and use colors to mark them for the first construction process definition (Figure 146).

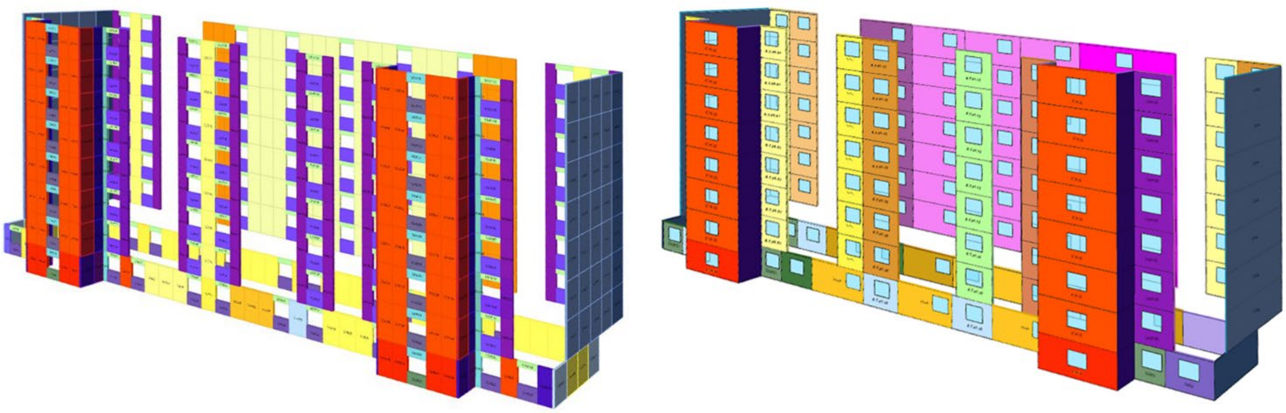


Figure 146: Panels' Catalogue per color of Lightweight Concrete Panels (left) and Timber Frame Panels (right)

6.3.2.9 Construction

The BOP list is the starting point to calculate time and cost by splitting costs into materials, labor and rent/transportation, plus General Business Expenses and Profit. The calculation is provided per square meter to easily extend the result to the whole envelope. According to the working teams involved, time analysis is provided per panel number and size. It is supposed to have only one working team equipped with a truck crane and workers basket for panels, while four teams over scaffolding mount ETICS system to make comparable and realistic the comparison of offsite solutions to onsite. The single values assigned to cost and timing are not the tool's focus because they can be easily changed according to market variation. The most important aspect is the capability of the tool to assess the quantity of resources allocated to different aspects and a general efficiency comparison of the three chosen technology (Figure

147). The simpler technology of ETICS solution is proven by the highest labor cost compared to materials and rent, while the offsite solutions require a specialized workforce with a higher price.

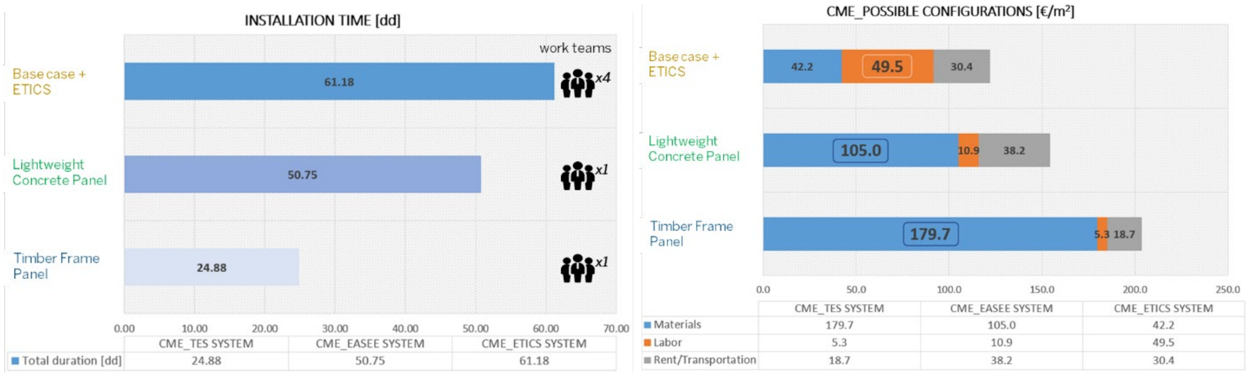


Figure 147: Time (left) and Cost (right) Analysis

6.3.2.10 End of Life

The last analysis concerns the Life Cycle Assessment for both the Embodied Impact and the Operational one in terms of renewable/non-renewable Primary Energy consumption. The calculation is provided by the Bombyx [179], an LCA tool developed by ETH Zurich in the GH environment according to EN 15978. PDT calculates impacts by assigning the material typology and the quantity.

The actual limitation of the tool is in the reference library, which is an LCA dataset provided by the Swiss Conference of the Construction and Real Estate Organs of Public Builders (KBOB) for typical material buildings in Switzerland and based on the Ecoinvent database. Furthermore, Bombyx – as many existing on the market - does not provide information for the transport onsite, construction (A4-A5), use (B1-B5) and deconstruction-transport (C1-C2) phase. Only production (A1-A3), operation (B6) and end of life-disposal (C3-C4) are taken into account, without benefits from reuse-recovery-recycling (D), which is an important advantage for offsite solutions compared to onsite ones.

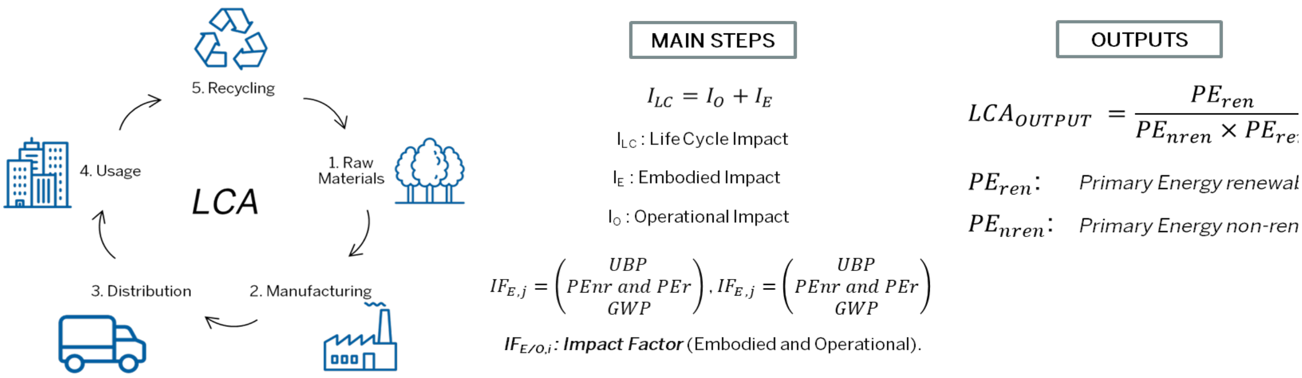


Figure 148: Life Cycle Assessment

6.4 Results

The design optioneering process output is a triple Spidergram, including the analytical analysis of each parameter (Figure 149), a Marked Radar (Figure 150) and a multiple BIM dimension score (Figure 152). The DSS provides a sensitivity analysis for each parameter scoring them according to norms, market analysis and constraints. Using radar or Spidergram allows faster and easier reading of all the outputs simultaneously.

6.4.1 Analytical Spidergram

According to the interviews, parameter selection is based on crucial aspects that designers, producers and investors consider. Most values are referred to a square meter instead of a total because the common design practice in the Early Design Stage provides cost and quantities starting from this functional unit and relating discounts/saving factors downstream to the total number of components. The domain range for each parameter is defined as follows, but they can be customized to fit the needs of stakeholders better.

- N°. Total panels/Total Area [n. panels/m^2]: $0 \leq$ Acceptable ≤ 1

The data are related to the square meter to define the efficiency of panel cladding for the entire envelope surface. The worst scenario has one panel per square meter, creating a mosaic of 1 m^2 of panel size. The closer the values are to the lower limit of 0, the larger the panels used, allowing the surface to be paneled more quickly.

- N°. Different panels/N°. Total panels [-]: $0 \leq$ Acceptable ≤ 1

This percentage shows the panels' mass production efficiency, independently from the total surface considered. In the worst configuration (value 1), every panel is unique and different from the others per size or typology.

- Thermal transmittance U [W/m^2K]: $0.13 \leq$ Acceptable ≤ 0.26

The lower limit of 0,13 W/m^2K is considered the lower realistic value, according to professional experience, as half of the maximum permissible value by law for opaque perimetral walls in climatic zone E (0,13 W/m^2K).

- H't [W/m^2K]: $0.30 \leq$ Acceptable ≤ 0.75

Opaque surface thermal transmittance increment due to thermal bridges and windows is 50% at least, while the upper limit by lay is 0,75 [W/m^2K]. Hence, the range is settled between 0,3 and 0,75 to appreciate the variation of closer scores as in the case study.

- LCA [PE_{REN}/PE_{TOT}]: $0 \leq$ Acceptable ≤ 1

Renewable energy percentage on total energy consumption is a fair value to assess the sustainability of the technological solution. Best (1) and worst (0) scenarios are hard to achieve but not impossible; this is why the range is not limited in this case.

- N°. Anchors/Total Area [anchors/m^2]: $0 \leq$ Acceptable ≤ 2

Value is converted to square meters regardless of the total area to understand how many anchors should be installed quickly. As an upper limit, it is considered two anchors per square meter. The plausibility of this value is verified by selecting the smallest panel in the case study (Concrete panel 1.84x0.41 m), with an area of 0.75 m^2 that need two shear anchors according to the load limit. Even though the minimum number of anchors per panel is four due to stability, the medium size of panels is around 3 m^2 (1 m width x 3 m height); this is why a medium value of 2 is considered the lower limit.

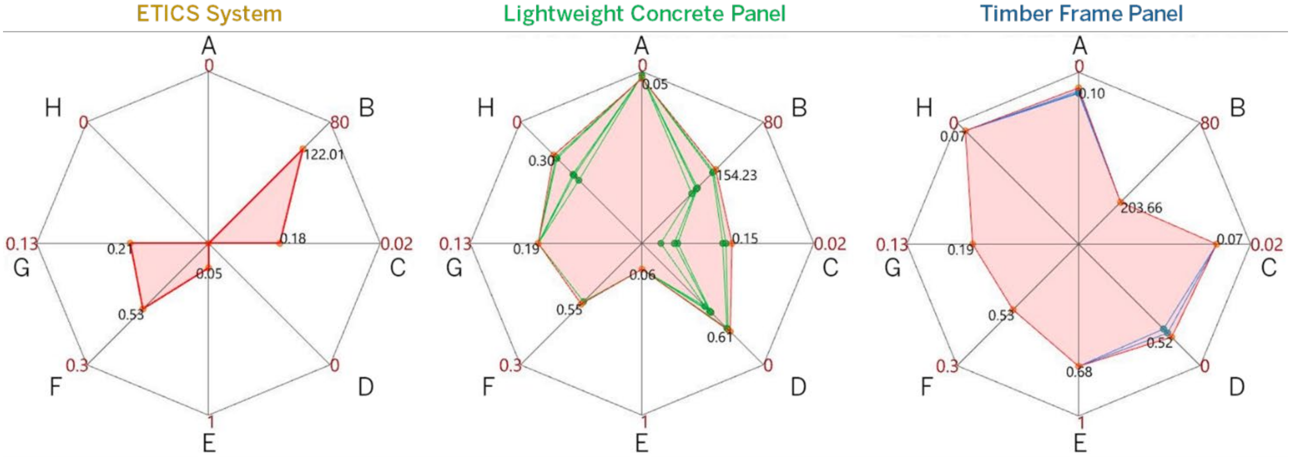
- Installation time [h/m^2]: $0.02 \leq$ Acceptable ≤ 0.27

Finding a normalized value to compare all three solutions directly is problematic because it is strictly related to the building size. For the actual case study – a medium-large building of 65 apartments – the shortest timing supposed (and very optimistic) is 7 working days by using multiple working teams in the offsite solutions and dividing it per the envelope surface (0,02 h/m^2). ETICS system total duration is calculated starting from the hours per square meter necessary for the operational team to complete the work; for the Concrete and Timber Systems, on the other hand, the total duration was calculated starting from the hours required to install a panel. Because the panels are of different sizes, it is more accurate to estimate the time needed for handling them with a mobile crane until the complete installation. As a maximum limit, we assumed that the client expressed the need to complete the work in a maximum of 3 months of work. For this reason, we have chosen 90 days as the upper limit, converted into hours per square meter equals 0.27 h/m^2.

