Chapter 8
Modularity and Prefabrication

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Abstract The concepts of "modularity" and "prefabrication" require a deeper understanding being crucial to investigate their relation with the circular economy. Prefabrication involves pre-manufacturing building elements off-site and their transport to the construction site and assembly. Prefabrication can be divided into different categories: Component, Non-volumetric, Volumetric, Modular construction, Hybrid structures, or Whole building prefabrication; and can be based on linear (e.g., columns or pillars), bidimensional (e.g., walls or floor panels), or tri-dimensional elements (e.g., modules or whole prefabricated houses). The most commonly used materials are steel, wood, and concrete, although plastic, composite, and nature-based materials are increasingly being explored. While comparing the prefabricated materials, steel has high embodied impacts but recycle and reuse potential, timber has biogenic content and high reuse potential, and concrete poses transport and assembly challenges. The refurbishment of prefabricated buildings and the use of prefabricated

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L. Bragança et al. (eds.), *Circular Economy Design and Management in the Built Environment*, Springer Tracts in Civil Engineering,
https://doi.org/10.1007/978-3-031-73490-8_8

elements in refurbishment are also discussed. The main benefits of adopting prefabrication are impact, cost, material, waste, and time reduction, with quality increase; and the challenges are cultural, technical, and market aspects with some investment required. A bibliometric analysis explores the relationship between modularity, prefabrication, and circular construction and concludes that the link between the three concepts seems fragile and unclear.

Keywords Buildings · Circular economy · Construction · Modularity · Prefabrication

8.1 Introduction

The concepts of "modularity" and "prefabrication" are closely linked and require a deeper understanding to grasp their similarities and differences. Furthermore, it is crucial to investigate the connection between prefabrication and modularity within the circular economy framework. This chapter will involve in-depth analysis and mapping of current knowledge across these three domains.

Prefabrication, often abbreviated as "prefab", involves a construction approach in which building elements are produced in specialised factories or temporary facilities off-site and then transported to the construction site for assembly into buildings [1, 2]. The assembled structures are composed of precast elements (for example, beams, columns, slab panels, and wall panels) that can form a part of the whole building or infrastructure [2]. Prefabricated buildings have different degrees of prefabrication and are categorised according to their size, complexity, configuration, and installation into buildings [3]. The degree of prefabrication significantly influences the amount of construction labour needed on-site; a higher degree of prefabrication results in

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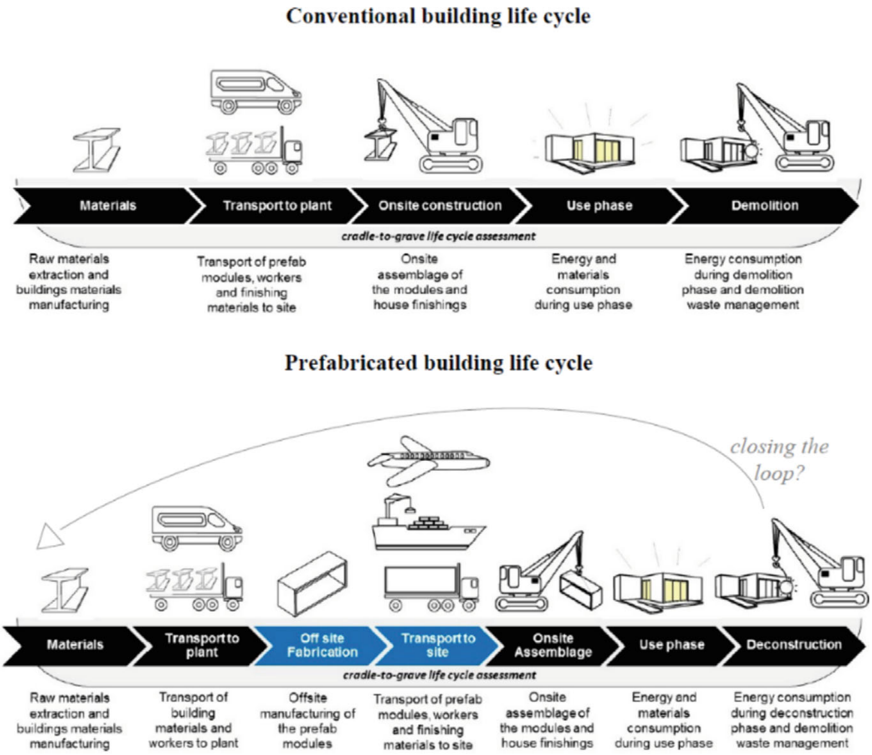


Fig. 8.1 Life cycle of a conventional building (on top) and prefabricated buildings (on the bottom). Based on [4]

reduced on-site construction labour, while a lower degree increases the need for on-site labour [3].

Compared to conventional buildings, prefabricated buildings have one extra stage, off-site fabrication, and one extra transport from plant to site. Figure 8.1 presents the life cycle (LC) of a conventional building (at the top) and the LC of prefabricated buildings (at the bottom). Table 8.1 presents the main terminology used in the field of prefabricated and modular buildings, including references.

8.2 Historical Context

One of the first references to prefabrication methodology emerged in 1624. The first houses were manufactured in England and transported to the fishing village of Cape Ann, the current city of Massachusetts. In 1790, simple timber-framed shelters also produced in England were shipped to New South Wales, in Australia, intended to be used as hospitals, warehouses, and cottages. Furthermore, some advantages related

Table 8.1 Terminology used in prefabrication and modularity, including references [4]

	Terminology	Reference (up to four)
Designations	Prefabricated	[5–7]
	Offsite	[8–11]
	Modern Methods of Construction	[12–14]
	Modular	[15–17]
	Pre-assembly	[18, 19]
	Precast	[20–22]
	Prefabricated	[1, 6, 23]
Type	By elements or components	[6, 24, 25]
	By panels	[26–28]
	By modules	[5, 29, 30]
Prefabrication level	Whole buildings	[31–33]
	Building parts (e.g., rooms, classroom, labs)	[5, 34, 35]
	Building components (e.g., walls, windows, stairs)	[15, 24, 36]
Structural materials	Wood	[37–39]
	Steel	[25, 40, 41]
	Concrete	[27, 42, 43]
	Light Steel Framed	[41, 44, 45]
	Plastic	[46–48]
	Container	[31–33]
Uses	Residential	[49–51]
	Educational	[6, 52, 53]
	Commercial	[54, 55]
	Industrial	[56, 57]

to the production of prefabricated components, such as the reduction of labour and time, were reported during the colonisation of South Africa in 1820 in the assembly of simple and shed-like systems in Freetown, Sierra Leone, and the Eastern Cape Province, compared to on-site construction methods [3].

In the 1830s, the London carpenter John Manning created a prefabricated home for his son, who was living in the Land Down Under in Australia. This way, the prefabricated components were produced in England and shipped to Australia to be easily assembled. This house was the first fully prefabricated house documented. The prefabricated house was made up of prefabricated systems of wood and panel infill. The roof was a pitched roof comprising grooved posts, floor plates, and triangulated trusses supported by vertical grooved posts. The grooved posts were bolted into a continuous floor plate, and the panels were composed of supported triangulated trusses, and wood panel cladding was fitted between them. After that, John Manning produced the Manning Portable Colonial Cottage for accommodating emigrants, which consisted of an improved prefabricated structure of the previous house with easy assembly and transport [58–60].

The most relevant example of prefabrication was the Exhibition of Great Britain in Hyde Park, London, in 1851, in which the Crystal Palace was presented. Joseph Paxton designed Crystal Palace in less than two weeks, and its construction took a few months. It is a building composed of prefabricated components manufactured off-site, using light and inexpensive materials, such as iron, wood, and glass, and assembled on-site [58]. After Britain's Great Exhibition, the Crystal Palace was disassembled and then assembled in another location [60].

Previously, balloon frame construction had emerged in the United States in 1833, near Chicago. The old city of Chicago was almost exclusively built with balloon frames before being destroyed by a fire. In the 1840s, modular construction reached the United States to meet the housing needs of the California Gold Rush. However, in the 1900s, the builder Augustine Taylor from Chicago improved balloon-frame construction by manufacturing walls off-site, transport, and speedy assembly [58, 60].

The Aladdin "built in a day" house reached popularity in the United States in the 1930s. These houses had a "ready cut" system that increased the efficiency of the assembly process of timber components. The main milestones achieved in 1932 were a wall system composed of a metal sandwich panel and the "House of Tomorrow". The "House of Tomorrow", built by George Fred Keck, is a three-story building composed of steel frames and glass infill walls, focused on cost-effectiveness, passive heating, and daylight modulation. Furthermore, for the Chicago World's Fair in 1933, the "Crystal House" was built, which allowed advances in the steel frame concept. Moreover, Sears Roebuck and Co. created a catalogue of prefabricated houses and sold more than 500 thousand in the United States from 1908 to 1940, some of which still exist. At that time, these houses cost two-thirds less than conventional buildings [58, 60].

