Master's Thesis Report

Measuring the circularity of modular units in modular construction projects

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Measuring the circularity of modular units in modular construction projects

By

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Preface

This thesis is the conclusion of my study in Building Engineering at the Faculty of Civil Engineering and Geosciences at TU Delft. During the course of my master's degree, I was exposed to a lot of knowledge about the circular economy and sustainability in construction and gradually gained insight into their importance. At the same time, modular construction is an emerging technology that has a wide range of applications and potential for development. I have combined these two areas of study with the aim of making useful recommendations for the future development of the construction industry.

Firstly, I would like to thank myself for overcoming the challenges and completing this thesis. In the year that I have been conducting my research and writing my thesis, I have not only learnt a lot about the circular economy and modular construction, but I have also learnt how to challenge myself, move through difficulties and setbacks, and learn how to manage my time and schedule. There are many things that will help me not only with this thesis research but also in my future life.

Special thanks are dedicated to my committee, Peter Rem, for taking on the role of chair of my committee and providing me with much guidance and inspiration from a higher perspective. My daily supervisor, Wenjun Cao, who provided me with this research topic, enabled me to research in this new field and guided me when I was lost, providing me with much guidance and encouragement. I would also like to thank Ellen van Bueren for using her expertise in each meeting to provide feedback and guidance on my research.

Finally, I need to thank my family who have fostered my interest in discovery, supported me in my master's studies and removed various obstacles for me to focus on the research and writing of this thesis. I also need to thank my friends who have often acted as bystanders to my research and have accompanied me through these two enjoyable years.

I hope you enjoy reading my thesis and are inspired by it.

Tong Wu

Delft, November 2022

Abstract

With the acceleration of global urbanization, most of us will live in cities in the future. As the urban population grows, the shortage of residential buildings has become a more and more severe problem. In response to the rising demand for housing, more and more builders in Europe, East Asia, Australia and other places have begun to adopt a method called modular construction to build houses. By pre-constructing building components off-site, then combining them into a complete modular unit and transporting them to the building site for assembly, this approach can cut construction time in half and significantly reduce on-site labour costs (Hong, 2020). Modular construction is well suited for tall buildings due to its inherent topological modular form and increased number of repeatable modules (Thai, Ngo and Uy, 2020).

However, most builders currently do not consider the concept of circularity when producing modules, let alone how they will be dismantled and reused in the future. It is conceivable that in the end a large number of discarded modular units will be sent to landfills, creating a large amount of solid waste and consuming many resources to dispose of them, while the functionality of the module still can work to fit the demand. Suppose we can consider the concept of circular economy at the beginning of the project and design the modular units to be easily disassembled and reused, in that case, we will benefit not only economically, but also significantly reduce the carbon footprint of the project.

Based on the problem, it can be found that there is currently a research gap between circular economy and modular buildings. And there is still no tool for evaluating the circularity of modular buildings based on their characteristics. Therefore, this study aims to propose a method for circularity measurement based on the characteristics of modular buildings and modular construction.

A review of design strategies for circular construction reveals a number of recognised strategies. Depending on the characteristics of modular construction, design for durability, adaptability, disassembling and reusability can be selected as suitable circular strategies for modular construction. From a structural point of view, an evaluation method called Module Circularity Indicator (MCI) was developed. The method takes into account the structure, the connection method and the loading capacity of modules and assigns a weight to each structural factor based on the results of a questionnaire in order to evaluate the circularity of the modular unit on a numerical basis. Project owners and designers, especially structural engineers, can use this method to evaluate the circularity of modular projects in terms of four dimensions.

A study using student accommodation as a case was carried out to explore the economic and environmental impact of MCI. Through the case study, it was found that a higher MCI score does not lead to better economic returns and that investors need additional incentives to invest in more sustainable modular buildings. Furthermore, a higher MCI can reduce the

environmental impact of a project to some extent, but the materials used in the modules are also important. In order to achieve a circular economy in the construction industry, MCI could be used as an indicator to subsidise highly circular modular buildings in order to encourage owners to invest in highly sustainable projects. This will allow the modular building industry to move towards more circular projects and reduce the environmental impact of the construction industry.

Content

1. Research framework

1.1. Relevance of Research

1.1.1. Circular economy

In recent years the concept of the circular economy has received increasing attention and many studies related to the circular economy have emerged. In a linear economy, natural resources are harvested to produce products that, because of the way they are designed and manufactured, are destined to end up as waste. This process is oft en summarised as 'take, make, waste' (Brydges, 2021). In contrast, the circular economy uses repair, sharing, refurbishment, reuse and recycling to create a closed-loop system that reduces resource inputs as well as waste and pollution generation (Geissdoerfer et al., 2017). The ultimate goal of the circular economy is to retain materials and resources that are recycled at the highest value within the boundaries of the planet, so that no additional natural resources are needed to produce goods and discarded materials are not considered waste (Guerra et al., 2021).

The construction industry is currently the world's largest consumer of resources and raw materials, with 2.2 billion tonnes of construction and demolition waste expected to be generated globally by 2025 (Ellen MacArthur Foundation, 2020). Governments and a growing body of academic research around the world are now focusing on implementing a circular economy in the built environment (Guerra et al., 2021). This rising concern suggests that the construction industry will also gradually move from a traditional linear model to a circular economy.

1.1.2. Modular building

With the acceleration of global urbanization, most of us will live in cities in the future. As the urban population grows, the shortage of urban building spaces has become a more and more severe problem. In response to the rising demand for residential, hotels and offices, more and more builders in Europe, East Asia, Australia and other places have begun to adopt a method called modular construction to build. By pre-constructing building components off-site, then combining them into a complete modular unit and transporting them to the building site for assembly, this approach can cut construction time in half and significantly reduce on-site labour costs (Hong, 2020). With the advantages of faster construction, lower requirements for construction sites, less demand for on-site labour and construction technology, better quality of work and fewer emissions, modular buildings are widely used in different types of buildings, especially in high-density urban areas (Ye et al., 2021). Temporary hospitals and quarantine hotels using modular construction techniques are also being built in many countries during the covid-19 pandemic.

There have been some studies showing that modular buildings have good circulation potential, but this has not been studied in much depth (Kamali and Hewage, 2016; Kyrö, Jylhä and Peltokorpi, 2019). In addition, most of the studies have only explored the sustainability of the production and construction phases of modular buildings, but not the use and end of life phases of the building. In fact, due to its high modularity, unitization and standardization, modular buildings have advantages in retrofitting, reuse and relocation, which is worth looking into.

1.2. Research Aim and Questions

1.2.1. Problem definition

The circular economy is a concept that has received much attention in recent years, with many arguing that society is currently in transition from a linear to a circular economy. At the same time, due to the high consumption and pollution characteristics of the construction industry, many researchers are focusing on circular construction (Wuni and Shen, 2021). Modular construction is an emerging form of building with the advantages of rapid construction, urban suitability and labour savings. Also due to relocatability, standardisation and unitisation, modular buildings are considered to have a good circularity potential (Kyrö et al., 2018). However, while there is some recognition of the circular potential of modular buildings, there is currently a research gap and a general lack of clear knowledge of the circularity concept of modular buildings. Although some studies related to this direction have recently emerged, they tend to focus only on waste reduction in the production and construction phases of modular buildings or on a particular circular strategy. As a result, there is still a lack of tools for measuring the circularity of modular buildings from a structural perspective. In this context, it is difficult for structural engineers to assess the circularity of a designed or completed modular building.

1.2.2. Research aim

As can be seen from the problem definition, research and design strategies for modular construction exist, and some methods for assessing the degree of circularity of building projects have been proposed. However, the characteristics of modular construction are such that the existing evaluation indicators are not always applicable. It is also true that there is currently no method for evaluating the circularity of modules in modular buildings. This leads to the research aim of the thesis:

To propose a method for circularity measurement based on the characteristics of modular buildings and modular construction.

1.2.3. Research questions

From the problem definition above, we have the main research question:

How can the circularity of module units in a modular construction project be measured from the perspective of structure?

The main research question would be answered by the sub-questions:

1. What are the design strategies for implementing a circular economy in the building industry?
2. What are the characteristics of the structure of modular buildings?
3. What are the circular design strategies suitable for modular buildings?
4. How can the circularity of module units be assessed based on these strategies?
5. What are the economic and environmental impacts of the module's circularity?

1.3. Methodology

The implementation process of this research can be mainly divided into three steps: gathering information, proposing methods, and case study.

1.3.1. Gathering

In the first part of the study, a literature review will be carried out to obtain relevant information. The concept of circular economy will be introduced. How to implement a circular economy in the construction industry will be explored to propose design strategies for circular construction. At the same time, the concept and characteristics of modular building will be introduced, and its building structure, modular unit structure and connection details will be analysed and classified. The latest research on the circularity of modular buildings will then be presented, and the circular design strategies applicable to modular buildings will be finalized. In addition, representative circularity measurement methods that are used in the building industry will also be studied for reference. Research questions Q1 to Q3 are answered in this part.

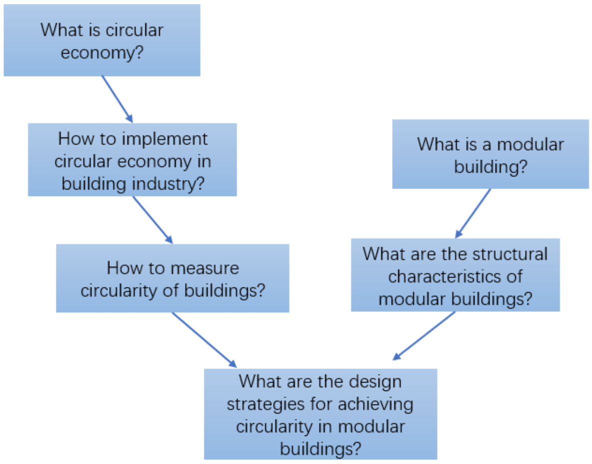


Figure 1. Overview of research questions for literature review.

1.3.2. Proposing

The assessment method for assessing the circularity of module units will be presented in this part. This method consists mainly of structural factors for the evaluation of the module units. Following this, a questionnaire survey of construction professionals will be carried out to obtain their views in order to develop the method and assign weights to each factor and indicator. Through this evaluation system, a module unit can be scored on four dimensions: durability, adaptability, disassembly and reusability. The Module Circularity Indicator (MCI) will be proposed in this part and research question Q4 will be answered.

1.3.2. Case study

In this chapter, the consequences of using different scores for the scoring of the modules in the project are studied. This is done through a case study of an envisaged student housing project. By making changes to the type of modules and connections as well as the load capacity, modules with different MCI scores are obtained. In addition, modules with different sizes under the same score are compared, which can explore the consequences of changes in the building material usage of the modules. Research question Q5 will be answered in this part.

1.4. Reading Guide

In this thesis, the research background, aim, questions and methodology are set out in chapter 1. In chapter 2, a full literature review and studies on design strategies are presented, in order to explore design strategies for implementing circular construction, the characteristics of modular construction, and which circular strategies are applicable to modular construction. In chapter 3, by extracting structural factors from previous studies, scoring the various types of structural factors and assigning weights to these structural factors through questionnaires, the Module Circularity Indicator (MCI) is presented. In chapter 4 a case study of a modular building for student housing is presented and the economic and environmental meaning of MCI are explored through the design of different modular options for this building. Chapter 5 will conclude this research and give some recommendations for future study.

2. Literature review

2.1. Circular economy

What is the circular economy? According to Het Groene Brein, “A circular economy is an economic system based on minimising the use of raw materials by reusing products, components and high-quality raw materials. It is a system of closed loops in which products lose their value as little as possible, renewable energy sources are used and systems thinking is at the core.” (Het Groene Brein, 2019). In the traditional economic framework, the life cycle of a product is linear: we obtain raw materials from nature, use them to manufacture, and discard the products after using them (Ellen Macarthur Foundation, 2021). But in the circular economy, we try to make all of this into a closed loop; that is, nothing is wasted or discarded, and the resources we grab from the earth will also be significantly reduced. When a product's life cycle is over, it will not be discarded but put into the subsequent use after proper modification.

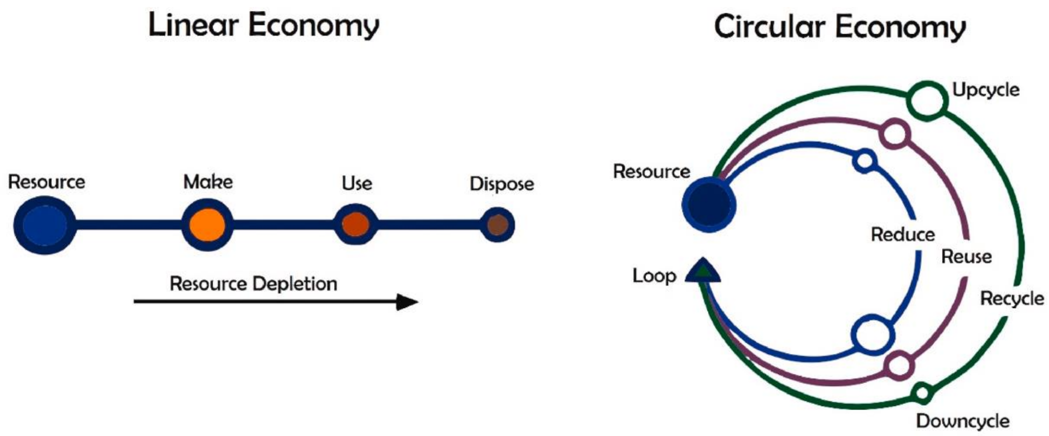


Figure 2. Comparison of linear and circular economy (Akhimien, Latif and Hou, 2020)

According to a report by Het Groene Brein, the global circularity in 2020 is 8.6%, compared with 9.1% two years ago, which shows that the linear economy is still the mainstream and this trend is intensifying. The circular economy still has enormous room for development (Circular Economy, 2021). Traditionally, the construction industry has been one of the biggest enemies of the circular economy. As a resource-intensive industry, construction consumes a lot of energy, emits excessive greenhouse gases to the air and generates a large amount of solid waste every year (Wuni and Shen, 2021). In 2020, the construction and operation of buildings were responsible for 37 per cent (11.7 gigatons) of global energy-related carbon dioxide (CO_2) emissions. Meanwhile, it consumed 36% of the world's energy (UN Environment Programme, 2020). It is estimated that construction waste from a construction site accounts for around 30% of the total weight of materials delivered to the site, while 75% of construction and demolition waste in the EU goes to landfills (Fishbein, 1998; Erlandsson and Levin, 2005). In the Netherlands, the construction industry is estimated to consume 50% of the country's resources, while also generating a large amount of waste, making it the largest source of waste

(Rijksoverheid, 2016).

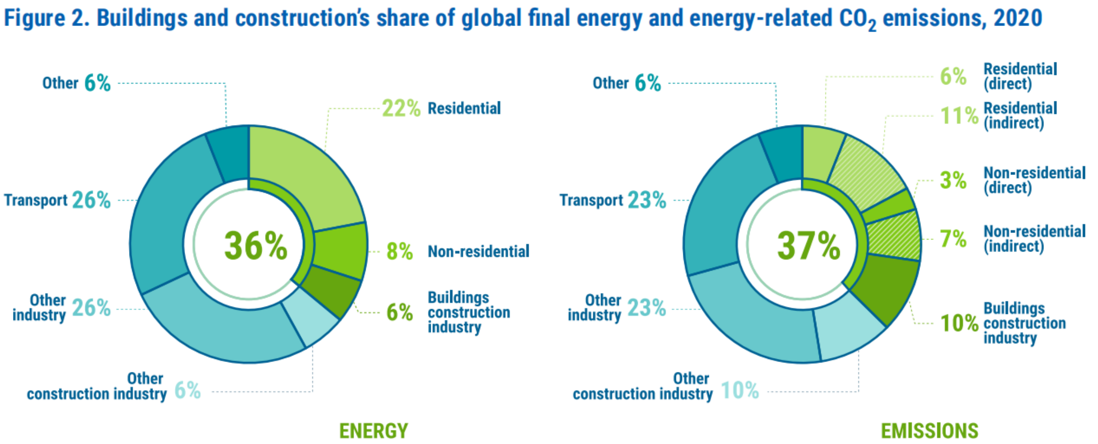


Figure 3. Building and construction's share of global final energy and energy-related CO2emission of 2020 (UN Environment Programme, 2021)

A circular economy can significantly reduce the use of primary resources, thereby protecting the environment and reducing costs. At the same time, the circular economy will promote the transformation and upgrading of the industry and provide a large number of jobs (Akhimien, Latif and Hou, 2020). According to Thelen et al., we are already in a transition phase from a linear economy to a circular economy, which is bound to affect many industries and alter existing business models (Thelen et al., 2018). Promoting circularity has gradually become a consensus across Europe; in 2015, the European Commission adopted a circular economy action plan; it helps stimulate Europe's transition to a circular economy, improve global competitiveness, promote sustainable economic growth and create new jobs (European Commission, 2015).

2.2. Design strategies for circular construction

As mentioned in the previous chapter, the current construction industry is a high-consumption and high-pollution sector. In order to avoid unnecessary resource consumption, environmental pollution and ecosystem degradation, the concept of circular economy should be put into practice in the construction field. A review of published research has identified a number of design strategies that contribute to circular construction, covering the construction, use and end-of-life phases of a building.

2.2.1. Design for material use

The use of different building materials will differ the environmental impact of the building. The purpose of design for material use is to effectively reduce the environmental footprint of the building and improve the cycle degree of construction while meeting the building performance goals through the selection of building materials.

For various building materials such as steel, cement, gravel, brick, sand, lime, wood, glass, etc., the embodied energy and carbon value of building materials will vary due to factors such as geographic location, transportation method, manufacturing technology and energy structure. (Chen et al., 2021). Designers can better reduce the environmental impact of buildings through reasonable design of buildings and reasonable allocation of materials, combined with tools such as life cycle assessment (LCA) databases. In addition to the choice of building materials, by improving traditional building materials, sustainability can also be better achieved. For example, by using geopolymer concrete (GeoC) instead of ordinary Portland cement (OPC) concrete, CO_2 emissions can be reduced by 22%-72% at the same production cost (Degefu, Liao, Berardi and Labbé, 2022).

Besides, in recent years there have been many studies on recycled construction materials and these studies have identified a number of advantages of recycled materials. Chen et al. (2020) tested the use of recycled bricks for the construction of a small-scale underground structure and found that the use of recycled bricks reduced the energy demand by 90% compared to new bricks, and by recycling damaged bricks, the resource demand for virgin material (clay) was reduced by 0.36 t/m for the entire length of the structure. Jesus et al. (2021) on recycled concrete aggregates showed that the overall environmental impact could be reduced by up to 5% when recyclable ultrafine recycled concrete particles were used in place of traditional cement-based materials.

2.2.2. Design for reduction

Since the construction industry is considered to consume a large number of materials and resources and generate a good portion of waste (Hussain, Paulraj and Nuzhat, 2022), the reduction here in this strategy includes the reduction of materials, resources and waste.

Much of the total construction waste is caused by inadvertent damage, loss and over-purchasing, and according to research, at least 10% of construction materials in the UK are wasted in these ways (Osmani, 2011). This massive misuse of resources leads not only to inefficient resource consumption, but also to monetary losses and environmental degradation (Hussain, Paulraj and Nuzhat, 2021). Ogunmakinde et al. (2021) argue that implementing lean construction through building information modelling (BIM) can effectively track building elements throughout the construction supply chain, making it possible to improve material usage efficiency.

Compared to traditional on-site construction methods, prefabrication is also considered a cleaner production technique. The use of building materials and the generation of waste can be greatly reduced by the unified management and industrial production of building components in off-site factories. According to Lu et al. (2021), prefabrication helps reduce construction waste by 17.58%, 15.05% and 52.15% in private construction projects, residential projects and commercial projects, respectively.

In addition, consumption and waste can be effectively reduced by optimizing the structure of buildings, using standardized construction methods and enhancing pre-construction preparation (Hussain, Paulraj and Nuzhat, 2021).

2.2.3. Design for durability

Durability is considered to be the ability to be given to a building through correct conceptual design, planning, choice of materials and proper construction and maintenance of the structure (Demis and Papadakis, 2019). Through design for durability, the lifespan of a building can be extended, thereby increasing the circularity and value of the building throughout its lifespan.

Extending the design life of a building may lead to the consumption of more raw materials and resources during the construction phase. However, due to its extended life cycle, the annual environmental impact of the building can be reduced. Studies have shown that the longer the life of a building, the lower the environmental impact. On average, a building life of 80 years reduces the environmental impact by 29%, 100 years by 38% and 120 years by 44% compared to a building life of 50 years (Marsh, 2016). Extending the life of a building is therefore considered a good strategy for achieving sustainable development. (Palacios-Munoz et al., 2019).

For the durability of buildings, two concepts should be considered separately: the durability of the works and the durability of the construction materials used (Peris Mora, 2007). When the non-permanent materials in a building reach their ultimate durability, they need to be repaired or replaced to protect the building. A building with good durability therefore requires less frequent maintenance and replacement in order to reduce the input of raw materials and resources, as well as the generation of waste.

2.2.4. Design for adaptivity

In practice, many buildings are demolished before they reach their physical endurance, despite being designed to have good physical durability. Studies have shown that the main reason for demolition of buildings is subjective perception (44%), followed by change of use (26%), while only 17% of projects are demolished due to structural deterioration (Marteinsson, 2005).

