

Article

Smart Green Prefabrication: Sustainability Performances of Industrialized Building Technologies

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Abstract: There is an urgent need to increase the environmental, economic, and social sustainability of buildings. Indeed, construction has one of the lowest rates of sustainability among productive sectors, associated with high energy demand and pollutant emissions, frequent cost increase and time delays, and poor and unsafe working conditions. Building prefabrication is a construction technique that can enhance the sustainability of buildings, in terms of predictability, product and process quality, and increased safety for workers. Recently, new approaches and concepts such as Industry 4.0 (Construction 4.0) and circularity of resources emerged in the field of prefabrication to potentiate the benefits of off-site construction. In this scenario, the scope of the work is to analyze the state of the art in the field of prefabricated building technologies in the light of these innovations and to evaluate their performances from a sustainability perspective. The work has been developed in two phases: (1) analysis of 13 case studies of prefabricated technologies in Europe; (2) comparative assessment of their sustainability performances according to 21 qualitative parameters. Based on the results of the work, a set of guidelines is proposed as the outcome, i.e., suggested strategies and approaches for designers and industry professionals that can be used to enhance the sustainability of prefabrication.

Keywords: prefabrication; industry 4.0; circular materials; sustainability assessment; sustainability strategies

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1. Introduction

Since the beginning of the 19th century, building prefabrication has emerged as an alternative strategy to traditional construction. Prefabrication is a construction technique according to which parts of the building are assembled and completed inside a factory, then transported and installed on-site [1]. The degree of prefabrication varies from the assembly of structural components to the integration of finishes in prefabricated elements (fixtures, cladding); the highest degree of prefabrication are three-dimensional modular units, i.e., building sections completed in the factory with finishing and technical systems already integrated. The use of such techniques has been proven to have several benefits for the building process [2–4]:

- Predictability, because construction activities are led within a controlled environment where it is possible to carry out tight quality controls over prefabricated components;
- Time and cost reduction, because construction activities are no longer affected by external conditions (e.g., weather, site accessibility, etc.)
- Increased safety because workers carry out their activities in a safe and protected environment;
- Reduction of the impact of the construction site on the surrounding activities.

Stakeholders that are involved in prefabricated construction (public administrations, designer, private companies, etc.) have to deal with increasing concern about the sustainability of building products and processes, which have been addressed by some recent international policies and programs:

- COP21 Conference agreements (Paris Agreement, 2015) and the European Green Deal (2020) that addressed zeroing of emissions by 2050;
- Green Paper for Integrated Product Policy (COM (2001) 68) that aims to reduce the economic and environmental impact of buildings life-cycle;
- Industrial Strategy 2050 of the European Commission (COM (2020) 102) and the Horizon Europe Framework Program Pillar 2 (Cluster Digital, Industry and Space) to enhance the competitiveness of the prefabrication sector through digital transformation.

Nevertheless, prefabricated construction is proving slow in achieving these goals, and the Architecture, Engineering, and Construction (AEC) sector has one of the lowest sustainability rates compared to other manufacturing activities [5].

From an environmental point of view, construction is responsible for one-third of global energy consumption and CO₂ emissions [6,7]. In Europe, buildings account for 40% of energy consumption, and the percentage is expected to grow in the upcoming years [8]. In Italy, in 2001–2015, the construction sector saw increasing growth in electricity consumption and pollutant emissions [9].

Concerning economic sustainability, the sector is showing generalized inefficiency and unpredictability of products and processes [10]; this is a consequence of the high degree of complexity of activities and phases, competencies, and actors involved, resulting in frequent cost increases and delays. It is calculated that, on average, the time initially estimated for a project extends by 20% causing an exceedance in costs of up to 80% [11].

Finally, regarding social sustainability, the AEC sector shows the highest rates of accidents in the workplace [12] as well as the highest costs associated with work-related injuries [13].

Recently, some new concepts introduced in the prefabrication sector have demonstrated their potential to increase the sustainability of building products and processes. Firstly, the innovations engendered by the Fourth Industrial Revolution triggered the transition of prefabrication towards industry 4.0 models (smart factory). Industry 4.0 concept has been firstly conceived in Germany in 2011 at the Hannover Fair Event [14] and means the exploitation of cyber-physical systems for the automation of manufacturing. The term refers to a general approach that can be implemented within any production sector [15] with automotive and aerospace sectors being the first in consolidating its principles. In prefabrication, the concept goes under the name of Construction 4.0 and hinges on the automation and digitalization of design-manufacturing, i.e., a “file-to-factory” approach [16]. Such a method is enabled by the use of digital technologies such as artificial intelligence (AI), augmented reality (AR), the Internet of things (IoT), and building information modeling (BIM) [17,18]. In manufacturing, it also implies the use of high-precision equipment, such as 3D printers and computerized numerical control (CNC) machines [19,20]. This allows the establishment of direct communication between the different building phases and actors involved, optimizing resources (materials, time, costs) according to a lean approach [16,21,22].

Secondly, recent industrial and academic research developed innovative building materials, characterized by high performances and—at the same time—reduced life-cycle impact [23]. For instance, some experimental research exploited the use of “unconventional” materials as cardboard, cork, or composite materials with vegetable fibers for building applications [24–26]. However, the examples are not consolidated in practices or available on the market, and their effectiveness as building materials has yet to be validated through long-term experimentation.

In the described scenario, the scope of the work is to analyze the state of the art in the field of prefabricated building technologies in light of the aforementioned innovations and to evaluate their performances from a sustainability perspective. Specifically, the question addressed is as follows:

Research question (RQ)—Which product-process innovations in prefabricated buildings enhance sustainability?

To answer this question, the work is developed in two phases:

1. Analysis of 13 case studies of prefabricated building technologies in Europe;
2. Evaluation and comparison of their performances according to sustainability qualitative parameters.

Finally, the result of the work led to the definition of a set of guidelines, i.e., suggested strategies and approaches that are intended for designers and industry professionals in the field of prefabrication that can be used to increase the sustainability of prefabricated construction.

2. Materials and Methods

The methodology adopted to answer the research question is divided into two phases (Figure 1):

1. Analysis of 13 prefabricated building processes of modular units and prefabricated panel systems developed in Europe. The analysis has been carried out through three subsequent phases, namely:
 - 1.1. Definition of the investigation sample: the sample includes 13 prefabrication technologies, divided into three macro-categories according to the classification of the MHCLG Joint Industry Working Group (UK) [27]. The prefabrication technologies analyzed are listed in Table 1 and their description is provided in Appendix A;
 - 1.2. Definition of analysis criteria and preparation of a data collection sheet. A total of 11 qualitative criteria have been identified (Table 2) and divided into three investigation categories:
 - Technology, referring to construction features of the building;
 - Materials, referring to the type of resources employed;
 - Manufacturing, concerning production techniques and methods.

Criteria selected for the analysis refer to common characteristics of prefabricated technologies, that is to say, they do not depend on specific organizations and/or commercial strategies adopted by manufacturers. To facilitate data systematization a synthetic filing sheet model has been developed; the sheet is structured in four sections according to the criteria categories that are being analyzed (Figure 2): (1) Overview, (2) Technology, (3) Materials, (4) Manufacturing.

- 1.3. Data collection and filing: descriptive and qualitative data have been collected through bibliographic research—articles in scientific journals, manuals, and publications accessible in open repositories such as Scopus, Mendeley, Web of Science, and Google Scholar. References for each case study are collected in Table 1, column (c). Information collected through the bibliographic research has been integrated by the direct experience of the authors who acquired, in the field, supplementary information that was necessary to complete the survey.
2. Assessment and comparison of 13 prefabricated technologies. The evaluation is developed according to 21 qualitative parameters of environmental, economic, and social sustainability (Table 3, column (b)). The parameters describe expected performances related to sustainability, i.e., product-process features that are proven to be directly linked to the achievement of sustainability goals (Table 3, column (a)) [3,22,25,28–36]. For each technology, the achievement of the identified parameters

has been verified through an analytical comparison of information and data collected in Phase 1. Hence, the results of the evaluation are reported in a summary matrix (Table 4) and discussed in section 3.

Finally, to summarize the research results, the work developed a set of guidelines for the field of prefabricated building technologies (section 4). The guidelines synthesize the strategies that, according to the results of Phase 1 and 2, have been demonstrated to enhance the sustainability of prefabricated building products and processes. The guidelines have been developed by the triangulation of information collected in Phase 1 and Phase 2, i.e., linking the current innovations of prefabricated technologies (analyzed in reading sheets) to the achievement of sustainability parameters described in Table 3, column (b).