- Total cost [€/m^2]: $80 \leq$ Acceptable ≤ 250

The cheapest ETICS solution available on the market is 50-100€/m^2, selected as the lower range (before the prices increment due to the COVID-19 Pandemic). The Concrete panel's upper limit is 150€/m^2 as supported by the European research application; according to this, the wooden solution is supposed to be around two times, resulting in 250€/m^2. It is important to remark that prices are based on the pre-covid market and should be updated frequently to comply with the actual economy.

Examining analytical values for each variable, the ETICS solution shows no results for the panel numbers and typologies (parameters A, D, H) because of its continuous surface on the external wall. In contrast, the number of panels (parameter H) is considerably lower (0,07 panels/m2) for timber solution compared to concrete (0,30 panels/m2) because of the larger size they have. On the other side, due to the bigger dimension of timber panels, the number of different elements over the total number of panels is higher than the smaller and repetitive concrete elements (parameter A), also resulting in a faster on-site application (C). The material cost affects the total cost of panels, resulting in a 25% saving for concrete to timber; the ETICS solution obtains the lower cost/m2 because of its lower technological complexity. Suppose the Thermal Transmittance has a better score for off-site panels than traditional insulation. In that case, the inclusion of H't represents the higher performance of ETICS in joints and corners, the weakest point for prefabricated solutions. Finally, the LCA analysis (parameter E) result is for the sixth time lower for concrete and ETICS because of the embodied carbon contained in the timber panels.



A. Number of different panel types /
B. Number of total panels (-) [0-1];
C. Total cost (€/m2) [80-250]
D. Installation time (h/m2) [0.02-0.27]
E. Number of anchors / m2 (no./m2) [0-2];
F. LCA (PEREN/PETOT) [0-1]
G. Global average heat exchange coefficient H't (W/m2K) [0.3-0.75];
H. Thermal transmittance U (W/m2K) [0.13-0.26];
I. Number of total panels / Total cladding surface (n/m2) [0-1];

Figure 149: Analytical Spidergram assessing the numerical numbers of each parameter in different scenarios (multiple green and blue lines for concrete and timber panels, respectively) for each technological solution.

6.4.2 Marked Radar

Although the selected parameters can highlight the main differences between the three solutions, to easier compare closer numbers more, the Analytical Spidergram (Figure 149) is transformed into a Marked Radar (Figure 150) by assigning a mark to every parameter from zero (in the figure center) to four. The solutions for every single technology (multiple green and blue lines for concrete and timber panels) are immediately comparable even though they have close analytical values. This way, users can choose the preferred technological solution by selecting the best-performing solution.

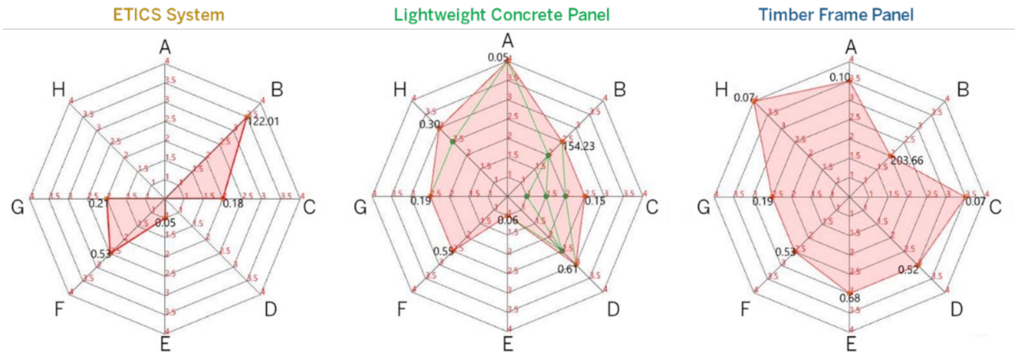


Figure 150: Marked Radar scoring the analytical values according to range (1-4) for each parameter.

6.4.3 BIM nDiagram

In the final comparison, considering the elevated number of variables analyzed and the need to facilitate the choice for non-technician decision-makers, parameters are collected into the related BIM n-dimensions from 2 to 7 (Figure 151). That enables a more clear perception of the characteristics of the different materials and a faster evaluation by overlapping the three technologies into the Final Comparison (Figure 152), where color s help to highlight ETICS (yellow line), Concrete (green) and Timber (Blue) panels.

- 2D Structure:
  - Number of anchors / m2 (n°/m2) [0-2];
- 3D Geometry:

  - Number of total panels / Total cladding surface (n°/m2) [0-1];
  - Number of different panel types / Number of total panels (-) [0-1];
- 4D Time:
  - Installation time (h/m2) [0.02-0.27]
- 5D Cost:
  - Total cost (€/m2) [80-250]
- 6D Sustainability:
  - Thermal transmittance U (W/m2K) [0.13-0.26];
  - Global average heat exchange coefficient H't (W/m2K) [0.3-0.75];
- 7D Management:
  - LCA (PEren/Petot) [0-1]

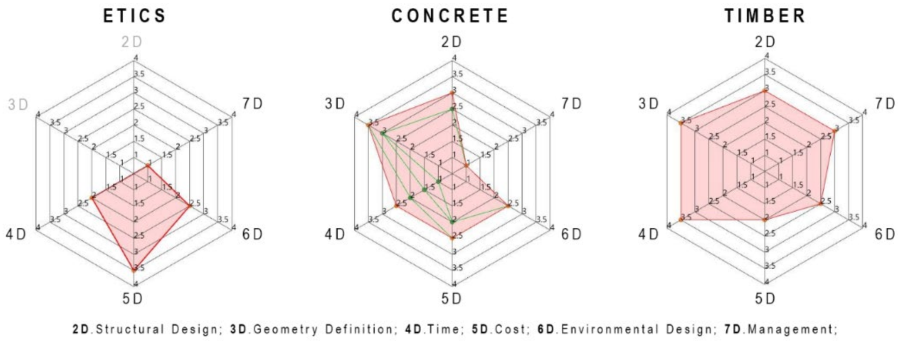


Figure 151: BIM nDiagram for marked results

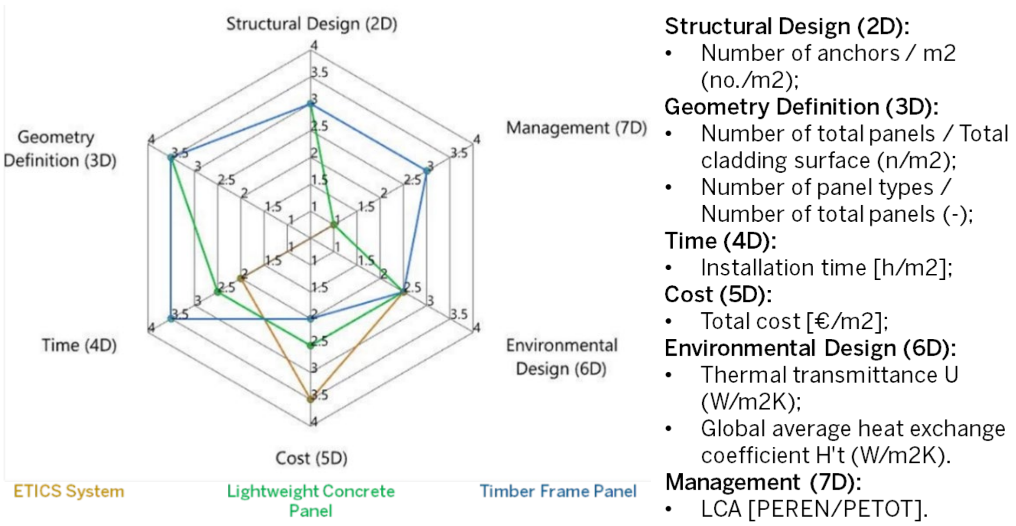


Figure 152: BIM nDiagram. Final technologies comparison collecting parameter in the BIM n-Dimensions

6.4.4 Web-based Result

The intent is to preserve the availability of results to the non-digital generation thanks to a comparative online viewer such as Design Explorer, which can cut out marks according to a range for each parameter up to the selected result (Figure 153).

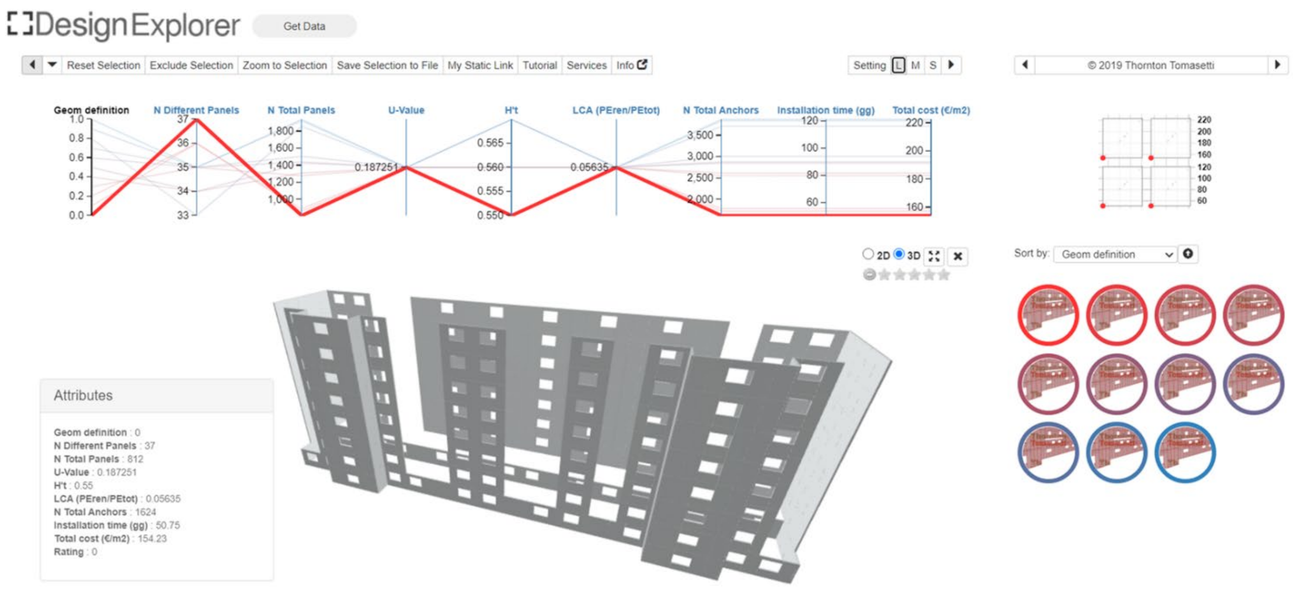


Figure 153: Graphical output comparison on the Design Explorer web app

6.5 Discussion

The process analysis figures out critical aspects and parameters to analyze (Need to have), together with adding information that can be provided or could be provided in the future by the tool (Nice to have) are shown in Figure 154. At the same time, it highlights the manual intervention required by the Designer and the automatic calculation of the tool, giving feedback on the effect needed for a comprehensive instrument result.

PHASES	Input	Pre-processing	Processing	Check	Analysis	Output
Hard Code Automatic output	• BIM Model • BIM panels families	• Window recognition • $U_{design} < U_{law}$ • Hygrothermal behaviour • Weight (kg/m2)	• Geometrical solutions (2D)	• Geometrical solutions (3D) • BIM Model • Anchoring positions • Deflections	• Time • Cost • LCA	• BOP • BOQ • Radars • BIM Model • XLS Datasheet
Soft Code Manual input	• Constraints	• Structural families	• Joint gap • Corners' priority	• H't • Anchoring typology • Screws n° • Seismic performance		• Design explorer
Nice to have	• New building application • Finishing choice • Steel panel technology	• Window choice • Opaque/Transparent surface			• Business investment analysis • Factory location	

Figure 154: Hard-Soft code for automatic-manual information provided by the tool and adding data that the tool could provide in the future developments

Furthermore, some critical aspects of PDT should be mentioned:

- The tool was shown to designers and manufacturers, receiving positive feedback for its potential.
- The fully developed case study application is only one: a single test is not enough to validate the tool's efficiency.