Design for adaptability is considered to be a proven design strategy in order to change the fate of buildings that are demolished prematurely (Scuderi, 2019). Adaptability can be thought of as the ability of a building to adapt to change and different functions, and there is a large body of literature on the meaning of both, which generally includes changes to building performance, spatial dimensions, and use (Schmidt et al., 2010). Adaptability is often considered to be more extensive than flexibility, as it even includes changes to building size and location (Pinder et al., 2017).

2.2.5. Design for disassembling, reusability and recycling

Design for disassembly is the practice of simplifying the process and procedure of deconstruction through design and planning, and deconstruction is the process of dismantling a building to obtain its materials for recycle and reuse, it is also known as reverse construction (Rios , Chong and Grau, 2015). The three concepts of disassembly, reuse and recycle are closely linked. Disassembly and deconstruction often occur at the end-of-life cycle of a building, and they aim to increase the reuse and recycling of structural components and materials, thereby reducing waste generation.

Design for disassembly requires changes to traditional methods of design, planning and construction, and its main principles include: designing connections that are accessible and easy to disassemble; good documentation of building materials and components; designing simple structures to achieve components standardization of dimensions and details; separate non-disposal, non-recyclable and non-reusable items, such as mechanical, electrical and plumbing (MEP) systems (Guy and Ciarimboli, 2008).

Reuse is considered a way to improve the environmental performance of buildings because it avoids the generation of waste from building demolition and replaces primary materials and products, with potential benefits in terms of greenhouse gas reduction and energy efficiency (Cai and Waldmann, 2019). Recycling is the process of collecting and processing materials that would otherwise be thrown away as trash and turning them into new products (US EPA, 2021). The difference is that reuse preserves the functionality of materials and components, while recycling aims to remove waste Reproduced into new materials (Bui, 2021). Therefore, reuse is more environmentally preferable than recycle, however, not all elements in buildings are salvageable in their initial state (Vonck, 2019). All processes of waste management are showed below.

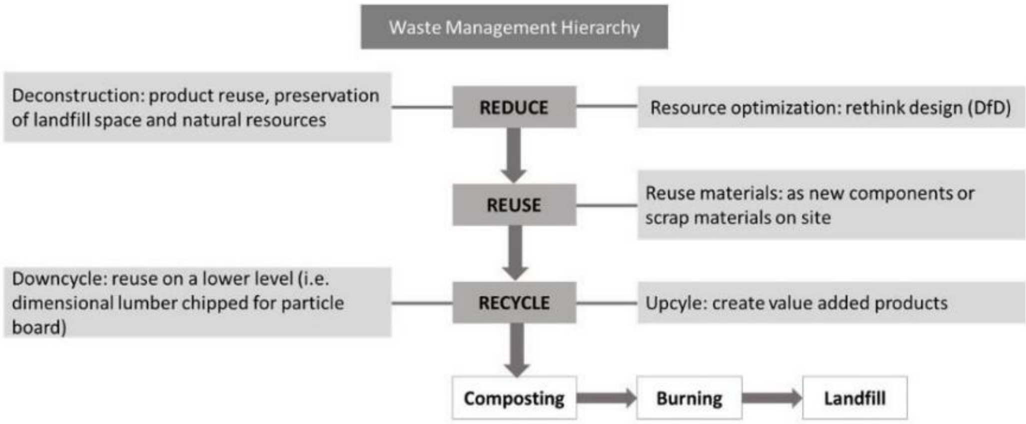


Figure 4. Waste management hierarchy (Kibert and Chini, 2000).

For modular buildings, deconstruction can be thought of as breaking the connection between modular units after the building's life cycle has ended, so that the modules can be detached from the building and transported elsewhere for reuse. Recycling, on the other hand, requires dismantling the various parts that make up the module, including wall cladding, non-structural wall panels, floors, kitchen and interior finishes, so that clean materials can be separated from the modules (O'Grady et al., 2021).

2.2.6. Conclusion

To achieve circular economy in building industry, nine design strategies for circular construction are derived from the literature, which are design for material use, design for reduction, design for durability, design for maintenance, design for flexibility, design for adaptability, design for disassembly, design for reusability and design for recycling.

The first two design strategies occur during the construction phase, while the middle four design strategies occur during the use phase, and the last three design strategies occur during the end-of-life phase of the building. Figure 4 below shows the strategies in different stage of the building life. It’s worth noting that design for adaptability also can be considered to be somewhere between use and end of life.

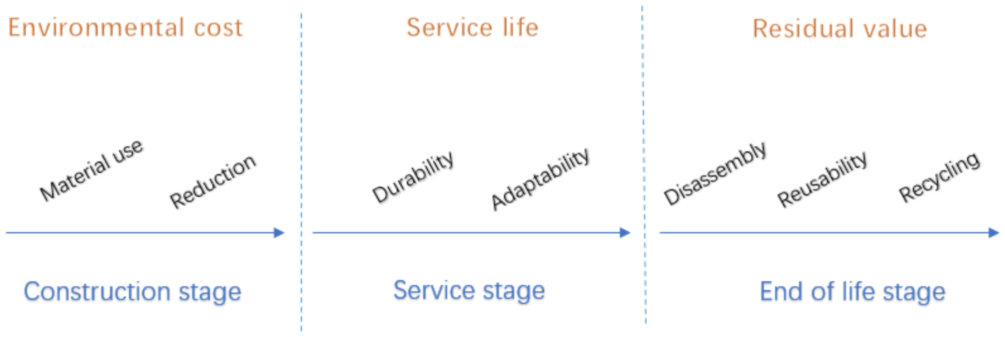


Figure 5. Circular design strategies in different stages of a building.

	(Rios , Chong and Grau, 2015)	(O'Grady et al., 2021)	(Chen et al,. 2021)	(Ogunmakinde, Egbelakin and Sher, 2021)	(Guerra et al., 2021)	(Benachio, Freitas and Tavares, 2020)	(López Ruiz, Roca Ramón and Gassó Domingo, 2019)	(Ghisellini, Ripa and Ulgiati, 2018)
Material use		X	X			X	X	X
Reduction	X	X	X	X	X		X	X
Durability	X		X	X	X			X
Adaptability				X		X		X
Disassembly	X	X		X	X	X	X	X
Reusability	X	X		X		X	X	X
Recycling	X	X		X	X		X	X

Table 1. Design strategies derived from various scientific papers.

2.3. Circularity measurement method

In the following, some representative methods used to assess the circularity of a building or construction are presented. Some of these methods are already widely used and some are still under development.

2.3.1. Environmental Cost Indicator & Life Cycle Assessment

The Environmental Cost Indicator (ECI) is a single-point indicator expressed in euros. It combines all relevant environmental impacts into an environmental cost score that represents the environmental shadow cost of a project or product (Hillege, 2019). Generally, data on environmental impacts come from many different sources and are measured in different impact categories, making comparisons often difficult. As a single-point indicator, ECI can simplify and unify different environmental data points into one monetary number (Hillege, 2019). The value of ECI is usually measured by conducting a Life Cycle Assessment (LCA).

As defined by the Dutch government, Life cycle assessment (LCA) is a methodological tool used to quantitatively analyse the life cycle of products/activities within the context of environmental impact (RIVM, 2011). It is a cradle-to-grave or cradle-to-cradle analysis technique that covers the extraction of raw materials to the processing, manufacture, distribution and use of materials (Muralikrishna and Manickam, 2017).

LCA research consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. In the first phase the purpose and boundaries of the study are identified, immediately afterwards in the second step the material and energy flows within the product system are described, which means that the total amount of material and transport is calculated. In the third step, the previously calculated material and energy are transformed into environmental impacts. In the final step, the results are reviewed, discussed and presented.

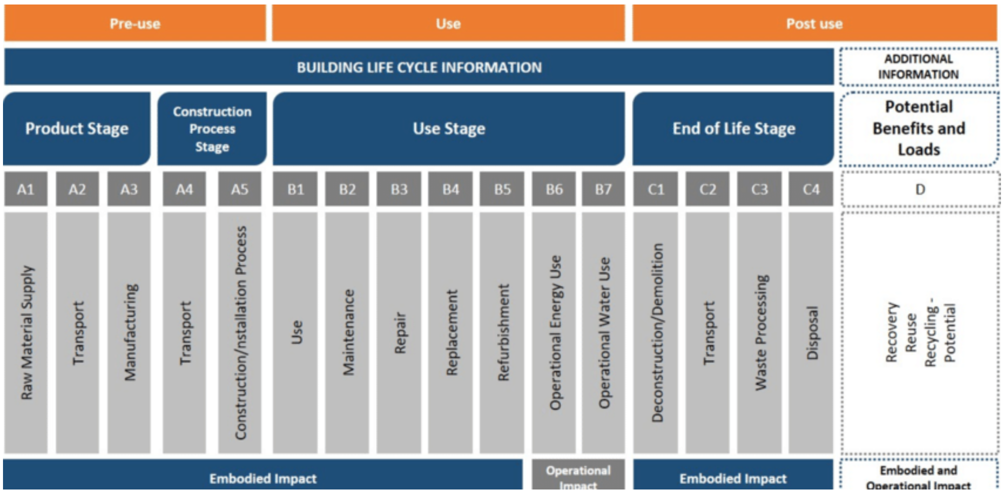


Figure 6. Stages of whole-building life cycle assessment (Silva and Pulgrossi, 2020)

LCA systematically analyzes the environmental impact of the entire production system, from raw material procurement to final disposal, helping to avoid the problem of shifting from one process to another in the product system (Farjana, Mahmud and Huda, 2021). It is part of the European standard EN 15804 and is widely used around the world.

2.3.2. Material Circularity Indicator

Currently, the most recognized and globally adopted indicator in the built environment is the Material Circularity Indicator (Cottafava and Ritzen, 2020). It is a measurement tool developed by The Ellen MacArthur Foundation and Granta Design to allow companies to identify additional circular value from their products and materials and reduce the risk of material prices volatility and material supply (Ellen MacArthur Foundation, 2015). The Material

Circularity Indicator is mainly calculated based on three properties of the product: the mass of virgin raw material used in manufacture, the mass of unrecoverable waste that is attributed to the product, and a utility factor that accounts for the length and intensity of the product's use (Ellen MacArthur Foundation, 2015). It gives a value between 0 and 1 for the circularity of the product, with higher values indicating higher circularity.

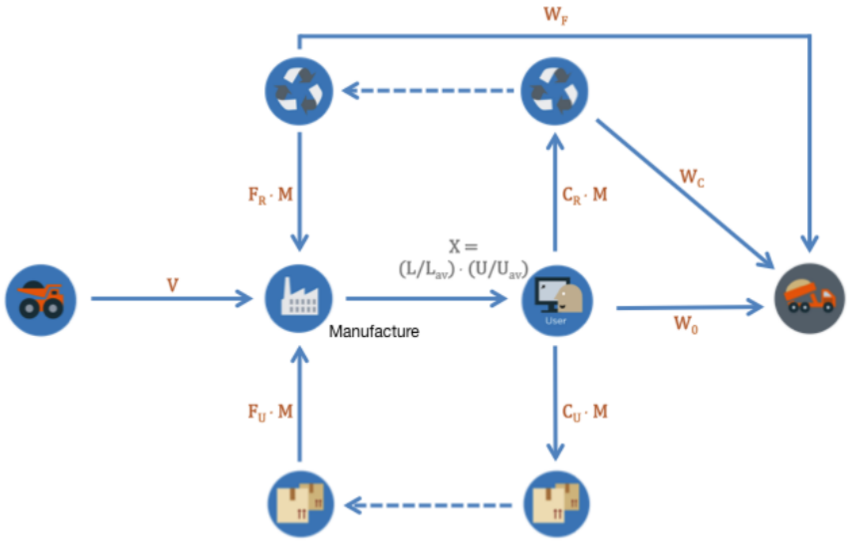


Figure 7. Diagrammatic representation of material flows (Ellen MacArthur Foundation, 2015)

2.3.3. Platform CB’23

Platform CB'23 (Circular Construction 2023) was set up by Rijkswaterstaat, the Dutch Central Government Real Estate Agency (Rijksvastgoedbedrijf), De Bouwcampus and NEN (Netherlands Standardization Institute). It is dedicated to drafting agreements for the entire construction industry in the Netherlands, including residential, non-residential and infrastructure works, in order to accelerate the transformation of the construction industry to circular construction. The platform brings together stakeholders in the construction cycle (including clients, designers, suppliers, construction companies, recyclers, policy makers and scientists) to work together and reach generally supported agreements. The main aim of Platform CB'23 is now to develop a national, construction industry-wide agreement on circular construction by 2023 (Platform CB’23, 2020).

CB'23 presents a guideline2.0 on measuring circularity in 2020, with the objective of developing a core methodology to measure circularity in the construction industry. The core measurement methodology consists of a set of core indicators and a method for their determination, which encompasses the three objectives of circular construction: protect stocks of materials, environmental protection, and value retention. For these three objectives, CB'23 has developed corresponding indicators. For protecting stocks of materials, the core indicators relate to the quantity of material used (input), the quantity of material available for the next cycle (output) and the quantity of material lost (output). For environmental protection, core indicators include climate change, ozone depletion, acidification, eutrophication and ionising radiation. For value retention, the core indicators include the quantity of initial value (input), the quantity of value available for the next cycle (output) and the amount of existing value lost (output), where value includes economic and techno-functional value (Platform CB’23, 2020).

However, as this assessment method is currently under development and some indicators and values have not yet been clearly defined and tested, the method is currently only used to gain understanding and as a reference for decision making and is not yet applicable to a full circularity assessment.

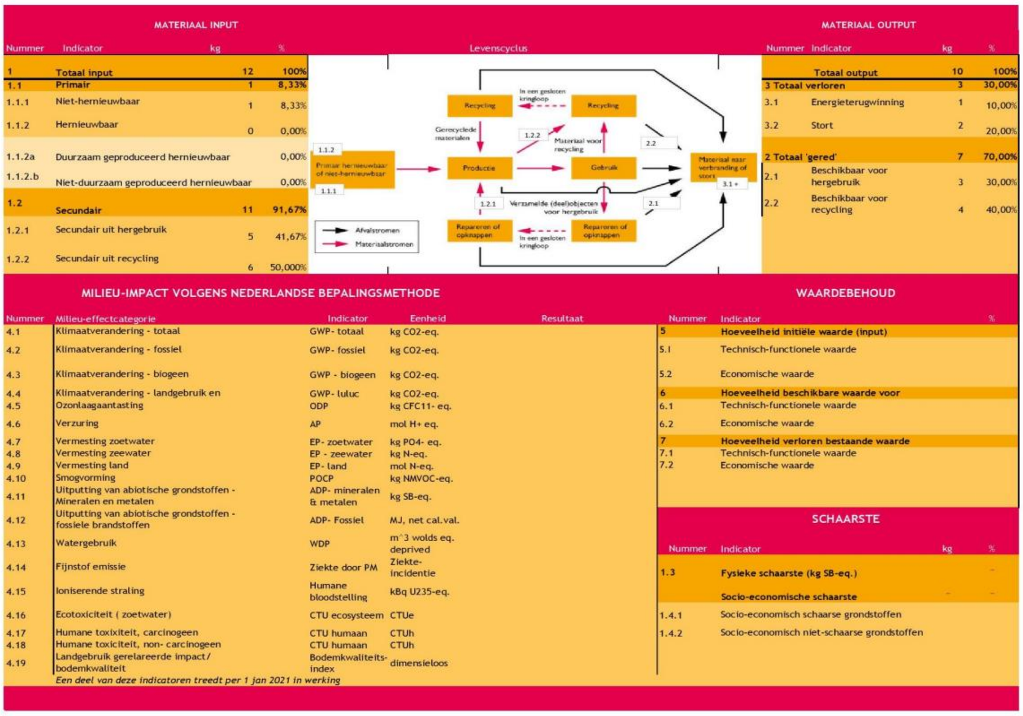


Figure 8. Example of a format to communicate the results of the core measurement method (Platform CB’23, 2020)

2.4. Modular building

2.4.1. Introduction

Modular construction is an emerging off-site construction technique in which structural volumetric modular components are produced in factories and transported to on-site assembly to form more significant permanent buildings (Sanches, Mercan and Roberts, 2018). Discrete modular units usually form a self-supporting structure, and it contains the floor, finishing, plumbing and some furniture (Chen et al., 2017). Modular construction is showing a rapid growth trend in many countries, and in Sweden, the market share of prefabricated building systems in the residential industry has even exceeded 80% (Navaratnam et al., 2019).

Modular construction is known as permanent modular construction (PMC) in the US, modular integrated construction (MiC) in Hong Kong, and prefabricated prefinished volumetric construction (PPVC) in Singapore (Park and Ock, 2015).

Compared with traditional construction methods, modular construction has the advantage of speed, reducing the project construction time by about 40% (Hammad et al., 2019). This is because multiple modular units can be manufactured simultaneously in the factory, while activities on the construction site can be carried out in parallel, and the impact of weather conditions on construction interruptions is significantly reduced. Furthermore, modular construction can reduce the total labour cost by about 25% due to reducing the amount of on-site labor (Navaratnam et al., 2019).

According to a McKinsey consultancy report on modular construction, the use of modular construction techniques can compress project schedules by 20% to 50% and save 20% of costs compared to traditional construction methods. However, it is worth noting that the use of modular construction also risks a 10% increase in costs (Bertam et al., 2019).

Figure 9,10. Progress comparison and cost saving of modular construction compared to traditional construction methods (Bertam et al., 2019)

2.4.2. Building structure

According to Styles et al. (2016) and Thai et al. (2020), the typical structure of modular buildings can be divided into three forms: core structure, frame structure and self-supporting structure. It is worth noting that modular buildings can take either a single structural form or a combination of any two or three of these forms.

2.4.2.1. Core structure

In core structure, all modules are clustered around one or more stable cores. The core of a modular building is usually a reinforced concrete structure where stairs, lifts and various pipes are integrated into it. The cores are usually constructed first, by means of prefabricated concrete elements or steel-concrete cast in situ. The modules are then placed from ground level and connected laterally to the core tube. In this structure, the modular units are only used to transfer the vertical gravity loads over the entire height of the building to the foundations, while the lateral forces from wind and seismic effects are resisted by the solid core. The lateral structure of the modules and the connections between the modules and the core should therefore be strong enough to transfer the lateral loads to the core (Srisangeerthanan et al., 2020; Thai et al., 2020). Due to its good resistance to lateral loads, this type of building construction is often used in high-rise modular buildings (Lawson, Ogden and Bergin, 2012).

2.4.2.2. Frame structure

Modular buildings of frame structure typically use a grid arrangement of beams and columns in which the modular units are placed within their gridded frames (Di Pasquale, Innella and Bai, 2020). In frame structure, columns and/or modular walls are used to resist vertical loads, while lateral loads such as wind and earthquake are resisted by bracing and/or moment-resisting connections in the frame. Depending on whether or not diagonal bracing is used, the frame structure can therefore be divided into bare frame and braced frame. Framed structures are usually constructed in two ways: the main frame structure including beams, columns and bracing is constructed on site by conventional methods and then the modular units are filled into the frame; or structural elements such as beams, columns and bracing are attached to the modules by prefabrication and then the modules are joined directly on site (Ramaji and Memari, 2013). Since in this building structure type one modular unit is supported by one frame grid, it offers good flexibility to designer (Di Pasquale, Innella and Bai, 2020).

2.4.2.3. Self-supporting structure

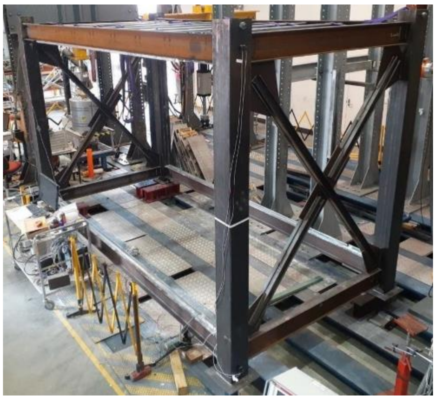
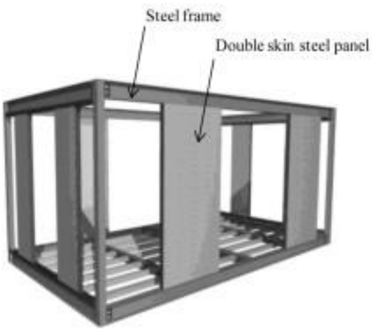
A self-supporting structure is a building structure built from prefabricated three-dimensional or volumetric modules that are stacked by horizontal and vertical connections (Lawson et al., 2014). The vertical and lateral loads of such structures are carried by load-bearing walls and floors. Common types of self-supporting modular buildings include temporary buildings built from stacked containers and accommodation built from concrete modules. This structure type is considered to be less flexible due to the difficulty of replacing, separating and modifying the lower modules without compromising the overall structural stability of the building (Di Pasquale, Innella and Bai, 2020). Furthermore, if a core tube is not combined, self-supporting structures are usually only used in low-rise buildings up to six storeys (Lawson et al., 2012).

Figure 11. Core structure, frame structure and self-supporting structure (Thai et al., 2020; Falcon Structures)

2.4.3. Module unit type

The structural strength, openness, connectivity and other properties of the modules will vary depending on the type of module. According to Ye et al. (2020) and Lacey et al. (2017), commonly used modular units can be classified into the following types based on their structure and materials: bare-frame module, continuous-column module, braced module, slender-panel module, container module, post-tensioned frame module, concrete module and timber module. Example pictures, materials and references for each module type can be found in Table 2 below.