The Structural Insulated Panel (SIP) is one of the most used prefabricated components for house construction, initially introduced in 1935 by Forest Product Laboratory (FPL) researchers in Madison, Wisconsin, in the United States and first commercialised by Dow in 1952. In the 60s, when rigid foam insulation was available, the use of SIP gained traction due to its affordability and improved thermal performance [61].

During World War II (1939–1945), prefabricated construction increased significantly due to the demand for cottages for military personnel [2]. "Quonset Huts" or "Nissen Huts" houses were implemented in the United Kingdom for domestic, military, and institutional purposes. After World War II, the United States faced a shortage of houses, being forced to appeal to prefabricated dwellings due to the return of soldiers. In addition, Europe and Japan also opted for prefabricated houses to overcome housing demands. Regarding modularisation, modular construction corresponded to 25% of all single-family houses in the United States between 1945 and 1968. Still in 1968, the prefabricated Hilton Palacio del Rio Hotel (a 500-room hotel) in San Antonio, Texas, was built in 202 days for the Texas World's Exposition [60].

In 1905, the first precast concrete panelled buildings were created in Liverpool, England. The man who invented the panels was engineer John Alexander Brodi. However, precast concrete was not widely used until the early 1950s. The prefabricated concrete panel buildings gained popularity not only in the UK but also in East European countries, the former Soviet Union and Nordic countries. The technology was picked up later in many parts of the world, where fast development created a need for affordable housing on a mass scale. The rise of concrete panel buildings in East Europe has been fuelled by the post-war housing shortage and the industrialisation programmes in the 1950s-1960s. The mass application of prefabricated concrete panel buildings in East Europe can be traced back to Khrushchev's 4–5 floor panel buildings built in the 1950s in the Soviet Union. In other East European countries, the large panel-house building programmes started later, for example, in 1965 in Hungary, 1956–1958 in Czechoslovakia, and 1958–1960 in Romania. By the end of the 1970s, prefabricated concrete panel buildings became the dominant form of construction.

In 1976, the building code started distinguishing permanent houses (which require a design based on the standard code) and mobile homes (based on the HUD code). After 1976, numerical control became widespread use and nowadays, small factories can model prefabricated components and have access to different tools, such as Building Information Modelling tools, Computer Numeric Control, and 2D laser cutting devices [60].

In conclusion, the lack of a workforce and the gradual digitalisation of the construction sector led some countries to embrace prefabrication as a construction method. Moreover, countries with cold climates also adopted prefabrication due to the weather conditions and less time working outside. For example, Sweden has approximately 84% of the total construction being prefabricated [2].

Although prefabrication is not a new methodology in the construction industry, its reputation has increased due to its multiple advantages in fostering Circular Economy principles in the built environment [60, 62]. Prefabricated components are also identified as more sustainable solutions with impact in economic, social, and environmental dimensions, and contributing to the Sustainable Development Goals (SDGs) of the 2030 Agenda of the United Nations (directly related to SDG 11, Sustainable Cities and Communities, and SDG 12, Responsible Consumption and Production) [1]. Opportunities and barriers to adopting prefabrication will be further discussed in Sects. 8.9 and 8.10, respectively.

8.3 Prefabricated Building Types

Prefabrication can be divided into different categories [3, 63, 64], namely:

- **Component sub-assembly** is the lowest degree of prefabrication and corresponds to single-assembled building elements, promoting a higher flexibility and customisation degree during the design and construction categories [3, 63, 64]. These components require joints and connections, careful alignments, and infiltration checks, so more work must be developed on-site. Some examples of component sub-assembly are stairs, roof trusses, wall frames, wood kits, and precast concrete [3].

- **Non-volumetric pre-assembly** (or panelised systems) are more complex components manufactured off-site and assembled on-site through traditional construction procedures and are not responsible for creating usable space [63, 64]. These non-volumetric pre-assembled components can be planar, skeletal, or complex units built from individual components, such as structural frames, cladding wall panels, and bridge units, among others [19].
- **Volumetric pre-assembly** units are prefabricated, pre-assembled, and pre-finished off-site and are responsible for creating usable space. These units are not part of the building structure but can be assembled within or onto an independent structural frame [19, 63]. Some examples of volumetric pre-assembly units are plant rooms, toilet pods, and shower rooms, among others [19].
- **Modularisation or modular construction** are volumetric units with a considerable dimension (such as a room-sized volumetric unit) that constitute the structure of the building itself [19, 65]. These units are standard modules that create usable space and can be manufactured in complete 3D boxlike (*volumetric*) sections, multi-section units, and stack-on units [3]. Modular construction is mostly pre-assembled and pre-finished off-site with a design for easy assembly to achieve rapid assembly on-site [3, 66]. The standard modules are predominantly finished in the factory (interior and exterior finishes), with approximately 80 to 95% of finishes completed off-site [3] and reducing the activities required on-site (reduces about 90% of activities needed in conventional construction) [63].
- **Hybrid structures** are a combination of more than one assembled prefabricated system in order to build a whole building, which is the most common combination of prefabricated panels and modular construction [3].
- **The unitised whole building prefabrication** corresponds to the highest degree of prefabrication and finishes [3, 64] and is pre-assembled volumetric units that form the actual structure and fabric of the building [64]. Although the unitised whole building is manufactured under controlled conditions of quality and speed, its bulk size and weight are limited by manufacturing and transportation capacity [3].

Regarding the manufacturing process, prefabricated components can be manufactured through two different types of methods, namely fixed platforms and production lines [1]. On the one hand, the fixed-platform method is a traditional method in which the mould is fixed on a stationary table [29, 67] and is more appropriate for profiled components with heights exceeding the limits of the line method, including beams, columns, and stairs [67]. On the other hand, the production line method is more mechanised compared to the previously mentioned one, as it consists of a production process with several operations at different stations where moulds are moving through a pallet rolling line, and workers are in a specific position in each station table [29, 67]. The production line is commonly used in producing components with standardised shapes, such as prefabricated wall panels, load-bearing walls, partitions, and laminated boards [1, 67].

8.4 Prefabrication Approaches

All buildings have some degree of prefabrication and include some prefabricated elements such as doors, windows, tiles, or equipment. However, when the prefabrication rate is increased–this is the percentage of buildings done offsite, in a plant, and after being transported and assembled onsite–buildings are considered prefabricated. Some prefabricated buildings are based on linear prefabricated elements such as columns or pillars, others on bidimensional prefabricated elements such as walls or floor panels, while others use tri-dimensional prefabricated elements such as complete modules or whole prefabricated houses. Some use a combination of linear, bi-dimensional, or tri-dimensional prefabricated elements. In fact, different degrees of prefabrication are implemented in the vast variety of prefabricated buildings.

Different approaches are also used in modular buildings, as various types of modules serve different functions within a completed building structure: four-sided modules (i.e. all four sides are clad), partially open-sided modules, open-sided (corner-supported) modules, modules supported by a primary structural frame, non-load bearing modules, special stair or lift modules, and hybrid modules that may rely on other elements to resist some or all of the imposed structural actions. Figure 8.2 summarises the different prefabrication and modular approaches.

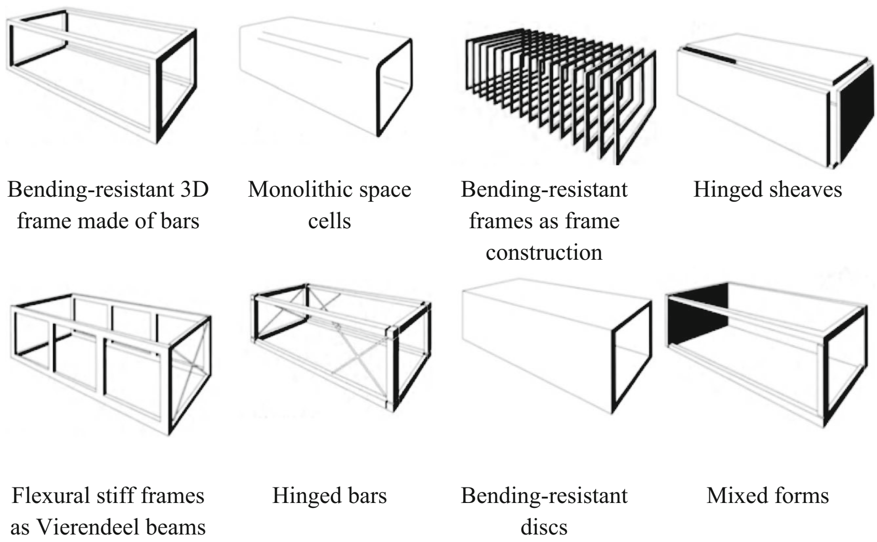


Fig. 8.2 Prefabrication and modular approaches, based on [68]

8.5 Prefabricated Building Material

As presented in Table 8.1 in Sect. 8.1, different structural materials are used in prefabricated and modular buildings. Most prefabricated buildings use conventional materials such as steel [4, 69] and wood [13, 70] which is the most widely used material, followed by concrete [57, 71]. Others use the combination of two or more materials in composite systems and usually combine concrete and steel elements. Recently, new materials have been used in prefabricated buildings, such as recycled plastic [7] or the reuse of shipping containers [32, 33].