- More case study applications are under development to show possible bottlenecks or critical aspects of its use.
- Due to market variation, time and cost values change frequently, so it is necessary to update values often.
- The cost evaluation is statical, based only on direct production costs. A broader LCC analysis, considering NPV, ROI and TOC, can provide a more comprehensive investment evaluation from an economic point of view.
- The stand-alone application on hardware requires a deeper knowledge of parametrical design and/or an exhaustive guide.
- Transferring the tool to a web-based app can be a good solution to preserve the knowledge and make the app more accessible to non-parametric skilled façade designers.
- An online tool also preserves the need to have hardware powerful enough
- The scores and ranks in specific values (transmittance, time and cost) should be manually modified according to the project restriction (place and intervention typology).
- The consistency of comparison results depends on the Accuracy (validity), precision (reliability) and provenance (origin) of data, especially in the Early Design Stage. The challenge/barrier to DSS diffusion is its limited accessibility and affordability. It can be helped by an open knowledge approach, where all the actors involved in this sector can implement their data. However, the open platform allows companies to set their internal database according to their KBE, making the results affordable and comparable.
- The PhygitArk decides the LOD/LOI of every technology model in the EDS according to the priority of the analysis (production phase, installation or use). This design act decides how and how much information the model is, risking diverging the coherence of one project from the others and putting too much effort (working hours) into one project without adding value to the extract.

Figure 155: Panelization Design Tool output

Figure 156: Timber Frame Panel, 2022, Koln, Germany

7. Conclusion

"The pencil and computers are, if left to their own devices, equally dumb and only as good as the person driving them."

NORMAN FOSTER

Scope:

The last chapter summarizes the research path and describes the results with an outlook of possible future developments.

The thesis goal - understanding "How to apply industry 4.0 to the construction sector" – is reached by the description of Construction 4.0 and its Tech Trends and the market analysis. The clear vision of the AEC sector is completed by barriers and opportunities of 4.0 and a historical overview of Building Industrialization and Lean Construction. It explains the gap between these consolidated concepts and why the digital revolution can be game-changing for the sector's future.

According to this scenario, Lean Construction 4.0 is suggested as an original framework to fill the built environment's productivity gap compared to other sectors. The application of this new paradigm suggests the use of digital instruments to enhance Process, Project and Product performances in themselves and among them, as crucial phases in which to act. In this perspective, interoperability assumes a key role as a pivot to have new Information Management based both on experience and data (Knowledge-Based Engineering), leading to a new Value Proposition.

Two instruments are proposed to support SMEs in their journey toward the concepts presented in the theoretical framework: the LC 4.0 Assessment and the Panelization Design Tool (PDT). The first one is the digital assessment level of companies, identifying the main weaknesses areas where they have to work to boost their efficiency. On the other side, Modern Methods of Construction (MMC) are identified as possible solutions to boost the housing need and the refurbishment targets of the Green Deal. PDT is a Decision Support System to help decision-makers (many different stakeholders) in having a more effective choice of different offsite facades technological solutions. It categorizes DfMA panels by various KPIs and scores collected in the BIM nD approach (geometry, structure, time, cost, sustainability and management) and sends back many different outputs according to the digital level of the actor.

At the end of the thesis, results are commented on and achieved results are highlighted for the thesis's theoretical and practical parts. What are the tool platform's possible implementation and the paradigm's reliability?

Contents:

Expected results:

- Attended and achieved results comparison
- Critical discussion of the effectiveness of the thesis
- Further implementation of the tools

Keywords:

Lean Construction 4.0; Digitalization; MMC; Offsite; SMEs; Large Enterprise; Italy; Decision Support System

The last chapter of the thesis explains the originality and added value provided by the research work. A change in the company's organization is suggested to embrace the 4.0 digital revolution. The Lean Construction 4.0 paradigm suggested a new theoretical approach in the architecture and information management between different areas (Product, Project, Process). A new approach to design production and construction phases completes the LC 4.0 ontology to optimize the management phase. With this purpose, the Panelization Design Tool can be an excellent instrument to facilitate decision-makers in the early design stage to have a more effective choice for refurbishing the old building stock with offsite solutions.

Interoperability is the key to the Phygital revolution in building construction. The PDT is designed to maintain every single tool's specialization from a data lake perspective instead of data centralization. The application of DO is fundamental in the first stage of the process, where a holistic approach can save time and cost by improving quality, overcoming the housing market need and filling the productivity gap compared to other sectors, like MMC shows.

The highly specialized construction process steered designers to add complexity levels to projects, leading them to explore several possible solutions according to the often-diverging interests of different actors. Furthermore, the integration of MMC in the existing building retrofit processes requires designers to push toward the following:

- a coherent BIM workflow including various disciplines and actors;
- the early engagement of suppliers in the first design process phases;
- a more straightforward representation of multiple different scenarios for non-technicians;
- applying more efficient technologies for new envelopes or the recladding of existing buildings.

7.1 Results and conclusion

The obtained result demonstrates the possibility of this kind of approach also in the Italian market through collaboration with companies and producers. Investors and public administrations are now conscious of the urgency of activating a deep industrialization process able to sustain the market requests for new and refurbished construction beyond the PNRR and fundraising. The theoretical and practical test focused on the Lombardy region because of its predisposition to innovation and the actual construction market opportunities. The purpose is to demonstrate the effectiveness of Lean Construction 4.0 in applying digitalization and offsite solutions for the design, production and construction phases. The defined instruments are the LC4.0 Assessment - validated by the test on various Italian companies – and the Panelization Design Tool – to compare offsite and onsite technologies to refurbish existing buildings. The second instrument is tested on a single case study; it is planned to validate the tool by applying it to further projects in future research development.

The thesis's value and originality consist of defining the digital and technological scenario regarding industry 4.0 in the construction sector to define the level of smartness and digital readiness for SMEs through an evaluation tool. The Lean Construction 4.0 assessment, based on the namesake paradigm, is tested on different case studies and applied by the PhygitArk and/or Phygital Coach figures, defined as digital enablers for the companies.

The second level of action is focused on one of the Secondary Technologies defined: adopting offsite panels to reclad existing buildings can improve construction productivity with better quality. A Decision Support System is created to facilitate the adoption of this high-content technology, where it is possible to compare different technological solutions (concrete and timber panels to simple insulation) in the Early Design Stage. The tool's validity is tested on a case study, but more applications are required to validate the instrument.

Lean Construction 4.0 proposes an incremental innovation in the existing framework of Lean Construction and Industry 4.0, proposing a different reconfiguration of the single Secondary Technologies to achieve a better application in the AEC sector. Furthermore, the Panelization Design Tool is a concrete proposal to fill the gap between the decision-making process and the design phase to improve the sector's productivity through the digital revolution. The PhygitArk and Phygital Coach are two different figures supporting SMEs in adopting the LC4.0 paradigm.

7.2 Objectives achieved

The main research question (*How to apply industry 4.0 to the construction sector?*) leading the thesis finds the answer in the description of state of the art (Chapter 0) and the suggestion of a new paradigm approach LC4.0 (Chapter 0) with all the potentiality and barriers explanation (§ 3.3.4.2 and § 3.4.5 answering to RQ 1.1). The fourth chapter also contains the answer to how the Digital Revolution can be adopted by different companies size (§ 3.4.6 answering to RQ 2.1), especially SMEs in Italy, which are crucial building process phases (§ 0 and §4.4, answering to RQ 3) and what are the different level of action (3 Performances § 0, answering to RQ 4).

The objectives listed in § 1.2.2 are developed across the thesis following the double path of the theoretical framework of LC4.0 (Obj 1, described in Chapter 0), plus the second practical one (Obj 2, described in Chapter 0). Both of them are better detailed by sub-Objectives:

- Obj 1.1: the LC4.0 Assessment (§ 5.3) as an instrument to test the digital level of companies
- Obj 1.2: Phygital coach figure (§ 4.2.3.2) as the figure to evaluate the digital level of companies by using the LC4.0 Assessment instrument
- Obj 1.3: PhygitArk (§ 4.2.3.1) as the figure helping manufacturers to move closer to 4.0 production and mass customization approach by using digital instruments, such as PDT
- Obj 2.1: PDT creation (§ 6.3) as an instrument to push the MMC and mainly offsite adoption in façade retrofit.

These objectives were completed by vertical research questions (§ 1.2.2.1), which define LC4.0 Assessment and PDT as possible instruments to facilitate the paradigm adoption (RQ 1.1) managed by experts like Phygital Coach and Ark (RQ 2.1). All the sub-questions about LC4.0 Assessment (RQ 3.1) and PDT (RQ 4.1) are answered in their relative chapters 5 and 6.

7.3 Further Development

The future possible research exploration concerns the two outputs: the digital assessment of companies and the façade decision support system. Both the DSS developed could be integrated with a performance measurement method like a Balanced Scorecard [180] – to embed qualitative and quantitative aspects - or a Key Performance Indicator – involving only quantitative aspects. The reason this aspect was not developed is different for the two instruments. The LC 4.0 Assessment's aim is not to compare different companies but to find the game-changer technology to invest in: it is an internal and introspective self-instrument for the company's digital transformation because of the sensitive information embedded after the assessment.

Differently, the PDT aim is precisely to compare different façade technological solutions, but the involvement of multiple stakeholders in the decision process makes it impossible to prioritize one aspect (BIM nDimensions and the relative parameters) over another. This is why the two instruments remain impartial in the result, requiring value judgment from the user, like all digital tools.

7.3.1 Lean Construction 4.0 Assessment

A more detailed weight criterion for stages and technologies, plus a product prioritization matrix, can be used to implement the accuracy of the level in the digital level of single technologies. Currently, the influence of technologies on Digitalness score and stages on Smartness score is the same. The addition of a weight criterion makes it possible to be more precise on the effectiveness of technologies in one stage. Simultaneously, the effect of digital adoption across the stages differs according to the company's business focus.

An interesting future analysis consists of re-assessing companies after some time, evaluating their improvement in Smartness and Digitalness and evaluating the effectiveness and the responsivity of the model proposed inside the same company. These tests would be summarized with the only one with double reiteration already performed.

7.3.2 Panelization Design Tool

The sectorization of the process preserves the Platform approach. According to BIM nDimension, also this DSS can be implemented by n other modules such as:

- 3D Structure:
    - Seismic analysis
- 4D-5D construction phase:
    - Automatic shop drawings output for each panel
    - Supplier collection near the construction site
    - Business investment analysis (ROI and NPV analysis)
- 6D sustainability:
    - Energy Certifications (LEED, BREEAM, etc.)
    - Renewable energy inclusion on the panel (e.g. Photovoltaic Panels)
- 7D facility management:
    - Maintenance program
    - Maintenance cost
    - LCA End of Life disposal (usually ignored by the actual LCA analysis because of the data lacking)
- 8D security:
    - Risk analysis for different technologies

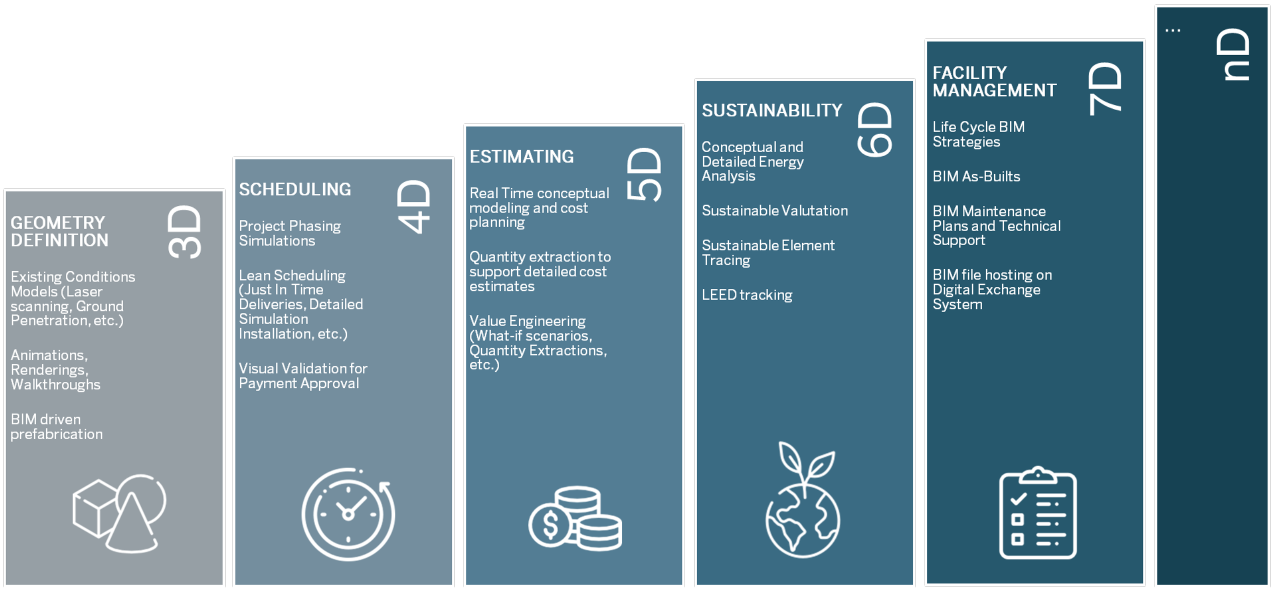


Figure 157: BIM nD approach of the PDT and further development

Furthermore, to prove the PDT's robustness from a single test to a validated tool, a multiple case study application is necessary, as a test with different BIM families from producers and a more profound reflection of the gamification score. The addition of a steel panel, a deeper LCC analysis and its application to new buildings are possible future research developments.