Bare-frame modules are modules with columns at the four corners only, where the four columns carry all the vertical loads. The continuous-column module has more columns on the side of the module than the former. The braced module is based on the bare-frame module with diagonal bracing on the sides. In the case of slender-panel modules, additional panels (usually double corrugated panels) are added to the sides of the module to provide lateral stiffness and strength to the module. The container module is similar to a shipping container, with a large part of its six surfaces covered by corrugated walls. It is the most ordinary type of module and is often used in temporary buildings and low-rise buildings with a relatively low load-bearing capacity. The post-tensioned frame module is similar in shape to the bare-frame module, but uses rectangular concrete filled steel tubes as columns, which provide a higher compression resistance. At the end of each column, there is a seal plate with stiffeners and holes spaced for pre-stressed strands or plugin bars (Chen et al., 2017). Concrete modules include the modules made of concrete, which generally have concrete walls on the sides. They are heavier in weight than the above-mentioned module types, but they also offer greater compression strength and stability. Timber modules have been increasingly used in recent years in educational, residential and commercial projects. Compared to steel and concrete modules, timber modules have a lower carbon footprint and are more sustainable, as well as being very architecturally and aesthetically attractive. It is important to note that timber has poorer structural properties than steel and concrete, so larger beams and columns are required in timber modules.

Type	Illustration	Material	Reference
Bare-frame module		Steel	(Lawson, Ogden and Goodier, 2014); (Prabowo, 2019)
Continuous-column module		Steel	(Lawson, Ogden and Goodier, 2014);
Braced module		Steel	(Rashidi et al., 2020)
Slender-panel module		Steel	(Hong, Cho, Chung and Moon, 2011)

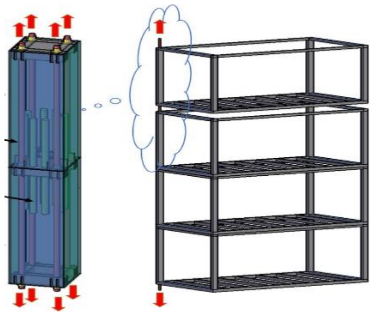
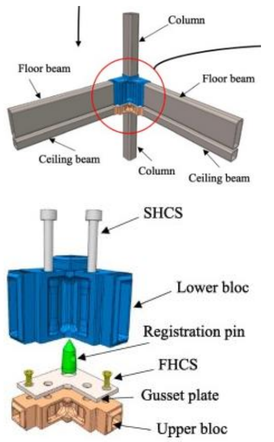
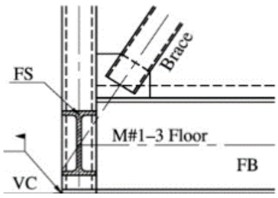
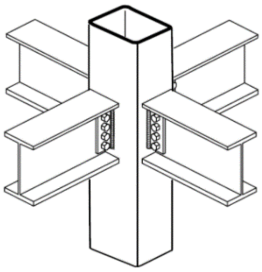
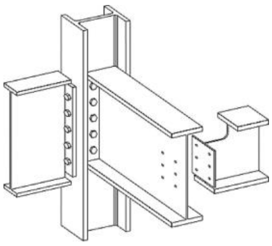
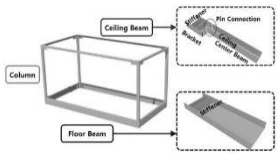
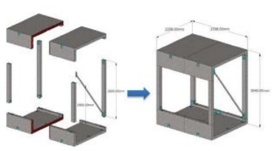
Container module		Steel	(Giriunas, Sezen and Dupaix, 2012); (Zha and Zuo, 2016)
Post-tensioned frame module		Concrete, steel	(Chen et al., 2017)
Concrete module		Concrete	(Pan, Wang and Zhang, 2022); (Philip and Kannan, 2021)
Timber module		Timber	(Lacey, Chen, Hao and Bi, 2019)

Table 2. Different types of module structures used in modular buildings.

2.4.4. Intra-module connection

The connection of modules can be divided into intra-module connections and inter-module connections. For intra-modular connections, the function is to connect structural elements such as beams, columns and load-bearing walls together. For modular construction, the connections of the structural elements in the modular units are often prefabricated in an off-site factory. Therefore, unlike inter-module connections, which seek efficiency and ease of construction, intra-module connections focus more on structural stability. Commonly used intra-modular connections are welded, bolted, wet, connector connections and combinations of these. For timber modules, nails, screw and dowels can also be used. Table below lists a variety of commonly used intra-module connection type.

ID	Illustration	Method	Description	Reference
I1		Welded & connector	The connection between the bloc and the beam and column sections are made by all around full-penetration fillet welds. Then the blocs help to connect modules.	(Dhanapal, Ghaednia, Das and Velocci, 2019)
I2		Welded	The beams, column and bracing are welded together with the plate.	(Annan, Youssef and El Naggar, 2008)
I3		Bolted	The fin plates are welded to the face of column and then the beams are bolted through the plates using bolts.	(Kim, 2019)
I4		Bolted	The end plates are welded to the end of the beam, then connect to the column with bolts.	(Rajanayagam et al., 2021)
I5		Bolted	A stiffener helps to connect beam and column with pin connection.	(Lee et al., 2017)
I6		Wet	The concrete panels and pillars are connected through rebars and concrete.	(Hu et al., 2017)
I7		Wet	The module is prefabricated by 3D steel moulds, it has no interface.	(Lindroth, 2021)

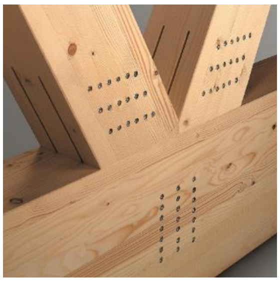
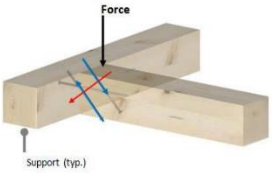
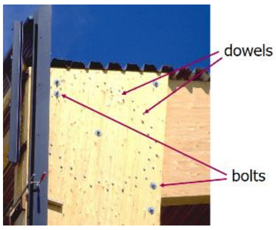
I8		Nail	The elements are joined together by being nailed to the steel plate in the middle.	(De Vries, 2021)
I9		Screw	The timber structural elements is joined together by screws.	(De Vries, 2021)
I10		Bolts & dowels	The timber beam and column are connected through bolts and dowels.	(De Vries, 2021)

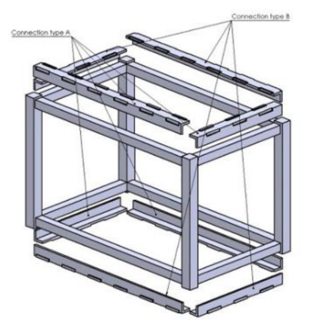
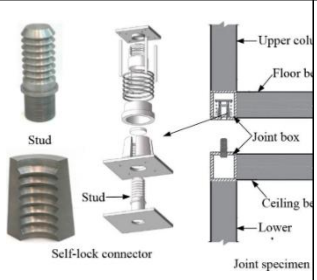
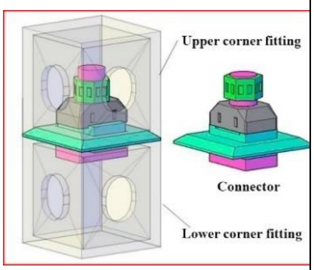
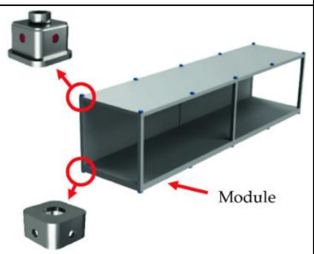
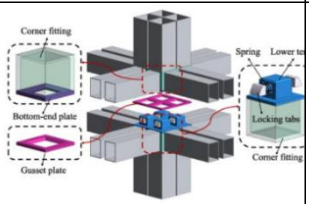
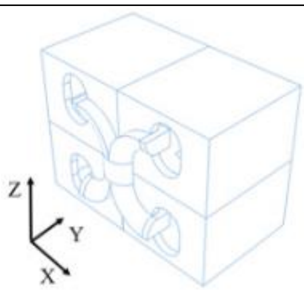
Table 3. Different types of intra-module connection

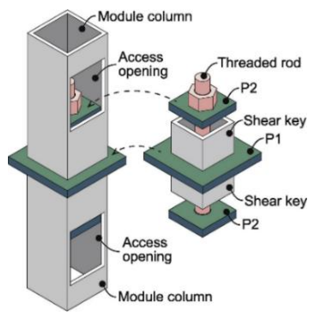
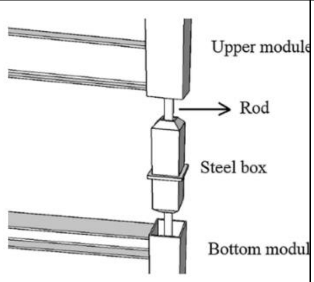
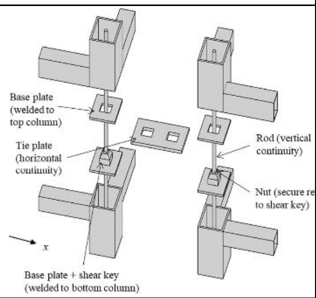
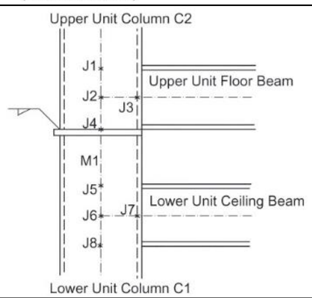
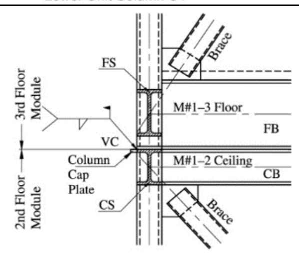
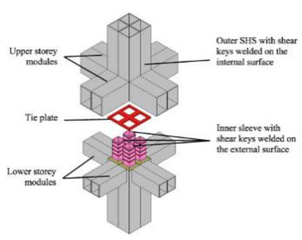
2.4.5. Inter-module connection

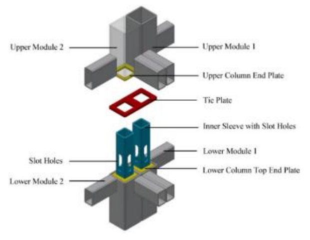
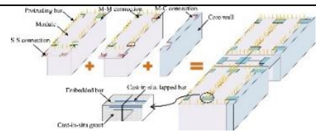
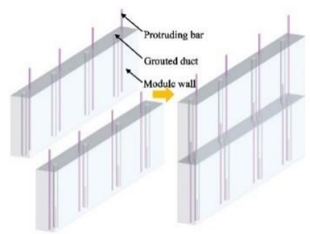
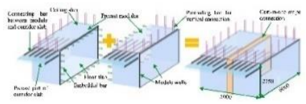
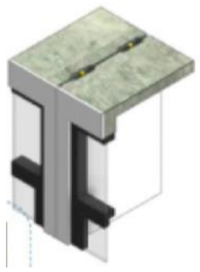
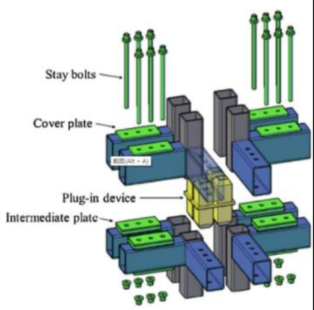
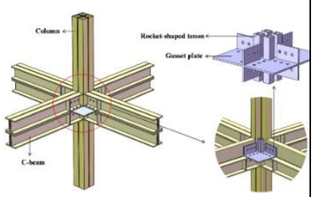
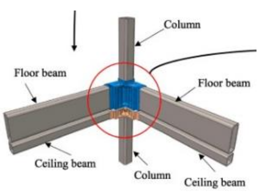
Many studies on the connection of modules have appeared in recent years, greatly expanding the range of connections available. There are various ways of classifying the structural connections of modules. Depending on the material used for the connection it can be classified as steel, concrete and their combination. Depending on the direction of the load they can be divided into vertical and horizontal connections. Depending on the type of connection, it can be interlocked, tensioned, welded, wet, bolted or combinations (Ye et al., 2020).

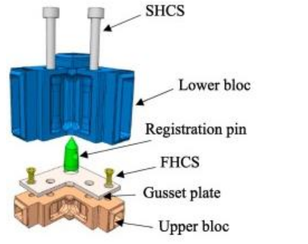
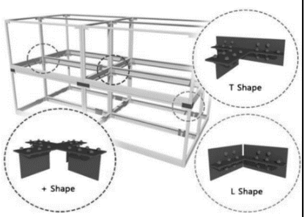
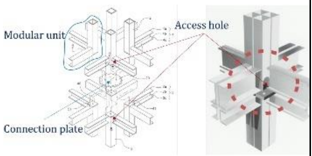
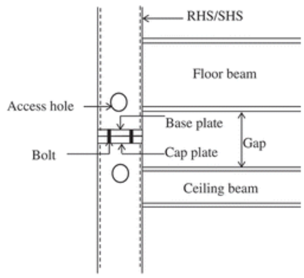
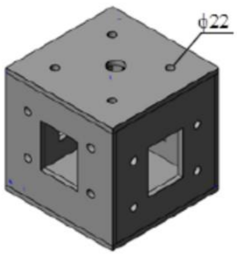
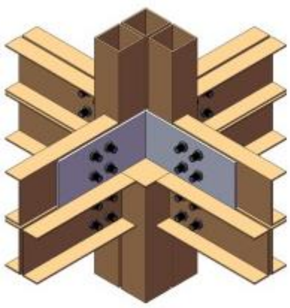
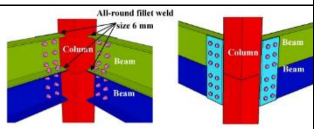
Based on the studies by Ye et al. (2020), Lacey et al. (2017) and Srisangeerthanan et al. (2019), and after adding more cases, Table below lists a variety of commonly used and recent researcher-proposed module connection types. Depending on the type of connection, the table gives each connection an ID, where IL represents an interlocked connection, T represents a tensioned connection, WD represents a welded connection, WT represents a wet connection, B represents a bolted connection, and C represents a combination connection. In addition, V represents vertical and H represents horizontal direction.

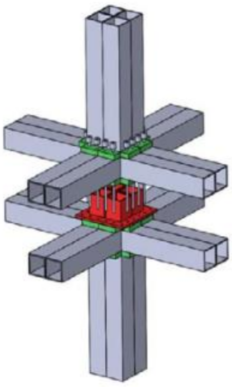
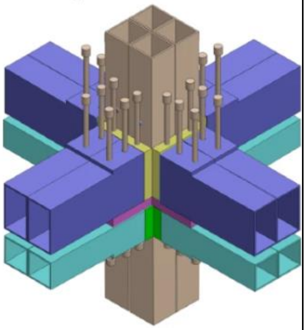
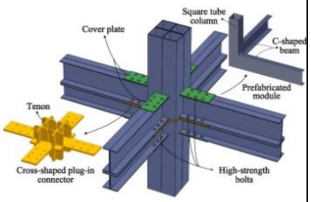
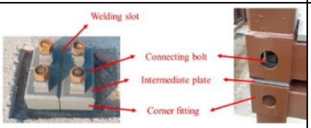
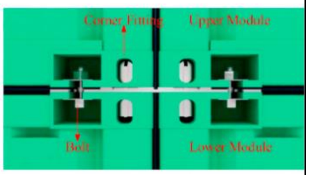
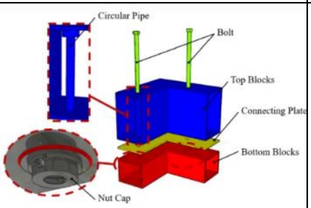
ID	Illustration	Direc-tion	Description	Reference

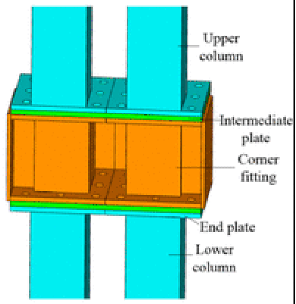
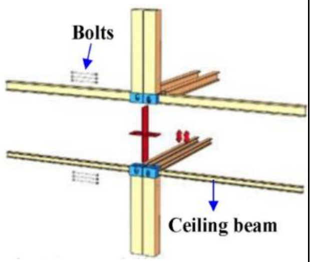
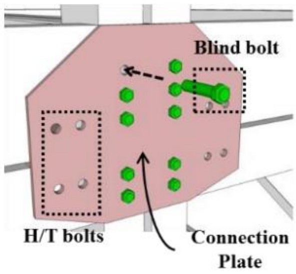
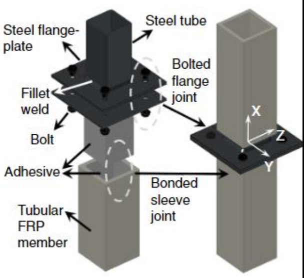
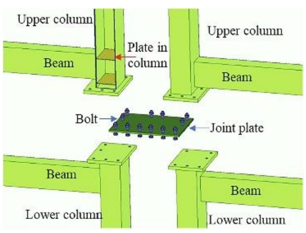
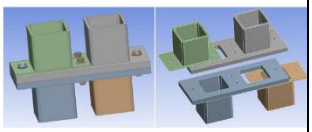
IL1		V&H	Interlocking strip on the four top and bottom sides of a module.	(Sharafi, Mortazavi, Samali and Ronagh, 2018)
IL2		V	Modules connect by a friction self-locked mechanism.	(Dai, Zong, Ding and Li, 2019)
IL3		V	The lower and upper modules locked tightly through the rotary inter-module connection.	(Chen, Liu, Zhong and Liu, 2019)
IL4		V	Semi-automatic torque-activated pin connector for vertical inter-module connection.	(Srisangeerthanan et al., 2021)
IL5		V&H	Self-locking tab through spring.	(Chen, Wang, Liu and Khan, 2021)
IL6		V&H	The X-shaped clamp is used to connect the joint of the four corner fittings from adjacent containers on the outer surface of the building.	(Feng, Shen and Yun, 2020)

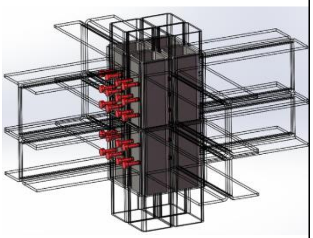
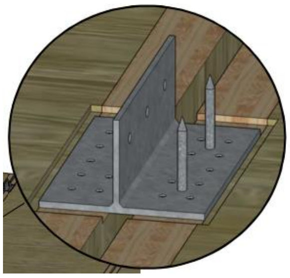
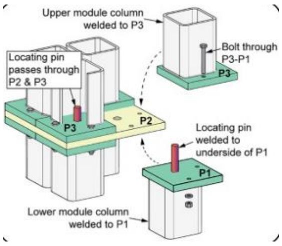
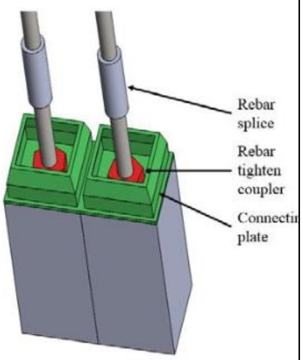
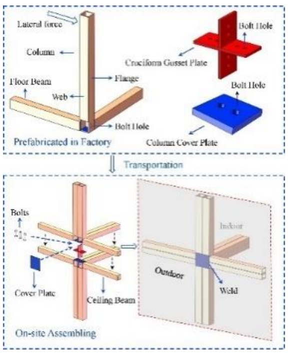
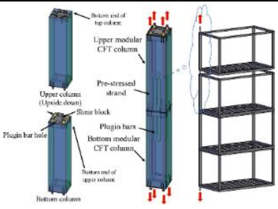
T1		V	A shear key combined with a post tensioned tie rod located inside of the square hollow column of the module.	(Lacey et al., 2019)
T2		V	The threaded rod goes through the hollow columns full height to establish vertical connectivity between the modules.	(Sanches, Mercan and Roberts, 2018)
T3		V	Vertical rods are used to connect the columns vertically while shear keys and base plates are used to connect the adjacent module horizontally.	(Liew, Chua and Dai, 2019)
WD1		V&H	The vertical connection of the modules is achieved by welding the upper and lower columns. Horizontal connection can be achieved by using welded steel plate.	(Annan, Youssef and El Naggar, 2009)
WD2		V&H	Components are connected together by direct welding of their members.	(Annan, Youssef and El Naggar, 2008)
WT1		V&H	The upper module is plugged into the sleeve on top of the lower module, the gaps between the two sections are then filled with high strength grout.	(Dai, Pang and Liew, 2020)

WT2		V&H	Similar to WT1, WT1 uses interfacial bond and compression struct actions for vertical bond, while WT2 uses the formed grout dowels and interfacial bond.	(Dai, Cheong, Pang and Liew, 2021)
WT3		H	The adjacent modules are connected by embedded bars in ceiling slabs, cast-in-situ lapped bars and grout.	(Pan, Wang and Zhang, 2022)
WT4		V	The adjacent modules are connected by embedded bars in ceiling slabs, cast-in-situ lapped bars and grout.	(Pan, Wang and Zhang, 2022)
WT5		H	Two adjacent modules are connected through cast-in-site stripe connection.	(Xu et al., 2017)
WT6		H	Cement is poured from the top into the void between the two modules to form the connection.	(Liew, 2018)
B1		V&H	Cast plug-in devices for horizontal connections and beam-to-beam bolting system for vertical connections.	(Chen, Liu and Yu, 2017)
B2		V&H	A component consisting of four socket-shaped tenons and a cruciform section plate is installed between the modules and bolted to the beam.	(Deng et al., 2017)
B3		V&H	Two separate blocs attached to the upper and lower modules are connected by two cap screws and a gusset plate.	(Dhanapal, Ghaednia, Das and Velocci, 2019)