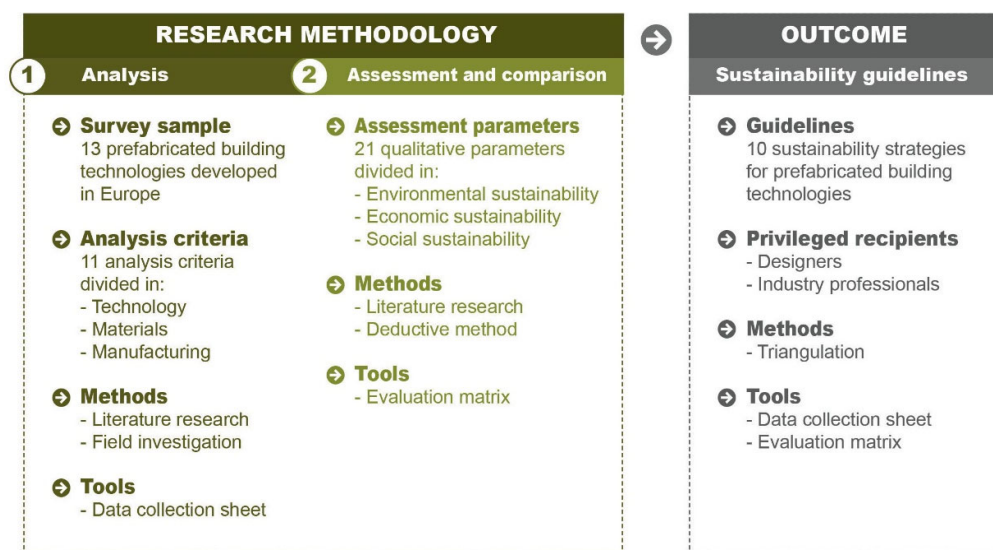


Figure 1. Research methodology and outcome.

Table 1. Prefabrication technologies analyzed.

MMC Category (a) [27]	Prefabrication Technologies (b)	References (c)
MMC Category 1: Pre-manufacturing, 3D primary structural systems A systemized approach based on volumetric construction involving the production of three-dimensional units in controlled factory conditions before final installation. Volumetric units can be brought to the final site in a variety of forms ranging from a basic structure only to a structure with all internal and external finishes and services installed, all ready for installation	T.01—Portable buildings	[1,37]
	T.02—ISO Shipping containers	[38,39]
	T.03—Light gauge steel modular units	[40–43]
	T.04—Timber-framed modular units	[40,42,43]
	T.05—CLT modular unit	[40,42,43]
	T.06—Concrete modular units	[40,43,44]
MMC Category 2: Pre-manufacturing, 2D primary structural systems A systemized approach using flat-panel units used for basic floor, wall, and roof structures of varying materials which are	T.07—SIP panels	[40,45]
	T.08—Lightgauge steel panels	[37,40,41]
	T.09—Timber-framed panels	[37,40,42]
	T.10—CLT panels	[37,40,42,46]
	T.11—Precast concrete panels	[37,40]
	T.12—Cardboard panels	[26,47,48]

produced in a factory environment and assembled at the final workforce to produce a final three-dimensional structure

MMC Category 4:

Additive manufacturing, structural and non-structural

The remote, site-based, or final workforce-based printing of parts of buildings through various materials based on digital design and manufacturing techniques (The category MMC 4—Additive manufacturing is not directly applicable to the concept of prefabrication, as it does not imply the assembly of components inside a factory. Nonetheless, for this work the technology T.13—3D printing is analyzed because the scientific literature promotes additive manufacturing as one of the ‘enabling technologies’ (Key Enabling Technologies, KETs) for industry 4.0 [15].)

T.13—3D printing

[49–51]

Table 2. Analysis criteria.

	Analysis Criteria (a)	Criteria Description (b)
Technology	Degree of prefabrication	Describes the maximum degree of prefabrication of the building components, (i.e., the percentage of completion of the work inside the factory evaluated compared to the final building)
	Flexibility and integration	Analyzes flexibility features of the technological system (i.e., the capability to be integrated with technical systems and/or other technologies and to be adapted during the time: additions, selective demolitions, replacement, etc.)
	Transport and installation	Analyzes the technological features related to the transport and installation of building components and parts, that is to say, the prefabrication strategies adopted to reduce transport and installation costs, identifying critical areas
	Estimated time saving	Describes the expected percentage of time construction saving compared to the use of traditional construction techniques
Materials	Structural material	Identifies the structural material employed
	Material supply sources	Analyzes the material supply sources highlighting the use of recycled materials and/or reused components as well as the supply sources management
	End-of-life options	Examines the possibility for reuse and/or re-emission of components and/or materials in the same building cycle or other production processes
Manufacturing	Design approach	Describes the methodological approach and operational strategies adopted for design and manufacturing management

Manufacture processing	Analyzes the type of processes and equipment used for sub-components and/or components manufacturing and their assembly as well as the productive chain organization
Manufacturing environmental impact	Describes the environmental impact of manufacturing processing regarding energy demand and pollutant emission generated
Customization approach	Describes the approach underlying the product-process regarding the possibility to customize products (i.e., the degree of flexibility of the product-process compared to the need for personalization), as well as the commercial approach and the level of standardization of components (market offer)

T.OX CASE STUDY	
OVERVIEW	
Case study overview	
MMC Category	
TECHNOLOGY	
Degree of prefabrication	Case study description according to the identified criteria
Flexibility and integration	
Transport and installation	
Estimated time saving	
MATERIALS	
Structural material	Case study description according to the identified criteria
Material supply sources	
End-of-life options	
MANUFACTURING	
Design approach	Case study description according to the identified criteria
Manufacture processing	
Manufacturing environmental impact	
Customization approach	

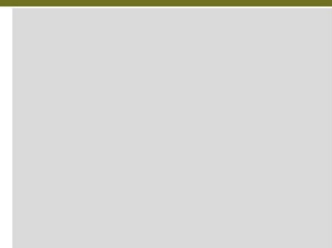


Image 01 – Image description
Image credits

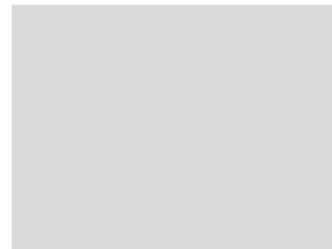


Image 02 – Image description
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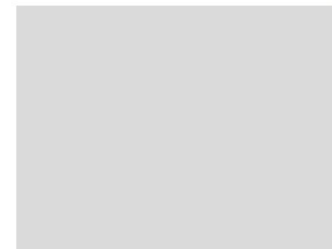


Image 03 – Image description
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Figure 2. Reading sheet structure.

Table 3. Sustainability goals and parameters used for assessment.

Sustainability Goals (a)		Sustainability Parameters (b)
Environment	Material circularity	SP. (1) Structural material can be recycled at the end of the building use without losing its performance
		SP. (2) Structural material supplied from recycled sources
	Building component circularity	SP. (3) Building components or sub-components can be relocated after their use
	Product-process predictability	SP. (4) Possibility to perform tight quality controls over the final product
		SP. (5) Possibility to control the building process (times and costs certainty)
	Reduction of material wastes	SP. (6) Optimization of material orders
		SP. (7) Optimization of material use in the manufacturing process
	Reduction of emissions	SP. (8) Low energy demand and CO2 emissions from processing
		SP. (9) Structural material supplied from sustainably managed sources
		SP. (10) Widespread material availability
Economy	Speed of construction	SP. (11) Reduction of construction time compared to traditional buildings
	Ease of construction	SP. (12) Building components can be easily handled and installed by workers without using crane equipment
		SP. (13) Stocking and installation of components do not require specific site protection measures against weather
	Economy of construction	SP. (14) Building components are optimized for transport
	Society	Product-process adaptability
SP. (16) Technology ensures space flexibility (variable space configuration, adaptation to specific design program)		
SP. (17) Components can be integrated and/or modified after manufacturing		
Work safety and health		SP. (18) Components can be removed and/or accommodate further changes in the space program
		SP. (19) Flexible manufacturing, i.e., changes in the building product requires minimum changes in the production chain
		SP. (20) Manufacture processing requires minimum interaction with workers (limited to machine setting and control)
Inclusion and collaboration	SP. (21) Design adopts an “open system” approach to ensure customization and integration of different specifications (structural, energetic, costs, etc.)	

Table 4. Evaluation matrix summarizing sustainability parameters (b) verified by the investigated prefabrication technologies (c).