Figure 158: Ridge Timber Frame hunged up

8. Acknowledgment

Univerlecco funds this thesis to understand the potentiality of industry 4.0 in the Italian construction sector and especially in Lombardy. Univerlecco is a territorial association that comprises the Province, Chamber of Commerce and Municipality of Lecco, pools, professional associations and local labor unions. It has been established to facilitate the presence and development of university-level education and research center in the Lecco area, focusing on Politecnico di Milano and CNR (the National Council of Research). Because of its nature and mission, it fosters the development of relationships among the economic, productive and scientific environments by supporting the local actors in participating in research and communication projects and facilitating the technological transfer from research to industry/institutions.

9. Abbreviations and acronyms

- AEC: Architecture, Engineering and Construction
- AI: Artificial Intelligence
- AH: Active House
- BAU: Building As Usual
- BEP: BIM Execution Plan
- BIM: Building Information Modeling
- BMS: Building Management System
- CAD: Computer Aided Design
- CAGR: Compound annual growth rate
- CLT: Cross Laminated Timber
- CNC: Computer Numerical Control
- CO_2: Carbon Dioxide (chemical formula)
- DD: Digital Design
- DO: Design Optioneering
- DR: Digital Revolution
- DSS: Decision Support System
- DT: Digital Twin
- EIR: Exchange Information Requirement, according to the international standard ISO 19650- 1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM) -- Information management using building information modeling
- EN: European Norm
- EPD: Environmental Product Declaration
- EU: European Union
- ET: Enabling Technologies
- GHG: Green House Gases
- IDR: Industrialized Deep Renovation
- IFC: Industry Foundation Classes
- IoT: Internet of Things
- ISO: International Organization for Standardization
- IT: Information and Technology
- LC: Lean Construction
- LCA: Life Cycle Assessment

- LOD: Level Of Development, according to the Italian standard - UNI 11337:2017 Level Of Development, according to the USA standard - BIMForum Specification 2016 and following the AIA Document G202™–2013 Project BIM Protocol Level Of Definition, according to the UK standards - PAS 1192-2:2013
- LOD: Level Of Detail, according to the USA standard - BIMForum Specification 2016 and following the AIA Document G202™–2013 Project BIM Protocol Level Of model Detail, according to the UK standards - PAS 1192-2:2013
- LOG: Level Of detail of objects - Geometric attributes, according to the Italian standard – UNI 11337:2017
- LOI: Level Of Information - associated attribute information, according to the USA standard - BIMForum Specification 2016 and following the AIA Document G202™–2013 Project BIM Protocol Level Of model Information, according to the UK standards - PAS 1192-2:2013 Level Of detail of objects - Information attribute, according to the Italian dastards – UNI 11337:2017
- MMC: Modern Methods of Construction
- NZEB: Nearly Zero Energy Building
- OSM: Offsite Manufacturing
- PGA: PhygitArk
- PGC: Phygital Coach
- PDT: Panelization Design Tool
- PEREN: Primary Energy renewable
- PENREN: Primary Energy non-renewable
- PNRR: Piano Nazionale di Ripresa e Resilienza (National Plan of Resumption and Resilience)
- PV: Photo-voltaic
- RE: Renewable Energy source
- SMEs: Small-Medium Enterprises
- ST: Secondary Technologies

10. Appendix

10.1 Companies interviews

1. What is the 4.0 level in Italy? Where is the 4.0 adoption advantage (production, delivery, etc.)?
2. How to have a productivity boost? Is 3D printing a feasible way? And robots?
3. Which are the main barriers to 4.0 adoption? (technology, infrastructure, legislators, personnel, costs, etc.)
4. What about your company? What do you use it for and what would you like to use it for?
5. Offsite/MMC usage level?
6. What is your In-flow? How do you receive and transmit data from/to suppliers/subcontractors?
7. Do you have Internal BIM libraries?
8. Which is your Hammer time compared to management time (in percentage)?
9. Do you have some productivity KPIs?
10. Is there any post covid digitization implementation?
11. How many refurbishment actions compared to existing buildings recladding?

Interviewed Companies

- XLAM Dolomiti
- Galloppini Legnami
- Wood Beton
- Rilegno
- Leap Factory
- Marlegno
- Irondom
- Pichler
- Velux

10.2 LC4.0 Assessment results

	1	2	3	4	5	6	7	8	9	Average	Variation
BIM nD Approach	2,50	2,40	3,10	2,30	2,50	2,20	2,50	2,40	3,70	2,62	0,35
Platform Approach	2,80	2,20	2,80	2,40	2,40	2,40	2,90	2,20	3,50	2,62	0,34
Servitization	1,90	1,70	2,60	2,00	1,90	1,90	2,20	2,20	3,40	2,20	0,36
Design Optioneering	2,30	2,80	3,40	2,40	2,30	2,50	2,70	2,30	3,20	2,66	0,33
DfMA/DfMD	3,10	2,70	3,80	2,40	2,60	2,60	3,00	2,40	3,20	2,87	0,36
Data Valorization	2,20	1,90	3,30	1,90	1,80	2,20	2,30	1,90	3,00	2,28	0,39
Supply Chain	3,10	2,40	3,20	2,50	2,60	2,30	3,00	2,50	3,70	2,81	0,39
Circular Economy	2,30	2,30	3,10	2,30	2,30	2,20	2,50	2,40	3,00	2,49	0,25
Mass customization	2,70	2,40	3,50	2,10	2,20	2,30	2,70	2,20	3,20	2,59	0,39
Automation	1,90	1,70	2,50	2,00	1,80	2,10	2,40	2,00	3,20	2,18	0,35
Process	2	2	3	2	2	2	3	2	4	2,44	0,59
Project	3	2	4	2	2	2	3	2	3	2,56	0,62
Product	3	2	3	2	2	2	3	2	3	2,44	0,49
											0,40
Digitization	2,8	2,4	3,4	2,5	2,6	2,6	3,1	2,4	3,6	2,82	0,36
Digitalization	2,6	2,5	3,3	2,4	2,4	2,3	3	2,6	3,6	2,74	0,37
Digital Transformation	2,9	2,5	3,5	2,5	2,5	2,5	3,3	2,5	3,5	2,86	0,40
Enabling technologies											
Secondary Technologies											
BIM	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**2,79**	**0,14**
PIM/PLM	4	4	4	4	4	4	4	3	3	3,78	0,35
DT (AIM)	2	3	2	2	2	2	2	2	2	2,11	0,20
Cyber Security	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**5**	**1,67**	**1,04**
BlockChain	1	1	1	1	1	1	1	3	5	1,67	1,04
Cloud Computing	**4**	**3**	**4**	**4**	**4**	**2**	**4**	**2**	**4**	**3,41**	**0,65**
Cloud Server	5	3	5	5	5	3	5	3	5	4,33	0,89
DMS	3	3	3	3	3	2	3	2	3	2,78	0,35
Digital Design	**2**	**3**	**5**	**2**	**2**	**2**	**2**	**2**	**3**	**2,42**	**0,67**
Parametric Design	1	3	5	1	1	2	1	3	4	2,33	1,26
Fast Mapping	1	2	4	1	1	2	1	1	1	1,56	0,74
Simulation	5	4	5	5	5	5	5	2	5	4,56	0,69
H-V Integration	**5**	**2**	**5**	**2**	**2**	**3**	**4**	**2**	**3**	**3,20**	**1,02**
ERP/CRM	5	3	5	2	2	3	4	1	3	3,11	1,04
MES	5	2	5	3	5	3	3	2	3	3,44	1,04
SCADA/OPC/DCS	4	1	4	2	4	4	4	2	4	3,22	1,04
PLC	5	2	5	5	5	5	5	4	4	4,44	0,74
AI	**1**	**1**	**3**	**2**	**1**	**1**	**2**	**3**	**3**	**1,87**	**0,83**
ML	1	1	3	2	1	1	2	3	3	1,89	0,79
HMI	1	1	3	2	1	1	2	3	3	1,89	0,79
LCSA	**4**	**3**	**4**	**3**	**4**	**2**	**3**	**3**	**4**	**3,17**	**0,46**
LCA	3	2	4	2	3	2	3	3	4	2,89	0,59
LCC	4	3	4	3	4	3	3	3	4	3,44	0,49
IoT	**2**	**1**	**1**	**2**	**2**	**3**	**2**	**2**	**2**	**1,88**	**0,34**
Sensorization	2	1	1	2	2	3	2	2	2	1,89	0,40
Big Data	**1**	**1**	**3**	**1**	**1**	**1**	**2**	**2**	**3**	**1,60**	**0,67**
5G	1	1	3	1	1	1	2	2	3	1,67	0,74
Intelligent Manufacturing	**2**	**3**	**3**	**3**	**2**	**2**	**4**	**2**	**4**	**2,73**	**0,39**
Off-site Manufacturing	1	3	4	2	1	1	5	4	5	2,89	1,46
Additive Manufacturing	1	2	1	3	1	1	4	4	4	2,33	1,26
Robots/Cobots	2	4	2	2	2	2	4	2	4	2,67	0,89
Drones	1	1	1	1	1	1	1	1	2	1,11	0,20
RFID	5	4	4	3	5	5	5	3	4	4,22	0,69
Advanced Materials	4	4	4	4	4	4	5	2	5	4,00	0,44
Extended Reality	**2**	**2**	**3**	**2**	**2**	**3**	**2**	**1**	**4**	**2,19**	**0,56**
VR, AR, MR	2	2	3	2	2	3	2	1	4	2,33	0,67
											0,71
Digitalness	**2,4**	**2,1**	**3,1**	**2,1**	**2,1**	**2,1**	**2,5**	**2,2**	**3,4**	**2,44**	**0,37**
Smartness	**2,6**	**2,0**	**3,0**	**2,4**	**2,4**	**1,9**	**2,7**	**2,0**	**3,0**	**2,44**	**0,34**
initiative	3	1	3	3	3	1	3	1,5	3	2,39	0,81
initiation	2,6	2	3,1	1,9	2,3	1,6	2,4	1,8	2,2	2,21	0,35
design	3,2	2,6	4,3	3,9	3	2,7	3,7	3,1	4,1	3,40	0,53
procurement	3,3	2,6	4	2,8	3,2	2,9	3,7	3	4,1	3,29	0,43
construction	2,1	2,9	3,5	1,7	2	2,3	2,9	2,7	4,4	2,72	0,62
use	2,8	1,9	2,2	2,2	2,2	2,1	2	1,1	2,2	2,08	0,27
end of life	1	1	1	1	1	1	1	1	1	1,00	-

10.2.1 Kobots tool

The Kobots tool is a cutting platform placed on site and manageable from the carpenter to cut boards and panels. Apart from the PLC cutting element, the device is completed by a dust aspiration system to protect the workman from the dangerous elements that the slicing process releases in the air.

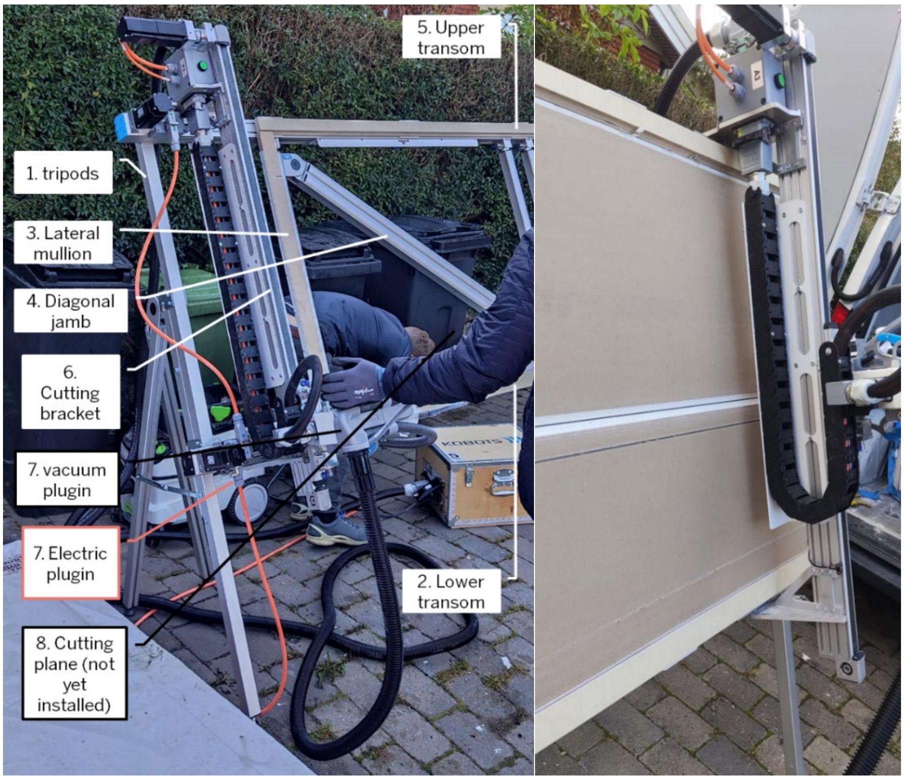


Figure 159: Installation of the tool with its components

The cutting machine and table are transported onsite inside a van, having various sizes according to the client's request. After the setup phase, the PLC can auto-align itself to the boards and the floor where it is lying.