				
B4		V&H	Steel brackets are used to bolted or welded to floor and ceiling beams.	(Lee et al., 2017)
B5		V&H	Modules are connected together by bolts and a connection plate.	(Lee, Park, Shon and Kang, 2018)
B6		V	The caps of upper and lower columns are connected by bolt. An access hole with 50mm diameter is used.	(Sultana and Youssef, 2018)
B7		V&H	Steel brackets are pre-welded to corner columns of modules, then bolted together on site.	(Hwan Doh et al., 2017)
B8		H	A bracket is bolted to the web of edge beams.	(Park et al., 2016)
B9		V	The pre-drilled plate is bolted on the beams.	(Lyu et al., 2021)

B10		V&H	Long bolt connection at the beam end with pate and inert sleeves.	(Pang, Liew, Dai and Wang, 2016)
B11		V&H	Modules are connected vertically through beam bolts and slotted-in tenons and horizontally by intermediate gusset plate.	(Khan and Yan, 2020)
B12		V&H	The floor and ceiling beams are bolted on the plug-in connector with the cover plate.	(Zhang, Xu and Li, 2021)
B13		V&H	Modules are connected vertically by bolted and horizontally by the intermediate plates.	(Yu and Chen, 2018)
B14		V&H	Modules are connected together through bolts and cover plate connection. Similar to B12.	(Shi et al., 2020)
B15		V&H	Modules are connected vertically by bolts and nut caps and horizontally by the connecting plate.	(Lee et al., 2021)

B16		V&H	The upper and lower columns, intermediate plates, as well as the integrated floor are connected with the corner fittings through bolt connection.	(Chen et al., 2019)
B17		V&H	Modules are connected through gusset plate, corner fittings and bolts.	(Lian et al., 2021)
B18		V&H	Four modules are connected through a steel connection plate and a number of blind and high-tension bolts.	(Cho, Lee, Kim and Kim, 2019)
B19		V	Modules are bolt connected through the steel flange plate.	(Qiu, Bai, Zhang and Jin, 2019)
B20		V&H	Modules are connected by bolts and the joint plate.	(Yang, 2020)
B21		V&H	Modules are connected through the end plate of columns by bolts.	(Gunawardena, 2016)

B22		V&H		In-build components are inserted to the columns, and the modules are locked by side-plate and tightening bolts.	(Ma et al., 2021)
B23		V&H		By using the T-shaped angle plate and screws, the timber module can be connected together.	(Gijzen, 2017)
C1		V&H	IL&B	A locating pin welded to underside of plate is introduced. Modules are connected through bolts, pins and the plate.	(Lacey, Chen, Hao and Bi, 2019)
C2		V&H	T&WT	Reinforcements are locked to the plate by specially designed rebar tighten couplers, concrete is cast into the hollow section column. The connecting plate can provide horizontal connection.	(Pang, Liew, Dai and Wang, 2016)
C3		V&H	B&WD	Cruciform gusset plate and column cover plates are used for modules to bolt together, then a cover plate will weld on the connection corner.	(Deng et al., 2018)
C4		V	T&WT	Pre-tensioned connection for concrete filled steel hollow section columns.	(Chen et al., 2017)

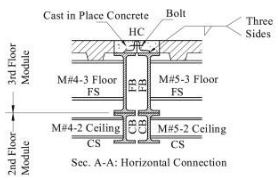
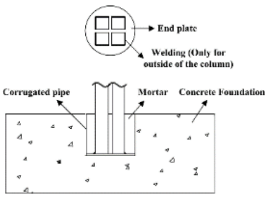
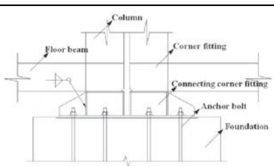
C5		H	WT& WD	The floor beams of the two adjacent modules are bolted together and concrete is then cast in the gap.	(Annan, Youssef and El Naggar, 2009)

Table 4. Different types of inter-module connection

2.4.6. Module to foundation connection

For the connection between modules and foundations, bolted, welded and wet connections are the usual methods. For concrete modules, pouring concrete on site is the most common method. For steel modules, bolted and welded connections are the most common, while wet connections are sometimes used to provide better stability. Fixing timber columns to foundations via steel plates or steel bearings is a useful method of connection for timber modules, which are somewhat similar to steel modules in that they both need to avoid direct contact between the modules and the foundations to prevent corrosion.

In the case of modular buildings, the ground floor is sometimes constructed using traditional methods to achieve greater openness, so that the first-floor modules are connected to the podium rather than to the foundations, which are usually made of steel or concrete and are connected to the modules in a way that is not very different from the connection between the modules and the foundations.

ID	Illustration	Method	Description	Reference
F1		Welded& wet	The columns and the welded end plate are placed at the recess of the foundation and connected with mortar.	(Park et al., 2016)
F2		Bolted	Precast foundation and connecting corner are connected using anchor bolts.	(China Steel Association, 2013)
F3		Bolted	The base plates are connected to the strip foundation by anchor bolts, and the modules are then bolted to the base plates.	(Hong Kong Sheng Kung Hui, 2022)

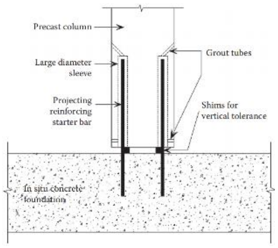
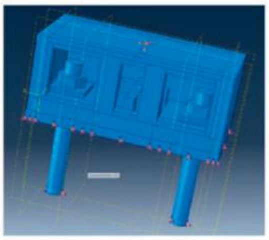
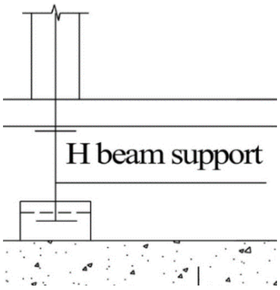
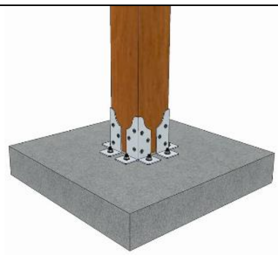
F4		Wet & welded	The reinforcing bars under the base plates are cast into the concrete foundations, the base plates are welded to the module.	(Giriunas, Sezen and Dupaix, 2012)
F5		Wet	The concrete module is connected to the concrete foundation by reinforcing bars and on-site grouting.	(Lawson, Ogden and Goodier, 2014)
F6		Bolted	The module connects to the podium with an embedded steel connector plate with two spigots welded on, and four embedded anchor rods with nuts.	(Shan et al., 2019)
F7		Bolted	The upper end of the steel buttress of the I-beam pier is connected to the module through bolts, and the lower end is connected to the foundation through wet connection.	(Yuan, Hou, Luo and Wu, 2020)
F8		Bolted	The timber column is bolted to the top plate of the steel ledger angle and the bottom late is bolted to the concrete slab.	(Connolly et al., 2018)
F9		Bolted	The bases are fastened to the timber column with structural screws, and to the concrete slab with epoxy and a concrete screw or a wedge type anchor.	(Cochran, 2021)

Table 5. Different types of module to foundation connection

2.5. Circularity in modular buildings

Despite the growing trend towards research on the circular economy and modular construction, only a few articles have been written on the combination of the two and are still in their infancy (Zairul, 2021). Below we have selected several representative and referenced articles for research.

The article by Wuni and Shen (2021) explores how the circular economy can be integrated into modular building projects in Hong Kong. They extracted 23 potential key success factors of circular modular construction projects through literature review. They then conducted a questionnaire survey of 117 construction practitioners, from which three principal success factors were drawn: effective supply chain management, competition and early commitment and collaboration and information management. The potential key success factors they propose and the method of setting up the questionnaire are very informative.

Minunno et al. (2018) extracted seven strategies for applying the circular economy to prefabricated buildings, along with their opportunities, barriers and solutions, through an analysis of published research on how the circular economy can be applied to different industries and production processes. The authors believe that due to the adaptability and disassembly of prefabricated buildings, waste can be reduced, and the second use of components can be facilitated.

	Strategy	Appling the Strategy to Prefabricated and Traditional Buildings	Barriers of Traditional Buildings
1.	Reduction of construction waste and the lean production chain	Adopt the lean production chain to reduce construction waste	TB degree of complexity and variable measures are a barrier toward lean production
2.	Integration of scrap, waste, and by-products into new components	Use of by-products in concrete	No barriers were found in the literature
3.	Reuse of replacement parts or entire components	Use of second-life components	Technically complex, elevated time, and cost requested
4.	Design toward adaptability (reduction through life extension) during operational stages	Adaptability during the operational phase	Low adaptability of components due to monolithic nature of the TB; knowledge gap on space adaptability
5.	Design toward disassembly of goods into components to be reused	Reusability at the EoL	Monolithic structures with chemically bonded connections
6.	Design for recycling of construction materials	Recyclability at the EoL	Concrete is intensively used in TBs; however, in the recycling process, its characteristics decrease with scarce saving of CO_2 emissions
7.	Systems to track materials and components within their supply chain	Tracking the components	Practicable only when component can be disassembled and reused

Table 6. The seven strategies, how they can be applied to buildings, and the barriers of traditional buildings that hinder their application. TB-traditional building; EoL-end of life. (Minunno et al.,

2018)

The potential of relocatable modular buildings to provide circularity and usability in the built environment was investigated by Kyrö et al. (2018) through a literature review, factory visits and interviews with modular building manufacturers. Through their research, the authors concluded that modular buildings are highly resilient, i.e., modules can be added or removed as space requirements change, and that the ability to relocate entire buildings represents the highest level of adaptability. Modular buildings help to recycle all aspects of the built environment, minimising resource use and enabling energy recycling through the reuse of modules. Furthermore, the multifunctionality and standardisation of modular buildings is important for circularity. And if the usability and circularity of modules and buildings is taken into account in the design and life-cycle management, modular buildings can lead to a high degree of customer adaptability.

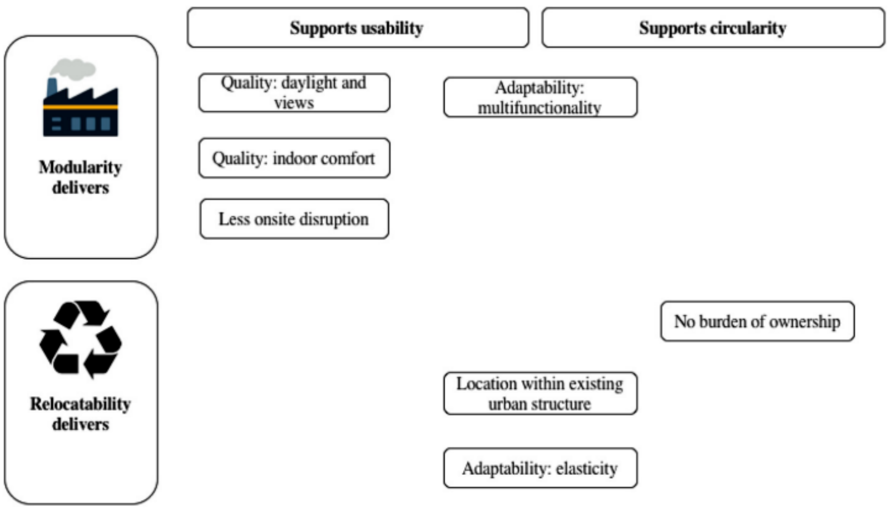


Figure 12. How modular buildings deliver circularity and usability (Kyrö, Jylhä and Peltokorpi, 2019)

In section 2.2, ten design strategies for circular economy implementation in the construction industry are presented. Among them, material use and reduction are for the construction stage of the building; durability, flexibility and adaptability are in the use stage; and disassembly, reusability and recycling are in the end-of-life stage.

There has been some research into the sustainability benefits of modular buildings in terms of production and construction, but not much research into the use and end-of-life phases of modular buildings. In fact, if circular strategies in the latter two phases of the building are not taken into account, a lot of waste will be generated. Therefore, in this study, circularity in the use and end-of-life phases is of interest.

In the case of modular buildings, the modular units can be repositioned and reused due to their characteristics. Therefore, recycling plays a greater role in normal buildings than in modular buildings. It is always possible to recycle the material inside the module, but to reuse the module unit is a more valuable option than recycling, as it saves more input and reduces waste. So recycling is considered to be less beneficial in this thesis.

In the end, durability, adaptability, disassembly and reusability are considered to be the most applicable circular strategies for modular buildings, and the measurement of these four of the performance of modular buildings is worth exploring.

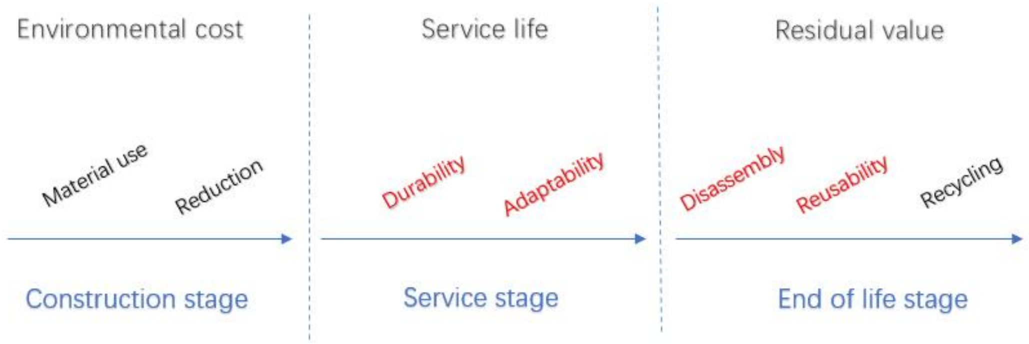


Table 6. The selected design strategies

2.6. Conclusion

In the literature review above, the concepts and characteristics of the circular economy and modular buildings are presented, while some design strategies used to promote the circularity of buildings are summarised. It was also found that among the currently commonly used methods for assessing the circularity of buildings, there are no evaluation methods that are specific to the characteristics of modular buildings. For the design strategies of circular building, the service stage and the end-of-life stage of the building are the stages of interest in this study, as the use and future value of the building is of greater appeal to people. Design for durability, adaptability, disassembly and reusability are considered to be the most appropriate design strategies for modular buildings, taking into account the high standardisation and unitisation of modular buildings, as well as the principle of waste reduction. These four design strategies will therefore be the focus in the following research, and some characteristics that related them in modular buildings will be investigated.

3. Module Circularity Indicator

As stated earlier, this study attempts to develop a tool to measure the circularity of module unit in a modular project from a structural point of view. In this chapter a tool for the measurement called the modular circularity indicator (MCI) is presented. It is divided into four dimensions, corresponding to the four design strategies described above: durability, adaptability, disassembly and reusability. Under each design strategy there are several structural factors.

The MCI is proposed by first extracting key information from the relevant literature to obtain the structural factors corresponding to the four strategies, and then by scoring each factor according to the reality of the situation, depending on the module structure used, the type of connection and the loading capacity. After this a questionnaire is carried out and practitioners with experience in construction industry are invited to rate the importance of the different structural factors. Based on the results of the questionnaire, weights are assigned to each of the structural factors and the four design strategies. After the scores and weights have been obtained, a complete MCI evaluation system is available. A number of existing examples of modular buildings are then analysed and their scores can be obtained by determining their modular structure, connection type and loading capacity. This scoring is compared to the reality to see if it makes sense, for example if long-term projects would stand out more in the durability strategy and if temporary projects will have a higher disassembly and reusability score.

3.1. Structural factors

First, structural factors related to modular buildings and four design strategies need to be extracted from the literature. Based on the circular design strategy for modular buildings obtained in section 2.6, the search steps in figure below were used in order to carry out a thorough literature review on the factors.

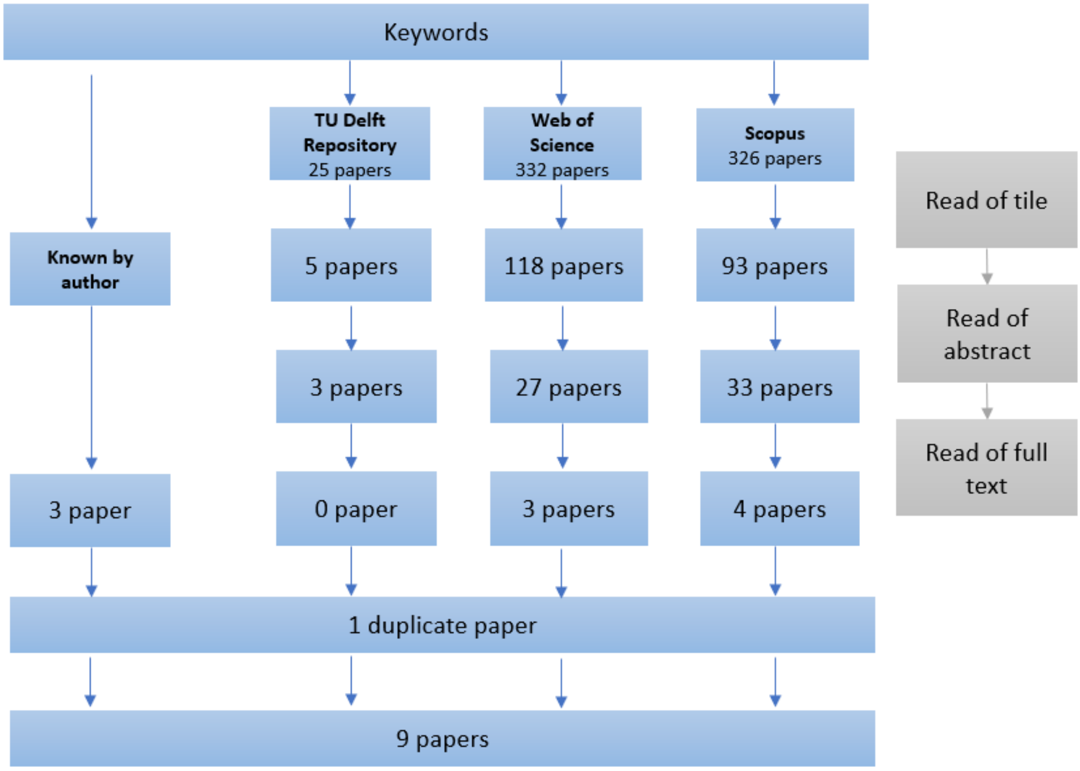


Figure 13. Approach for literature research

As design for durability, adaptability, reusability and disassembly were desired in modular buildings, the following table lists the keywords for search term. In much of the literature, flexibility sometimes has a similar meaning to adaptability (Pinder et al., 2017), so it is also used as a keyword. The wildcard symbol (*) was used to search for different word endings, for example durable and durability for durabl*. To broaden the search, words with a similar meaning to indicator are used as search terms. In addition, modular project, modular construction and prefabricated* are also considered to be keywords with a similar meaning to modular building. The entire searching keywords are:

(flexib OR adaptab* OR reus* OR disassembl* OR durab*) AND (indicators OR characteristics OR categories OR classification OR factors OR measures OR features OR concepts) AND (modular building OR modular project OR modular construction OR prefabricat*)*

Durab* *Durability* *Durable* Flexibl* *Flexibility* *Flexible* Adaptab* *Adaptability* *Adaptable* Reus* *Reusability* *Reusable* Disassembl* *Disassembly* *Disassembling* *Disassemble*	**AND**	Categories Characteristics Classification Concepts Factors Features Indicators Measures	**AND**	Modular building Modular project Modular construction Prefabricat* *Prefabricate* *Prefabricated* *Prefabrication*

Table 7. Keywords for search term

The academic search engines used are TU Delft Repository, Web of Science and Scopus. To keep the total amount of hit papers manageable, the filtering function is used to exclude papers in unrelated fields. After a three-step screening process of reading the article titles, abstracts and full text, a total of seven papers were obtained, one of which was a duplicate. In addition, three papers that mentioned in section 2.5 were also added as already known by author which are relevant to the research questions.

The obtained papers and their corresponding design strategies are shown in the table below, it is worth noting that most of the articles were published in recent years.

Source	Authors	Year	Title	Strategy
Scopus	Corfar, D., Tsavdaridis, K.D.	2022	A comprehensive review and classification of inter-module connections for hot-rolled steel modular building systems	Adaptability, disassembly, reusability,
Web of Science/ Scopus	Atta, I., Bakhoum, E.S., Marzouk, M.M.	2021	Digitizing material passport for sustainable construction projects using BIM	Disassembly, reusability
Scopus	Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L.	2020	Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building	Adaptability, disassembly, reusability
Scopus	Jaillon, L., Poon, C.-S.	2010	Design issues of using prefabrication in Hong Kong building construction	Durability, adaptability disassembly,
Web of Science	Kucan, G., Greaser, K., Grossmann, D., Hall, D.M.	2022	Modular adaptable hospital design (MAHD): proposing a design and construction methodology for flexible and adaptable hospitals	Adaptability
Web of Science	Kirschke, P., Sietko, D.	2021	The function and potential of innovative reinforced concrete prefabrication technologies in achieving residential construction goals in Germany and Poland	Disassembly, reusability
Known	Wuni, I.Y., Shen, G. Q.	2021	Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong	Disassembly, reusability
Known	Kyrö, R., Jylhä, T., Peltokorpi, A.	2019	Embodying circularity through usable relocatable modular buildings	Adaptability
Known	Minunno, R., O'Grady, T., Morrison, G., Gruner, R., Colling, M.	2018	Strategies for applying the circular economy to prefabricated buildings	Durability, adaptability, disassembly, reusability

Table 8. Papers for indicator study

From the above papers the following structural factors can be extracted regarding the circularity of modular buildings and their meanings are listed in the table below.