8.5.1 Wood Prefabricated Buildings

Wood prefabricated buildings typically involve either factory-built three-dimensional modules made of wood, shipped to the site, assembled (modular construction) or wood components made from conventional light-frame construction or mass timber systems assembled on-site to form the building. Light frame construction comprises repetitive framing members, such as rafters or trusses with wood panel decking. Oriented strand board (OSB) and plywood are used interchangeably as decking and sheathing materials for floors, walls, and roof decks. Mass timber products are thick, compressed layers of wood that serve as the load-bearing structure of a building. Such components are usually made from cross-laminated timber (CLT), glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT).

8.5.2 Concrete Prefabricated Buildings

Concrete prefabricated buildings consist of whole, three-dimensional building units or building components. Both types are made in the factory using precast reinforced concrete. In the first case, the construction is usually modular, i.e. several prefabricated concrete building units are transferred on-site and assembled to form the whole building structure. In the second case, the building components (beams, slabs, columns, etc.) are made of precast concrete in the factory and, after being transferred on-site, form the central part of the building. The walls can be either constructed from preconstructed panels, such as curtain wall elements, or concrete panels or by integrating a conventional building technique, such as brick masonry, non-bearing partitioning wall elements, etc. In the latter case, the rate of prefabrication is lower.

8.5.3 Steel Prefabricated Buildings

Steel prefabricated buildings consist of a steel framework, which forms the main structural system of the building. They are composed of steel columns and beams and slab elements, more frequently concrete slabs, either prefabricated or cast in situ. In most cases, the wall elements are made of curtain walls and lightweight panels, designed primarily to support gravity and wind loads without participating in the structural performance of the building.

8.5.4 Composite Systems

Composite systems employ more than one material to form their primary structure. Among the most common are the ones made from steel frames and precast concrete walls, which are either monolithic or have the form of sandwich panels, i.e. comprise of two (or three) concrete wythes that embed a layer of thermal insulation. The main characteristic of composite prefabricated systems is that the steel and the concrete elements work together to ensure the structural performance of the building. Within this framework, it is essential to employ specially designed connectors to safeguard the structural continuity of the system and the proper load transfer.

8.5.5 Nature-Based Solutions

Some prefabricated nature-based solutions have recently been developed on a prefabricated building element scale. Vertical greening systems (VGS) can be incorporated into buildings to promote circularity through the materials and associated functions. Vertical greening refers to "vegetated surfaces in the building envelope, which include the spread of plants that may or may not be attached to the façade and can either be rooted into the ground or in pots" [72]. An example of a VGS is the vertical garden "WallGreen", a modular system that allows diverse design using the vertical space available in the building envelope. The main benefits contributing to circularity are the structure made of recycled plastic, mainly recovered from the sea, and individualised automatic watering for each plant, with the possibility of optional fertilisation (Fig. 8.3). Other operational benefits include: (i) the possibility of individual change of each plant of the system; (ii) deficient maintenance that can be carried out by undifferentiated personnel; (iii) the plants living in a good volume of substrate and can grow naturally; (iv) very resilient system to maintenance failures and irrigation system; (v) the possibility of dismantling the structure and taking it to another location; and (vi) it can be used for indoor or outdoor applications, providing different ecosystem services (Fig. 8.4).

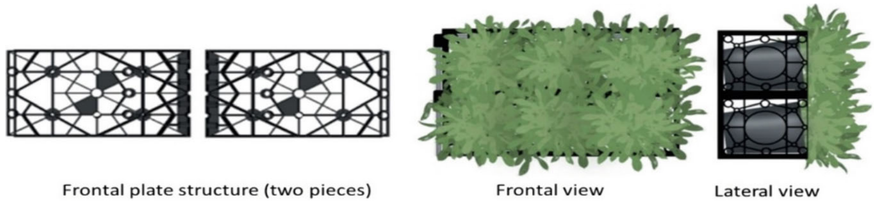


Fig. 8.3 Schematic representation of the modular system WallGreen. *Source* technical sheet from the producer

Fig. 8.4 Indoor modular system of the vertical garden WallGreen in an office building (Porto Office Park, Porto-Portugal). Credits: Cristina Calheiros

8.6 Comparison Between Prefabricated Buildings

Several research papers compare the environmental performance and cost of timber, concrete, and steel prefabricated buildings [43, 73]. Some conclude that prefabricated steel buildings have higher embodied costs and associated greenhouse gas emissions. However, steel recycling and reuse potential may compensate for initial burdens [5, 74, 75], balancing the initial impacts these buildings have at the end of life.

Timber in prefabricated buildings can be easily recovered with a high potential for reuse [75]. This is of particular significance, as wood retains a higher value when reused [74]. If not recovered in any other way, wood can be transformed into energy, as waste to energy (WtE). Finally, wood is considered a viewable material, being a solution inspired and supported by nature, simultaneously providing environmental, social, and economic benefits and helping build resilience [76].

Concrete buildings pose some challenges along the life cycle: during the transport stage because of the heavyweight; throughout the assembly, requiring specific connections; and at the end-of-life, being difficult to disassemble, often resulting in damaged components. Therefore, reusing structural concrete elements is typically unfeasible [5, 75]. Additionally, while concrete can be recycled as aggregate for new concrete production [5], it is generally in a downcycling process, in a new process with low value.

Recycled materials (e.g. plastic in [47])) and reused components (e.g. aluminium in [77]) present new prefabricated approaches that strive from circular economy principles being aligned with two of the CE principles [78]: Eliminate waste and pollution and circulate products and materials (at their highest value).

8.7 Prefabricated Buildings' Refurbishment

As described in Sect. 8.2, prefabrication was widely used during World War II (1939–1945) to respond to the demand for housing for military personnel and, after the war, to address the need for housing and all the other infrastructures the population needed in the post-war. All these prefabricated buildings built before energy efficiency codes (first introduced in the 70 s) currently need more profound renovations (if not already demolished or refurbished). Renovating and updating these prefabricated buildings is a challenge in Europe and the United States. Some research has focused on the optimised approach for refurbishing these prefabricated old buildings [79], and some national investment plans have been implemented (e.g. Portuguese national plan to refurbish schools, including prefabricated schools from the 1970s and 1980s). Moreover, some misconceptions against prefabrication exist in some European countries due to some lack of quality of these first prefabricated buildings, mainly due to some assembly error (leading to construction defects and use phase pathologies) and lack of durability. Up-to-date prefabricated buildings with modern design and construction approaches have recently overcome this misconception.

8.8 Prefabricated and Modular Components in Buildings' Refurbishment

Prefabricated components can be one answer to the EU challenge of doubling the annual renovation rate from 1 to 2% over the next decade [80]. Several EU-founded projects have focused on building stock renovation: (i) IMPRO Buildings project (2006–2008) assessed the potential to decrease the EU-15 stock impacts by implementing refurbishment measures [81]; (ii) TABULA (2009–2012) mapped residential building technologies [82]; (iii) EPISCOPE (2012–2014) aimed to assess refurbishment processes and forecast energy consumption in future building stock models [83].

One EU-founded project has supported timber-based prefabricated panels for the energy refurbishment of existing Italian buildings' façades [84] and a country-scale, while a Nordic project has focused on process optimisation being more concerned with business models [85]. Some papers have assessed how prefabricated modules or elements can be used in building refurbishment. A matching kit interface for building refurbishment processes with 2D timber modules has decreased installation time and fitting deviation [86], and a prefabricated timber façade for the energy refurbishment was studied for the Italian building stock [84]. A concrete prefabricated envelope-cladding system for building energy renovation has been shown to have lower payback times in terms of carbon, followed by energy, but a high payback cost, being superior to a building's lifespan [87]. As a potentially cheaper, faster, and more efficient solution, prefabricated and modular components may support the necessary renovation wave [88].

8.9 Benefits and Challenges of Prefabricated and Modular Construction

Prefabrication presents clear advantages within the construction activities and for buildings themselves; however, it poses some challenges that need to be discussed. In a critical review of modular buildings using a life cycle perspective, the authors identified schedule, cost, onsite safety, product quality, workmanship and productivity, and environmental performance as key benefits, and project planning, transport retrains, negative perception, high initial cost and site constraints, and coordination and communication as main challenges [34].