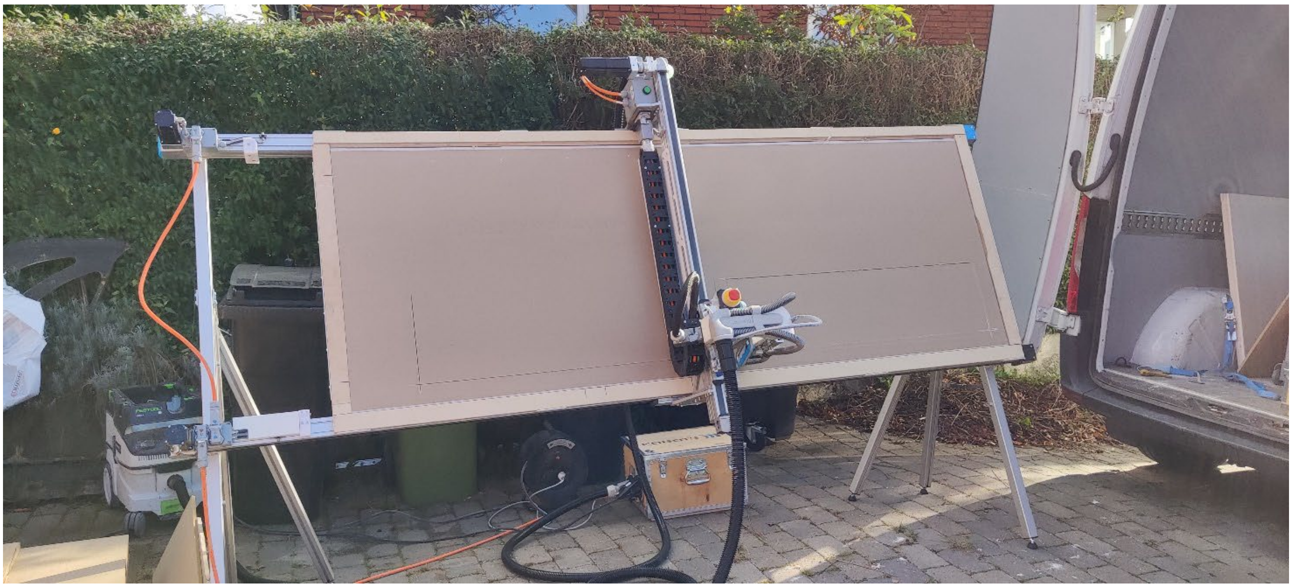


Figure 160: final setup of the tool

Through a smartphone app, the workman draws the shape and inserts the size of each board to cut. The PLC develops its work autonomously, saving the carpenter time for other activities, such as installing the boards or measuring the new slabs to cut.

Figure 161: Kobots App to set tables cutting and various materials to cut

Thanks to the adoption of the automatic cutting tool, it is possible to save time in the lining installation, which represents the most timing consuming activity in the roof window installation due to the various roof slopes and the requirement from owners of different finishes.

The activity tracked are:

- Tool setup
- Hole creation (in the roof slope)
- Template measurement
- Underlayment setting (of metal profile to which hang the boards)
- Cutting
- Gypsum board installation with details finishing

Traditional installation time is 2 hours and 18 minutes, compared to 1 hour and 2 minutes. It results in 55% time-saving that allows you to install a double number of windows in the same time. According to the income from installing 300 single windows for a SME and the initial cost of buying the tool, it is possible to exploit the payback period of 1,5 years.

Table 1: Manual and Robot lining creation comparison in terms of time

Time Table

PHASES		TIMING						SAVING	
MAIN PHASE	DETAILED STEP	Manual			KOBOTS	VELUX			
		total	start	end				total	%
Amigo setting		00:00:00			00:20:00			-00:20:00	-100%
	machine and pods installation	00:00:00	00:00:00	00:00:00	00:20:00	13:54:00	14:14:00		
Hole Creation		00:22:00			00:22:00			00:00:00	0%
	cutting gypsum from raw hole	00:12:00	00:00:00	00:12:00	00:12:00	00:00:00	00:12:00		
	geometry definition	00:10:00	00:24:00	00:34:00	00:10:00	00:24:00	00:34:00		
Template		00:12:00			00:06:00			00:06:00	50%
	hard papir cutting (gypsum for Kobots)	00:12:00	00:12:00	00:24:00	00:06:00	15:30:00	15:36:00		
Underlayment		00:43:00			00:17:00			00:26:00	60%
	metal perimetral profile setting	00:43:00	00:34:00	01:17:00	00:17:00	15:53:00	16:10:00		
Amigo cutting		00:00:00			00:07:00			-00:07:00	-100%
		00:00:00	00:00:00	00:00:00	00:05:00	15:47:00	15:52:00		
					00:02:00	16:00:00	16:02:00		
Gypsum installation		01:01:00			00:17:00			00:44:00	72%
	mounting	01:01:00	01:17:00	02:18:00	00:14:00	16:39:00	16:53:00		
	details	00:00:00	00:00:00	00:00:00	00:03:00	16:56:00	16:59:00		
cumulatiove time		02:18:00			01:29:00			00:49:00	36%
effective time		02:18:00			01:22:00			00:56:00	41%
effective time		02:18:00			01:02:00			01:16:00	55%

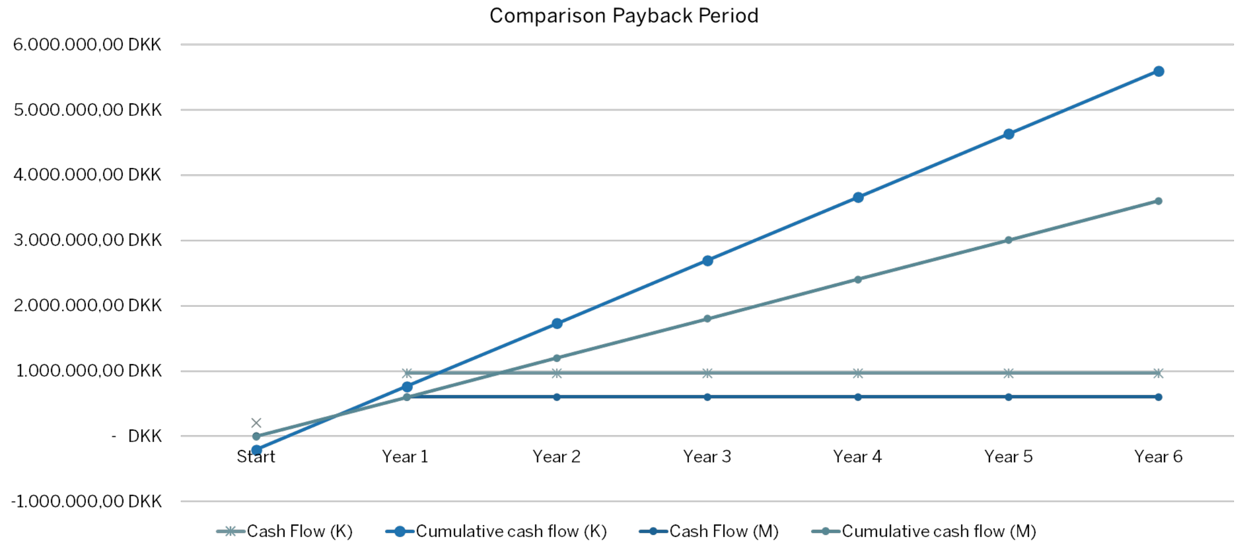


Figure 162: Payback period comparison between the manual (M) and the Kobots (K) annual year production

11. Bibliography

[1] Y. Liao, E. R. Loures, F. Deschamps, G. Brezinski, and A. Venâncio, "The impact of the fourth industrial revolution: A cross-country/region comparison," *Production*, vol. 28, 2018, doi: 10.1590/0103-6513.20180061.

[2] Microsoft and RIBA, "Digital Transformation in Architecture," 2018. [Online]. Available: https://www.architecture.com/-/media/gathercontent/digital-transformation-in-architecture/additional-documents/microsoftribadigitaltransformationreportfinal180629pdf.pdf

[3] Istat, "Rapporto sulla competitività dei settori produttivi," Roma, 2020. [Online]. Available: https://www.istat.it/storage/settori-produttivi/2020/Rapporto-competitivit%C3%A0.pdf

[4] F. Barbosa *et al.*, "Reinventing Construction: A Route To Higher Productivity," 2017. [Online]. Available: http://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution

[5] Industry 4.0 Research (HSRC), "Industry 4.0 Technologies, Industry & Global Markets 2019-2023," 2019. [Online]. Available: https://industry40marketresearch.com/wp-content/uploads/2018/05/TOC_V1_V5_Industry-4.0-Technologies-Industry-Global-Markets-2019-2023.pdf

[6] European Commission, "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives," vol. 53, no. 9. Bruxelles, pp. 1689–1699, 2020. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

[7] European Commission, "Indice di digitalizzazione dell'economia e della società (DESI) 2020. Italia," pp. 1–15, 2020, [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/desi-italy

[8] G. Origoni, "'Italy Tomorrow' -The Italian National Recovery and Resilience Plan (PNRR)", [Online]. Available: https://www.gop.it/doc_pubblicazioni/939_aeez2tkik5_ita.pdf

[9] F. Monosilio *et al.*, "Osservatorio congiunturale sull'industria delle costruzioni - Febbraio 2022," 2022. Accessed: Mar. 09, 2022. [Online]. Available: https://ance.it/wp-content/uploads/allegati/Osservatorio_Febbraio2022.pdf

[10] F. Monosilio *et al.*, "Osservatorio congiunturale sull'industria delle costruzioni - ANCE 2019," 2019. [Online]. Available: https://portale.assimpredilance.it/articoli/pubblicazione-dell-osservatorio-congiunturale-sull-industria-delle-costruzioni-ance

[11] R. de Laubier, A. Burfeind, S. Arnold, S. Witthoftt, and M. Wunder, "The Offsite Revolution in Construction," 2019. [Online]. Available: https://www.bcg.com/publications/2019/offsite-revolution-construction

[12] F. Cumo, G. Piras, F. Giustini, and E. Pennacchia, "Stato dell'arte di soluzioni tecnologiche di involucro edilizio esistenti come base per interventi di Deep Renovation del patrimonio immobiliare nel settore abitativo." [Online]. Available: https://www.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/adp-mise-enea-2019-2021/efficienza-energetica-dei-prodotti-e-dei-processi-industriali/report-rds_ptr2019_073.pdf

[13] BCA, "BIM for DfMA (Design for Manufacturing and Assembly) Essential Guide," Singapore, Oct. 2016. [Online]. Available: https://www.corenet.gov.sg/media/2032999/bim_essential_guide_dfma.pdf

[14] D. Sinclair, A. Tait, and L. Carmichael, "RIBA Plan of Work 2020 Overview," 2020. doi: 10.4324/9780429346637-2.

[15] M. Carpo, "Storia della svolta numerica in architettura," *Casabella*, vol. 914, pp. 28–35, 2020, [Online]. Available: https://dialnet.unirioja.es/servlet/articulo?codigo=7922881

[16] K. Kuma, "What Comes After Industrialized Society," *KKAA Newsletter*, vol. 32, 2020, [Online]. Available: https://kkaa.co.jp/newsletter/kkaa-newsletter-32/?language=en

[17] S. Montali, Overend, Pelken, "Towards facades as Make-To-Order products – the role of Knowledge-Based-Engineering to support design," *Journal of Facade Design and Engineering*, vol. 5, no. 2, pp. 101–112, 2017, doi: 10.7480/jfde.2017.2.1744.

[18] B. Daniotti *et al.*, "Workshop: BIM4EEB: A BIM-Based Toolkit for Efficient rEnovation in Buildings," p. 17, 2021, doi: 10.3390/proceedings2020065017.