Structural factors	**Sources**	**Meaning**
Module structure	(Corfar and Tsavdaridis, 2022); (Minunno et al., 2020); (Jaillon and Poon, 2010); (Kucan et al., 2022); (Wuni and Shen, 2022); (Kyrö, Jylhä and Peltokorpi, 2019)	The main structural systems and materials of the module units.
Connection	(Corfar and Tsavdaridis, 2022); (Atta, Bakhoum and Marzouk, 2021); (Minunno et al., 2020); (Jaillon and Poon, 2010); (Kirschke and Sietko, 2021); (Kyrö, Jylhä and Peltokorpi, 2019); (Minunno et al., 2018)	Intra-module connection, inter-module connection and module to foundation connection of modular buildings.
Loading capacity	(Corfar and Tsavdaridis, 2022); (Jaillon and Poon, 2010)	Capacity of modules to carry higher loads than its initially required.

Table 9. Characteristics that extracted from the papers

Among these factors, connections can be further divided into intra-module connection, inter-module connection and module to foundation connection, which correspond to different design strategies, as shown in the table below.

	Durability	**Adaptability**	**Disassembly**	**Reusability**
Module structure	X	X	X	X
Inter-module connection	X		X	X
Intra-module connection	X		X	X
Foundation-module connection	X		X	X
Loading capacity		X		

Table 10. Design strategies for each structural factor

Once the structural factors and their corresponding design strategies have been obtained, the scoring principles for each design strategy also need to be set in order to facilitate the scoring of the different module types, connections and loading capacities later on. The table below shows the scoring principles for the design strategies durability, disassembly, reusability, and adaptability. Each design strategy is scored on a three-point scale, with 1 being the worst and 3 being the best.

Strategies	Score	Description
Durability	1	Frequent maintenance is required; difficult to maintain; the components are easy to corroded
	2	Moderate maintenance is required; moderate to maintain; the components are moderate to corroded
	3	Minor maintenance is required; easy to maintain; the components are difficult to corroded
Disassembly	1	Difficult to disassemble
	2	Moderate to disassemble and some components need to be replaced
	3	Easy to disassemble and most components can be reused
Reusability	1	Limit using scenarios after disassembling
	2	Moderate using scenarios after disassembling
	3	Good using scenarios after disassembling
Adaptability	1	Barriers existing on the four sides, small openings on the wall; poor loading capacity
	2	Barriers existing on two sides, sufficient openings on the wall, moderate loading capacity
	3	Good openness, no barriers on the four sides; good loading capacity

Table 11. Scoring principles of different design strategies for structural factors

3.1.1. Intra-module connection

For the factor of intra-module connection, the design strategies that associated with it are design for durability, disassembly and reusability. The table below shows the scores for each of the three design strategies for each type of intra-module connection, which are described in detail in section 2.4.4.

ID	Durability	Disassembly	Reusability
I1	2	2	2
I2	2	2	2
I3	1	3	3
I4	1	3	3
I5	1	3	3
I6	3	1	1
I7	3	1	1
I8	2	3	2
I9	1	3	2
I10	1	3	2

Table 12. Scores for the intra-module connections

In the above ratings, connection type I6 and I7 received a score of 3 for durability as they are wet connections and are very robust. Type I6 and I7 received lower scores for disassembly and reusability as concrete connections are difficult to disassemble and difficult to reuse after disassembling. For bolted connections, due to the discontinuity of the cross-section, they are not as strong as welded, and their durability is poor due to corrosion, but they are easy to disassemble, cause no damage to the components after disassembly and are also utilised for reuse. For welded connections, their durability, disassembly and reusability are between those of wet and bolted connections.

For timber module connections I8, I9 and I10, nailed, screwed and bolted are all very easy to disassemble connections, the disassembled wood will have a certain amount of material loss, but it can still be reused. The durability of timber connections tends to be relatively low, but since the I8 uses a combination of steel plate and timber, it can get 2 points for its durability.

3.1.2. Inter-modular connection

For the factor of intra-module connection, the design strategies that associated with it are also design for durability, disassembly and reusability. The table below shows the scores for each of the three design strategies for each type of inter-module connection, the connections are described in detail in section 2.4.5.

	durability	**disassembly**	**Reusability**
IL1	2	3	2
IL2	2	3	2
IL3	2	3	2
IL4	2	3	2
IL5	2	3	2
IL6	1	3	3
T1	2	3	2
T2	2	2	2
T3	2	2	2
WD1	2	2	2
WD2	2	2	2
WT1	3	1	1
WT2	3	1	1
WT3	3	1	1
WT4	3	1	1
WT5	3	1	1
WT6	3	1	1
B1	2	3	3
B2	1	3	3

B3	2	3	3
B4	1	3	3
B5	2	3	3
B6	2	3	3
B7	1	3	2
B8	1	3	3
B9	1	3	3
B10	2	3	3
B11	2	3	3
B12	1	3	3
B13	2	3	3
B14	2	3	3
B15	2	3	3
B16	2	3	3
B17	2	3	3
B18	1	3	3
B19	1	3	3
B20	2	3	3
B21	2	3	2
B22	2	3	3
B23	2	3	2
C1	2	3	2
C2	2	1	1
C3	2	2	2
C4	2	1	1
C5	3	1	1

Table 13. Scores for the inter-module connections

For the above scoring, some representative connection types are selected and explained to clarify the mechanics of the scoring. For connection type IL1, this connection type has a moderate degree of durability. And as this type of connection is demountable, it gets a score of 3 for the aspect of disassembly. However, due to the nature of interlocking, when the module is reused, it can only be connected to a module that also uses this type of connection, or the module needs to be modified to remove the interlocking strip from the frame, thus it only gets a score of 2 in the reusability category.

As for connection type T1, it scores 2 for durability as the steel is more susceptible to corrosion but the key components are protected in hollow steel tubes. The use of access opening and bolted construction makes this connection very easy to remove, so the disassembly score is 2. Similarly, as this connection mechanism allows the module to be connected only to identical modules, the reuse scenario is limited, so the score is 1.

For connection type B4, the durability rating is 1 due to the exposed steel brackets to water and air. When disassembling, the worker only needs to loosen the bolts on the steel bracket to easily remove the module from the building without any damage to the module, and the module is also very easy to combine with various types of modules, so disassembly and reusability are scored 3.

For connection type C6, the durability score is 3 because the connection interface is protected in the concrete. However, because the concrete is poured over the gap, the module is difficult to disassemble, so the disassembly score is 1. The structural components may be damaged during disassembly, but given that the bolted connection modules have a good reuse case, the reusability score is 2.

3.1.3. Module to foundation connection

For the factor of module to foundation connection, the design strategies that associated with it are design for durability, disassembly and reusability. The table below shows the scores for each of the three design strategies for each type of intra-module connection, which are described in detail in section 2.4.6.

ID	Durability	Disassembly	Reusability
F1	3	2	2
F2	2	3	3
F3	2	3	3
F4	2	2	2
F5	3	1	1
F6	2	3	3
F7	1	3	3
F8	2	3	2
F9	1	3	2

Table 14. Scoring of the module to foundation connection

For the types that use wet connections, namely type F1 and F5, the connection parts are well protected, the connection is strong and not easily corroded, so they can get 3 points in durability. But at the same time, F5 is difficult to be disassembled and reused, so it can only get 1 point. F1 can be dismantled by cutting steel modules on the ground. Although there will be material loss, it still has a certain reuse value, so its disassembly and reusability can get two points. Types that use bolted connections can get 3 points in disassembly, because this connection method is very easy to remove, and they also get better reusability. For connection types F7 and F9, due to their lack of protection, the bottom of the module is very susceptible to corrosion, so they only get 1 point in durability.

3.1.4. Module structure

For the factor of module structure, the design strategies that associated with it are design for durability, disassembly, adaptability and reusability. The table below shows the scores for each of the four design strategies for each type of module unit. The description of each module structure type can be found in section 2.4.3.

Type	Durability	Disassembly	Adaptability	Reusability
Bare-frame module	2	3	3	2
Continuous-column module	2	2	2	2
Braced module	2	2	2	2
Slender-panel module	2	2	2	2
Container module	1	3	1	3
Post-tensioned frame module	2	1	3	1
Concrete module	3	1	1	1
Timber module	1	3	2	2

Table 15. Scoring of the module structure types

The durability of the modules is mainly based on their material, with concrete modules having better durability than steel modules, and container modules having the lowest durability score due to their simplicity and lightness. However, concrete modules tend to use wet connection for inter-module and intra-module connections and are therefore relatively less disassembled. For flexibility, modules with unobstructed walls receive a higher score, so bare-frame and post-tensioned frame modules are rated 3. For reusability, however, post-tensioned frame and concrete modules are difficult to reuse after dismantling due to the nature of their connections, so they get a score of 1. The container module, on the other hand, is often used in temporary construction, where its weight and size make it easy to transport, and its connection mechanism makes it relatively easy to install and dismantle, thus giving it the highest score for reusability.

For timber modules, due to the fact that wood requires more maintenance and is more susceptible to corrosion compared to steel and concrete, there is only a score of 1 for durability. However, timber modules are usually attached using bolt, screw, nail etc. and are very easy to disassemble, so they get a score of 3 for disassembly. Due to the material characteristics of timber, its load-bearing capacity is less than that of steel and concrete, but timber modules are very easy to retrofit and therefore score 2 points for both adaptability and survivability.

3.1.5. Loading capacity

The loading capacity indicator refers to the load bearing capacity of the module floor and the ability of the module's walls/columns withstand the weight from its upper modules. The values for the load bearing capacity of modular floors are taken from Eurocode 1991-1-1. For domestic and residential buildings, the imposed load on the floor is 1.75 kN/m^2, which is the smallest value for all building functions. The highest value in the scoring table is 5 kN/m^2, which is due to the fact that this value is higher than the imposed load for building functions of resident, office and shopping. In Eurocode 1991-1-1, only areas susceptible to crowds have an imposed load greater than 4 kN/m^2. Thus, in the scoring, minimum refer to capacity equal or smaller than 1.75 kN/m^2, maximum refer to capacity bigger than 4 kN/m^2, and normal to high are distributed between 1.75 and 4 kN/m^2.

For the load bearing capacity of walls/columns, studies have shown that a steel modular unit weighs between 10 and 15 tonnes, while a concrete modular unit weighs between 20 and 35 tonnes (Liew, Chua and Dai, 2019). Thus, a module with a bad bearing capacity can only withstand the addition of one concrete module or 3 steel modules above it, while a module with a best capacity can withstand more than roughly 10 concrete modular units or 17 steel modular units stacked above it.

Floor bearing capacity	
Maximum	> 4kN/m^2
High	2.5 - 4kN/m^2
Normal	1.75 – 2.5kN/m^2
Minimum	< 1.75kN/m^2

Walls/columns bearing capacity	
Best	> 250 tonnes
Better	150-250 tonnes
Normal	35-150 tonnes
Bad	< 35 tonnes

Score	**Description**
3	minimum/bad; minimum/normal; normal/bad; high/bad; maximum/bad
2	minimum/better; normal/normal; normal/better; high/normal; high/better; maximum/normal
1	minimum/best; normal/best; high/best; maximum/better; maximum/best

Table 16. Scoring of the module loading capacity

3.2. Development

3.2.1. Introduction

A questionnaire was carried out to measure the importance of structural factors on the circularity of modular buildings. The full questionnaire form can be found in the appendix. The questionnaire was divided into two main sections, the first of which sought relevant background information from the respondents, including occupation, workplace, experience in the field, experience of modularisation and perceptions of recycled buildings. The second section asked respondents to rate the importance of 16 structural factors on a 5-point scale, including 1 (very insignificant), 2 (insignificant), 3 (moderately significant), 4 (significant) and 5 (very significant) . The set-up of the questionnaire and the analysis of the results refer to the research methodology used in Wuni and Shen's (2021) study of critical success factors for modular construction projects in Hong Kong.

The target respondents were practitioners in the construction industry and experts with experience and knowledge of modular construction. Respondents were mainly drawn from academics and engineers who have published research related to modular construction, as well as companies involved in the modular construction industry. The survey invitation was sent to respondents from all over the world via their email address, LinkedIn, ResearchGate and a consultation form on the company's website, which included a link to the online questionnaire and a proposal for the study. Over 60 invitations were sent to companies and individuals, and 31 responses were collected.

Category	**Attribute**	**Frequency**	**Percentage**
Profession of respondent	Engineer	17	54.8%
	Architect	2	6.5%
	Academic/Researcher	4	12.9%
	Project Manager	5	16.1%
	Client	1	3.2%
	Commercial Manager	1	3.2%
	Managing Director	1	3.2%
Institution of respondent	Consultancy	8	25.8%
	Government Sector	1	3.2%
	Academic/Research Institute	6	19.4%
	Manufacturing/Supply Company	4	12.9%
	Construction Company	5	16.1%
	Developer	4	12.9%
	Architectural Firm	2	6.5%
	Engineering Firm	1	3.2%
Years of construction industry experience	1-5 years	10	32.3%
	5-10 years	12	38.7%
	10-15 years	2	6.5%
	15-20 years	2	6.5%
	More than 20 years	5	16.1%
Number of modular construction project involved	0	8	25.8%
	1-3	11	35.5%
	3-7	3	9.7%
	7-10	3	9.7%
	More than 10	6	19.4%
Awareness of	Never heard of	4	12.9%

circular construction	Have heard of	9	29.0%
	Informed	11	35.5%
	Very well informed	7	22.6%

Table 17. Background of the respondents

These practitioners all work in different organisations involved in the construction industry, with the largest number of responses coming from consultancy (25.8%), academic/research institute (19.4%), construction company (16.1%), manufacturing/supply company (12.9%) and developer (12.9%) also made up a portion of the respondents. This survey allows for a rich diversity of opinions due to the different occupational and professional backgrounds of the respondents. More than half of the respondents were engineers (54.8%), while some were academic/researchers (12.9%), project managers (16.1%) and architects (6.5%). These are all professions that are deeply involved in the construction industry, and the background knowledge required for these allows respondents to gain insight into the questions in the second part of the questionnaire. The majority of respondents (67.7%) have more than 5 years of experience in the construction industry and 74.2% have actually been involved in the construction of modular projects, making them more qualified and better placed to assess the cyclical elements of modular construction. In addition, the majority (87.1%) of respondents were able to understand the concept of circular construction.

In addition to background information, respondents' perceptions of circular construction were also surveyed to gain insight into how the circular economy is currently perceived in the construction industry. The question was a multiple choice and respondents were asked to make a choice based on their perception of implementing a circular economy in the construction sector. The results of the survey are shown below. The results show that the majority of respondents believe that the implementation of a circular economy in the construction sector is useful and necessary. However, three respondents also felt that the concept is currently difficult to implement.

Opinions	**Frequency**	**Percentage**
Difficult to achieve	3	8.8%
No need to worry about this for now	0	0.0%
Not that important	2	5.9%
Not sure	3	8.8%
Might be useful	6	17.7%
Generally necessary	15	44.1%
Very necessary	5	14.7%

Table 18. Respondent’s' perceptions about circular construction

3.2.2. Survey result

The mean score and weighting of structural factors under each design strategy can be calculated by the following formulas:

$$\mu_i = \frac{\sum(X_i \times F_i)}{N}$$

$$W_i = \frac{\mu_i}{\sum_{i=1}^{n} \mu_i}, 0 \leq W_i \leq 1, \sum(W_i) = 1$$

Where X_i represents the score assigned to structure factors in the questionnaire results, ranging from 1 to 5; F_i represents the frequency of each rating (ie, 1 – 5) assigned to structure factors, and N represents the sample size, which is the response obtained by the questionnaire total. μ_i represents the average score of the structural factors; W_s represents a set of weights of the structural factors in the aspect; n represents the number of structural factors in the aspect; Σ (W_i) represents the sum of the weights.

For the mean score and weighting of the four design strategies, the calculation method is the same as that of structural factors. By calculation, the results of the questionnaire can be obtained. The table below details the values.

Strategies/Structural Factors	Mean	Weightings
Durability	**4.22**	**0.274**
Module structure	4.32	0.256
Intra-module connection	4.23	0.250
Inter-module connection	4.32	0.256
Module to foundation connection	4.00	0.237
Adaptability	**4.21**	**0.268**
Module structure	4.13	0.498
Loading capacity	4.29	0.518
Disassembly	**3.65**	**0.232**
Module structure	3.94	0.270
Intra-module connection	3.16	0.217
Inter-module connection	3.97	0.272
Module to foundation connection	3.52	0.241
Reusability	**3.61**	**0.230**
Module structure	3.94	0.272
Intra-module connection	3.52	0.243
Inter-module connection	3.71	0.257
Module to foundation connection	3.29	0.228

Table 19. Result for the questionnaire

As can be seen from the table, the design strategy that achieved the highest average rating was durability, with each of its sub-items exceeding four points, which is understandable since only durable modules can be cycled for the next cycle. In second place is adaptability, while disassembly and reusability come in third and fourth respectively.

For factors, durable module structure and inter-module connections, as well as module loading capacity are considered to be the most important. In contrast, the lowest mean score occurs on the intra-module connection of disassembly and module to foundation of reusability, which is realistic, as the circularity of modules usually provides for the reuse of the entire modular system without the need to take the modular structure apart, while the connection of modules to foundations is relatively cheap and has a low probability of being reused.

3.2.3. Conclusion

In the above section the weights of each structural factor and the weights of each of the four design strategies were obtained, thus the circularity indicator of module units can be obtained as:

$$Strategy = \sum_{i}^{n} Factor_i W_i$$

$$MCI = \sum_{i}^{4} Strategy_i \, W_i$$

Where $factor_i$ means the score for each structural factor, $strategy_i$ means the score for each loop design strategy, and W_i means the weighting factor obtained from the questionnaire. It can be seen from the two formulas that the score of each design strategy is obtained by the sum of the weighted structural factors, while the total score of MCI is obtained by the sum of the weighted scores of each design strategy.

In addition to these structural factors, some factors were also mentioned by the interviewees. Standardisation of modules, economic efficiency, installation time and aesthetics were mentioned by several respondents as points of great interest. One interviewee mentioned that inter and intra-module connections are very different and therefore deserve separate attention. A project manager with more than 20 years' experience from a module manufacturing company said that materials should deserve more attention, as "bad materials" such as steel and concrete need to be prevented from entering the circle.

There was also valuable information from an engineer with over 20 years' experience from a modular manufacturing company who said that the design life of their products is typically 60 years but often the owner / operator wishes to relocate or remodel their buildings before this time and the ability to dismantle and reassemble is very important to them. And a lot of project owners will sell their projects to someone else after 5-10 years, so if these new owners realize that, they will benefit from that. He also said that modular construction can greatly help the circulation of projects, and they currently have two modular projects that have been disassembled and relocated in new locations after being in use for a few years

3.3. Existing modular project studies

In the context of the rise of modular construction techniques, many buildings are being built around the world using the modular approach, some of them as apartments that are expected to be used for a long time, while others are used as temporary buildings that will be demolished after a period of use. The type of modules, connections and loading capacity of these projects can be analysed in order to implement and validate the previously proposed module circularity indicator.

In addition, these five typical modular building projects will also be used as references for the case study in the next chapter.

3.3.1. Clement Canopy

3.3.1.1. General information

Clement Canopy is a 50,200 m^2 residential condominium project in Singapore, comprising two 40-storey towers and a multi-storey car park with a basement. The basement, multi-storey car park and ground floor are conventionally constructed, while floors 2 to 40 are built using volumetric modular construction methods. The project consists of 1899 modules and contains 505 luxury residential flats, making it the tallest concrete PPVC building in the world (Building and Construction Authority, 2021). The first and last PPVC modules of the project were installed on 7 April 2017 and 12 April 2018 respectively, with a little over a year apart.

The construction team at Clement Canopy says that by building modularly, waste on site and off site can be reduced by around 70% and 30% respectively （pbctoday, 2019）. And following the project's successful construction, the team now plans to continue their approach on various projects in the UK, Australia, the US and Hong Kong.

Project	**Clement Canopy,**
Location	Clementi, Avenue, Singapore
Owner	UOL Venture Development
Architecture	ADDP Architects
Structural Engineer	TW-Asia Consultants
Contractor	Dragages Singapore
Commencement year	2016
Complete year	April, 2018
Storeys	40
Height	140m
Gross floor area	About 50200 m^2
Number of modules	1899

Table 20. Summary project details of Clement Canopy

Figure 13. Clement Canopy (Dragages, 2018)

3.3.1.2. Structure review

Clement Canopy's building structure is a core plus module stacked structure. The concrete core is located at the centre of the building and the modular units are arranged around the core. Traditional construction methods are used on the core, built while the modules are stacked and installed.