Sustainability Goals (a)	Sustainability Parameters (b)	Prefabricated Technologies (Case Studies) (c)												
		MMC Category 1					MMC Category 2					MM C Cat. 4		
		T.01	T.02	T.03	T.04	T.05	T.06	T.07	T.08	T.09	T.10		T.11	T.12
Environment	Material circularity	SP. (1) Structural material can be recycled at the end of the building use without losing its performance	•	•	•				•			•	•	•
		SP. (2) Structural material supplied from recycled sources	•	•	•			•	•	•		•	•	•
	Building component circularity	SP. (3) Building components or sub-components can be relocated after their use	•	•	•			•	•				•	
	Product-process predictability	SP. (4) Possibility to perform tight quality controls over the final product	•		•	•	•	•	•	•	•	•		•
		SP. (5) Possibility to control the building process (times and costs certainty)	•		•	•	•	•	•	•	•			•
	Reduction of material wastes	SP. (6) Optimization of orders			•	•	•	•	•	•	•	•	•	•
		SP. (7) Optimization of material use in the manufacturing process	•	•	•				•				•	
	Reduction of emissions	SP. (8) Low energy demand and CO2 emissions from processing				•	•			•	•		•	•
		SP. (9) Structural material supplied from sustainably managed sources				•	•			•	•		•	•
		SP. (10) Widespread material availability	•	•	•			•	•	•			•	•

Economy	Speed of construction	SP. (11) Reduction of construction time compared to traditional buildings	•	•	•	•	•	•	•	•	•	•	•	
	Ease of construction	SP. (12) Building components can be easily handled and installed by workers without using crane equipment	•						•				•	
		SP. (13) Stacking and installation of components do not require specific site protection measures against weather	•	•	•			•		•			•	
	Economy of construction	SP. (14) Building components are optimized for transport	•	•					•				•	
Society	Product-process adaptability	SP. (15) Technology can be easily integrated with other building systems and components		•	•	•				•	•			
		SP. (16) Technology ensures space flexibility (variable space configuration, adaptation to specific design program)							•	•	•	•	•	•
		SP. (17) Components can be integrated and/or modified after manufacturing		•	•	•				•	•	•		
		SP. (18) Components can be removed and/or to accommodate further changes in the space program	•	•	•					•	•			

	SP. (19) Flexible manufacturing, i.e. changes in the building product requires minimum changes in the production chain	•	•	•	•	•	•	•	•
Work safety and health	SP. (20) Manufacture processing requires minimum interaction with workers (limited to machine setting and control)					•		•	•
Inclusion and collaboration	SP. (21) Design adopts an “open system” approach to ensure customization and integration of different specifications (structural, energetic, costs, etc.)		•	•	•	•		•	•

3. Results

The result of the first phase of the work is an updated catalog of current prefabrication technologies in Europe. The catalog consists of 13 analysis sheets (Appendix A), developed with a homogeneous and comparable structure that describes technological, productive, and material features of prefabricated technologies. The descriptive contents of the sheets summarize recent contributions and findings from scientific and industrial research.

Based on the investigation, in the second phase, we developed a qualitative assessment and comparison of sustainability performances achieved from each case study. As described in section 2 the evaluation is based on 21 qualitative parameters of environmental, economic, and social sustainability, i.e., performances directly related to the achievement of sustainability goals. Referring to each sustainability parameter, the main findings of the second phase are described as follows:

Environmental sustainability

- Material circularity:
 - SP. (01) Structural material can be recycled at the end of the building use without losing its performance.
 - SP. (02) Structural material supplied from recycled sources.
 - SP. (03) Building components or sub-components can be relocated after their use.

Among the materials examined, steel (used in T.01, T.02, T.03, T.08) shows the best performances in terms of circularity. Indeed, the steel used for building components can be recycled and is recyclable at the end of its use, minimizing the need of processing raw material [37]. Besides, material circularity is intrinsically connected with the possibility to relocate and reuse building components and/or sub-components. From this perspective, steel technologies are those offering the highest degree of circularity; in fact, the high du-

rability of the material and the use of dry-assembling (fastening) techniques allow repeated assembly and disassembly of modular units and/or steel-framed panels, maximizing building components circularity [1].

Nevertheless, the environmental sustainability of steel has to be read in the light of the high impact associated with the material production, as further described in SP.10.

Similarly, concrete mixtures (used in T.06, T.11) can be obtained using recycled material and can be recycled at the end of the building use; however, its processing is also energy-intensive with associated high levels of pollutants emissions [40]. Moreover, concerning building circularity SP.03, i.e., the possibility to relocate concrete modular units or concrete panels, the analysis demonstrates that technology types T.06 and T.11 do not allow for multiple building uses, since modules and panels cannot be relocated but only disassembled and recycled at the end of the use.

Referring to prefabricated wooden technologies (T.04, T.05, T.09, T.10), the material shows a limited performance of circularity compared to the previous. In fact, despite the majority of suppliers being certified as sustainably managed sources, the material quality needed for building application requires the use of raw material [46]. Moreover, the overall circularity of wooden technologies is further limited considering SP.03, because wooden modular units and panels, once disassembled, cannot be re-assembled and relocated. That is a consequence of the type of fastening and sealing techniques used for assembly which compromises the structural integrity of components that cannot be re-installed. Hence, wooden components resulting from disassembly can only be recycled, but the products obtained do not have the same properties, i.e., the material can be only downcycled.

The two best practices that emerge from the evaluation of material circularity are cardboard panels (T.12) and 3D printing (T.13). In the first case, prefabricated panels can be disassembled and relocated, and the paper used is supplied from recycled sources, and can be recycled at the end of the use [47]. However, the investigation shows that external treatments used for fire-proofing the panels can compromise the possibility for recycling; in this case, it is suggested that alternative technical solutions should be explored to verify legislation standards (fireproofing safety) while preserving future possibilities of recycling.

Instead, in the case of 3D printing (T.13), parameter SP.03 is not met because building components and/or parts cannot be reused once disassembled. Rather, circularity is strictly related to the type of material used as the binder. Recent applications have demonstrated the feasibility of using nature-based material as raw soil or natural fibers, which can achieve high building performances (strength, durability, thermal performances) and can be entirely recycled at the end of the use [51].

- Product-process predictability:
 - SP. (04) Possibility to perform tight quality controls over the final product
 - SP. (05) Possibility to control the building process (times and costs certainty)

The majority of case studies demonstrate that design-manufacturing methods used for prefabrication can enhance product-process quality control compared to traditional methods of construction. Specifically, this possibility is always enabled by the use of file-to-factory approaches (Industry 4.0/Construction 4.0), i.e., the use of BIM and CAD-CAM (computer aided design—computer aided manufacturing) software to manage design and manufacturing phases. Thanks to the use of the aforementioned tools it is possible to directly transfer design specifications to production equipment, without losing information and minimizing the possibility of errors. Furthermore, quality control is enhanced by the use of CNC machines, which guarantee high precision and tight tolerances in the final product [16].

From a sustainability perspective, the achievement of SP.04 and SP.05 ensure product and process predictability, that is to say, control over performances, time, and cost of prefabricated buildings.

Concerning T.02—ISO Shipping Containers and T.07—SIP panels, this possibility is limited because off-site prefabrication for the mentioned technologies concerns structural components only (respectively, steel skeletal frame and composite panels) requiring additional assembly outside the factory to complete the building.

For T.12—Cardboard panels, the analysis shows a limited capacity to control both product and process quality; this is a consequence of a missing direct communication between design and manufacturing. Indeed, design is currently led by a computer-aided design (CAD) approach, while manufacturing is performed manually by workers, with a high margin of error in terms of product, time, and cost.

- Reduction of material wastes:
 - SP. (6) Optimization of orders
 - SP. (7) Optimization of material use in the manufacturing process

Among the case studies, those that did not verify the SP.6 parameter are those adopting made-to-stock (MtS) or assembled-to-stock (AtS) commercial approaches (namely T.01, T.02, and T.07). These refer to stocking building components or building “kits” in the warehouse ready to be sold according to customer demands [40]. Although these approaches are justified by high market demand for portable buildings and containers (for other uses as construction sites or temporary emergency settlements), MtS and AtS have impacts on economic sustainability, since stocked material needs to be properly maintained. In this case, improved approaches are assembled-to-order and made-to-order, i.e., the production of building components according to customer demands. In such a way, the accumulation of unutilized material is avoided with advantages for both environmental and economic sustainability [21].

Regarding SP.7, the technologies that demonstrate better material optimization are steel (T.01, T.02, T.03, T.08) and cardboard prefabrication (T.12). Specifically, this is a consequence of the type of sub-components used as the input for manufacturing. Indeed, in the first case, steel coils are continuous strings that are shaped and cut according to panel dimensions, with minimum material waste. Similarly, for prefabricated cardboard panels, manufacturing is based on cardboard sheets purchased (from external sub-suppliers) according to panel dimension; that means once sheets are folded and glued wastes of material are minimized.

- Reduction of emissions:
 - SP. (8) Low energy demand and CO² emissions from processing
 - SP. (9) Structural material supplied from sustainably managed sources
 - SP. (10) Widespread material availability

The most intensive manufacturing processes are those associated with steel and concrete (T.01, T.02, T.03, T.06, T.08, T.11), which require high energy demand and produce high pollutant emissions. On the contrary, wooden-based technologies (T.04, T.05, T.06, T.07, T.09, T.10) show limited environmental impact related to manufacturing; moreover, the material itself has the capacity to stock CO₂ and contributes to reducing the overall impact of the life-cycle [46]. Similarly, cardboard manufacturing has been proven to involve low-energy processing, even if specific investigations regarding the entire manufacturing process of cardboard panels are not available in the literature.

Economy

- Speed of construction:
 - SP. (11) Reduction of construction time compared to traditional buildings

As already proven by the literature presented in Section 1, prefabricated technologies demonstrate an increase in the speed of construction compared to traditional methods. Based on quantitative data, time reduction is emphasized for modular construction (MMC Category 1, T.01–T.06), varying between 50–70%, while is reduced to 20–30% for panelized systems (MMC Category 2, T.07–T.12). Nonetheless, when evaluating the overall technical

performance of speed of construction, it must be taken into account that time reduction can be influenced by specific construction requirements, as better described in SP.12.