8.9.1 Benefits of Prefabrication

Prefabricated and modular construction presents some clear opportunities for the construction sector, enabling a faster construction speed, ensuring the compliance of the project schedule, as well as cost savings [2, 63, 89]. This construction approach capitalises on the inherent properties of prefabrication to provide the main advantages relative to conventional construction:

- **Impacts reduction** [6] through materials use reduction and waste generation;
- **Cost reduction** [89] achieved through economy of scale and a more precise construction process;
- **Waste reduction** [90] reduces error as offsite manufacturing is done in a more controlled environment;
- **Time reduction** [34] considering that offsite fabrication can be simultaneously done with site preparation works;
- **Quality improvement** [91] due to the industrialisation of the manufacturing process.

Additionally, less significant benefits include:

Reduced risks due to bad weather and reduced on-site works;
Superior quality due to factory-based quality control, repetition, and pre-design of similar modules;
Reduced on-site labour force: that can be moved for off-site, with increased value;
Improved sustainability: due to less wastage generated and upcycling of waste in controlled manufacturing environments;
Less disruption: to neighbourhood construction sites from multiple truck movements associated with conventional onsite construction.

Besides these advantages, prefabrication enables the adoption of some circular economy principles, including **Design for Deconstruction** to encourage future re-location, re-use, re-sale, and recycling of products and materials and **Design for Flexibility** to extend building lifetimes and, where possible, further extend the life of buildings by renovation and refurbishment.

Some prefabrication advantages are enhanced when comparing lightweight prefabricated buildings with conventional heavyweight ones. Table 8.2 summarises the main advantages and disadvantages of lightweight prefabricated and modular buildings compared to heavyweight traditional construction.

Regarding the perception of prefabrication among stakeholders in the Architecture, Engineering, and Construction (AEC) industry in Hong Kong, identified advantages encompass frozen design at the early design stage, reduced construction cost, shortened construction, aesthetics issues, integrity of the building, and improved environmental performance. Opposingly, the identified hindrances include inflexible to design changes, lack of research information, higher initial construction cost, time consumption, conventional method, limited site space, monotone in aesthetics, leakage problems, lack of experience, and no demand for prefabrication [106].

Indeed, modular units require the least amount of on-site construction time, as all plumbing, electrical, and even design finishes have typically already been installed in the facility. This leaves only the task of assembling the modular units to form a completed building. As modular buildings spend more time in off-site facilities during the construction process, the conditions are meticulously controlled for a significant portion of the process, leading to unparalleled efficiency and quality in large-scale commercial construction.

Modular buildings offer exceptional versatility and can be tailored to fulfil any purpose virtually. They are particularly well suited for buildings such as hotels, apartments, student housing, and any other types that typically consist of repetitive units serving similar functions.

This production approach is smarter than conventional construction methodologies with a higher flexibility and material efficiency, boosting the reduction of waste, energy, carbon footprint, and operational and environmental impact in line with circularity principles, which could be integrated into modular construction projects by identifying the most critical success factors [2, 107, 108]. It also has the potential

Table 8.2 Advantages and disadvantages (in bold) of lightweight prefabricated and modular buildings compared with heavyweight conventional construction (including references)

LC stages[a]	HEAVYWEIGHT	PREFABRICATED / MODULAR	REFERENCES
A1-A3 Product stage	Normally HEAVYWEIGHT materials + CUSTOMISED PRODUCTION More materials Increased embodied impacts Increased transport-related impacts	Normally LIGHTWEIGHT materials + MASS PRODUCTION Fewer materials Decreased embodied impacts Decreased transport-related impacts Extra material used during transport	[36, 51, 92, 93]
A4-A5 Construction stage	IMPRECISE construction process More waste generated More water used Dependency on the weather conditions	(more) PRECISE construction process Less waste generated Less water used Independence from weather Extra transport to- and from-plant Extra plant stage impacts	[94–96]
B1-B7 Use stage	HARD MAINTENANCE Unpredicted maintenance and more difficult to perform Poor performance (due to design and construction failures) Low adaptability	EASY MAINTENANCE Programmed maintenance and easier to perform Predicted performance High adaptability	[36, 97, 98]
C1-C4 End-of-life stage	DEMOLITION More waste generated Difficult to separate waste by streams	DISASSEMBLY Less waste generated Easier to separate waste by streams	[99–102]
D Benefits and loads beyond the system's boundaries	LANDFILL CDW sent to landfill Downcycling	REUSE AND RECYCLE CDW recycled Parts and modules reused Upcycling	[99, 103–105]

[a] LC stages are defined according to ISO 21930

to foster lean construction and Industry 4.0 in the construction sector (Turner et al., 2021), such as 3D printing [66]. Furthermore, prefabricated components, especially modular construction, foster the applicability of the design for disassembly in the built environment [110, 111] because they facilitate future alterations and dismantlement of a part or the whole building recovering the components and expanded their lifespan. For example, concrete columns, floor systems, and roof structures can be re-incorporated into the market and minimise waste generation from the built environment [110], which could be enhanced by construction digitalisation [112].

Prefabrication seeks to effect significant efficiencies in the construction process that should also result in considerable cost savings. A shorter project schedule further enhances cost savings. The shorter the construction period, the less construction period carrying costs, such as real estate taxes, insurance, interest, and other construction period carrying costs typically referred to as “soft costs”, and the sooner the building can start generating revenue.

Summing up, prefabricated components provide certain advantages compared to traditional on-site construction, including greater control over weather, quality, and supervision; reduced environmental impact due to reduced waste, air, water, and noise pollution; streamlined project schedules by fabricating building components while the construction site is being prepared; fewer logistical challenges associated with organising crews and deliveries; more convenient storage leading to minimal instances of lost or misplaced materials; increased safety through limited exposure to unsafe weather and working conditions.

8.9.2 Challenges of Prefabrication

Although prefabricated construction offers several benefits, as mentioned above, it faces limitations that impede its widespread adoption in the industry. Factors such as transport, lifting, and other logistical considerations present challenges that must be identified. A significant initial capital investment is required to upskill labour and establish a prefabrication plant. Additionally, the costs and reservations posed by the learning curve are accentuated by the lack of expertise and knowledge regarding the design, logistics, and installation of prefabrication components, the absence of technical standards regarding the structural, fire, acoustic, and thermal performance, sustainability, and overall viability of prefabricated construction and its structural and non-structural elements, contribute to these limitations [113]. Also, some extra planning and managing effort, high initial cost, lack of skilled workers or qualified supply chain, and constraints in transport and logistics [114]. Furthermore, some threats are identified in the literature, such as difficulties in installation management due to compact spaces, extra cost-border logistics, and insufficient information on storage [115].

Some of these barriers have been grouped in the literature [113]:

Cultural aspects, including lack of necessary technical experience, the absence of technical standards, and preconception of prefabrication adoption, will reduce jobs;

Economic aspects, even though prefabrication may represent high savings, if not managed appropriately, may have high-cost overruns and difficulties in financing;

Practical aspects related to transport and handling, the lack of skilled workforce, and the inability to make changes on-site;

Technical aspects, such as BIM adoption and automation, are due to the sector's reluctance to change.

Some constraints along the life cycle stages are:

During the planning phase, there are significant expenses associated with securing funding for plant establishment, securing project financing, and dealing with resource supply shortages;

During the design phase, challenges arise due to the absence of standards and regulations, a lack of experienced designers, and constraints on design and architectural creativity;

During the off-site manufacturing phase, challenges include a scarcity of skilled labour, logistical hurdles, repetitive components, and limited tolerance;

During the on-site assembly phase, obstacles encompass difficulties in transportation and handling, a shortage of skilled labour, limitations in making on-site modifications, the intricacy of installation, and restricted tolerance.

8.10 Modularity, Prefabrication and Circular Construction

In implementing a circular economy in the built environment, prefabrication and modularity are identified as enabling production technologies. Still, the contributions of prefabrication and modularity to implementing circular buildings are unclear. We define the following questions:

- Are modular building systems in themselves circular buildings?
- If not, which strategies/principles employed in modular buildings facilitate the implementation of circular buildings?

To reply to these questions, we planned to analyse a set of case studies selected based on the three main types of modular building systems [116, 117]: frame, panel, and room module systems - to evaluate their ability to implement circular buildings. The hybrid systems will not be included.

A circular building is a building designed, built, used, and disassembled according to (i) the Circular Economy Principles [118]–eliminate waste and pollution, circulate products and materials (at their highest value), regenerate nature–(ii) the nR strategies [119]–refuse, rethink, reduce, re-use, repair, refurbish, remanufacture, repurpose, recycle, and recover–and (iii) other Circular Economy strategies. Even though circular strategies can be implemented along the building life cycle, the early stage is crucial to striving for circular design [120].