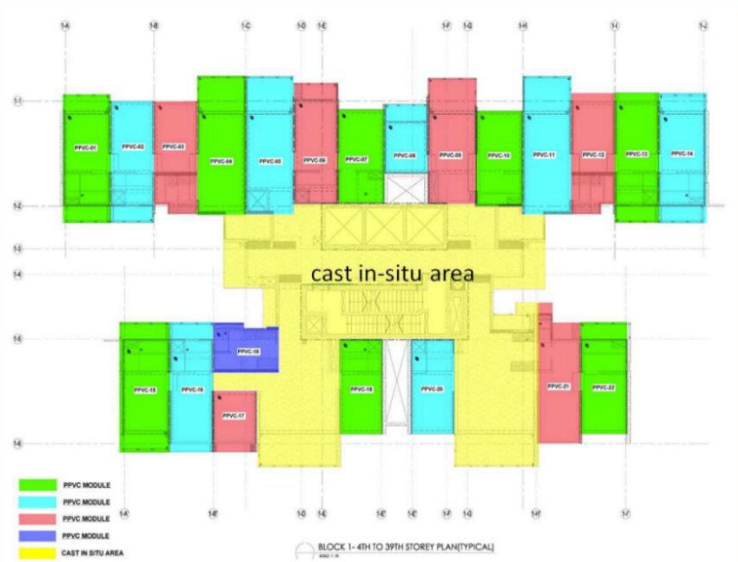


Figure 14. Floor plan for one of the towers (Seng et al., 2021)

The modules used for the project were six-sided concrete modules, which ranged in weight from 26 to 31 tonnes (Building and Construction Authority, 2021). The frames of the modules were prefabricated in a factory in Malaysia and then transported to Singapore for the fit-out, including painting, window frames and glazing, doors, wardrobes and MEP (mechanical, electrical and plumbing). The modules were fabricated in 2D with their walls being fabricated first, then the floors and ceilings were poured and joined together to form the final 3D modules. Prior to casting, precise coordination of the M&E equipment embedded in the wall and floor slabs was carried out. Structural water ponding tests were also carried out to check the water tightness of the completed floor slabs and wall/slab joints.

Figure 15. Module in production and after completion (Seng et al., 2021)

The maximum size of the modules used is 3.1m x 8.35m x 3.15m (width x length x height) and the minimum is 3.0m x 5.75m x 3.15m (Seng et al., 2021). In addition to the design requirements, the size of the modules is also limited by transport vehicles, local transport regulations and the lifting capacity of heavy-duty cranes.

The module-to-module connections are made using wet connections. The walls and floor slabs of the modular units are designed with recesses in which adjacent modules are connected together by means of structural ties in the vertical and horizontal directions. The modules are further connected to reinforcement bars with sufficient anchorage or lap lengths and the voids are then filled with high strength grout. In addition, the modules are provided with alignment guide pins at the corners for easy installation of the modules.

This connection has good durability and load resistance, allowing horizontal diaphragm action to be ensured as the modules transfer lateral loads to the core wall structure.

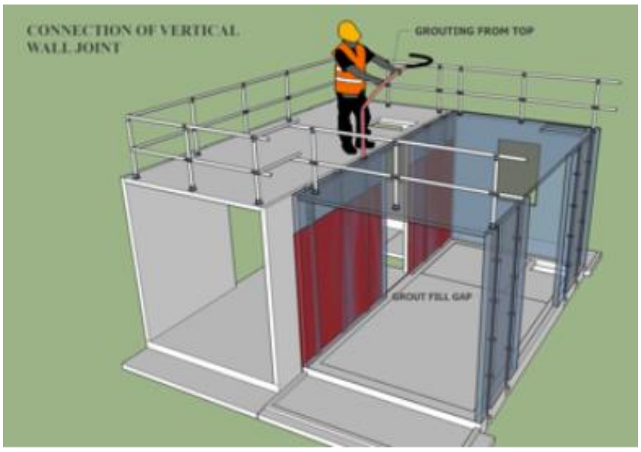


Figure 16. Grouting in between modules (Building and Construction Authority, 2021)

The underground garage and ground floor are concrete structures built in the traditional way, the podium and the modules on top of it are connected in the same way as inter-module connection.

3.3.1.3. Score

From the structure review, the connection type, module type and building structure of Clement Canopy can be determined. Its intra-module connection, inter-module connection and module to foundation connection correspond connection type I7, WT6 and F5 in the literature review respectively. As the function is of the project is residential, and the ground floor modules need to bear the load from more than 30 storeys above, the floor and wall bearing capacity of the modules can be considered as normal and best respectively. So base on the previously proposed evaluation method, the circularity score for the structure of this project can be found in the table below.

	Durability	Disassembly	Reusability	Adaptability
Intra-module connection	3	1	1	/
Inter-module connection	3	1	1	/
Module to foundation connection	3	1	1	/
Module type	3	1	1	1
Loading capacity	/	/	/	3
Score	3.00	1.00	1.00	2.02

Table 21. Scoring for modules of the Clement Canopy project

By weighting the scores of the four design strategies, the module circularity indicator score can be obtained as 1.81.

3.3.2. 461 Dean Street

3.3.2.1. General

461 Dean is a 32-storey modular building in Brooklyn, New York, completed in 2016, comprising 363 flats, using a total of 930 modules. The modules were built by a new factory located in Brooklyn Navy Yard. 461 Dean was the tallest volumetric modular building in the world at the time (CTBUH, 2017), and it was built to provide affordable housing for the growing New York City housing market and to demonstrate the benefits and capabilities of using modular construction techniques on high-rise buildings. Due to the design of the façade and the different shapes of each modular unit, a total of 225 module types were used in the project. The details of the project are summarised in the table below.

Figure 17. 461 Dean Street, New York (Dezeen Magazine 2012)

Project	**461 Dean**
Location	New York, USA
Owner	Brookfield Asset Management
Architecture	SHoP Architects
Structural Engineer	Arup
Contractor	Forest City Ratner Companies and Skanska (previous)
Start exploitation year	2012
Complete year	November, 2016
Storeys	32
Height	109.4m
Gross floor area	32144.5 m^2

Number of modules	930

Table 22. Summary project details of 461 Dean Street

3.3.2.2. Structural review

The main building structure of the tower is steel bracing frame, with a podium at the base built using traditional methods. The arrangement of the module units is essentially in the form of 3 distinct building masses (right, middle and left) as show in figure.

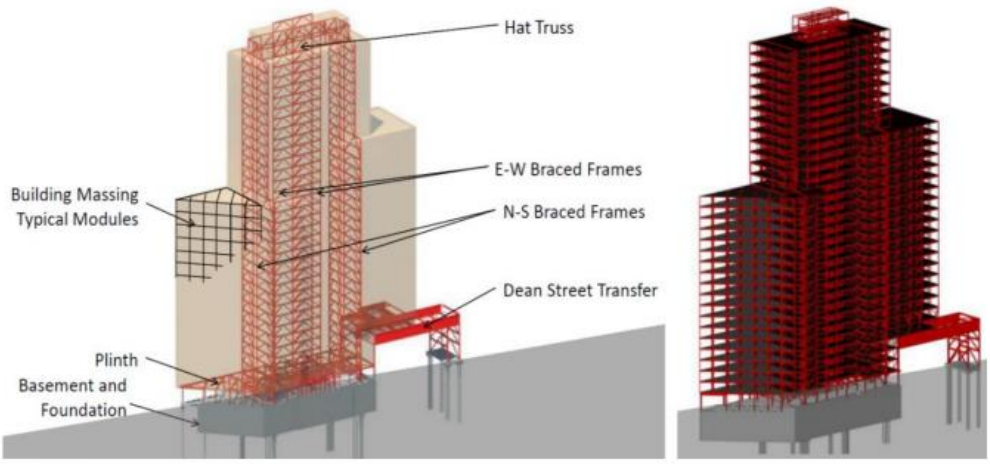


Figure 18. Structural scheme of the 461 Dean tower (Kim, 2019)

Taking into account various architectural features, 461 Dean Street has a total of 225 unique fully-welded, open-ended steel modules ranging in weight from 7 to 24 tons. Strap bracing is used to resist loads and keep the structure stable. The figure of the module structure shows below.

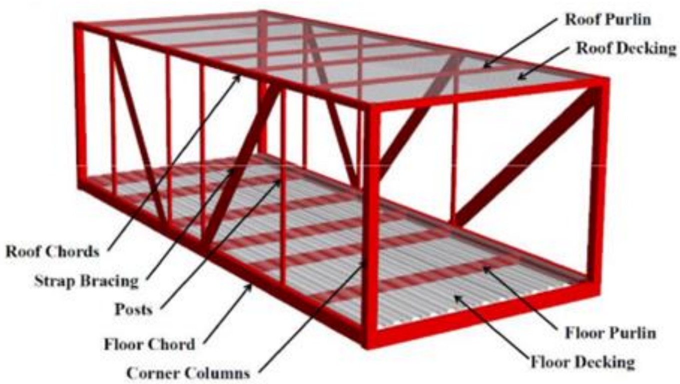
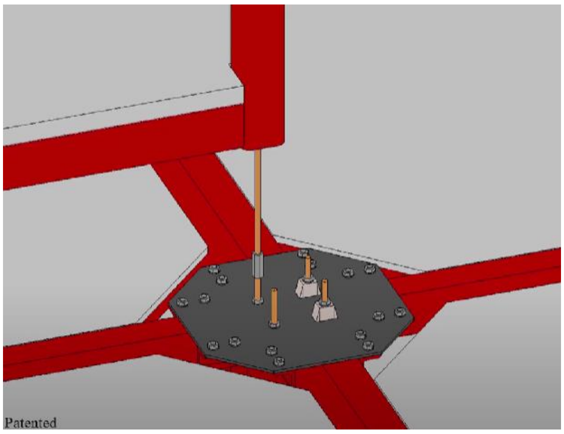


Figure 19. Structural scheme of the module in 461 Dean Street (Kim, 2019)

In the connection of the upper and lower modules, tension rods are used, which pass through the hollow steel sections. For the connection of horizontally adjacent modules, a steel plate that bolted on top of the modules is used.



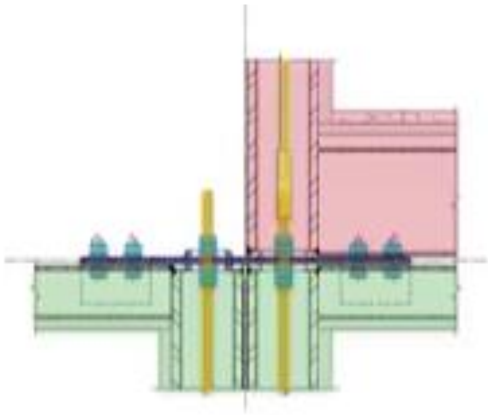


Figure 20. Connection mechanism of the modules (Edelson, 2019)

3.3.2.3. Score

As discussed above, the intra-module connection, inter-module connection and module to foundation connection of the project correspond connection type I2, T3 and F6 in the literature review respectively. The type of the module can be thought of as continuous-column module with open-ended. Loading capacity is rated 3 for the high-rise residential building. The scoring table is showed below.

	Durability	Disassembly	Reusability	Adaptability
Intra-module connection	2	2	2	/
Inter-module connection	2	2	2	/
Module to foundation connection	2	3	3	/
Module type	2	2	2	2
Loading capacity	/	/	/	3
Score	2.00	2.24	2.23	2.51

Table 23. Scoring for modules of the 461 Dean Street project

By weighting the scores of the four design strategies, the module circularity indicator score can be obtained as 2.25.

3.3.3. Nanyang student hostel

3.3.3.1. General

Located on the campus of Nanyang Technological University, the project is the third PPVC project in Singapore, including one 11-story and three 13-story student dormitories, as well as a four-story car park and supporting facilities. Completed in June 2017. (Zheng Keng Engineering and Construction Pte Ltd., 2022) Its gross floor areas are 48,550m2, a total of 676 modules are used, and there are 1,539 student housing units in the whole project. According to the project construction company, by using modular construction, labor costs for the entire project were reduced by 25% and productivity was increased by 40%.

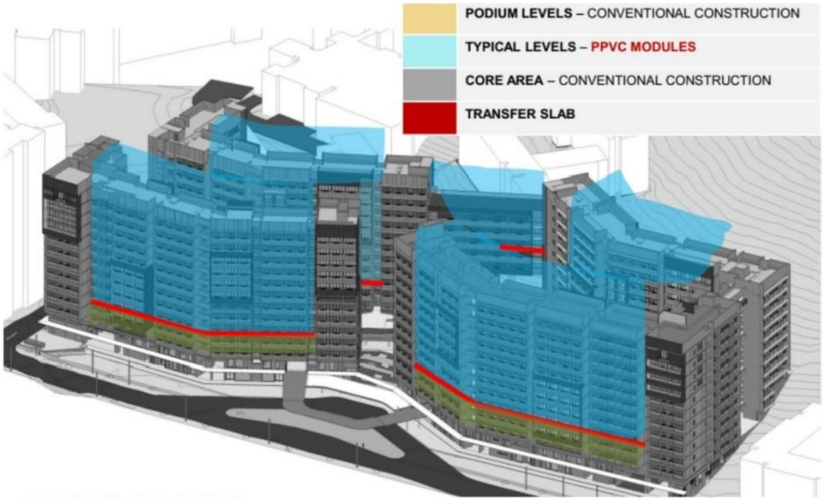


Figure 21. Schematic of Nanyang student hostel (Chiew, 2019)

The construction period of the project is only 6 months, and the floor period is shortened to about 4 days. It is estimated that only 7 workers can install a module in 30 minutes. The module's steel chassis is manufactured in Zhangjiagang, China. After the modules are imported into Singapore, the rest of the exterior and interior finishes, such as lighting, windows and fans, are carried out at the fitting-out factory. (Xu, Zayed and Niu, 2020).

Project	**Nanyang Crescent Hostel**
Location	NTU, Singapore
Owner	Nanyang Technological University
Architecture	SAA Architects
Structural Engineer	KTP Consultants
Contractor	Santarli-Zheng Keng JV
Start exploitation year	December, 2014
Complete year	June, 2017
Storeys	1block of 11-storey and 3 blocks of 13-storey
Gross floor area	48550 m^2
Number of modules	676

Table 24. Summary project details of Nanyang student hostel

3.3.1.2. Structure review

The modules used in this project are slender-panel steel modules, the floor beam, roof beam, column, bracing and other structural elements of the module are welded together in off-site factories. The maximum module dimensions are 3.25 m wide, 10.76 m long and 3.14 m high. The largest module weighs 17.6 tons, and the average steel tonnage per module is 4.8 tons (Xu, Zayed and Niu, 2020).

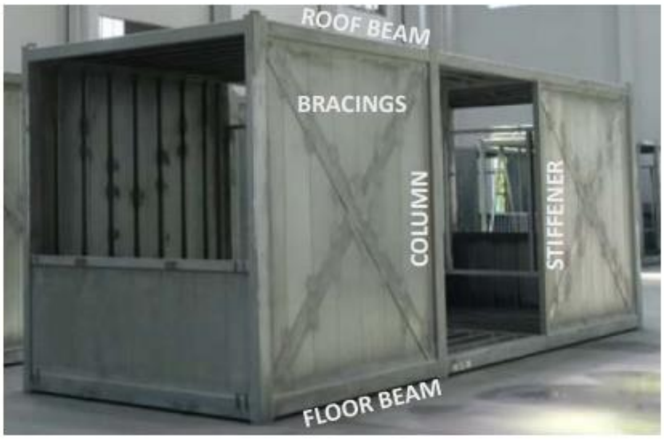


Figure 22. Module of Nanyang student hostel project (Chiew, 2019)

The connection between modules mainly uses bolts, steel plates are used to connect horizontally adjacent modules, and bolts are used to connect upper and lower modules. This connection can be considered to be approximately the same as B20 mentioned in the literature review. The detail diagram and force analysis diagram of the connection between modules are show below.

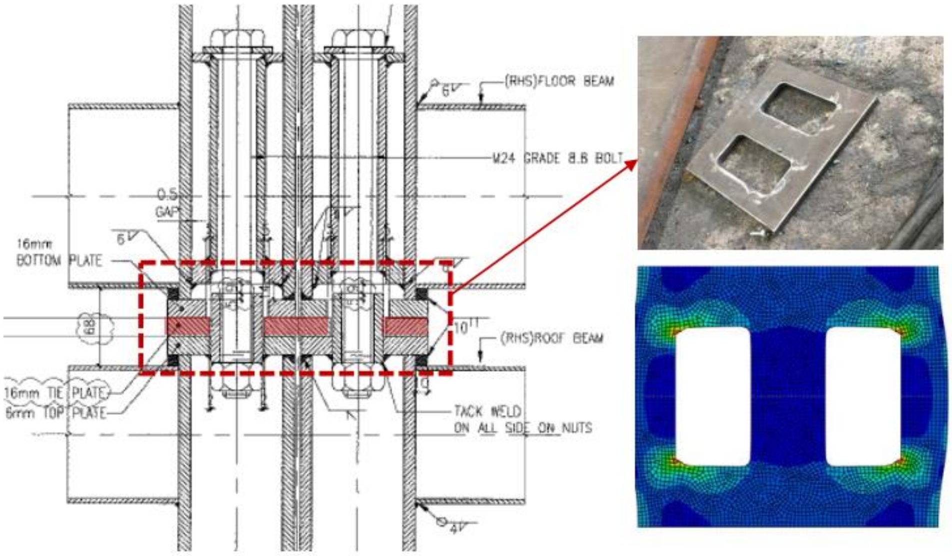


Figure 23. Detail and force analysis diagram of the connection (Chiew, 2019)

Since the bottom layer of the modules is built using traditional methods, the modules on the lowest layer need to be joined together with the concrete transfer slab on top of the podium. The connection method shown in the figure below is used. This is a bolted connection, the same as the connection F2 mentioned in the literature.

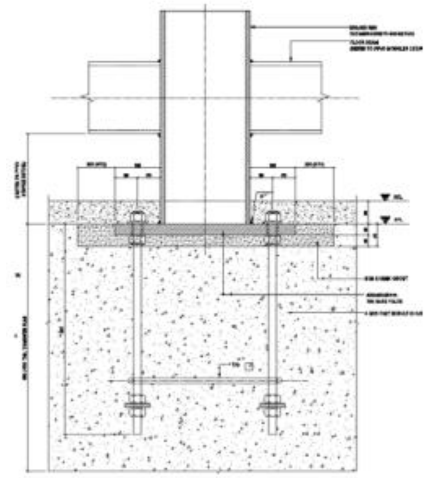


Figure 24. Connection mechanism between modules and the podium. (Chiew, 2019)

Score

As discussed above, the intra-module connection, inter-module connection and module to foundation connection of the project correspond connection type I2, B20 and F2 respectively. The type of the module is slender-panel. The load bearing capacity for the floor and wall is "normal", so the loading capacity is rated as 2. The scoring table is showed below.

	Durability	Disassembly	Reusability	Adaptability
Intra-module connection	2	2	2	/
Inter-module connection	2	3	3	/
Module to foundation connection	2	3	3	/
Module type	2	2	2	2
Loading capacity	/	/	/	2
Score	2.00	2.51	2.48	2.00

Table 25. Scoring for modules of the Nanyang student hostel project

By weighting the scores of the four design strategies, the module circularity indicator score can be obtained as 2.23.

3.3.4. Leishenshan Hospital

3.3.4.1. General

Located in Wuhan, China, the Leishenshan Hospital is an emergency hospital built to treat patients with severe cases of New Coronavirus pneumonia and was the largest investment in

China during the epidemic. The entire medical isolation area is distributed in a fishbone shape, with all wards and corridors in the form of modular units. The project covers an area of 220,000 square metres, with a construction area of 79,000 square metres, a total of 1,500 beds, a capacity of 2,300 medical staff and 32 wards.

The entire project was completed in just 12 days. Due to the tight timeframe, a modular construction method was used. All modules were built in an off-site factory and transported to the site for assembly. Under normal circumstances it would take three to five years to build a hospital of this size using a conventional construction model (Chen et al., 2021).

Figure 25. Leishenshan Hospital under construction (the Design Museum, 2020)

BIM technology is widely used in the design and construction phase of the hospital to allow hundreds of designers from all over China to share information. The BIM platform can classify and save engineering information, and use the model to call the required information, such as door and window statistics, connector types, to provide manufacturers with corresponding processing drawings and schedules. At the same time, a suitable transportation plan can be drawn up by the platform to ensure that the prefabricated elements arrived on time at the construction site (Chen et al., 2021).

Project	**Leishenshan Hospital**
Location	Wuhan, China
Owner	Wuhan Municipal Government
Architecture	CSADI
Structural Engineer	CSADI
Contractor	China Construction Eighth Engineering Division
Start exploitation time	January, 2020
Complete time	February, 2020
Storeys	1
Gross floor area	About 79700 m^2
Number of modules	3300

Table 26. Summary project details of Leishenshan Hospital

3.3.4.2. Structure review

During the project design, due to the urgency of time, the selection of the module unit mainly considered the production and inventory of the module manufacturer, and finally selected the size of 3. 0m×6. 0m×2. 9m modular unit in two sizes.

The modular units use a steel skeleton and composite panel walls. The skeleton is made of cold-formed thin-walled sections and is connected by welding, resulting in a strong structural integrity and high load-bearing capacity. The modular units can be transformed in a variety of ways according to the needs of use, and can be freely spliced. Wall panels can be dismantled to form a flexible use space through different combinations in the horizontal and vertical directions. For the stacking of modules in the vertical direction, no more than three layers is allowed (Yuan et al, 2020).