Concerning T.13 (3D printing), the achievement of SP.11 could not be verified because no quantitative data have been found in the literature to compare the speed of construction with traditional technologies.

- Ease of construction:
 - SP. (12) Building components can be easily handled and installed by workers without using crane equipment
 - SP. (13) Stacking and installation of components do not require specific site protection measures against weather

The possibility to install building components without using heavy-duty crane equipment ensures adaptability to different urban and social contexts, as well as reduces the total cost of construction from an economic sustainability perspective. However, only a few technologies can respond to this need, specifically, T.01, T.07, and T.12 (Portable buildings with a “flat-packed” option, SIP panels, and cardboard panels). In fact, in these cases, the lightweight building components make it possible for a few workers to assemble a one-story building without using complex equipment [45,47].

Conversely, innovative technologies such as 3D printing (T.13) require highly specialized professionals who can set and control printing machines, with a proportional increase in construction cost and the consequent reduction of economic sustainability [49].

Concerning SP.13, as already mentioned in SP.11, the analysis shows that the majority of the technologies (T.01, T.02, T.03, T.06, T.08, T.12, T.13) require the installation of a specific protective structure in the construction site, to preserve building components from weather, resulting in a more complex site and construction planning, and an increase in cost. For this reason, and especially for large-scale projects, an accurate organization and scheduling of construction activity is paramount, to optimize transport, times, and costs.

- Economy of construction:
 - SP. (14) Building components are optimized for transport

For the scope of this work, the unit costs of technologies have not been evaluated, since such parameters are strictly dependent on the installation context. The economy of construction is here related to the transport of building components, i.e., their optimization in the perspective of reducing costs. With these premises, the investigation demonstrated that panelized systems (MMC Category 2, T.07–T.12) better optimize transport from an economic perspective; in fact, the possibility of stacking panels minimizes the need for multiple transports, as well as the economic impact of transport from the factory to installation site [37].

Conversely, for prefabricated modular units (MMC Category 1, T.01–T.06) the need to transport empty volumes increases the economic impact of transport, especially for exceptional loads and long-distance locations. Moreover, the investigation shows that the bearing structure of modular units needs to be over-engineered to support dynamic loads during the transport, causing additional costs for the project. Regarding this criticism, an effective solution has been developed for technology T.01 (Portable buildings); portable units can be delivered in a “flat-packed kit of components”, i.e., disassembled units that can be stacked as panelized systems to reduce the economic impact of transport [37].

Society

- Product-process adaptability
 - SP. (15) Technology can be easily integrated with other building systems and components
 - SP. (16) Technology ensure space flexibility (variable space configuration, adaptation to specific design program)
 - SP. (17) Components can be integrated and/or modified after manufacturing

- SP. (18) Components can be removed and/or to accommodate further changes in the space program
- SP. (19) Flexible manufacturing, i.e., changes in the building product requires minimum changes in the production chain

Case study comparison shows that panelized systems (MMC Category 2, T.07–T.12) allow for enhanced adaptability in terms of the spatial configuration of a building (SP.16) since panels can be aggregated in different and flexible space layouts. Nevertheless, evaluating SP.18, i.e., the possibility for further changes in the functional program, it must be noticed that load distribution in panelized systems represents a constraint for further modification of spatial layout [1,37,40]. Such features have to be taken into account starting from the design stage to leave maximum space for adaptation; one effective strategy is to conceive space aggregation as a series of repeatable and independent units that can be added or removed according to the variation of user needs.

For this reason, modular buildings (MMC Category 1, T.01–T.06) perform better in terms of space adaptability. In fact, despite space configuration being initially limited by dimensional constraints, the structural functioning of modules, which is mutually independent, allows for further building adaptation; compatibly with technological limitations explained in SP.03, modules can be added and/or removed to accommodate changes in the space program without compromising the integrity of the building as a whole [1].

Regarding SP.17, i.e., the possibility to modify components after manufacturing, the investigation proves that the majority of case studies do not allow for further modifications (T.01, T.03, T.04, T.08, T.09). In the case of T.01 (Portable buildings), this is a consequence of product standardization as a commercial approach, while in the other cases results from intrinsic technical constraints. For instance, in CLT technology the structural behavior of the panel is closely related to its shape (dimensions, openings) and integrity, and only slight changes can be made to the final product. For concrete technologies, the shape and dimensions of panels and/or monolithic modules must be defined before casting, and again only minimum variations can be integrated during and after manufacturing. Such limitations not only require high control during the design phase, but also a tight collaboration and dialog with customers to ensure the final product corresponds to initial ideas.

Concerning manufacture adaptability (SP.19), the majority of case studies show the possibility to reconfigure the production chain to adapt final products. Customization varies from choosing within a catalog of pre-determined options (e.g., standard set of dimensions, range of finishing, etc.) to bespoke design solutions. This is enabled by a lean management model for production, as well as the use of an automatized design-production chain, which enables direct communication between different design specifications and processing equipment [18]. For T.12 (Cardboard panels), the parameter is not met because design-manufacturing is tailored for each customer; design specifications are elaborated for each project individually and panel manufacturing is currently led manually by workers that have to adapt the manufacturing process to executive design. Instead, for prefabricated concrete technologies (T.06, T.11), the possibility for easy reconfiguration is limited because of the need to adapt molds, which is a cost and time-intensive process.

- Work safety and health
 - SP. (20) Manufacture processing requires minimum interaction with workers (limited to machine setting and control)

Despite all prefabrication technologies contributing to improving working conditions and safety, the majority of manufacturing processes still require substantial interaction with workers, and their contribution is mainly focused on sub-component assembly. This condition is exacerbated in T.12 (Cardboard panels), since panels are manufactured manually by workers, exposing them to a higher risk of injuries. In this scenario, technologies that satisfy SP.20 are limited to CLT prefabrication (T.05, T.10) and 3D printing (T.13); in these cases, workers' contributions are limited to machine setting, control, and

intervention in cases of malfunction [50,51]. Moreover, recent IT technology for industry 4.0, and above all machine learning, have made it possible for equipment to run self-repairing actions, reducing the need for human interaction within manufacturing.

- Inclusion and collaboration
 - SP. (21) Design adopts an “open system” approach to ensure customization and integration of different specifications (structural, energetic, costs, etc.)

The adoption of an “open system” approach concerns those technologies that have a higher degree of customization, such as T.02–T.05 and T.08–T.10. In these cases, the technological system is organized into “hard” components, i.e., standardized structural elements, and an open set of solutions to personalize the envelope (wall and roof), windows, external, and internal finishing. The interaction with different stakeholders (contractor, suppliers, clients, etc.) and between design phases (structural, architectural, energetic, etc.) varies according to the strategy adopted by the company, and, thus, the achievement of social sustainability performances related to “collaboration” could not be generalized to all the case studies.

4. Discussion

The sustainability of the AEC sector is an increasing concern for international policies and private and public professionals and it is sustained from investments focused on the reduction of the environmental, economic, and social impact of buildings. From this perspective, stakeholder design choices, implemented in different phases of the building process, are paramount to determine overall building sustainability.

Building prefabrication can help meet sustainability goals in construction and find renewed potential in light of recent concepts as Construction 4.0 and circular materials. These innovations in the field of prefabrication led to the development of new technological systems, with enhanced performances and quality. Nonetheless, designers and actors involved in the building process have to be guided, from an early stage, by proper decision-support tools to gain awareness of the effect of design and manufacturing strategies. The literature investigation did not provide an exhaustive map of existing prefabrication technologies that analyze the effect of technological, material, and manufacturing options for the sustainability of the building life-cycle. In fact, some recent research [3–5,24,29,32,35,36,43] identified qualitative and quantitative parameters affecting the sustainability of building processes; however, these studies focused on analyzing the effect of single design and manufacturing choices, without evaluating the mutual contribution of the strategies on the final sustainability of buildings.

From this perspective, the work contributes to the open debate with an updated analysis of prefabrication technologies in Europe that evaluates their sustainability performances considering the synchronous effect of technological, production, and use of materials strategies.

The first phase of the work developed an updated state-of-the-art investigation in the field of building prefabrication through 13 case studies analysis. Then, to evaluate their sustainability performances, the second phase produced a comparative assessment according to 21 qualitative sustainability parameters. The results of the work make it possible to answer the research question (RQ), i.e., to define which innovations and strategies enhance the sustainability of prefabricated buildings (Figure 3). The answer to the research question is not univocal, but is a complex set of connected design and manufacturing choices, the effectiveness of which have to be assessed in the light of the context and design requirements.



Figure 3. Building sustainability can be achieved with a different approach to technology, manufacturing, and materials, i.e., integrating prefabricated construction with industry 4.0 manufacturing and the use of circular materials [4,19,23].