Several frameworks are available in the literature to support the design and assessment of circular buildings; a selection has been analysed in that subtask. We compared them to identify the most appropriate framework for the case study research.

Prefabricated building systems can be designed as closed or open systems [116]:

- *Closed system:* it integrates all part systems. The entire building or partial systems (load-bearing structures, façades, or internal fit-out) are produced by a manufacturer. Elements can be only used within that system, and variety is quite limited due to the integration of the building parts;

– *Open system:* it combines various prefabricated building part systems for the shell, interior fit-out, and building envelope. The elements are standardised and dimensionally coordinated. Elements from different manufacturers can be variably combined as a partial system or for the entire building, allowing for a wide range of construction projects.

Building prefabrication is generally recognised as a potentially more energy-efficient and less resource-demanding construction method than traditional ones [117]. It reduces material waste through efficient ordering, indoor protection, pre-planning, and cutting. The final building also benefits from increased energy efficiency performance and lower energy use during its lifecycle. Prefabricated buildings can also reduce carbon footprint by minimising transportation to sites [117]. Recently, building prefabrication has raised interest in the implementation of circular buildings. Minunno et al. [110] identified seven circular strategies that building prefabrication could apply to implement circular buildings: (1) reduction of waste and lean production; (2) integration of waste and by-products; (3) reuse of components or parts; (4) design for adaptability; (5) design for disassembly; (6) design for recycling; (7) materials and components track system). Furthermore, strategies to integrate Circular Economy into modular constructions are:

– Design toward adaptability (reduction through life extension) during operational stages;
– Design toward disassembly into components to be reused;
– Design for recycling of construction materials;
– Reduction of construction waste and the lean production chain;
– Integration of scrap, waste, and by-products into new components;
– Modular buildings can be extended on demand;
– Modular units can be reused in other applications;
– Use of systems to track materials and components within their supply chain.

8.11 Bibliometric Analyses

A bibliometric analysis identified research trends in modular and prefabricated buildings toward CE in the construction sector. A five-step approach was followed: (1) conceptualisation and design; (2) data collection; (3) selection and assessment; (4) results visualisation; and, finally, (5) interpretation and discussion. This section briefly describes the bibliometric research process and summarises the main results:

(1) **conceptualisation and design:** In this stage, the research question is formulated, and the search process is defined, including the identification of the database, the formulation of the search query, the selection of the search keywords, and the definition of the inclusion and exclusion criteria for the keywords selection;

(2) **data collection:** a list of publications containing the following keywords: Circular economy; Construction sector; Prefabrication; Modular construction; and equivalent or related terms were used to select over 4500 peer-reviewed articles and reviews published in English were initially identified;
(3) **selection and assessment:** After a filtering process removed duplicated and out-the-scope articles ended up with over 600 articles, and some visuals were then built around them;
(4) **results visualisation:** two graphics present the number of publications per country (Fig. 8.5) and the number of occurrences of a keyword (Fig. 8.6);
(5) **interpretation and discussion:** figures are presented, and results are further discussed**.**

Figure 8.5 shows the country network with the average annual number of publications per country (between 1989 and 2023 and a minimum of 10 documents). Of the total of 68 countries, 21 countries meet this condition. This figure shows that China has the most published papers, followed by the United States and the United Kingdom. Emerging countries in this field are Australia, Canada, Italy, and Hong Kong (as special administrative regions of China).

Figure 8.6 presents a map of author keywords considering a minimum number of occurrences of a keyword of 5. Of the total of 1457 keywords previously identified, 96 meet this condition. This figure shows that the term "life cycle assessment" is undoubtedly the most used, followed by the terms "prefabrication" and "circular economy" (that were the main terms in this bibliometric research), and in a second level by "lean construction", "sustainability" and "construction industry". "Modular construction" appears subtly, and the link between the three initial terms; "modular construction", "prefabrication" and "circular economy" seems fragile and unclear (Fig. 8.6).

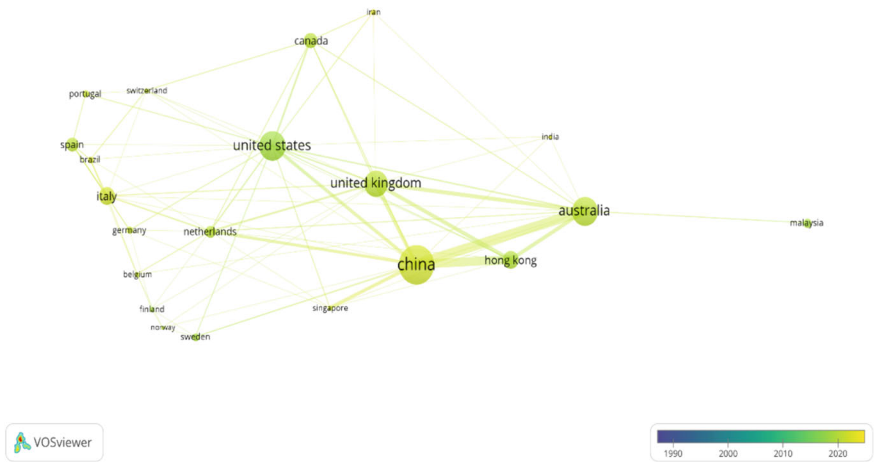


Fig. 8.5 Countries network with the average annual number of publications per country. The cutoff criteria stipulated a minimum of 10 documents per country

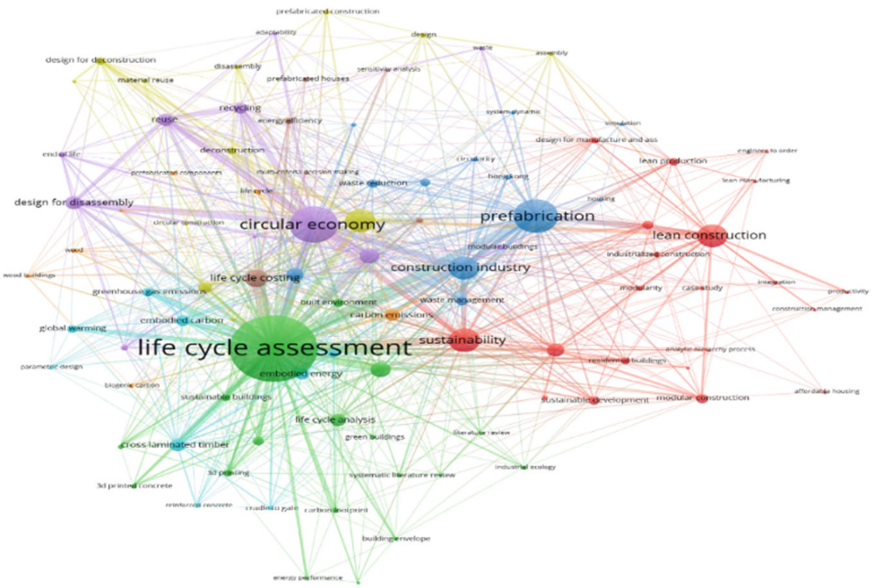


Fig. 8.6 Co-occurrence map of keywords considering. The cutoff criteria stipulated a minimum of 5 keywords

8.12 Case Studies

Based on this review, we established the criteria for selecting the case studies. Case studies will be chosen to provide a representative sample for each type of the following categories:

- types of prefabrication systems: frame, panel, room module, hybrid, and complete;
- types of prefabricated building systems: open or closed;
- types of product architectures: modular or integral.

Case studies regarding circular buildings will be analysed to establish how and in which measure modularity and prefabrication contribute to implementing circular buildings. Several frameworks are available in the literature to support the design and assessment of circular buildings; a selection was made in Sect. 8.1. For comparison, we selected the framework developed by the Arup & Ellen Macarthur Foundation [118] to apply in the case study research since it provides a set of strategies that considers the building lifecycle; modularity, and prefabrication; and indicators to assess the case studies are formalised.

A matrix was developed and implemented to identify CE principles within the prefab and modular case studies; see Fig. 8.7.

CASE STUDY DESCRIPTION

Case study name (if the case study has a name):

____

Type (e.g. Prefabricated, Modular, both, other):

____

Data source (e.g. published paper, design team, contractors, others)

____

Link to data (e.g. URL):

____

Case study description:

- authors (e.g. design team, contractors, other):

  ____

- scale (e.g. component, building element; building, neighbourhood, other):

  ____

- if building, gross floor area (GFA/m^2))

  ____

- use typology (e.g. residential, office, commercial, industrial, other):

  ____

- location (e.g. country, city):

  ____

- description:

  ____

figures: (e.g. floorplan, elevation, pictures, others)

- impact categories and units (e.g. GHG/kgCO_2eq):

  ____

- other indicators (e.g. circular material rate):

  ____

- main results:

  ____

Describe Circular Economy design strategies based on the Circular Buildings Framework (Arup, 2021) reported below. Further information on strategies, sub-strategies, and indicators is available here: https://ce-toolkit.dhub.arup.com/framework

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm]
	Design for longevity	EU Level(s) Whole Life Cycle Costs [\$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

Case study discussion and conclusions:

____

Fig. 8.7 Matrix to assess CE principles in case studies

CASE STUDY 1–Existing Building Extension, Timber

Case study name (if the case study has a name): Vertical Timber Extensions on Existing Building: new 10 stories hotel on the top of the existing commercial centre.