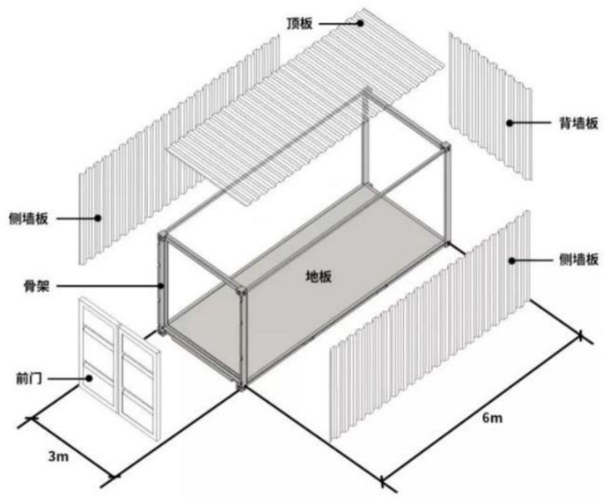


Figure 26. Structure of the module for the project (Yuan et al, 2020)

Like previously described, the structural skeleton of the modules and the walls are connected by welding. The modules were connected to each other by bolts, which greatly accelerated the construction schedule of the project, and the connections were approximated to those of B13 in the literature review. The foundations of the modules used the original hardened flooring of the site and the H-beams were placed on the flooring with the bottom poured concrete attached to the ground. The columns of the modules were bolted to the I-beams to be secured, in the same way as the connection F7 mentioned in the literature review.

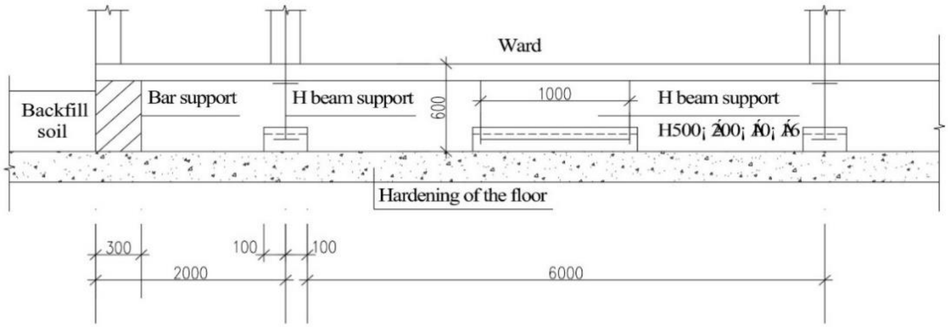


Figure 27. Connection mechanism between modules and the podium (Chen et al., 2021)

3.3.4.3. Score

With the description above, the structure of the modules and the type of each connection can be known. For loading capacity, as this is the module used for medical functions, its floor load capacity is approximately 2kN/m^2 and the modules are generally stacked vertically in no more than 3 layers, so its loading capacity is scored as 1.

	Durability	Disassembly	Reusability	Adaptability
Intra-module connection	2	2	2	/
Inter-module connection	2	3	3	/
Module to foundation connection	1	3	3	/
Module type	2	3	2	3
Loading capacity	/	/	/	1
Score	1.76	2.78	2.48	1.98

Table 27. Scoring for modules of the Nanyang student hostel project

By weighting the scores of the four design strategies, the module circularity indicator score can be obtained as 2.22.

3.3.5. United Court

3.3.5.1. General

United Court is a transitional housing project located in Hong Kong with an expected life span of 2022 to 2028. It is designed to alleviate the hardship of families waiting for public rental housing and other under-housed households, and will provide approximately 1,800 habitable units for needy families. There will be eight residential blocks of four storeys, including 1-person, 2-person, 3-person, 4-5-person and barrier-free units, to meet the needs of different residents and families (Housing Bureau, 2022). The land on which the project is located has been loaned by the property company free of charge until 2028, at which point it is expected to be demolished and the land returned.

The housing units are entirely modular in construction and are being built by CIMC Modular Building Systems, with the modules being built off-site at a factory in Jiangmen, Guangdong. While the modules are being manufactured and assembled, the project undergoes land levelling and foundation construction to reduce the timeline. The modules are then transported by ship to the project for assembly, while the next batch of modules continues to be built at the off-site factory. This has resulted in a much shorter construction time, with the project taking less than a year from development to completion.

Project	**United Court**
Location	Hong Kong, China
Owner	Hong Kong Sheng Kung Hui Welfare Council
Architecture	ALKF+ Architects
Structural Engineer	Arcadis
Contractor	Hip Hing
Start exploitation year	May, 2021
Complete year	March, 2022
Storeys	4
Gross floor area	68048 m^2
Number of modules	2076

Table 28. Summary project details of United Court

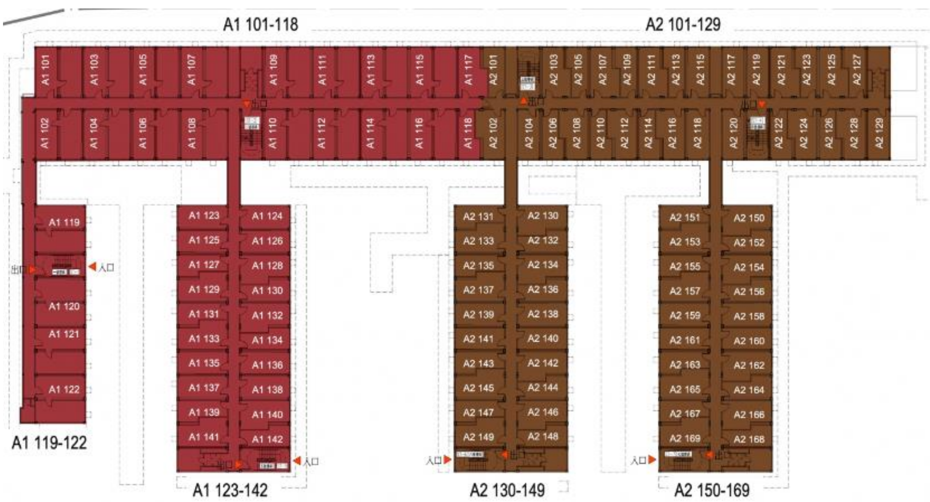


Figure 28. Floor plan for one building of the project (Housing Bureau, 2022)

3.3.5.2. Structure review

The modules used in the project are container-like modules, which have the advantages of light weight, low cost and good reusability. The structural elements within the module are welded together at the factory to form the module.

The connection between modules uses the patented connection method of CIMC Modular Building Systems, as shown in the figure below. This is a kind of bolt connection, the horizontally adjacent modules are connected by the iron sheet in the middle, the upper and lower modules are tightened by bolts, and there are 4 pins to help align the modules. All modules have a hole at the bottom to facilitate the operation of tightening the nut during construction and subsequent maintenance. This connection method is similar to B13. For the connection of the module to the foundation, connection type F3 is used. As the steel base plate and the concrete foundation are pre-cast together, and then the module can be connected to the base plate by means of bolts.

Figure 29. Inter-module connection (CIMC Modular Building Systems, 2022)

3.3.5.3. Score

From the above description, the structure of the module and the type and score of each connection can be known. As for the loading capacity, since this module is used for residential functions, its floor bearing capacity is about 2kN/m2, and the vertical stacking of modules is up to 4 layers, both of which are normal, so the rating of its loading capacity is 1.

	Durability	**Disassembly**	**Reusability**	**Adaptability**
Intra-module connection	2	2	2	/
Inter-module connection	2	3	3	/
Module to foundation connection	2	3	3	/
Module type	1	3	3	1
Loading capacity	/	/	/	1

Score	1.74	2.78	2.76	1.00

Table 29. Scoring for the modules of the United Court

By weighting the scores of the four design strategies, the module circularity indicator score can be obtained as 2.28.

3.3.6. Conclusion

A comparison of the module circularity indicator scores for each item is shown below.

	Clement Canopy	**461 Dean Street**	**Nanyang Student Hostel**	**Leishenshan Hospital**	**United Court**
MCI score	1.81	2.25	2.23	2.22	2.28

Table 30. Module circularity indicator score for the projects

It can be seen that the Clement Canopy project, which uses concrete modules and wet connection, has the lowest MCI score, indicating that the modules in this building have a low degree of circularity and that the modules are more difficult to remove and reuse at the end of the building's life cycle. The building is the tallest concrete modular building in the world and the modules are designed to provide very long-term housing for the occupants, so the designers did not take circularity into account.

The other four projects are probably close in score due to the fact that they all use welded modules made of steel and three of them have a bolted inter-module connection.

For a comparison between the design strategies of each project, the radar charts of the five projects are shown below. It can be seen that the three high-rise projects have better durability than the two low-rise projects, while for the two low-rise projects they score higher in terms of disassembly and reusability. This is realistic, as the three high-rise projects were originally designed as long-term residential projects and the disassembly and reuse of modules was not considered at the design stage. In the case of Leishenshan Hospital and United Court, which are not permanent projects but will be demolished after use, they score better in the disassembly category. I t is also reported that the designers of these two projects took into account the reuse of the modules from the outset, and that their reusability scores were indeed higher, suggesting that the scoring system is proven to be realistic.

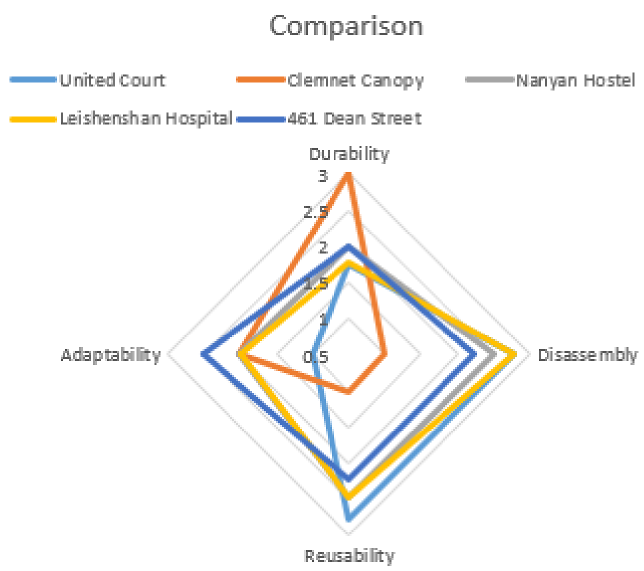


Figure 30. Radar chart for the comparison of the five projects

The module at 461 Dean Street has a higher adaptability than the other projects because it is a high-rise project and the module already has a better load bearing capacity. And the use of open-ended modules, which are more adaptable, results in a higher score.

Although Clement Canopy has the lowest rating, its modules are the most durable, thanks to the use of concrete modules and wet connections. In fact, improving the durability of the project is also a circular strategy, that is, extending the first life span of the project as much as possible. As mentioned in Marsh's paper, the longer the lifespan of a building, the smaller the impact on the environment (Marsh, 2016). Therefore, although extending the design life of a building may result in the consumption of more raw materials and resources during the construction phase, it is still considered a good strategy for achieving sustainable development. It is worth noting that concrete modules are more difficult to reuse and recycle than timber or steel modules, which will be discussed in the case study in Chapter 4.

4. Implementation

In this chapter the consequences of using different scores for the scoring of the modules in the project are studied. This is done through a case study of an envisaged student housing project. By making changes to the type of modules and connections as well as the load capacity, modules with different MCI scores are obtained. In addition, modules with different area under the same score are compared, which can explore the consequences of changes in the building material usage of the modules.

As the Netherlands is currently facing a shortage of housing, especially student housing with the increase in the number of international students, modular housing is seen as an effective solution to this problem. Therefore, a case study with this as a background might be helpful to the current reality.

4.1. Case of student housing

4.1.1. Introduction

In many parts of the Netherlands, the increase in the number of local and international students has led to an even greater shortage of housing, which is already very tight. As a result, there are plans to build student residences in many campuses. Due to the relatively simple layout and the high degree of standardisation, student residence is ideally suited to the use of modular construction techniques. At the same time, modular student accommodation can be easily dismantled when the housing market or enrolment changes, or when land resources become scarce as campuses grow, and the old modules can still be sold at a profit, giving the university greater flexibility to deal with changing realities.

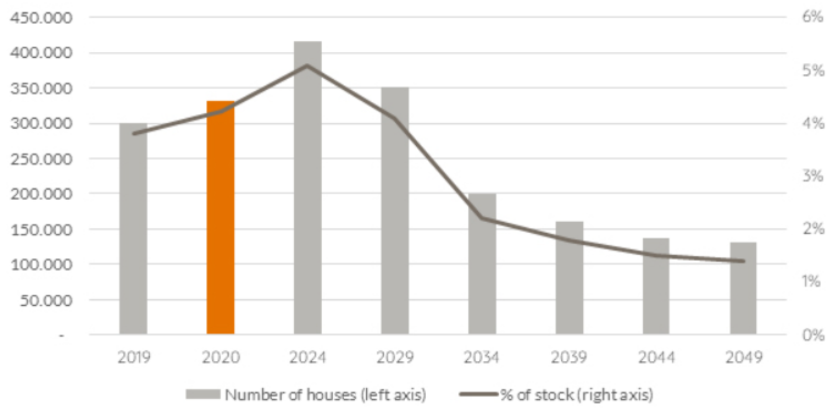


Figure 31. Forecast housing shortage in the Netherlands (Capital Value, 2020)

Modular student housing is used on many campuses in the Netherlands, such as the Keetwonen project in Amsterdam and the Spacebox in Delft, as a supplement to the insufficient number of halls of residence. However, Spacebox modular units have been widely criticised by students for their use of lightweight structural materials such as foam panels, glass fibre and plywood, which make the modules less sound and vibration resistant. This paper therefore focuses on concrete, steel and timber modules, which are already widely used in residential and hospitality projects and are more comfortable to live in.

Figure 32. Keetwonen student housing in Amsterdam, it was built in 2005 and was demolished in 2018. (Tempohousing, 2019)

Figure 33. Spacebox in TU Delft, built in 2004 and demolished in 2017 (Tijdelijk Gebruiken, 2016)

4.1.2. Building layout

The dimensions and layout of the student accommodation refer to the layout of the United Court in the case study, and the Keetwonen student accommodation in Amsterdam, both typical modular building projects. The floor plan of the building is shown below. The structure and layout of the building refer to (Ye et al., 2020) research on modular buildings, using his recommended corridor-spanned layout. The project consists of three parts, left and middle, which are connected by corridors. The dormitory building on the right is completely composed of large modular units, while the dormitory buildings on the middle and right are small units.

The central courtyard enclosed by the three buildings is a green space that can be used as a meeting place and parking lot.

The building has a total of 4 floors with a height of 3 meters, which is equivalent to the height of the modular units. Each floor contains 20 large rooms and 70 small rooms. Each room corresponds to a modular unit. Therefore, two types of modules are used, the larger module is called module type A, and the smaller module is called module type B. Module type A has dimensions of 9.8 meters long, 3 meters high and 3 meters wide and is used in large rooms. Module type B has dimensions of 6.7m long, 3m high and 3m wide and is used in small rooms. Due to the restrictions of transportation regulations, the size of the module should not be too large or too small. The module dimensions set in this case refer to some real-life module unit products.

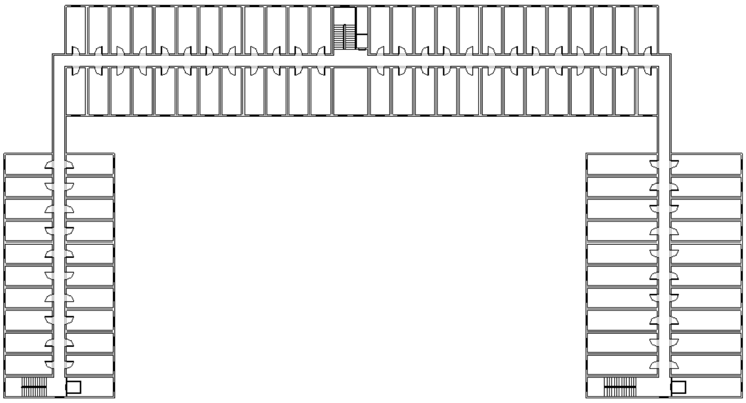


Figure 34. Floor plan of the student housing

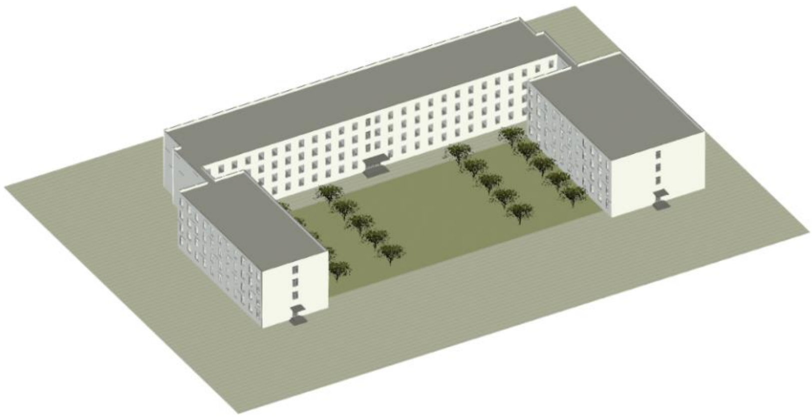


Figure 35. 3D view of the student housing

4.1.3. Module options

A total of four options were provided for the study, all of which are open-ended modules, the models of which are shown below. The dimensions of the structural elements of the steel and timber modules were obtained through detailed force analysis and structural calculations, the exact process of which can be found in the Appendix B. The structure of the concrete module refers to the product parameters of Compact Habit Company, and the amount of reinforcement in the module refers to the calculation method proposed by Lawson (Lawson, Ogden and Goodier, 2014).

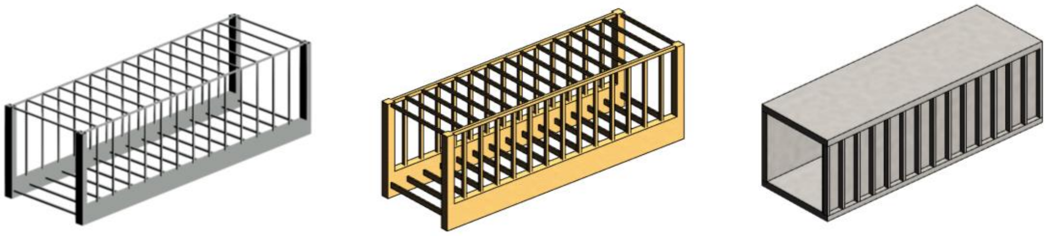


Figure 36. Model for module option 1/2, option 3 and option 4

The module types, connection types, loading capacity and their scores used by each option are shown in the following table. Among them, option 1 and 2 are steel module with continuous-column, their structure and element size are the same, but different connection methods are used. The intra-module connection and inter-module connection of option 1 are both bolted, while option 2 is manufactured by welding, and the connection between modules is also welded. This is to study the differences caused by different connection types when the module types are the same. Option 3 is a timber module and adopts the corresponding connection method. Option 4 is a concrete module, and the connections are mainly wet connections.

	Option 1	**Option 2**	**Option 3**	**Option 4**
Module type	Steel continuous-column module	Steel continuous-column module	Timber module	Concrete module
Intra-module connection	I3	I2	I7	I10
Inter-module connection	B10	WD2	WT4/6	B23
Module to foundation connection	F3	F4	F5	F8
Loading capacity	1	1	1	2

Table 31. Structural factor of different module options

	Option 1	**Option 2**	**Option 3**	**Option 4**
Durability	1.75	2.00	1.49	3.0
Adaptability	1.51	1.51	1.51	1.53
Disassembly	2.73	2.00	3.00	1.0
Reusability	2.73	2.00	2.00	1.0
MCI	2.14	1.87	1.96	1.67

Table 32. Scoring for different module options

It can be seen that option 1 has the highest MCI score, followed by option 3 and option 2, and option 4 has the lowest score. For each design strategy, option 4 has the highest durability score because it uses concrete modules and wet connections, and the corresponding timber module option 3 has the lowest durability score, but the performance of these two options in disassembly is exactly the opposite. Option 1 performs better in disassembly and reusability than option 2 due to its bolted connection, but its durability score is not as good as option 2.

Because this building has two types of rooms, each option can be divided into two types of modules: type A and type B. Type A is a large module, and type B is a small module. The scores are the same for large and small modules. For the steel module and the timber module, the different dimensions will cause different force conditions, and the section dimensions of the bottom chord and corner column will therefore be different.

In addition, the modules need to meet fire safety requirements in accordance with building regulations. For steel and timber modules, gypsum board is often used as a wall and ceiling material to meet fire requirements. By reference to some modular buildings (Lawson, Ogden and Goodier, 2014; Kim, 2019), in this study, the ceiling of the steel and timber modules is made of steel sheet and gypsum board 16mm*2, the walls are made of gypsum board 16mm*2 and the floor is made of cement particle board 40mm and steel ribbed decking. These materials guarantee a fire protection requirement of 60 min, which is often used as standard for modular buildings (Palaima, 2021). In the case of concrete modules, the module itself already contains the walls, ceiling and floor and is thick enough to support the 60min fire protection requirement.