For this reason, and given the complexity of the variables involved in buildings sustainability, to answer the RQ, a system of interrelated options was developed, summarizing strategies and design alternatives that have to be considered starting from the early design stage to achieve the highest degree of sustainability. The identified strategies are described in the form of suggested guidelines, and are linked to the achievement of the sustainability goals defined in Table 3, column a. The strategies can be grouped in four major areas of decision, each of which summarizes the main findings from the analysis:

- S.1—Material and technology

The use of prefabricated steel technologies help to achieve the sustainability goal of circularity of building components and material resources; for this reason, their adoption should be preferred for buildings with short but repeated cycles of use, such as transitional and/or emergency accommodation for student housing, temporary housing for workers, schools, and events. Such a strategy ensures maximizing steel durability and reduces the high environmental impact associated with production. On the contrary, the use of wooden and concrete prefabrication proves to have reduced circularity over building components and material resources; consequently, these technologies are demonstrated to be more suitable for long-term installation to exploit their potential before downcycling.

Finally, the use of cardboard shows high sustainability potential in a circular perspective, but more research efforts are needed to exploit its performance during the life cycle. Regarding this, open questions emerged from the analysis concerning its durability and the development of fireproofing solutions that allow paper recycling.

- S.2—Assembly and construction

Starting from the design phase, the integration of low-complexity assembling techniques proves to meet sustainability goals, such as economy, ease, speed of construction, adaptability, and integration. Moreover, an accurate design of the assembly and sealing methods potentiates circularity performances, allowing for multiple assembly and disassembly of building components and/or material selection for final recycling. Suggested improvements concern the development of assembly techniques that enable the circularity of building components (such as modular units or panels) and material resources, and particularly for wooden and concrete prefabrication that showed critical performances in this field.

- S.3—Transport

The impact of transport plays a key role in the economic and environmental sustainability of prefabricated buildings, as it can increase the cost of construction and the amount of pollutant emissions. For this reason and given their impact, the use of modular buildings is more suitable for small-scale buildings requiring a limited number of units. For larger-scale projects, the use of modular buildings should be evaluated together with the availability of local manufacturers. Otherwise, an alternative is the manufacturing of sub-components that are further transported and assembled in a second location, close to the final installation site.

- S.4—Industrialized manufacturing

The transition of prefabricated technologies towards industrialized smart manufacturing (Industry 4.0/Construction 4.0) potentiates the benefits of prefabrication within design and manufacturing and guarantees the achievement of sustainability goals as product-process predictability and adaptability, reduction of material wastes, work safety and health for workers, inclusion, and collaboration between different actors. On the operational level, this requires a shift from traditional approaches to design and manufacturing, implying a substantial increase in the complexity of technical and procedural design variables, in terms of information, stakeholders, and competencies involved.

In this case, design has to embrace a design for manufacture and assembly strategy to facilitate prefabrication of building elements, i.e., to reduce changes from concept to executive design. In this scenario, emerging IT technologies for design-manufacturing management have innovative potential for construction, offering the possibility to control, simulate, and verify building performances alongside the process as well as to communicate design specifications between different phases. Among these, BIM-based (building information modeling) approaches emerged as a method to integrate design, performance simulation and verification, and manufacturing-related information. Moreover, the proposed strategy is to develop a tight collaboration between designers, manufacturers, and suppliers starting from the early phases of design, to streamline the design-manufacturing process (cost and time reduction), optimize design specification, and minimize wastes.

The identified guidelines represent a set of suggested strategies to be adopted from designers and manufacturing professionals in the prefabrication sector to address the sustainable transition of the AEC sector. Indeed, starting from the investigation of current prefabrication technologies in Europe, the work established a link between the implementation of the described strategies and the achievement of sustainability goals.

5. Conclusions

This research defines a decision-support tool for designers and industry professionals involved in the prefabrication sector. The results of the evaluation led to the identification of a set of guidelines that support stakeholders in evaluating the effects of design and manufacturing choices on the final sustainability of the building process. Moreover, the work identifies effective strategies to enhance the sustainability of the building process considering specific design and manufacturing requirements. Furthermore, starting from the qualitative assessment, directions for future research in specific technologies have been identified to improve critical aspects detected during the investigation.

In the first stage of this work, a qualitative research approach has been adopted to provide a scientific framing of the complexity of the variables involved. Starting from the research results, further development of the work concerns the evaluation and comparison of sustainability parameters according to quantitative data. The implementation requires the definition of assessment quantitative parameters, starting from existing literature [4] as a base, and their application to case studies, i.e., prefabricated building designs that can be compared. The goal is to contribute to recent research works defining quantitative assessment benchmarks to evaluate the environmental, economic, and social sustainability of current prefabricated technologies available in Europe.

A further implementation of the work involves the development of a web catalog based on the technologies inventory (Appendix A); the tool will be connected to the open-source libraries made available from manufacturers, to provide information to designers and stakeholders about the performance and sustainability characteristics of their technologies. This represents a further step toward providing building stakeholders (design, manufacturers, decision-makers) with a decision-support tool to evaluate the sustainability of their choices starting from the early phases, as well as to project their effects within the building life-cycle.

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Appendix A. Analysis of Prefabricated Building Technologies: Reading Sheets

T.01 | PORTABLE BUILDINGS

OVERVIEW

Commonly referred as “portables”, these modular building solutions are widely used to provide emergency spaces or temporary accommodation for a variety of uses (construction sites, events, etc.). Their large use depends on limited time and costs required for installation, as well as the possibility to easily combine modules to accommodate different programs. Portables are built with a skeletal steel frame and steel sandwich panels as infill; despite their economy and ease of transport and installation, portables are often blamed to provide low environmental and comfort performances for the users.

MMC Category	MMC1 - Pre-manufacturing: 3D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 95%
Flexibility and integration	Portable building technology ensures space flexibility , since modules can be easily add or removed to accommodate space program changes, despite they limit space configurations due to dimensional constraints. However, portable buildings show little degree of technological integration with other building technologies and/or components
Transport and installation	Portable buildings dimensions are optimized for transport ; moreover, flat-packed solutions are available to reduce the impact of transport
Estimated time saving	50-70%

MATERIALS

Structural material	Steel
Material supply sources	Steel employed in portable buildings partly come from recycled material , allowing reducing the impact of raw material processing
End-of-life options	Modules and/or building components can be easily disassembled, relocated or reused at the end of their use thanks to the use of dry-assembling techniques

MANUFACTURING

Design approach	---
Manufacture processing	Building components are manufactured with semi-automated cold forming processes, allowing for standardization and quality control . Modules are assembled by workers according to streamlined sequences
Manufacturing environmental impact	Steel production is proven to be energy-intensive and to produce high levels of CO ₂ emissions
Customization approach	Portable buildings are a standardized, mass-produced technology, i.e. are manufactured according to a Made-to-stock commercial approach, limiting bespoke design customization



Image 01 – Portable modular units employed for a post-earthquake school (Malpighi School in Mirandola, Italy)

Credits: Fae Terni S.p.a.



Image 02 – Portable modular units assembled inside the controlled environment of the factory. The picture shows the steel skeletal structure infilled with steel sandwich panels

Credits: Algeco S.p.a.



Image 03 – Portable units in “flat-packed” delivering option are mass-produced in batches and stocked for orders

T.02 | ISO SHIPPING CONTAINERS

OVERVIEW

ISO Containers are used worldwide as an effective solution to transport goods. Their dimensions have been standardized in 1970 by International Standard Organization. They are optimized for transport, have a good structural robustness and can be easily disassembled and reuse. For these reasons, and due to the great amount of units available, in the last years containers have been used also for architecture. Containers are built with a steel skeletal structure and corrugated steel sheets for the envelope. Usually, an additional wooden floor system is provided to increase the strength. The cost per unit ranges from 1'500 to 4'000\$.

MMC Category	MMC1 - Pre-manufacturing: 3D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 95%
Flexibility and integration	The use of modular building units ensures space flexibility , since modules can be easily add or removed to accommodate space program changes, despite they limit space configurations due to dimensional constraints. Container buildings can also be used as infill in steel or concrete structures and/or be integrated with different envelope technologies (prefabricated sandwich panels, light steel frame, wooden frame)
Transport and installation	Modules' dimensions are optimized for transport by road, railway and ship.
Estimated time saving	50-70%

MATERIAL

Structural material	Steel
Material supply sources	Steel employed in portable buildings partly come from recycled material , allowing reducing the impact of raw material processing
End-of-life material options	According to design strategies and modules assembling techniques, containers and/or their components can be disassembled, relocated or reused at the end of their use.