Type (e.g. Prefabricated, Modular, both, other): both.

Data source (e.g. published paper, design team, contractors, others): design team WSP.

Link to data (e.g. URL): https://www.wsp.com/en-gl/projects/55-southbank

Case Study Description:

– authors (e.g. design team, contractors, other): design team
– scale (e.g. component, building element; building, neighbourhood, other): building
– if the building, gross floor area (GFA/m2) 13,000 m2 of new space
– use typology (e.g. residential, office, commercial, industrial, other): hotel
– location (e.g. country, city): Australia, Melbourne
– description: At 55 Southbank Boulevard, a six-story commercial building erected in 1989, WSP embarked on a project to enhance its capacity by adding ten additional stories using cross-laminated timber (CLT), yielding 13,000 square meters of extra space. The extension's height was constrained by existing pile capacity, precluding the possibility of installing new piles within the structure. After considering various options, including concrete slabs and composite deck slabs, CLT was chosen for its ability to accommodate ten stories without surpassing the pile capacity, unlike concrete slabs that could only feasibly support a six-story extension. Collaborating with specialists, WSP devised a Future Ready solution wherein existing building columns were reinforced, and core walls strengthened to bear the added load, incorporating CLT walls between hotel rooms. A composite slab transfer deck was designed to distribute vertical loads from walls to existing concrete columns. Two new steel cores were introduced to address heightened lateral loads, incorporating existing concrete walls into the stability system and fortifying existing core walls. Additionally, a new raft under the steel core was engineered to transfer loads to existing piles, negating the need for new piles. To maintain panoramic views, steel beams and columns were meticulously designed to support CLT floor panels and accommodate larger wall spacing around curved sections of the building.
– impact categories and units CO2 OFFSETS (TONNES): 4200
– other indicators (e.g. circular material rate): CROSS LAMINIATED TIMBER (TONNES) 5,300 NEW FLOOR SPACE (m2) 13,000
– main results:

The Future Ready design and construction of this project presented several challenges that our team had to consider, such as working on construction while the occupied floors below remained in use, integrating existing utilities and services, and avoiding the need for additional foundation piles. By employing prefabricated cross-laminated timber and embracing Circular Economy principles to repurpose the existing building, we were able to save time and money while reducing the environmental impacts associated with demolition and reconstruction. The building was inaugurated in August 2020, with a section transformed into the Adina Apartment Hotel Melbourne Southbank.

Describe Circular Economy design strategies based on the Circular Buildings Framework developed by Arup is reported below. Further information on strategies, sub-strategies and indicators is available here (Fig. 8.8):

https://ce-toolkit.dhub.arup.com/framework.

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm] 24/sqm
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

Case study discussion and conclusions: The solution implemented Cross Laminated Timber (CLT) construction, enabling the existing building to support an additional 10 levels, achieving the desired room count across 13,000 square meters of new floor space. CLT, weighing approximately 20% of concrete, effectively doubled the feasible number of levels above the existing structure. Prefabricating components off-site with CLT enhanced construction efficiencies and minimised impacts on nearby buildings, presenting a more sustainable method for densifying urban areas. In light of limited available development sites, lightweight timber structures offer increased yields compared to traditional concrete and steel methods. This shift towards sustainability extends to reduced transport costs and carbon emissions, facilitated by CLT's lightweight nature. The substantial amount of CO_2 sequestered within the timber, around 4,200 tonnes, equivalent to the annual emissions of 130 homes, emphasises the environmental benefits. Timber procurement for the hotel adhered to Forest Stewardship Council certification standards, reflecting Adina Southbank's commitment to sustainability. As the world's tallest timber vertical extension, this project stands as a pioneering example of CLT and Mass Timber construction, showcasing innovative building reuse practices that have significantly enriched the site and its surroundings.

Awards:

2022 Council on Tall Buildings and Urban Habitat (CTBUH) International Conference Tall Excellence award for Renovation.

Fig. 8.8 Pictures and floorplans of an existing building extension with a timber structure

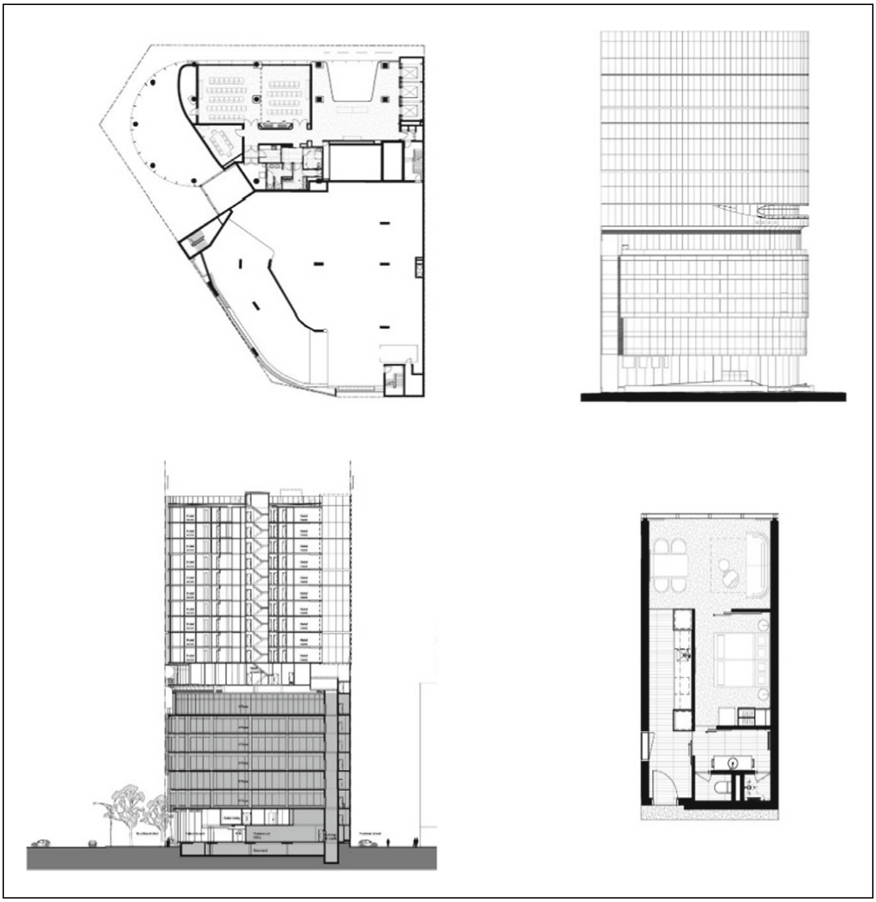


Fig. 8.8 (continued)

CASE STUDY 2–New Modular Building

Case study name: FrameUp - Optimisation of frames for effective assembling.

Type (e.g. Prefabricated, Modular, both, other): Both.

Data source (e.g. published paper, design team, contractors, others): RFSR-CT-2011–00,035 Final Report.

Link to data (e.g. URL): https://doi.org/https://doi.org/10.2777/766842 [121]

Case study description:

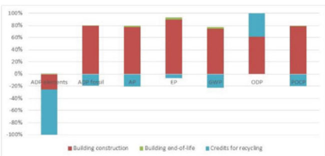
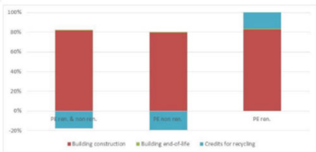
- authors (e.g. design team, contractors, other): M. Veljkovic et al.
- scale (e.g. component, building element; building, neighbourhood, other): Building
- if the building, gross floor area (GFA/m^2) 638 m^2
- use typology (e.g. residential, office, commercial, industrial, other):Residential
- location (e.g. country, city): Lulea, Sweden
- description:

The project aims to conceptualise and conduct feasibility tests for an innovative execution technique for skeletal systems, incorporating structurally integrated 3D modules and assessing the structural performance of novel joints. The new technique involves initially assembling the roof and top floor to form a rigid body, which is then lifted using lift towers and jacks, safeguarding the structure from precipitation and moisture damage during assembly. Through research, the project will delineate the competitive scope of application for the concept compared to existing building alternatives, incorporating a comprehensive sustainability assessment (Fig. 8.9).

- impact categories and units (e.g. GHG/kgCO_2eq):
- other indicators (e.g. circular material rate):

Results of environmental categories.