[19] I. Faiella *et al.*, "La povertà energetica in Italia," 2020. [Online]. Available: https://www.mise.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf

[20] I. S. MacKenzie, "Scientific Foundations," in *Human-computer Interaction*, Morgan Kaufmann, 2013, pp. 121–156. doi: 10.1016/b978-0-12-405865-1.00004-2.

[21] D. Sinclair *et al.*, "RIBA Plan of Work 2013 Designing for Manufacture and Assembly overlay," 2016. [Online]. Available: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work

[22] ILKE, "It all stacks up Building homes using volumetric manufacturing," 2019. [Online]. Available: https://www.offsitehub.co.uk/industry-news/news/it-all-stacks-up-for-ilke/

[23] McGraw Hill Construction, "Information Mobility: Improving Team Collaboration Through the Movement of Project Information," 2013. [Online]. Available: https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products

[24] N. Bertram, S. Fuchs, J. Mischke, R. Palter, G. Strube, and J. Woetzel, "Modular construction: From projects to products," 2019.

[25] Kier Group, "Offsite and modern methods of construction," 2020. [Online]. Available: https://www.kier.co.uk/media/3011/brochure-offsite-mmc-brochure-2020-digital.pdf

[26] B. Daniotti *et al.*, "An interoperable bim-based toolkit for efficient renovation in buildings," *Buildings*, vol. 11, no. 7, pp. 1–16, 2021, doi: 10.3390/buildings11070271.

[27] H. Kagermann, W. Wahlster, and J. Helbig, "Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0 - Final Report of the Industrie 4.0 Working Group," *Industrie*, no. April, p. 82, 2013, doi: 10.13140/RG.2.1.1205.8966.

[28] M. W. Waibel, G. A. Oosthuizen, and D. W. du Toit, "Investigating current smart production innovations in the machine building industry on sustainability aspects," in *Procedia Manufacturing*, 2018, vol. 21, pp. 774–781. doi: 10.1016/j.promfg.2018.02.183.

[29] Y. Lu, "Industry 4.0: A survey on technologies, applications and open research issues," *J Ind Inf Integr*, vol. 6, pp. 1–10, Jun. 2017, doi: 10.1016/j.jii.2017.04.005.

[30] M. Ghobakhloo, "The future of manufacturing industry: a strategic roadmap toward Industry 4.0," *Journal of Manufacturing Technology Management*, vol. 29, no. 6, pp. 910–936, Oct. 2018, doi: 10.1108/JMTM-02-2018-0057.

[31] M. Hermann, T. Pentek, and B. Otto, “Design principles for industrie 4.0 scenarios,” *Proceedings of the Annual Hawaii International Conference on System Sciences*, vol. 2016-March, pp. 3928–3937, 2016, doi: 10.1109/HICSS.2016.488.

[32] M. Rangraz and L. Pareto, “Workplace work-integrated learning: supporting industry 4.0 transformation for small manufacturing plants by reskilling staff,” *International Journal of Lifelong Education*, vol. 40, no. 1, pp. 5–22, 2021, doi: 10.1080/02601370.2020.1867249.

[33] M. Bucchi, *Per un pugno di idee. Storie di innovazioni che hanno cambiato la nostra vita.* Bompiani, 2016.

[34] B. Stiegler, *La società automatica. L'avvenire del lavoro*, Meltemi. Meltemi, 2019.

[35] R. Buckminster Fuller, *Nine Chains to the Moon*. Cape, 2019. doi: 10.1515/9783035617764.

[36] N. Foster, “Winy Maas,” *Domus Guest Editor*, 2019. [Online]. Available: https://www.domusweb.it/en/speciali/guest-editor/winy-maas/gallery/2019/11/20/norman-foster-history-helps-us-realise-that-the-only-constant-is-change.html

[37] J. Fenn and M. Raskino, “Understanding Gartner's Hype Cycles,” *Analysis*, no. July, pp. 1–35, 2009, [Online]. Available: https://www.gartner.com/en/documents/3887767

[38] J. L. Bower and C. M. Christensern, “Disruptive technologies: catching the wave,” *Harv Bus Rev*, vol. 28, no. 2, p. 155, Apr. 1995, doi: 10.1016/0024-6301(95)91075-1.

[39] World Economic Forum, “Digital Transformation of Industries: Automotive Industry,” *World Economic Forum*, no. January, p. 45, 2016, [Online]. Available: http://reports.weforum.org/digital-transformation/wp-content/blogs.dir/94/mp/files/pages/files/digital-enterprise-narrative-final-january-2016.pdf%0Ahttp://reports.weforum.org/digital-transformation-of-industries/wp-content/blogs.dir/94/mp/files/pages/fil

[40] T. S. Kuhn, *La struttura delle rivoluzioni scientifiche*. Einaudi, 1969.

[41] E. Medi, *Il mondo come lo vedo io*. Newton Compton, 2008.

[42] B.-C. Han and S. Aglan-Buttazzi, *Le non cose: come abbiamo smesso di vivere il reale*. 2022.

[43] G. Falciasecca, “L'Infosfera: uno spazio per le tendenze in atto nel mondo ICT,” in *54 Conferenza GARR_11 Selected Papers. Da 20 anni nel futuro.*, 2012, pp. 54–63. [Online]. Available: https://cris.unibo.it/handle/11585/119909

[44] L. Floridi, *Infosfera. Etica e filosofia nell'età dell'informazione*. Giappichelli, 2009.

[45] A. Campioli, “Le culture del progetto,” in *Aspettando il progetto*, Franco Angeli Editore, 1997.

[46] B. T. Business, “The IT Roadmap for Digital Business Transformation,” *Gartner*, p. 11, 2020, [Online]. Available: https://emtemp.gcom.cloud/ngw/globalassets/en/information-technology/documents/insights/the-gartner-it-roadmap-for-digital-buisness-transformation-excerpt.pdf

[47] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, “Industry 4.0 technologies: Implementation patterns in manufacturing companies,” *Int J Prod Econ*, vol. 210, no. September 2018, pp. 15–26, 2019, doi: 10.1016/j.ijpe.2019.01.004.

[48] F. Zezulka, P. Marcon, I. Vesely, and O. Sajdl, “Industry 4.0 – An Introduction in the phenomenon,” *IFAC-PapersOnLine*, vol. 49, no. 25, pp. 8–12, Jan. 2016, doi: 10.1016/j.ifacol.2016.12.002.

[49] T. D. Oesterreich and F. Teuteberg, "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry," *Comput Ind*, vol. 83, pp. 121–139, Dec. 2016, doi: 10.1016/j.compind.2016.09.006.

[50] Osservatorio Industria 4.0, "Industria 4.0: la rivoluzione si fa con le persone!," 2019. [Online]. Available: https://www.som.polimi.it/event/osservatorio-industria-4-0-200619/

[51] M. Štefanič *et al.*, "The 2018 World Manufacturing Forum Report, Recommendations for the Future of Manufacturing," *Informed Architecture: Computational Strategies in Architectural Design*, vol. 0, no. 9783319044224, p. 94, 2018, doi: 10.1007/978-3-319-53135-9.

[52] M. Semini, D. E. Gotteberg Haartveit, E. Alfnes, E. Arica, P. O. Brett, and J. O. Strandhagen, "Strategies for customized shipbuilding with different customer order decoupling points," *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, vol. 228, no. 4, pp. 362–372, 2014, doi: 10.1177/1475090213493770.

[53] Council of Europe, "Artificial Intelligence for Europe," 2018. [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/european-approach-artificial-intelligence#:~:text=The%20EU%E2%80%99s%20approach%20to%20artificial%20intelligence%20centres%20on,and%20businesses%20can%20enjoy%20the%20benefits%20of%20AI

[54] R. Sacks, I. Brilakis, E. Pikas, H. S. Xie, and M. Girolami, "Construction with digital twin information systems," *Data-Centric Engineering*, vol. 1, 2020, doi: 10.1017/dce.2020.16.

[55] Build Offsite, "Off-site manufacture Maximising value and Your guide to specifying Off-site manufacture Maximising value and minimising risk," 2019. [Online]. Available: https://www.buildoffsite.com/content/uploads/2019/09/Your-guide-to-specifying-modular-buildings.pdf

[56] M. P. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems, 6th Edition*. Wiley, 2016.

[57] Joshua Southern, "Smart construction. How offsite manufacturing can transform our industry," 2016. [Online]. Available: https://assets.kpmg.com/content/dam/kpmg/pdf/2016/04/smart-construction-report-2016.pdf

[58] Dodge Data & Analytics, "Prefabrication and Modular Construction 2020 SmartMarket Report," 2020. [Online]. Available: https://proddrupalcontent.construction.com/s3fs-public/SMR1219_Prefab_2020_small-compressed.pdf

[59] N. Bertram, S. Fuchs, J. Mischke, R. Palter, G. Strube, and J. Woetzel, "Modular construction: From projects to products," 2019. [Online]. Available: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/modular-construction-from-projects-to-products

[60] T. J. van Vuuren and C. Middleton, *Methodology for quantifying the benefits of offsite construction*. 2020. [Online]. Available: https://www.ciria.org/ItemDetail?iProductCode=C792F&Category=FREEPUBS&WebsiteKey=3f18c87a-d62b-4eca-8ef4-9b09309c1c91

[61] BOPAS, "Recognised assurance for innovative or non-traditional methods of construction," 2018. [Online]. Available: https://www.bopas.org/

[62] C. Goodier, F. Fouchal, N. Fraser, and C. Price, "The role of Standards in offsite construction A review of existing practice and future need," pp. 1–28, 2019, [Online]. Available: https://repository.lboro.ac.uk/articles/The_role_of_Standards_in_offsite_construction_A_review_of_existing_practice_and_future_need/9459104%0Ahttps://www.bsigroup.com/globalassets/localfiles/en-gb/bsol-construction/offsite-construction-report-web.pdf

[63] Royal Institute of Chartered Surveyors (RICS), "Modern Methods of Construction Modern Methods of Construction," *Rics*, no. September, p. 62, 2018, [Online]. Available: https://www.rics.org/globalassets/rics-website/media/news/news--opinion/modern-methods-of-construction-paper-rics.pdf

[64] M. Thompson, "RIBA Plan of Work DfMA Overlay to the RIBA Plan of Work - MAINSTRE AMING DESIGN FOR MANUFACTURE AND ASSEMBLY IN CONSTRUCTION," 2021. [Online]. Available: https://www.architecture.com/knowledge-and-resources/resources-landing-page/dfma-overlay-to-the-riba-plan-of-work

[65] Building and Construction Authority and Bryden Wood, "BIM for DfMA (Design for Manufacturing and Assembly) Essential Guide," Singapore, Oct. 2016. [Online]. Available: www.bca.gov.sg

[66] R. Kelly, "Your guide to specifying Modular Buildings Off-site manufacture Maximising value and minimising risk," 2009. [Online]. Available: https://www.buildoffsite.com/content/uploads/2019/09/Your-guide-to-specifying-modular-buildings.pdf

[67] HM Government, "Construction 2025. Industrial Strategy: Government and industry in partnership," London, Jul. 2013. [Online]. Available: http://www.bis.gov.uk/assets/biscore/innovation/docs/b/12-1327-building-information-modelling.pdf%5Cnhttps://www.gov.uk/government/publications/construction-2025-strategy%5Cnhttps://www.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/

[69] M. Farmer, "The Farmer Review of the UK Construction Labour Model - Modernise or Die. Time to decide the industry's future," 2016. [Online]. Available: https://www.cast-consultancy.com/wp-content/uploads/2021/03/Farmer-Review-1-1.pdf

[70] M. J. Ribeirinho *et al.*, "The next normal in construction. How disruption is reshaping the world's largest ecosystem," 2020. [Online]. Available: https://www.mckinsey.com/~/media/mckinsey/industries/capital projects and infrastructure/our insights/the next normal in construction/executive-summary_the-next-normal-in-construction.pdf

[71] J.-R. Jiang, "An improved cyber-physical systems architecture for Industry 4.0 smart factories," *Advances in Mechanical Engineering*, vol. 10, no. 6, p. 168781401878419, Jun. 2018, doi: 10.1177/1687814018784192.

[72] F. Parisi, A. M. Mangini, and M. P. Fanti, "Enabling Technologies for Smart Construction Engineering: A Review," *IEEE International Conference on Automation Science and Engineering*, vol. 2020-Augus, pp. 1546–1551, 2020, doi: 10.1109/CASE48305.2020.9216951.

[73] M. A. Hossain and A. Nadeem, "Towards digitizing the construction industry: State of the art of construction 4.0," in *ISEC 2019 - 10th International Structural Engineering and Construction Conference*, 2019. doi: 10.14455/ISEC.res.2019.184.