MANUFACTURING

Design approach	---
Manufacture processing	Building components are manufactured with semi-automated cold forming processes, allowing for standardization and quality control . Once installed, modules are adapted and integrated by workers in the construction site
Manufacturing environmental impact	Steel production is proven to be energy-intensive and to produce high levels of CO ₂ emissions
Customization approach	ISO containers are standardized and mass-produced units (Made-to-Stock), primarily employed for commercial purposes. Their use in construction sector requires consistent changes and bespoke design solutions in order to adapt container modules to living requirements



Image 01 – Shipping containers used in Cité A Docks in Le Havre, France

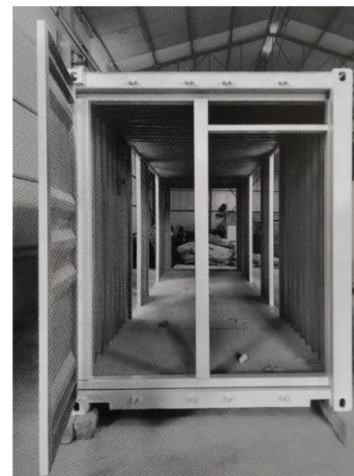


Image 02 – Containers require off-site integrations (envelope, systems) to be able to perform correctly during the use
Credits: Doone Silver Kerr



Image 03 – Common use in architecture for modular shipping containers is student housing, because of their space repeatability. In the picture, Qubic Student Housing in Amsterdam (Netherlands) by Studionedots

T.03 | LIGHTGAUGE STEEL MODULAR UNITS

OVERVIEW

Steel modular units are constructed using a Lightgauge Steel Frame (LSF) technology that provides a robust structural systems while ensuring speed of installation. Modules can be integrated with various components and systems allowing for a greater degree of flexibility. Modular units are assembled inside a factory and then transported to the site almost completed. For this reason, specific attention has to be placed in structural engineering, since modules have to resist to exceptional loads during transport and craning.

MMC Category	MMC1 - Pre-manufacturing: 3D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 95%
Flexibility and integration	Modular units ensure space flexibility , since they can be stacked in multiple storeys, add or removed to accommodate changes. For large-scale projects, steel frame modular units provide a valuable solution for technical cores , i.e. stackable service units commonly referred as "pods"
Transport and installation	Modular units' dimensions need to be limited according to transport regulations . Moreover, structural design often requires over-engineering steel sections to support dynamic loads with consequent increase in modules weight
Estimated time saving	50-70%

MATERIAL

Structural material	Steel
Material supply sources	Steel employed for skeletal frames partly come from recycled material , allowing reducing the impact of raw material processing
End-of-life material options	According to design strategies and modules assembling techniques, modules and/or their components can be disassembled, relocated or reused at the end of their use.

MANUFACTURING

Design approach	Modules executive design is led according to a file-to-factory approach , i.e. employing BIM and CAD-CAM software to directly communicate design specification to manufacturing machines
Manufacture processing	Steel sections are cold-formed with CNC machines allowing for enhanced quality control, material optimization and reduced wastes . Assembling is performed in single-station semi-automated cells, i.e. according to easily-reconfigurable sequences to guarantee product customization
Manufacturing environmental impact	Steel production is proven to be energy-intensive and to produce high levels of CO ₂ emissions
Customization approach	Modules are design and delivered according to a mass customization approach ; common commercial strategies are Assembled-to-Stock and Made-to-Order



Image 01 – Modular units are off-site manufactured following streamline sequences of assembly
Credits: American Modular Systems (AMS)



Image 02 – Installing sequences of steel modular units
Credits: American Modular Systems (AMS)



Image 03 – Steel modular units are also widely used for technical pods i.e. service cores usually employed for large-scale building complexes

T.04 | TIMBER FRAMED MODULAR UNITS

OVERVIEW

Wooden framed modular units are constructed using wooden framed panels that are off-site assembled and partly completed before loaded in trailers for being installed in the site. The technology offers a high degree of flexibility and customization options in terms of finishing and systems. Although technically feasible, wood modules are used in buildings up to three storeys, since over this limit structural requirements make the modules uneconomical. The use of wooden modules is common in areas with great material availability.

MMC Category	MMC1 - Pre-manufacturing: 3D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 95%
Flexibility and integration	Wooden modular units show reduced space flexibility compared to steel modules due to tighter dimensional limitations . Connections and sealing between modules compromises possibility for adding and/or remove modules over time.
Transport and installation	Modular units' dimensions need to be limited according to transport regulations . Moreover, structural design often requires over-engineering steel sections to support dynamic loads with consequent increase in modules weight
Estimated time saving	50-70%

MATERIAL

Structural material	Wood
Material supply sources	The wood used for components manufacturing comes from raw material ; depending on the company, the material can be supplied by sustainably managed woods (FSC certified) , but often requires long and high-impact transport due to its limited availability.
End-of-life material options	The type of connections and sealing limits the possibility to relocate modules at the end of their use. Components can be disassembled and wood can be recycled in other manufacturing processes (down-cycling)

MANUFACTURING

Design approach	Modules executive design is led according to a file-to-factory approach , i.e. employing BIM and CAD-CAM software to directly communicate design specification to manufacturing machines
Manufacture processing	Wooden sections are cut with high-precision machines allowing for enhanced quality control over the final products . Assembling is performed in single-station semi-automated cells, i.e. according to easily-reconfigurable sequences to guarantee modules customization.
Manufacturing environmental impact	Wooden manufacturing is a low energy process with limited CO ₂ emission
Customization approach	Modules are design and delivered according to a mass customization approach ; commercial strategy is primarily Made-to-Order



Image 01 – Wooden modular units employed for Temporary Social Housing (Florence, IT - 2013), the first building in Italy delivered with wooden units

Credits: Casa S.p.a.



Image 02 – Modular units are off-site manufactured following streamline sequences of assembly

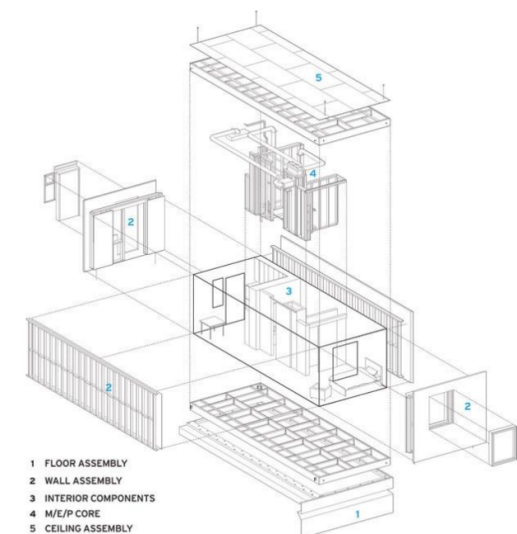


Image 03 – Exploded technological layout of wooden modular units. Technology allows for integrating different components and parts, so modules become flexible and can be customized

Credits: Guerdon Modular Buildings

T.05 | CLT MODULAR UNITS

OVERVIEW

Cross Laminated Timber (CLT) modular units use a massive wooden technology to build pre-assembled structures that are finished with various degree of prefabrication inside a factory, then transported and installed on site. CLT allows for enhanced envelope performances, especially for thermal insulation and thermal mass. Nevertheless, this results in heavier weights and associated higher costs.

MMC Category	MMC1 - Pre-manufacturing: 3D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 95%
Flexibility and integration	CLT modular units show reduced space flexibility compared to steel modules due to tighter dimensional limitations . Connections and sealing between modules compromises possibility for adding and/or remove modules over time. Moreover, CLT modular demonstrates limited integrability, since modules once manufactured can no longer be modified.
Transport and installation	Modular units' dimensions need to be limited according to transport regulations . Moreover, the use of CLT panels results in heavyweight modules , requiring high-duty and expensive transport and craning equipment
Estimated time saving	50-70%

MATERIAL

Structural material	Wood
Material supply sources	The wood used for components manufacturing comes from raw material ; depending on the company, the material can be supplied by sustainably managed woods (FSC certified) , but often requires long and high-impact transport due to its limited availability.
End-of-life material options	The type of connections and sealing limits the possibility to relocate modules at the end of their use. Components can be disassembled and wood can be recycled in other manufacturing processes (down-cycling)

MANUFACTURING

Design approach	Modules executive design is led according to a file-to-factory approach , i.e. employing BIM and CAD-CAM software to directly communicate design specification to manufacturing machines
Manufacture processing	Wooden panels are cut with high-precision machines allowing for enhanced quality control over the final products . Assembling is performed in single-station automated cells, i.e. according to easily-reconfigurable sequences to guarantee panels customization .
Manufacturing environmental impact	Wooden manufacturing is a low energy process with limited CO ₂ emission
Customization approach	Modules are designed and delivered according to a mass customization approach ; commercial strategy is primarily Made-to-Order



Image 01 – CLT modular units being assembled and integrated with cables and services inside a factory



Image 02 – Modular units can be off-site finished with exterior cladding, internal finishes and doors and windows



Image 03 – In order to optimize transport, MADI Home has patented a pop-up residential modular unit built with CLT technology
Credits: MADI Home

T.06 | CONCRETE MODULAR UNITS

OVERVIEW

Despite being accounted as one of the first experimental technology used for modular construction, concrete modular units are now less employed. This mainly depends on their weight and consequent heavy-duty equipment needed for transport and installation. Nevertheless, there are still examples of concrete modular used to provide accommodation for residential or commercial purposes, mostly because its intrinsic thermal and fire-proofing features. Modules can be manufactured from 2D panels (walls, ceiling, roof) or as 3D monolithic units with an open base.