Indicator	Total	Unit
Abiotic Depletion (ADP elements)	-7.46E-01	kg Sb-Equiv.
Abiotic Depletion (ADP fossil)	1.61E+06	MJ.
Acidification Potential (AP)	3.75E+02	kg SO2-Equiv.
Eutrophication Potential (EP)	4.41E+01	kg Phosphate-Equiv.
Global Warming Potential, excl biogenic carbon	1.33E+05	kg CO2-Equiv.
Ozone Layer Depletion Potential (ODP)	4.56E-03	kg R11-Equiv.
Photochem. Ozone Creation Potential (POCP)	8.68E+01	kg Ethene-Equiv

Results of environmental categories per life cycle stage.
Results of energy categories (net cal. Values) per life cycle stage.
Results of the categories of energy use.

Indicator	Total	Unit
Primary energy demand from renewable and non-renewable resources (gross cal. value)	1.91E+06	MJ
Primary energy demand from renewable and non-renewable resources (net cal. value)	1.80E+06	MJ
Primary energy from renewable raw materials (gross cal. value)	1.72E+06	MJ
Primary energy from renewable raw materials (net cal. value)	1.62E+06	MJ
Primary energy from resources (gross cal. value)	1.84E+05	MJ
Primary energy from resources (net cal. value)	1.84E+05	MJ

– main results:

The main achievement of the research project is the development of a construction process for a modular building based on a lifting-up technique. This includes the execution of a building from the roof to ground floor and the assembly of frames and 3D room modules. This process is fully visualised for the identification of possible conflicts during the execution and to promote the project goals towards industry and society for benefit of stakeholders. A portable lifting device consisting of a self-climbing device and climbing columns are developed and tested. Different types of beam-column joints are investigated in order to ensure quick assembling and to guarantee the stability of the non-braced structure even in certain earthquake regions. Verification of the resistances of joints at ambient and elevated temperatures, under monotonic and cyclic loadings are done by means of experiments and Finite Element studies. Furthermore, the robustness of a six-storey modular building is assessed, and a risk assessment of potential perilous situations are carried out. A pilot building structural frame is executed at indoor conditions and monitored in order to investigate the feasibility of the construction process. Sustainability aspects are addressed and a comparative LCC analysis is performed to verify the advantages of the concept. Experiments are conducted to investigate the building physics performances of the 3D room modules. Subsequently, design models and guidelines are developed to predict the analytical behaviour of column bases, beam-to-column joints, and column splices using the component method. These design recommendations align with and complement EN1993-1–8 standards.

– describe Circular Economy design strategies based on the Circular Buildings Framework (Arup, 2021) reported below. Further information on strategies, sub-strategies and indicators is available here: https://ce-toolkit.dhub.arup.com/framework

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm]
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [$kgCO_2eq/m^2$/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

case study discussion and conclusions:

Feasibility of the novel erection concept, FRAMEUP concept, for multi-story buildings based on in situ work at the ground level and using jacks for lifting up the structure has been proved.

Beam-column joints for tubular sections, using the reverse channel and long bolts have sufficient stiffness and strength for application in non-braced frames. The beam-column joint using long bolts are more cost effective compared to the solution using the reverse channel.

The column base investigation has led to new models for possible implementation in Eurocodes.

The complete design verification, including accidental loads and assessment of robustness during the erection and at the final stage, has shown sufficient resistance for most of application within EU.

Sustainability aspects, energy efficiency and building comfort have shown satisfactory performance.

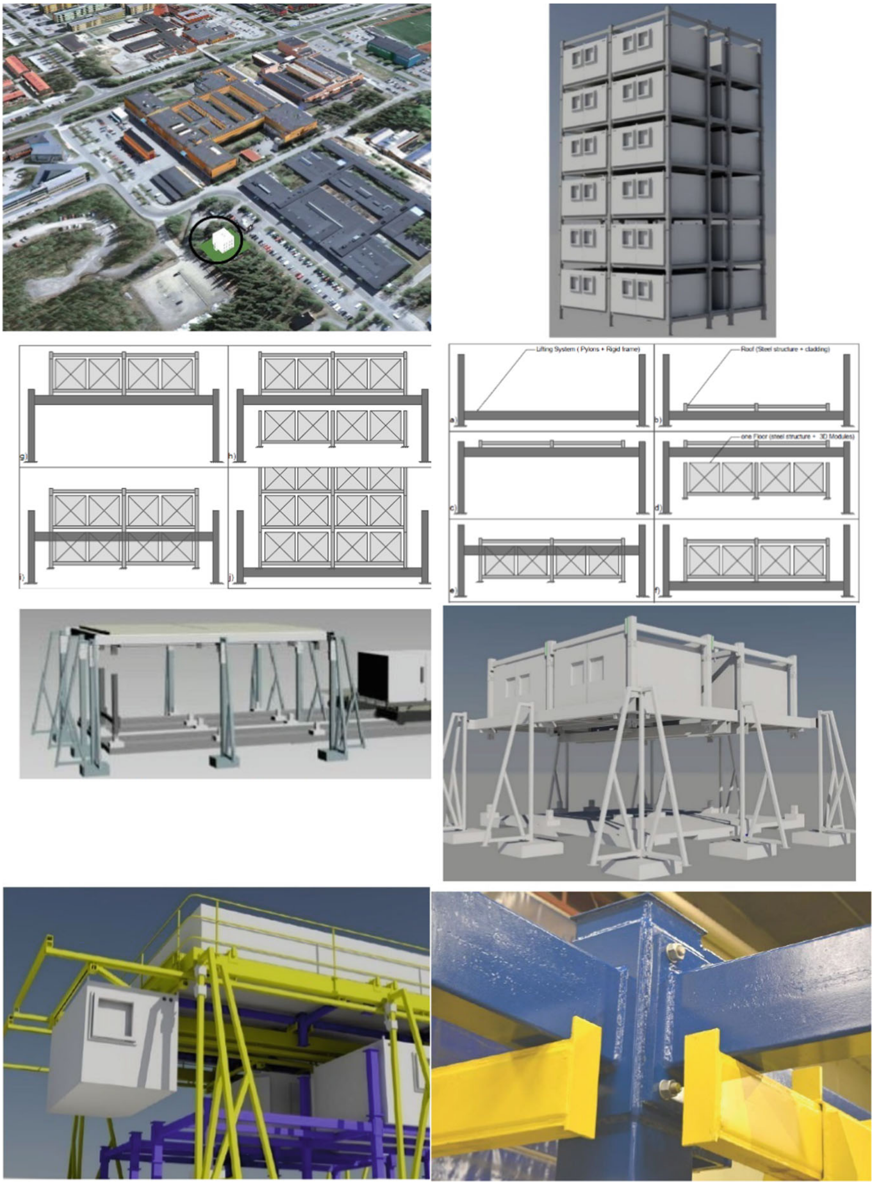


Fig. 8.9 3D views, floorplans and section from FrameUp project

Fig. 8.9 (continued)

CASE STUDY 3–Single-Family Steel Structure

Case study name (if the case study has a name): SUPRIM case study.

Type (e.g. Prefabricated, Modular, both, other): Prefabricated.

Data source (e.g. published paper, design team, contractors, others published paper, report, patent filing.

Link to data (e.g. URL):

Case Study Description:

Authors (e.g. design team, contractors, other): Research team of the Laboratory of Building Construction and Building Physics of the Civil Engineering Department of the Aristotle University of Thessaloniki & Theodoros Iliadis.

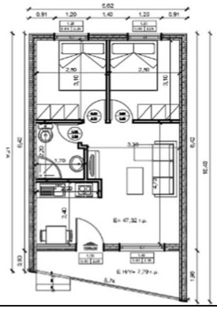
scale (e.g. component, building element; building, neighbourhood, other): building component, building.

if building, gross floor area (GFA/m^2) 47,32.