[74] R. Gautam and P. Singh, "Human machine interaction and robotics," no. 04, pp. 154–154, 2017, doi: 10.1109/hsi.2017.8005018.

[75] H. Min, "Artificial intelligence in supply chain management: Theory and applications," *International Journal of Logistics Research and Applications*, vol. 13, no. 1, pp. 13–39, 2010, doi: 10.1080/13675560902736537.

[76] Cambridge Dictionary, "'Product' meaning in the Cambridge English Dictionary," 2018. https://dictionary.cambridge.org/dictionary/english/product

[77] MTC, "Transforming Performance and Productivity in the Construction Industry," 2017. [Online]. Available: http://digipub.htdl.co.uk/books/wxxk/#p=1

[78] M. Bolpagni, R. Gavina, and D. Ribeiro, *Industry 4.0 for the Built Environment*, vol. 20. Cham: Springer International Publishing, 2022. doi: 10.1007/978-3-030-82430-3.

[79] J. T. Mentzer *et al.*, "DEFINING SUPPLY CHAIN MANAGEMENT," *Journal of Business Logistics*, vol. 22, no. 2, pp. 1–25, Sep. 2001, doi: 10.1002/j.2158-1592.2001.tb00001.x.

[80] K. Helmrich, M. Board, and S. Ag, "On the Way to Industrie 4.0 – The Digital Enterprise," 2014. [Online]. Available: https://assets.new.siemens.com/siemens/assets/api/uuid:a5ba430f-5c4d-4650-87a9-a63dff2a968d/presentation-summary-e.pdf

[81] World Manufacturing Foundation, "The 2018 World Manufacturing Forum Report, Recommendations for the Future of Manufacturing," 2018. [Online]. Available: https://worldmanufacturing.org/report/report-2018/

[82] R. E. Smith, *Prefab Architecture: A Guide to Modular Design and Construction*, John Wiley. 2011.

[83] M. M. Tseng, Y. Wang, and R. J. Jiao, "Mass Customization," in *CIRP Encyclopedia of Production Engineering*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2017, pp. 1–8. doi: 10.1007/978-3-642-35950-7_16701-3.

[84] S. Kotha, "Mass Customization: The New Frontier in Business Competition.," *Academy of Management Review*, vol. 19, no. 3, pp. 588–592, Jul. 1994, doi: 10.5465/amr.1994.9412271820.

[85] F. Longo, L. Nicoletti, A. Padovano, G. d'Atri, and M. Forte, "Blockchain-enabled supply chain: An experimental study," *Comput Ind Eng*, vol. 136, pp. 57–69, Oct. 2019, doi: 10.1016/j.cie.2019.07.026.

[86] M. Bianchi, "Infrastructure Inversion: IOTA and the IoT - Noteworthy - The Journal Blog," *08/06/2018*, 2018. https://blog.usejournal.com/infrastructure-inversion-iota-and-the-iot-1e5ff221eb9b

[87] Kier Group, "The Choice Factory Volume 2," 2019. [Online]. Available: https://www.kier.co.uk/media/4717/the-choice-factory-volume-2.pdf

[88] ESCO, "Digitalisation in the Construction Sector," 2021. [Online]. Available: https://www.buildup.eu/en/news/overview-digitalisation-construction-industry

[89] D. M. Considine and G. D. Considine, "Robot Technology Fundamentals," in *Standard Handbook of Industrial Automation*, Springer, Boston, MA, 1986, pp. 262–320. doi: 10.1007/978-1-4613-1963-4_17.

[90] ISO 8373:2012, *Robots and robotic devices — Vocabulary*. 2012, p. 1. [Online]. Available: https://www.iso.org/standard/55890.html

[91] J. Manyika *et al.*, "A Future That Works: Automation, Employment, and Productivity," Jan. 2017. [Online]. Available: https://www.mckinsey.com/featured-insights/digital-disruption/harnessing-automation-for-a-future-that-works/de-de

[92] Bryden Wood and Construction Innovation Hub, "Platforms - Bridging the gap between construction + manufacturing," vol. 2, 2018, [Online]. Available: https://www.cdbb.cam.ac.uk/files/platforms_bridging_the_gap_small.pdf

[93] IMARC, "Construction 4.0 Market Size, Share, Trends, Forecast 2022-2027." https://www.imarcgroup.com/construction-4-0-market

[94] Osservatorio Transizione Industria 4.0, "L'industria digitale in un mondo che cambia," 2021. [Online]. Available: https://www.osservatori.net/it/eventi/on-demand/convegni/convegno-risultati-ricerca-osservatorio-transizione-industria-40-convegno

[95] "World Urbanization Prospects - Population Division - United Nations." https://population.un.org/wup/

[96] M. Petrullo, S. A. Jones, B. Morton, and A. Lorenz, "Improving Performance With Project Data Contributors. How Improved Collection and Analysis Is Leading the Digital Transformation of the Construction Industry," 2019. [Online]. Available: https://info.viewpoint.com/wc-na-dodge-report-project-data.html

[97] Istat, "L'innovazione nelle imprese," 2020. [Online]. Available: https://www.istat.it/it/files/2022/05/REPORT_INNOVAZIONE-IMPRESE_2018_2020.pdf

[98] European Construction Sector Observatory, "European Construction Sector Observatory. Renovating the building envelope-Quo vadis?," 2021. [Online]. Available: https://single-market-economy.ec.europa.eu/document/download/a184e840-bd0e-433a-800c-beb6e8e762b8_en

[99] Istat, "Edifici residenziali 2019," 2019. [Online]. Available: http://dati-censimentopopolazione.istat.it/Index.aspx?DataSetCode=DICA_EDIFICIRES

[100] Ioppolo and Mondini, "REPORT DI MERCATO MATERIALI DA COSTRUZIONE 2020-21," 2022. [Online]. Available: https://it.arteliagroup.com/sites/default/files/news/files/reportcaromateriali_29mar.pdf

[101] ALERT Centro Studi, "Materie prime: verso un nuovo scenario di prezzi elevati e crescente volatilità," Jun. 2022. [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/european-approach-artificial-intelligence#:~:text=The%20EU%E2%80%99s%20approach%20to%20artificial%20intelligence%20centres%20on,and%20businesses%20can%20enjoy%20the%20benefits%20of%20AI

[102] GAD, "Construction Cost Report 2021," 2021. [Online]. Available: https://gadstudio.eu/construction-cost-report/

[103] Centro studi FederlegnoArredo, "Rapporto FederlegnoArredo 2019," 2019. [Online]. Available: https://www.federlegnoarredo.it/it/servizi/centro-studi-dati-e-ricerche/rapporti-e-numeri-di-settore

[104] J. Švajlenka and M. Kozlovská, "Modern method of construction based on wood in the context of sustainability," *Civil Engineering and Environmental Systems*, vol. 34, no. 2, pp. 127–143, Apr. 2017, doi: 10.1080/10286608.2017.1340458.

[105] G. Pajchrowski, A. Noskowiak, A. Lewandowska, and W. Strykowski, "Wood as a building material in the light of environmental assessment of full life cycle of four buildings," *Constr Build Mater*, vol. 52, pp. 428–436, Feb. 2014, doi: 10.1016/j.conbuildmat.2013.11.066.

[106] F. Asdrubali, B. Ferracuti, L. Lombardi, C. Guattari, L. Evangelisti, and G. Grazieschi, "A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for

building applications," *Building and Environment*, vol. 114. Elsevier Ltd, pp. 307–332, Mar. 01, 2017. doi: 10.1016/j.buildenv.2016.12.033.

[107] F. Pittau, L. E. Malighetti, G. Masera, and G. Iannaccone, "A new modular preassembled timber panel for the energy retrofit of the housing stock," in *WCTE 2016 - World Conference on Timber Engineering*, 2016. [Online]. Available: https://www.scopus.com/record/display.uri?eid=2-s2.0-85010993623&origin=inward&txGid=bdf1465d173b4b939af663ea282c42c1

[108] L. Feifer, M. Imperadori, G. Salvalai, A. Brambilla, and F. Brunone, *Active House: Smart Nearly Zero Energy Buildings*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-90814-4.

[109] FederlegnoArredo.it, "Contratti Pubblici: l'OS32 'Strutture in Legno' è una categoria Super-specialistica," *2019*. https://www.federlegnoarredo.it/it/associazioni/assolegno/approfondimenti-news/contratti-pubblici-l-os32-strutture-in-legno-e-una-categoria-super-specialistica

[110] Ministero delle Infrastrutture e dei Trasporti, "Norme tecniche per le costruzioni. DM 17/1/2018," *Gazzetta Ufficiale della Repubblica Italiana*, vol. 20, pp. 1–198, 2018, [Online]. Available: https://www.gazzettaufficiale.it/eli/gu/2018/02/20/42/so/8/sg/pdf

[111] M. Mazzucato, "Mission Italia Investment, Innovation and Imagination," 2020. [Online]. Available: www.ucl.ac.uk/IIPP

[112] F. Monosilio *et al.*, "L'Osservatorio congiunturale sull'industria delle costruzioni è curato dalla Direzione Affari Economici, Finanza e Centro Studi dell'Ance," Feb. 2022. [Online]. Available: www.ance.it

[113] Istat, "PREVISIONI DELLA POPOLAZIONE RESIDENTE E DELLE FAMIGLIE," 2021. [Online]. Available: https://www.istat.it/it/archivio/274898#:~:text=La%20popolazione%20residente%20%C3%A8%20in,uno%20a%20uno%20nel%202050

[114] F. Estrafallaces, "L'IMPATTO SOCIALE ED ECONOMICO DEI SUPERBONUS 110% PER LA RISTRUTTURAZIONE DEGLI IMMOBILI: STIME E SCENARI," Nov. 2021. [Online]. Available: https://www.cni.it/images/News/2021/05_Limpatto_sociale_ed_economico_dei_Superbonus_110.pdf

[115] M. Imperadori, *Le procedure Stuttura/Rivestimento per l'edilizia sostenibile. Tecnologie dell'Innovazione*. Strumenti, 1999.

[116] Le Corbusier, *Verso una architettura*, II. Milano, 1986.

[117] BeAware, "Modern Methods of Construction (MMC)," 2009.

[118] W. Gropius, GIZMO, and C. De Marchi, *Apollo nella democrazia*. 2009.

[119] L. Koskela, "Application of the new production philosophy to construction," 1992. [Online]. Available: https://www.researchgate.net/publication/243781224_Application_of_the_New_Production_Philosophy_to_Construction

[120] G. Ballard and T. Zabelle, "Project Definition. White Paper," *Lean Construction Institute*, vol. 9, pp. 1–10, Oct. 2000, [Online]. Available: http://p2sl.berkeley.edu/wp-content/uploads/2016/03/W009-Ballard_Zabelle-2000-Project-Definition-LCI-White-Paper-9.pdf

[121] S. Smith, “Implementing Lean in construction. Lean benefits realisation management,” 2013.

[122] G. Ballard and G. A. Howell, “Competing Construction Management Paradigms,” *Construction Research Congress, Winds of Change: Integration and Innovation in Construction, Proceedings of the Congress*, vol. 1, no. October, pp. 321–328, 2003, [Online]. Available: https://www.academia.edu/811475/Competing_construction_management_paradigms

[123] Joanna Kloppenburg, “The Humble Revolution: Kengo Kuma’s Fight Against ‘Arrogant, Alienating’ Architecture - Architizer Journal,” *Architizer*, 2020, [Online]. Available: https://architizer.com/blog/practice/materials/architecture-not-the-protagonist-kengo-kuma/?utm_source=Architizer&utm_campaign=34b63451fe-EMAIL_CAMPAIGN_2018_11_01_01_02_COPY_01&utm_medium=email&utm_term=0_da3caaef3d-34b63451fe-27350895

[124] Italo. Calvino, *Lezioni americane: Sei proposte per il nuovo millennio*. Mondadori, 2016.

[125] Monash University, *Handbook for the Design of Modular Structures*. 2017.

[126] Supply Chain Sustainability School, Arkerlof, and University of Salford Manchester, “Delivering social value through offsite construction,” 2022. [Online]. Available: https://learn.supplychainschool.co.uk/local/tlactionplans/resource_intro.php?id=9038&modtype=resource

[127] O. Iuorio, L. Napolano, L. Fiorino, and R. Landolfo, “The environmental impacts of an innovative modular lightweight steel system: The Elissa case,” *J Clean Prod*, vol. 238, Nov. 2019, doi: 10.1016/j.jclepro.2019.117905.