MMC Category	MMC1 - Pre-manufacturing: 3D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 95%
Flexibility and integration	Concrete modular units show reduced space flexibility due to tighter dimensional limitations . Moreover, CLT modular demonstrates limited possibility for integration and adaptability, since modules once manufactured can no longer be modified.
Transport and installation	Modular units' dimensions need to be limited according to transport regulations . Moreover, monolithic structures result in heavyweight modules , requiring high-duty and expensive transport and craning equipment
Estimated time saving	50-70%

MATERIAL

Structural material	Concrete
Material supply sources	Concrete employed in modular units partly come from recycled material and material wastes from other manufacturing processes and/or construction demolitions (e.g. roof tiles)
End-of-life material options	The type of connections limits the possibility to relocate modules at the end of their use. Modules can be dismantled and concrete can be recycled in other manufacturing processes (down-cycling)

MANUFACTURING

Design approach	---
Manufacture processing	Monolithic modular units are manufactured with single-station automated casting machines. Product variability is limited due to the complexity of molds required for casting
Manufacturing environmental impact	Concrete manufacturing is an energy-intensive process with high levels of CO ₂ emissions
Customization approach	Modules are design and delivered according to a mass production approach ; bespoke designs are possible but require economic and time expensive reconfiguration of molds. Commercial strategy is primarily Made-to-Order

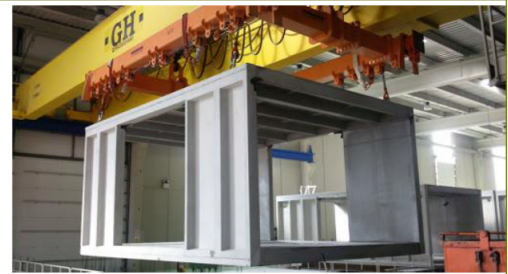


Image 01 – Concrete panels are manufactured by casting and assembled to form volumetric modular units inside a factory



Image 02 – Installation phases of modular units on site. Volumes come with a lower degree of completion and need further on-site operations to be finished
Credits: Solid Box



Image 03 – Modular units installed on-site: due to dimensional restrictions, space layouts and flexibility are reduced

T.07 | SIP PANELS

OVERVIEW

Structural Insulated Panels are pre-engineered lightweight panels that are off-site manufactured and assembled for building applications. SIPs are made out of a core rigid foam insulation sandwiched between two structural skins. Usually, the skin is made of Oriented Strand Board (OSB) with expanded polystyrene (EPS) or polyurethane (PUR) as insulating core materials. In the factory, panels are provided with holes for windows and doors and technical services integration. Once assembled, they can be completed in a variety of options.

MMC Category	MMC2 - Pre-manufacturing: 2D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 60%
Flexibility and integration	The use of SIPs for buildings ensures high degree of space flexibility , since panels can be aggregated in diversified layouts according to space requirements. However, distribution of loads can limit further possibilities to dismount single panels. Moreover, adaptability is limited because once manufactured panels can no longer be modified
Transport and installation	SIPs are easily transported and installed thanks to their lightweight; the possibility to stack panels ensure transport optimization
Estimated time saving	20-30%

MATERIAL

Structural material genre	Composite
Material supply sources	The panel core is made with plastic insulation coming from raw and/or recycled material; shearing boards use material wastes from wood manufacturing processes.
End-of-life material options	At the end of the use, panels can be disassembled and each material recycled .

MANUFACTURING

Design approach	---
Manufacture processing	Insulation core and shearing boards are manufactured by heat pressing; SIPs panels are then cut by high-precision machines ensuring tight quality control over the final product and possibility for customization.
Manufacturing environmental impact	---
Customization approach	SIPs are standardized and mass-produced, but each panel can be customized according to specific design requirements (dimensions, holes for windows and doors, etc.), i.e. they are available on the market according to a mass-customization approach . Commercial approaches vary from Made-to-Stock, Assembled-to-Stock and Made-to-Order



Image 01 – SIP Panels being installed on site for further integration



Image 02 – Panels are assembled inside a factory, where they are provided with holes for allocating services, windows and doors. This limit possibility for future integration and modifications



Image 03 – OSB panels used to encase insulation are produced gluing together wooden shreds coming from production wastes, offering the opportunity to reduce the use of raw materials

T.08 | LIGHTGAUGE STEEL FRAME PANELS

OVERVIEW

Lightgauge Steel Frame (LSF) panels among the most common prefabrication systems, currently used for a varied number of application (residential, commercial, interiors, etc.). Framed panels are manufactured with galvanized, cold-formed steel profiles obtained by cold pressing a continuous steel sheet. This significantly reduces material wastes during the production. LSF panels combine lightweight with high durability and strength, and can be integrated with different systems and components.

MMC Category	MMC2 - Pre-manufacturing: 2D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 60%
Flexibility and integration	The use panelized systems ensures high degree of space flexibility , since panels can be aggregated in diversified layouts according to space requirements. However, distribution of loads can limits further possibilities to dismount single panels to adapt building over time.
Transport and installation	Panelized systems are easily transported and installed thanks to their lightweight; the possibility to stack panels ensure transport optimization reducing the need for multiple transport
Estimated time saving	20-30%

MATERIAL

Structural material	Steel
Material supply sources	Steel employed for skeletal frames partly come from recycled material , allowing reducing the impact of raw material processing
End-of-life material options	At the end of their use, steel frames can be disassembled and/or reused . Steel components can be recycled in other manufacturing processes (recycling-upcycling)

MANUFACTURING

Design approach	Panels executive design is led according to a file-to-factory approach , i.e. employing BIM and CAD-CAM software to directly communicate design specification to manufacturing machines
Manufacture processing	Steel sections are cold-formed with CNC machines allowing for enhanced quality control, material optimization and reduced wastes . Assembling is performed in single-station semi-automated cells, i.e. according to easily-reconfigurable sequences to guarantee product customization
Manufacturing environmental impact	Steel production is proven to be energy-intensive and to produce high levels of CO ₂ emissions
Customization approach	Panels are design and delivered according to a mass customization approach , based on standardized steel sections that can be assembled in variable panel configurations. Common commercial strategies are Assembled-to-Stock and Made-to-Order



Image 01 – Cold Formed Steel profiles are off-site assembled by welding and mechanical fastening

Credits: Drywall Systems Plus



Image 02 – LSF panels offer the possibility for integrating technical services, optimizing internal space distribution

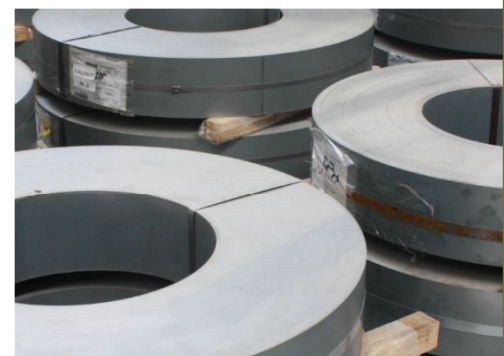


Image 03 – Steel profiles are manufactured starting from **steel coils** and then shaped with pressing machines as Howick Frama™

T.09 | TIMBER FRAMED PANELS

OVERVIEW

Emerged as evolution of traditional “balloon frame” technology, platform frame is now widely used for different applications, mostly because its lightweight and speed of construction. Moreover, technology has evolved from on-site works to off-site manufacturing of panels that are pre-assembled and completed with services, windows, doors, etc. Structural panels are made of timber studs with standardized sections, sheared with OSB or gypsum board and insulated with various materials. Frames provide a flexible structure for systems’ integration.

MMC Category	MMC2 - Pre-manufacturing: 2D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 60%
Flexibility and integration	The use of panelized systems ensures high degree of space flexibility , since panels can be aggregated in diversified layouts according to space requirements. However, distribution of loads can limit further possibilities to dismount single panels to adapt building over time.
Transport and installation	Panelized systems are easily transported and installed thanks to their lightweight; the possibility to stack panels ensure transport optimization reducing the need for multiple transport
Estimated time saving	20-30%

MATERIAL

Structural material	Wood
Material supply sources	The wood used for components manufacturing comes from raw material ; depending on the company, the material can be supplied by sustainably managed woods (FSC certified) , but often requires long and high-impact transport due to its limited availability.
End-of-life material options	The type of connections and sealing limits the possibility to re-install panels at the end of their use. Components can be disassembled and wood can be recycled in other manufacturing processes (down-cycling)

MANUFACTURING

Design approach	Modules executive design is led according to a file-to-factory approach , i.e. employing BIM and CAD-CAM software to directly communicate design specification to manufacturing machines
Manufacture processing	Wooden sections are cut with high-precision machines allowing for enhanced quality control over the final products . Assembling is performed in single-station semi-automated cells, i.e. according to easily-reconfigurable sequences to guarantee modules customization.
Manufacturing environmental impact	Wooden manufacturing is a low energy process with limited CO ₂ emission
Customization approach	Modules are design and delivered according to a mass customization approach ; Commercial strategy is primarily Made-to-Order



Image 01 – Sub-components and parts are assembled in panels following streamline sequences of industrial operations
Credits: RubnerHaus



Image 02 – During manufacturing pipes and cables can be integrated providing holes in the panels in order to reduce on-site operations for services



Image 03 – Wood framed panels during installation phases

T.10 | CLT PANELS

OVERVIEW

Cross Laminated Timber (CLT) is an engineered-wood technology that uses massive wooden panel manufactured off-site and then assembled in site. Panels are manufactured gluing together perpendicular layers of softwood. This provide a heavyweight structure that ensure high envelope performances, especially in terms of thermal mass. Panels are pre-engineered, and then manufactured according streamline sequences of assembly and can be completed with a wide variety of components.