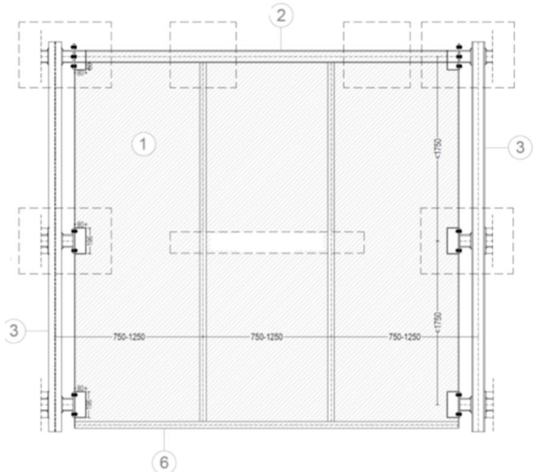
- use typology (e.g. residential, office, commercial, industrial, other): residential
- location (e.g. country, city): Greece, Thessaloniki
- description:

The case study pertains to a small, single-family building showcasing a prefabricated composite construction. Its rectangular plan extends along the south-north axis, featuring openings solely on the south and north walls. The building structure utilises a steel framework, while the walls are constructed using the SU.PR.I.M. (Sustainable Preconstructed Innovative Module) wall system. This prefabricated system underwent comprehensive testing, including structural, hygrothermal, energy, acoustic, and fire

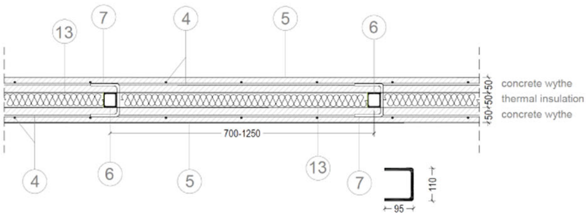
Building floorplan



Building 3D



Sketches of the SU.PR.I.M. system



1.Composite wall element; 2. HEA100 beam; 3. HEA100 column; 4. Steel bar mesh; 5. Concrete; 6. Hollow steel section (RHS/SHS); 7. Steel bar shear connector; 8. Void; 9. Steel plate (120 x 120 x 8); 10.Steel plate (150 x 196 x 8); 11. Short HEA unit; 12. M12 bolts; 13. Thermal insulation

Fig. 8.10 Floorplan, 3D image, structural system and wall composition of the SUPRIM case study performance studies, resulting in optimisation. The SU.PR.I.M. wall system comprises composite panels comprising two 5 cm thick reinforced concrete plates sandwiching vertical (occasionally diagonal) metal hollow elements. Thermal insulation boards fill the cavity between the metal elements, with the entire wall insulated using ETICS. Specially designed shear connectors link the concrete plates and steel elements, while bolted joints connect the wall panels to the main steel framework, specifically engineered for this construction type. [The SU.PR.I.M. wall system is protected by a Greek patent, with a pending European patent.] The building's inclined roof is covered with clay tiles and insulated with a 10.0 cm XPS layer, while the floor, in contact with the ground, is reinforced concrete, insulated with a 10 cm thick XPS layer. Windows feature PVC frames with double low-e glazing, boasting an average value of 2W/(m^2 K). (Fig. 8.10)

impact categories and units (e.g. GHG/kgCO_2eq): 1950kgCO_2eq for 40 years.

other indicators (e.g. circular material rate): NA.

Main Results:

The development of the innovative prefabricated wall system was shaped in order to satisfy high requirements for its operation and performance. Specifically, it was designed in order to be able to bear and deliver safely all the imposed building loads; display advanced energy performance; demonstrate excellent hygrothermal behaviour; provide acoustic insulation protection and resistance against fire actions; and minimise its environmental footprint during its life cycle.

Studies [122] showed that the examined building configuration shows better environmental performance when constructed with the SU.PR.I.M. wall system in comparison to using the conventional construction (reinforced concrete beams and columns and brickwork masonry).

Describe Circular Economy design strategies based on the Circular Buildings Framework reported below. Further information on strategies, sub-strategies, and indicators is available here: https://ce-toolkit.dhub.arup.com/framework.

Strategy	Sub-strategy	Indicators
Build nothing	Refuse new construction	Reused floor area (% of total GFA)
Build for long-term value	Increase building utilisation	Total building utilisation [h/sqm]
	Design for longevity	EU Level(s) Whole Life Cycle Costs [$/m^2/year]
	Design for adaptability	EU Level(s) Adaptability Rating
	Design for disassembly	EU Level(s) Disassembly Potential Rating
Build efficiently	Refuse unnecessary components	Material use intensity per functional unit [kg/unit/year]
	Increase material efficiency	Material use intensity by area [kg/sqm /year]
Build with the right materials	Reduce the use of virgin materials	EMF's Material Circularity Indicator (MCI)
	Reduce the use of carbon-intensive materials	Embodied Carbon Intensity [kgCO_2eq/m^2/year]
	Design out hazardous polluting materials	Environmental Impact Cost [€/m^2/year]

Beyond its improved energy and environmental performance, the building constructed with the SU.PR.I.M. wall system has additional advantages, as it is prefabricated and constructed according to a number of circularity design principles, such as design for longevity, adaptability and disassembly. There is further potential to increase its circularity, as:

- it can be disassembled and part of it can be reused, so it can be regarded as a partially reversible one
- part of its materials can be reused/recycled
- part of its materials can be substituted with circular materials, i.e. the concrete on the panels, etc.

Bibliography [122]

8.13 Discussion

Different types and approaches of prefabricated and modular buildings exist, offering unique benefits and applications. These can be categorised into component sub-assembly, non-volumetric pre-assembly (panelised systems), volumetric pre-assembly, modular construction, hybrid structures, and unitised whole-building prefabrication. The degree of prefabrication ranges from individual components such as stairs and wall frames to the volumetric units that make up the structure of the building itself. Manufacturing methods for these components include fixed platforms and production lines, each tailored to different types of prefabricated elements. The diversity in prefabrication types allows for greater flexibility, speed, and efficiency in construction projects.

Structural materials used in prefabricated and modular buildings encompass a range of options, including conventional materials such as steel, wood, and concrete; and novel materials such as composite systems that combine multiple materials for improved structural performance, recycled materials to promote circularity and sustainability; or nature-based solutions (e.g. incorporating vertical greening system). The choice of materials impacts the environmental performance and cost of prefabricated buildings, deeply influencing reuse, recycling potential, and end-of-life scenarios (and associated impacts). Understanding these differences and disclosing trade-offs are crucial to assessing prefabricated buildings' cost and environmental burdens.

Refurbishing prefabricated buildings presents a contemporary challenge in Europe and the United States. Initially built without energy efficiency codes, these buildings now require deep renovations. Modern design and construction advancements have overcome the misconception surrounding the quality of early prefabricated buildings. Prefabricated components play a crucial role in addressing the European Union's target of doubling the annual renovation rate, offering efficient solutions for building stock renovation and energy refurbishment. Several projects and studies have explored applying prefabricated elements in building rehabilitation, highlighting the potential for cost-effectiveness, speed, and efficiency in the renovation process.

Prefabrication and modular construction offer a set of benefits to the construction sector, reducing time and cost, and leveraging sustainability. These advantages stem from reducing environmental impact through reduced material usage and waste generation, achieving cost efficiency through economies of scale and precise construction, and improving quality due to controlled off-site manufacturing. The approach also leads to reduced project timelines by allowing concurrent off-site fabrication and onsite preparation, minimising risks associated with weather and on-site labour. Additional benefits include improved sustainability through reduced waste and circular economy principles, such as design for deconstruction and flexibility for building longevity and renovation.

However, the widespread adoption of prefabrication is hindered by several challenges. Initial capital investment and the need to up-skill labour for prefabrication plants pose economic barriers, along with challenges related to logistics, transportation, and handling. Insufficient technical standards and knowledge further limit its widespread implementation. These challenges are evident throughout the construction life cycle, from the planning and design phases to off-site manufacturing and on-site assembly, necessitating strategic planning, investment, and collaboration to overcome these obstacles and maximise the benefits of prefabrication in the construction industry.

The advancement of technology, including 3D printing and Building Information Modelling (BIM), is driving a revolution in low-cost mass production. This revolution promises more affordable construction with increased creativity, aesthetics, and flexibility. Prefabricated and modular building techniques are improving, accelerating construction timelines, and reducing costs. However, it is still being determined if these methods will consistently deliver long-term quality improvements at a lower cost compared to traditional approaches, as we are currently in a learning phase. Nevertheless, technology is expected to enable larger-scale and more cost-effective construction in the near future.

The integration of a circular economy in the built environment is facilitated by prefabrication and modularity, acting as crucial production technique enablers. However, it remains unclear how prefabrication and modularity specifically contribute to the implementation of circular buildings. This raises fundamental questions, such as whether modular building systems are inherently circular and, if not, which strategies within modular buildings support circular buildings. To address these questions, modular and prefabricated case studies, are analysed to evaluate their potential in implementing circular buildings. The distinction between closed and open prefabricated building systems is crucial, allowing for either limited integration within a single system or a flexible combination of elements from various manufacturers in a wide range of construction projects.

Prefabricated building systems, often viewed as energy-efficient and less resource-demanding, offer benefits in reducing material waste, improving energy efficiency performance, and reducing the carbon footprint. The implementation of circular strategies in prefabrication can further boost sustainability, focusing on waste reduction, waste reduction, and waste integration in new materials, design for adaptability and disassembly, recycling, and efficient material tracking systems. To align with the Circular Economy principles, design should prioritise adaptability, disassembly into reusable components, recycling of construction materials, reduction of waste, integration of waste and by-products into new components, potential extension and reuse of modular units, and effective tracking of materials and components throughout their supply chain.

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