[128] M. Horner *et al.*, “Advanced Industrialised Methods for the Construction of Homes (AIMCH). Work Package 2: Productivity Mapping & Literature Review,” 2019. [Online]. Available: https://www.aimch.co.uk/images/docs/AIMCH_-_Productivity_mapping_and_literature_review_-_Final_version_with_cover.pdf

[129] T. Stocks *et al.*, “Implementing Lean in construction : Overview of CIRIA guides and a brief introduction to Lean,” 2013. [Online]. Available: https://documents.pub/document/implementing-lean-in-construction-implementing-lean-in-construction-overview-of.html?page=2

[130] NHBC and Cast, *Modern Methods of Construction: Who’s doing what?* 2018. [Online]. Available: https://www.nhbcfoundation.org/wp-content/uploads/2018/11/NF82.pdf

[131] G. Britian, “Modern methods of construction, Introducing the MMC Definition Framework,” 2019. [Online]. Available: https://www.gov.uk/government/publications/modern-methods-of-construction-working-group-developing-a-definition-framework

[132] M. Farmer and J. Thornton, “Pre-Manufactured Value-Cast Technical Manual,” 2021, [Online]. Available: www.cast-consultancy.com

[133] Buildoffsite and CIRIA, “Challenges and barrier to adoption and implementation of offsite and MMC,” 2021. [Online]. Available: https://becg.com/wp-content/uploads/2021/07/BECG-Buildoffsite-Challenges-and-barriers-to-adoption-and-implementation-of-offsite-and-MMC.pdf

[134] P. Nervi, “Corretto Costruire,” *Strutture. Rivista di scienza e arte del costruire*, vol. 1, 1947.

[135] United Nations, “Transforming our world: the 2030 Agenda for Sustainable Development,” 2015. [Online]. Available: https://sdgs.un.org/2030agenda

[136] M. Wahlström, "Sendai Framework for Disaster Risk Reduction 2015 - 2030," 2015. [Online]. Available: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

[137] E. Kaufmann, "Architecture in the Age of Reason," *Architecture in the Age of Reason*, 2014, doi: 10.4159/harvard.9780674182288.

[138] F. Brunone, M. Cucuzza, M. Imperadori, and A. Vanossi, *Wood Additive Technologies*. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-78136-1.

[139] K. Kuma and M. Ferrari, *L'anti-oggetto: dissolvere e disintegrare l'architettura*. Ilios, 2012.

[140] D. Pasini, S. Mastrolembo Ventura, S. Rinaldi, P. Bellagente, A. Flammini, and A. L. C. Ciribini, "Exploiting internet of things and building information modeling framework for management of cognitive buildings," *IEEE 2nd International Smart Cities Conference: Improving the Citizens Quality of Life, ISC2 2016 - Proceedings*, vol. 40545387, no. 40545387, 2016, doi: 10.1109/ISC2.2016.7580817.

[141] MTC - Manufacturing Technology Centre, "i3P Programme," 2016. https://www.the-mtc.org/what-we-do/projects/i3p-programme/

[142] P. E. Giana, M. Schievano, F. Paleari, and E. Seghezzi, *Introduzione al BIM. Protocolli di Modellazione e Gestione Informativa*. Bologna, 2019.

[143] A. Vanossi and M. Imperadori, "BIM e optioneering in edifici S/R di piccola scala BIM and optioneering in dry technology small-scale building," no. May, 2015, doi: 10.13140/RG.2.1.2353.0400.

[144] E. Seghezzi and G. Masera, "Identification of Technological and Installation-related Parameters for a Multi-criteria Approach to Building Retrofit," in *Procedia Engineering*, 2017. doi: 10.1016/j.proeng.2017.04.265.

[145] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, *BIM Handbook: A guide to Building Information Modeling for owners, managers, designers, engineers and contractors*, 3rd Edition., no. 3. Hobocken: Wiley, 2018.

[146] Y. Ji *et al.*, "A BIM-Based Study on the Comprehensive Benefit Analysis for Prefabricated Building Projects in China," *Advances in Civil Engineering*, vol. 2019, 2019, doi: 10.1155/2019/3720191.

[147] K. Jones, A. Davies, L. Mosca, J. Whyte, and J. Glass, "Platform thinking for construction," 2019. [Online]. Available: https://www.ucl.ac.uk/bartlett/construction/sites/bartlett/files/digest-platform-thinking-for-construction.pdf

[148] Bryden Wood Technology Limited, "Delivery Platforms for Government Assets," 2017. [Online]. Available: https://www.cdbb.cam.ac.uk/system/files/documents/DigitalBuiltBritainbook_screen.pdf%

[149] European Union, "Waste statistics, Eurostat, 2018," no. October, pp. 1–12, 2020, [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics

[150] A. L. C. Ciribini, "Dal cantiere digitalizzato al cantiere digitale: the Internet of the Decision Making Processes e l'impresa di Costruzioni," pp. 1–5, 2019, [Online]. Available: https://www.ingenio-web.it/articoli/dal-cantiere-digitalizzato-al-cantiere-digitale-internet-of-the-decision-making-processes-e-Impresa-costruzioni/

[151] I. Paoletti, "Mass customization in the era of industry 4.0: Towards immaterial building technology," in *Informed Architecture: Computational Strategies in Architectural Design*, Cham: Springer International Publishing, 2017, pp. 77–87. doi: 10.1007/978-3-319-53135-9_8.

[152] M. Imperadori, A. Brambilla, F. Brunone, L. Feifer, G. Salvalai, and A. Vanossi, *Active House. Progettazione e innovazione con tecnologie di costruzione stratificata a secco*. Maggioli, 2019.

[153] Z. Yuan, C. Sun, and Y. Wang, "Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings," *Autom Constr*, vol. 88, no. April 2016, pp. 13–22, 2018, doi: 10.1016/j.autcon.2017.12.021.

[154] D. Acharya, R. Boyd, and O. Finch, "From Principles to Practices: Realising the value of circular economy in real estate," *Ellen MacArthur Foundation & Arup*, p. 54, 2020. [Online]. Available: https://www.arup.com/perspectives/publications/research/section/realising-the-value-of-circular-economy-in-real-estate

[155] R. Jin, J. Hong, and J. Zuo, "Environmental performance of off-site constructed facilities: A critical review," *Energy and Buildings*, vol. 207. Elsevier Ltd, Jan. 15, 2020. doi: 10.1016/j.enbuild.2019.109567.

[156] X. Cao, X. Li, Y. Zhu, and Z. Zhang, "A comparative study of environmental performance between prefabricated and traditional residential buildings in China," *J Clean Prod*, vol. 109, pp. 131–143, Dec. 2015, doi: 10.1016/j.jclepro.2015.04.120.

[157] E. Bonamente *et al.*, "Environmental impact of industrial prefabricated buildings: Carbon and Energy Footprint analysis based on an LCA approach," in *Energy Procedia*, Jan. 2014, vol. 61, pp. 2841–2844. doi: 10.1016/j.egypro.2014.12.319.

[158] E. Alfieri, E. Seghezzi, M. Sauchelli, G. M. Di Giuda, and G. Masera, "A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study," *Architectural Engineering and Design Management*, vol. 16, no. 4, pp. 247–269, 2020, doi: 10.1080/17452007.2020.1726725.

[159] M. Thompson, "DfMA Overlay to the Plan of Work," 2021. Accessed: Mar. 02, 2023. [Online]. Available: https://www.buildoffsite.com/content/uploads/2021/09/DfMA-Overlay-to-the-RIBA-Plan-of-Work-2020-2nd-edpdf.pdf

[160] Bryden Wood, "Data Driven Infrastructure From digital tools to manufactured components," 2017. [Online]. Available: https://www.cdbb.cam.ac.uk/system/files/documents/data_driven_infrastructure_screen.pdf

[161] J. Montali, M. Overend, P. M. Pelken, and M. Sauchelli, "Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends," *Architectural Engineering and Design Management*, vol. 14, no. 1–2, pp. 78–94, 2018, doi: 10.1080/17452007.2017.1364216.

[162] A. Whicher, G. Raulik-Murphy, and G. Cawood, "Evaluating Design: Understanding the Return on Investment," *Des Manage Rev*, vol. 22, no. 2, pp. 44–52, 2011, doi: 10.1111/j.1948-7169.2011.00125.x.

[163] R. Doherty, C. Wrigley, J. Matthews, and S. Bucolo, "Climbing the Design Ladder: Step by step," *Revista D.: Design, Educação, Sociedade e Sustentabilidade*, vol. 7, no. 2, pp. 60–82, 2015, [Online]. Available: https://core.ac.uk/download/pdf/33504648.pdf

[164] T. D. Oesterreich and F. Teuteberg, "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the

construction industry," *Comput Ind*, vol. 83, pp. 121–139, Dec. 2016, doi: 10.1016/J.COMPIND.2016.09.006.

[165] J. H. J. Yun and T. Yigitcanlar, "Open innovation in value chain for sustainability of firms," *Sustainability (Switzerland)*, vol. 9, no. 5, May 2017, doi: 10.3390/SU9050811.

[166] Construction Innovation Hub, "The digital innovation imperative: advancing progress towards a digital built Britain," *Information Technology for Development. London, UK: Construction Innovation Hub*, pp. 1–33, Sep. 2021, [Online]. Available: https://nic.org.uk/app/uploads/Data-for-the-Public-Good-NIC-Report.pdf

[167] C. Eastman, G. M. Di Giuda, and V. Villa, *Il BIM: guida completa al Building Information Modeling per committenti, architetti, ingegneri, gestori immobiliari e imprese*. 02/2016, 2016.

[168] BSI, *BS EN 15643 Sustainability of construction works. Framework for assessment of buildings and civil engineering works*. United Kingdom, 2021. [Online]. Available: https://landingpage.bsigroup.com/LandingPage/Series?UPI=BS EN 15643

[169] Z. Turskis, "Multi-attribute contractors ranking method by applying ordering of feasible alternatives of solutions in terms of preferability technique," *Technological and Economic Development of Economy*, vol. 14, no. 2, pp. 224–239, 2008, doi: 10.3846/1392-8619.2008.14.224-239.

[170] European Construction Sector Observatory, "European Construction Sector Observatory. Renovating the building envelope-Quo vadis?," 2021. Accessed: Sep. 09, 2022. [Online]. Available: https://single-market-economy.ec.europa.eu/document/download/a184e840-bd0e-433a-800c-beb6e8e762b8_en

[171] B. Munari, B. Finessi, and M. Meneguzzo, *Bruno Munari*. Silvana, 2008.

[172] B. Daniotti *et al.*, "The Development of a BIM-Based Interoperable Toolkit for Efficient Renovation in Buildings: From BIM to Digital Twin," *Buildings*, vol. 12, no. 2, p. 231, 2022, doi: 10.3390/buildings12020231.

[173] M. Cucuzza *et al.*, *A Panelization Design Tool to Inform Decisions About Façade Geometry and Environmental Performances*, vol. 263. Springer Singapore, 2022. doi: 10.1007/978-981-16-6269-0_44.

[174] M. Cucuzza, A. G. Di Stefano, G. Iannaccone, and G. Masera, "A BIM-enabled Decision Support System to support large-scale energy retrofitting processes and off-site solutions for envelope insulation," in *IOP Conference Series: Earth and Environmental Science*, Nov. 2022, vol. 1101, no. 4, p. 042031. doi: 10.1088/1755-1315/1101/4/042031.

[175] E. Zambelli, "Innovazione Edilizia in Giappone," *Modulo*, pp. 700–706, 1989.

[176] EASEE, "Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-storey multi-owner residential buildings," *285540*, 2016. https://cordis.europa.eu/project/id/285540

[177] Y. Cronhjort, M. Nuikka, and H. Hirsi, "TES Energy Facade Timber based element systems for improving the energy efficiency of the building envelope," 2009. [Online]. Available: https://www.researchgate.net/publication/294521160

[178] M. Cucuzza, A. G. Di Stefano, G. Iannaccone, and G. Masera, "A BIM-enabled Decision Support System to support large-scale energy retrofitting processes and off-site solutions for envelope

insulation," *IOP Conf Ser Earth Environ Sci*, vol. 1101, no. 4, p. 042031, Nov. 2022, doi: 10.1088/1755-1315/1101/4/042031.

[179] S. Basic, A. Hollberg, A. Galimshina, and G. Habert, "A design integrated parametric tool for real-time Life Cycle Assessment - Bombyx project," *IOP Conf Ser Earth Environ Sci*, vol. 323, no. 1, 2019, doi: 10.1088/1755-1315/323/1/012112.

[180] K. K. Choong, "The Fundamentals of Performance measurement systems: A Systematic Approach to Theory and a Research Agenda," *International Journal of Productivity and Performance Management*, vol. 63, no. 7, pp. 879–922, Sep. 2014, doi: 10.1108/IJPPM-01-2013-0015.