MMC Category	MMC2 - Pre-manufacturing: 2D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 60%
Flexibility and integration	The use of CLT panels for buildings ensures high degree of space flexibility , since panels can be aggregated in diversified layouts according to space requirements. However, distribution of loads can limits further possibilities to dismount single panels. Moreover, adaptability is limited because once manufactured panels can no longer be modified
Transport and installation	The use of monolithic panels results in heavy-weight building components , requiring high-duty transport and craning equipment
Estimated time saving	20-30%

MATERIAL

Structural material	Wood
Material supply sources	The wood used for components manufacturing comes from raw material ; depending on the company, the material can be supplied by sustainably managed woods (FSC certified) , but often requires long and high-impact transport due to its limited availability.
End-of-life material options	The type of connections and sealing limits the possibility to reinstall panels at the end of their use. Components can be disassembled and wood can be recycled in other manufacturing processes (down-cycling)

MANUFACTURING

Design approach	Panels executive design is led according to a file-to-factory approach , i.e. employing BIM and CAD-CAM software to directly communicate design specification to manufacturing machines
Manufacture processing	Wooden panels are cut with high-precision machines allowing for enhanced quality control over the final products . Assembling is performed in single-station automated cells, i.e. according to easily-reconfigurable sequences to guarantee panels customization .
Manufacturing environmental impact	Wooden manufacturing is a low energy process with limited CO ₂ emission
Customization approach	Panels are design and delivered according to a mass customization approach starting from standardized sub-components. Commercial strategy is primarily Made-to-Order



Image 01 – Panels are assembled by pressing and adhesive following streamline sequences of industrial operations



Image 02 – CLT panels are off-site manufactured in batches and then shipped for installation on site



Image 03 - Panels can be transported on-site with a lower degree of prefabrication, i.e. structural wooden panels without external and internal finishes

T.11 | PRECAST CONCRETE PANELS

OVERVIEW

Precast concrete panels are off-site manufactured structural panels constructed using reusable molds to cast concrete. From an economical point of view a good strategy is to limit the number of different type of panels resulting in little degree of customization. Currently on the market there are different types of precast panels: sandwich concrete panels are pre-assembled with core insulation and have lighter weight, while double-skin panels require additional casting on site

MMC Category	MMC2 - Pre-manufacturing: 2D primary structural systems
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TECHNOLOGY

Degree of prefabrication	Up to 60%
Flexibility and integration	The use of concrete panels ensures high degree of space flexibility , since panels can be aggregated in diversified layouts according to space requirements. However, distribution of loads can limit further possibilities to dismount single panels. Moreover, adaptability is limited because once manufactured panels can no longer be modified
Transport and installation	The use of monolithic panels results in heavy-weight building components , requiring high-duty transport and craning equipment
Estimated time saving	20-30%

MATERIAL

Structural material	Concrete
Material supply sources	Concrete employed in prefabricated panels partly come from recycled material and material wastes from other manufacturing processes and/or construction demolitions (e.g. roof tiles)
End-of-life material options	On-site casting limits the possibility to disassembly and relocate panels at the end of their use. Panels can be dismantled and concrete can be recycled in other manufacturing processes (down-cycling)

MANUFACTURING

Design approach	---
Manufacture processing	Monolithic panels are manufactured with single-station automated casting machines. Product variability is limited due to the complexity of molds required for casting
Manufacturing environmental impact	Concrete manufacturing is an energy-intensive process with high levels of CO ₂ emissions
Customization approach	Modules are design and delivered according to a mass production approach ; bespoke designs are possible but require economic and time expensive reconfiguration of molds. Commercial strategy is primarily Made-to-Order



Image 01 – Precast concrete panels can be off-site manufactured and finished with different degrees of prefabrication (from raw structural panels to those integrated with doors and windows)



Image 02 – Manufacturing sequences: double mould for precast of sandwich panels, insulated with rigid polymer core

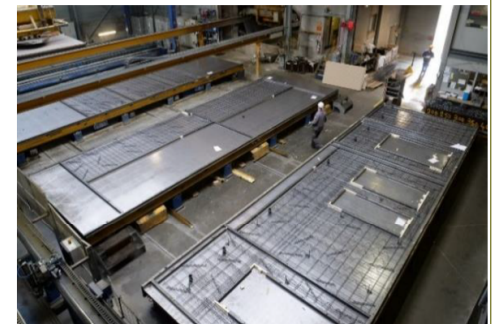


Image 03 – Architectural variability in dimensions and openings may be limited because of the need to provide a great number of molds

T.12 | CARDBOARD PANELS

OVERVIEW

Cardboard as a building material has been explored in recent times because of its natural low environmental impact, its possibility to be recycled. Moreover, despite its lightweight the material shows good mechanical resistance features and has a valuable anti-seismic resistance. Common components employed are tubes and panels, with the last one being off-site manufactured and then simply assembled on site by few workers.

MMC Category	MMC2 - Pre-manufacturing: 2D primary structural systems
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TECHNOLOGY

Degree of prefabrication	---
Flexibility and integration	The use of cardboard panels ensures high degree of space flexibility , since panels can be aggregated in diversified layouts according to space requirements. However, distribution of loads can limit further possibilities to dismount single panels. Moreover, adaptability is limited from tight dimensional constraints and panels can not be modified after manufacturing
Transport and installation	Panels are easily transported and installed thanks to their lightweight; the possibility to stack panels ensure transport optimization. In the construction site, panels must be protected against weather until they are installed and covered with external waterproofing layers.
Estimated time saving	---

MATERIAL

Structural material	Paper
Material supply sources	The paper used in cardboard panels manufacturing partly come from recycled sources . The percentage of raw materials employed is supplied by sustainably managed sources
End-of-life material options	At the end of their use, panels can be relocated and reinstalled. Concerning material, inner cardboard sheets can be recycled , while external sheets treated with fireproofing layers have to be delivered to landfill.

MANUFACTURING

Design approach	Design is led according to Computer Aided Design approach, i.e. describing bespoke specification for each project
Manufacture processing	Panels are manufactured by cutting, folding and glueing of cardboard sheets. Manufacturing and assembling sequences are performed in single-station cells and require constant interaction of workers
Manufacturing environmental impact	---
Customization approach	Panels are customized for each project and manufactured according to a Made-to-Order commercial strategy

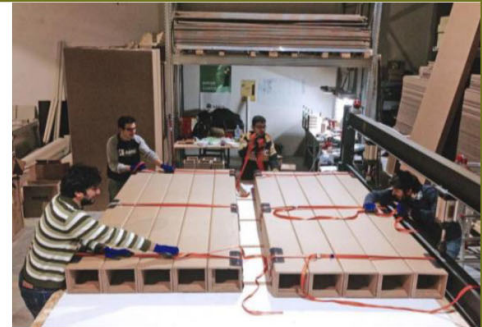


Image 01 – Cardboard panels are manually assembled by four workers inside the factory
Credits: Archicart



Image 02 – Cardboard panels are infilled with eco-friendly and recycled insulation
Credits: E. Belardi

T.13 | 3D PRINTING

OVERVIEW

3D printing in construction is one of the latest innovation introduced in the field of Modern Methods of Construction (MMC). Using a 3D printing machine, buildings are erected directly on site with building specifications being automatically transferred from digital to the built model. Materials used for printing vary from concrete to composite mixtures, allowing providing different envelope specifications and structural performances.

MMC Category	MMC4 - Additive manufacturing
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TECHNOLOGY

Degree of prefabrication	---
Flexibility and integration	3D printing for buildings guarantee high design flexibility in space configuration. However, being the structure monolithic this limits possibility for further intervention as dismounting, maintenance and components substitution, as well as space integrations and configurations.
Transport and installation	The construction site must be accessible for large machinery (printers); moreover, the site must be protected against unfavourable weather conditions.
Estimated time saving	---

MATERIAL

Structural material	Composite
Material supply sources	Materials used as binder vary depending on specific projects; these can be concrete-based binders as well as eco-friendly resources as raw soil and natural fibres.
End-of-life material options	At the end of building use, building components can not be dismounted; according to their specific nature, materials can be recycled

MANUFACTURING

Design approach	Executive design requires a file-to-machine approach, in order to transfer building specifications to printing machines. This ensure limiting errors and promoting enhanced quality control over the final building.
Manufacture processing	Manufacture consists on on-site automated 3D printing ; interaction of workers is limited to machine setting and operational control
Manufacturing environmental impact	Researches demonstrate that 3D printing is a low energy consumption process and generates limited CO ₂ emissions
Customization approach	3D printed building are realized as bespoke designs according to an Engineered-to-Order commercial approach.



Image 01 – 3D printing machine used for residential building project
Credits: COBOD



Image 02 – Automated printing process: human interaction is limited to machine setting and control
Credits: COBOD



Image 03 – The binder can be constituted of different materials and mixtures; natural and eco-friendly resources as raw soil can also be used as part of the binder
Credits: COBODO

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