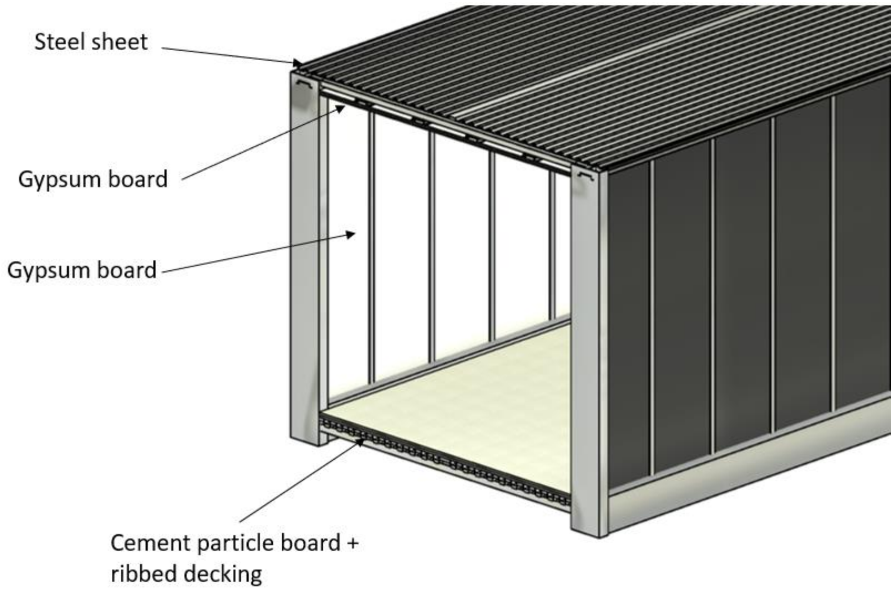


Figure 37. View of the steel module with ceiling, wall and floor element

4.2. Economic analysis

4.2.1. Life cycle costing

Life cycle costing (LCC) analysis is an accurate method of increasing savings in building projects by comparing different design options. It assesses all costs incurred during the life cycle of a building, including construction costs, maintenance, operations and end-of-life related costs (Oviir, 2018). As a decision-making tool, LCC can help identify the key cost drivers of a project and highlight the differences between alternatives.

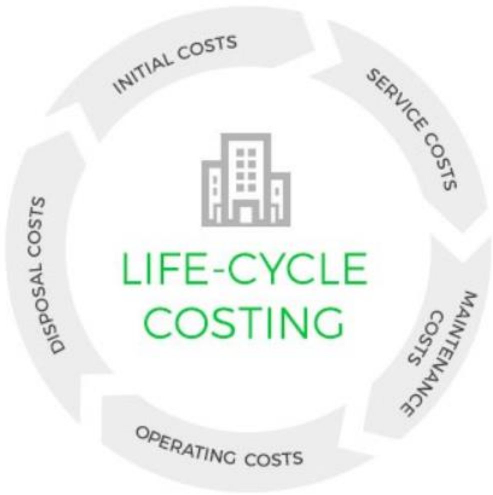


Figure 38. Costs for LCC analysis (Oviir, 2018)

For modular construction projects, LCC can be thought of as an overlay of the following costs: module manufacturing costs + construction costs + operation and maintenance costs + disposals costs - residual costs.

For engineering projects, the LCC result can be expressed as Net Present Value (NPV) in Euros, which is equal to the present value of the benefits minus the present value of the costs. The decline in value is therefore expressed by the following formula:

$$PV = \frac{FV_n}{(1+d)^n}$$

In this formula, FV_n means the future value at the end of period n, n means the year, and d means the real discount rate.

The NPV of a project over the next n years can be obtained by adding up the present value for each future year (Straub, 2021). As shown in the following equation:

$$NPV_n = \sum_{i=0}^{n} PV_i = \sum_{i=0}^{n} \frac{FV_i}{(1+d)^i}$$

In addition, inflation is taken into account in the calculation as some expenditure and income on modular projects will occur in the future.

4.2.2. Calculation set up

In order to calculate the LCC for a case, the value of costs need to be set. The values mentioned below will be used in the calculation.

Initial investment:

The initial investment of the project includes the cost of materials, manufacturing, lifting, onsite labour, and transportation. Materials consider the various structural elements that make up the module. In addition to the structure itself, the price of the steel module also needs to consider the material of the wall, floor and ceiling. This is for a fair comparison with concrete modules. For the concrete module, since the structural frame itself already includes walls, ceilings and floors, only the amount of cement and steel bars needs to be considered. The price for manufacturing modules was set at 220 euro/m^2 (Lawson, 2010). For the prices of lifting and transport, reference is made to a price study on the Dutch modular construction market, set at 300 euro and 500 euro per module respectively (150 km transport distance) (Palaima, 2021).

For the cost of onsite labour, according to McKinsey's report, it is 15%-30% of the total cost of the module (Bertam et al., 2019). However, due to the different connection methods of each option, for example, bolted connection is simpler and less troublesome than welded connection, and welded connection is simpler than wet connection. For options 1, 2, 3 and 4, based on the actual situation, the onsite labour cost is set as 15%, 20%, 15% and 30% of the total module cost respectively.

The initial investment for the different options can be obtained by calculation, as shown in the figure below. The calculation process can be found in Appendix C. As can be seen from the figure, for the same option, type A has a higher investment than type B. This is due to the fact that the larger modular units use more material and have higher manufacturing costs. Option 4, the concrete module, will have a lower initial investment than the other options because concrete is a relatively cheap material.

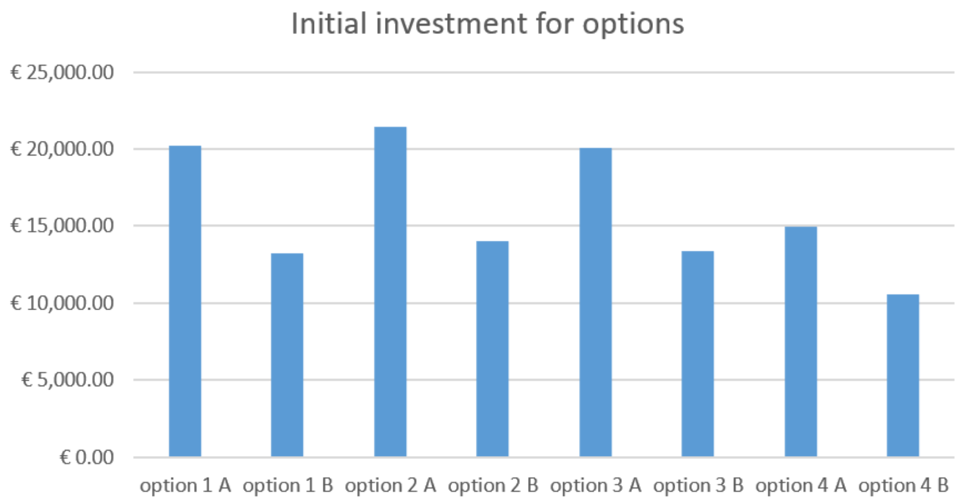


Figure 39. Initial investment for different options

Operation and maintenance costs:

As this study focuses on the structure of the module, which is essentially a non-investment over the life of the building, operation and maintenance costs are not part of the calculation. However, if new calculations are set up in the future taking into account the building's installations, envelope and maintenance plan, then this part could be considered.

Rent:

The income from the rental of the modular rooms is set at 16.9 euro/m^2/month, based on the average rent in the Netherlands in Q3 2022 (Pararius, 2022). So for module type A the rental income for one year is 5962.32 euro and for module type B the rental income for one year is 4076.28 euro.

Demolish cost：

According to the Arcadis report, for a typical project, the cost of disassembly in the Dutch market is typically 33-40 euro/m2 (2020). The difficulty of disassembly varies from one option to another due to the type of modules and connections used, so this cost will be linearly distributed from 33 euro to 40 euro depending on the rating of one aspect of each option's disassembly, as shown in the table below.

	Option 1	**Option 2**	**Option 3**	**Option 4**
Disassembly score	2.73	2.00	3.00	1.0
Demolish cost	34.2 euro/m^2	36.5 euro/m^2	33 euro/m^2	40 euro/m^2

Table 33. Cost for demolish of different options

Residual value：

According to a study (Palaima, 2021), module manufacturers in the Netherlands are willing to take back modules of different lengths of use at a reduced price, they are willing to take back modules at an price of 35% of the initial cost in the 5th year, 20% in the 10th year, 15% in the 15th year and 10% in the 20th year after they have been put into service. After 20 years, the manufacturer will take back the module for the cost of dismantling and transportation. Therefore, in this study, the cost that the manufacturer is willing to pay to recycle the module will be used as the residual value of the module, and its decline curve is shown in the graph below. The value of a module after 20 years of use is equal to the cost of dismantling plus the cost of transportation. If the recovery price of the module in 20 years is less than the cost of dismantling plus the cost of transportation, the latter will be used as the residual value of the module.

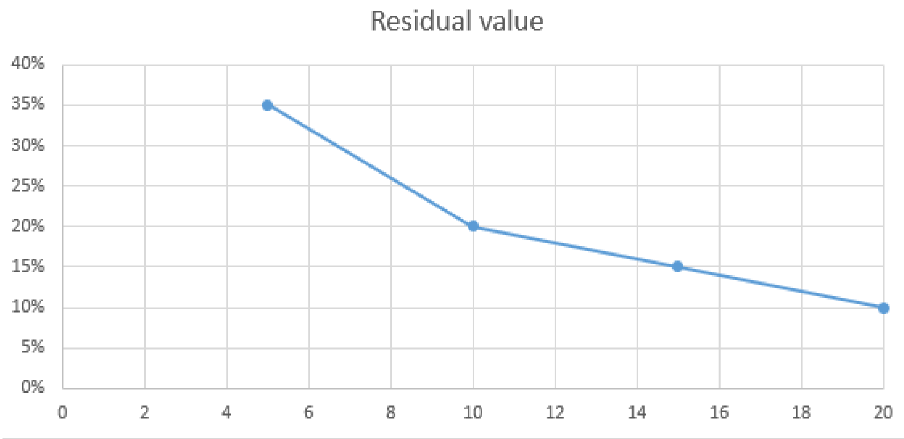


Figure 40. Residual value of the modules

For concrete modules using wet connections, they can only be destructively demolished after the end of the building's service life, and the demolition waste will be landfilled or recycled. So they cannot be reused as modular units or structural elements. Therefore, when considering residual value, the residual value of concrete modules with wet connections is set to 0.

For each option, initial investment, rental income, demolish cost and residual value of the module are considered. For the calculation of the real discount rate, a value of 6.5% is used, which is a common value used in the Dutch real estate market survey (Savills Valuation, 2018). For inflation, a value of 3.3% is used, which is the average inflation figure for the Netherlands from 1961 to 2020 (WorldData, 2022).

4.2.3. Result

In this analysis, each option has two sizes (type A and type B), so a total of 8 scenarios are compared. The NPV calculation starts from the fifth year, since the student residence building is unlikely to be demolished within five years of being put into use, for these 8 scenarios, the NPV for each year from the 5th year to the 30th year of its use is calculated. Numerical results are converted to graphs as follows:

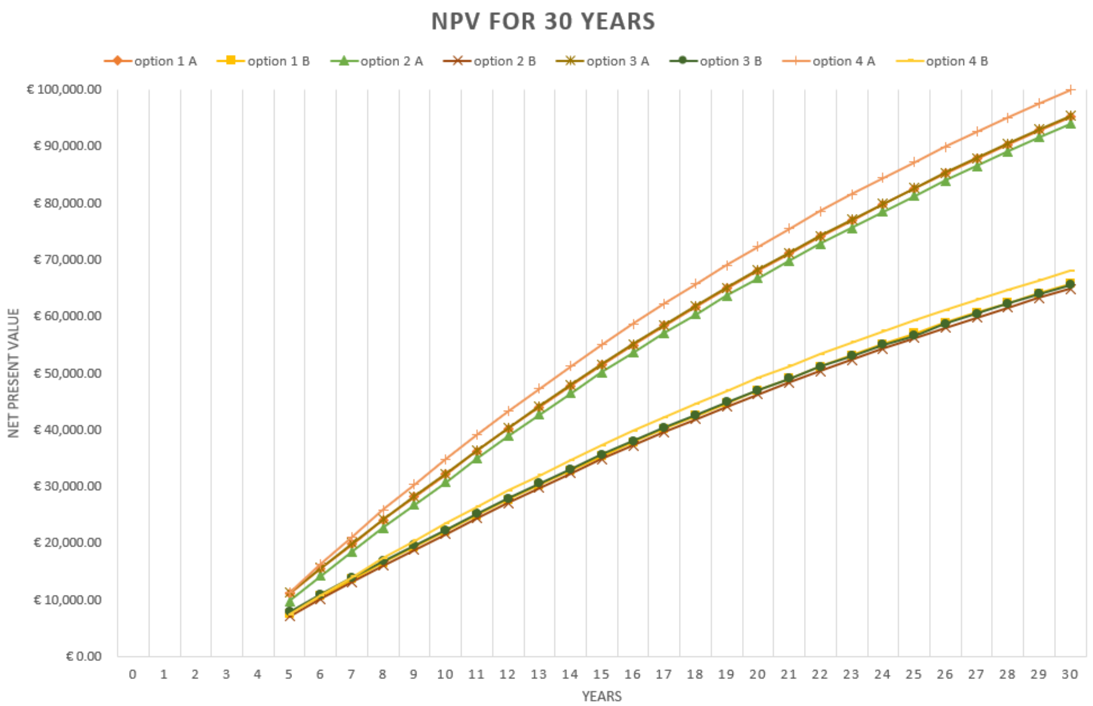


Figure 41. 30-year NPV for the options

The first and easiest thing to see is that for the four types of modules, although the initial investment is higher for the larger modules, the NPV of the larger modules is higher than that of the smaller modules due to the higher rents associated with the larger areas and the higher residual value of the larger modules at the end of their life cycle. As can be seen from the table, the difference between type A and type B is not very large for each option in the fifth year, but as time progresses the difference between them becomes larger and larger. This shows that economically, investing in a larger module can bring better economic returns, despite the fact that it requires more raw materials and production costs.

Although timber and steel modules can be brought back and are easier and cheaper to dismantle, it is still difficult to compete with concrete modules. The high NPV of option 4 is not affected by the fact that the initial investment in concrete modules is less than in other options, despite the fact that the highest demolition costs are paid at the end of the life cycle, and that the economic advantage of option 4 increases over time as the residual value of other options decreases. It can be seen that for projects with a large time horizon, option 4 is a good choice economically, which corresponds to its high score on the strategy of durability.

Option 1 and 3 both have very similar NPVs in type A and B, with the two curves nearly coinciding. For option 2, although it is the same module type as option 1, it has a lower NPV value than option 1 due to the difference in connection type, which will cost more in the installation and removal of the module.

The continuous rise in the curve for each option also shows that although the earlier the project is demolished the more revenue can be gained from the residual value of the modules, this is not significant compared to the rental income and in general the project is more profitable to hold for the long term than to use for the short term and then demolish.

For investors, even though the concrete module option 4 has the lowest MCI score, investors may still prefer option 4 because it is the most profitable. For them, there is little incentive to invest in the significant increase in MCI of options 1 and 3, and they need additional motivation to invest.

4.2.4. Discussion

The reality is that field conditions are always more complex than theoretical calculations and some price factors change from time to time. In this study material prices are used for the month of April 2022, but the actual prices of materials fluctuate. For example, the price of glulam timber remains low at around €400 per m³ in the second half of 2019 and the first half of 2020, but by April 2022 it is €715 per m³, nearly doubling in price. The same applies to steel prices, which are around 50% higher in April 2022 than they will be in 2021. This will result in a change in the cost of investing in wooden and steel modules.

Concrete modules tend to have a greater weight, which will require a higher investment in foundations, which may balance out the cost difference between concrete and timber/steel modules. However, as the cost of foundations is closely related to the local geological conditions of the building and also to the different types of foundations and pile distribution, there is a high degree of uncertainty, so the cost of foundations is not studied in this study. However, in general heavier buildings will result in higher foundation construction costs.
This is a factor that could be considered and calculated in future studies.

In addition, in this calculation, the value taken for the residual value is only a reference to the prevailing buy-back price in the Dutch market, but in fact the residual value of the module will be related to many factors, such as the size of the project, the value taken, the material, structure and maintenance of the module. This can be used as a recommendation for future studies.

4.3. Environmental impact analysis

4.3.1. Introduction

In the previous article, several methods for analysing the circularity of buildings were described. The ECI takes into account the material use of the building and calculates the environmental impact based on the shadow cost of the project. In this study, the method of calculating the environmental impact based on the shadow cost per rental area per year is adopted, which refers to a research report (Weener, 2021). The shadow cost of a material only applies to its product stage, i.e. raw materials, transportation and manufacturing processes are included. The standard value of shadow cost comes from the Nationale Milieudatabase (NMD) database, the calculation process of which can be found in Appendix D.

By dividing the total shadow cost of each module option by the module area and its lifetime, its environmental impact can be obtained. In this study, the score of the module circularity indicator was also included because if a module has a higher MCI score, it means it has better circularity and it is also more likely to have a second life, as show in section 3.3.6. The reuse probability of a module is related to MCI. Therefore, for simplicity, the MCI score is set to be linearly related to the probability of reuse, which means that for a module with an MCI score of 1, the probability of reuse is 0, and a module with a score of 2 has a probability of 0.5 and a score of 3 module with probability 1. In future studies, a more extensive study of the correlation between MCI scores and reuse probability is recommended.

By correlating the MCI score with the probability of the module having a second life span, the environmental impact of each module option can be calculated, with the first life span assumed to be 30 years, by the following formula：

$$Environmental\ impact = \frac{shadow\ cost}{A\ \times (n + 30\ \times reuse\ probability)}$$

where A is the area of the module and n is the first life span. n is capped at 30 years, as a modular product typically has a design life of approximately 60 years. It is also worth noting that since option 4 can only be demolished destructively, its second life span equals to 0.

4.3.2. Result

The MCI score, second life span probability, shadow cost and environmental impact of each module are shown in the table below.

	option 1 A	**option 2 A**	**option 3 A**	**option 4 A**
MCI Score	2.14	1.87	1.96	1.67
Probability	0.57	0.435	0.48	0.335
Shadow cost	€ 280.65	€ 280.65	€ 146.35	€ 458.50
n = 5	€ 0.43	€ 0.53	€ 0.26	€ 3.12
n = 10	€ 0.35	€ 0.41	€ 0.20	€ 1.56
n = 20	€ 0.26	€ 0.29	€ 0.14	€ 0.78
n = 30	€ 0.20	€ 0.22	€ 0.11	€ 0.52

	option 1 B	option 2 B	option 3 B	option 4 B
MCI Score	2.14	1.87	1.96	1.67
Probability	0.57	0.435	0.00	0.00
Shadow cost	€ 160.21	€ 160.21	€ 88.36	€ 314.82
n = 5	€ 0.36	€ 0.44	€ 0.23	€ 3.12
n = 10	€ 0.29	€ 0.35	€ 0.18	€ 1.56
n = 20	€ 0.21	€ 0.24	€ 0.13	€ 0.78
n = 30	€ 0.17	€ 0.19	€ 0.10	€ 0.52

Table 34. Results of environmental impact

It can be seen that since option 3 uses wood, which is considered a sustainable building material, its unit shadow cost is the lowest, so its environmental impact is minimal. Conversely, concrete has the highest environmental impact due to its high shadow cost and only one life span. So despite the economic advantages of concrete modules, if project investors are concerned about the environmental impact of modules, they may not choose this option. For the concrete module using wet connection, although I t cannot be reused, it has very good durability, so the environmental impact can be reduced by extending its first life span. When option 4 in the case has a life span of 60 years, its environmental impact can be reduced by half. This may also answer why concrete modules are chosen for many high-rise projects, since demolition of the building is generally not considered in high-rise projects.

For options 1, 2 and 3, type A, which is a smaller module unit, will have a lower environmental impact. Therefore, when designing, if you want to reduce the environmental impact, choosing a module with a smaller area is a feasible method.

It is also worth comparing between Option 1 and 2. Although they have the same shadow cost, because option 1 has a higher score, it is more likely to be reused, so it can have a lower environmental impact. In this case, modules with higher MCI scores can reduce environmental impact.

4.4. Conclusion

In this chapter, a student housing project in the Netherlands is presented as a case study. For this building, four different modular options are proposed, which have different module types, connection types and loading capacities, and therefore different module circularity indicator (MCI) scores.

By calculating the life cycle costing (LCC) of the project, the net present value (NPV) of each option can be obtained and compared. It can be seen that option 4, the concrete module with the lowest MCI score has the best profit prospects, which shows that higher MCI scores do not lead to better economic returns.

The environmental impact of the different options was also studied and it was found that option 4 has the highest environmental impact due to its high shadow cost, while the timber module option 2 has the lowest environmental impact due to the materials it uses. By comparing the environmental impact of the options with the MCI scores, a relationship was found, with higher scores leading to higher reuse potential, allowing the environmental impact to be reduced. When looking at the economic and environmental aspects, options 1 and 3 are attractive to investors who want to combine profitability with sustainability. These two options also have the first and second highest MCI scores.

For the same option, modules of two sizes have been studied. It is found that the use of larger modules results in higher economic benefits, but also in higher environmental impacts.

As part of its commitment to achieve a fully circular economy by 2050, the Dutch government has set an important medium-term goal to halve the use of key resources by 2030 by retaining existing materials in the economy (Netherlands and you, 2021). The construction industry, and the materials industry that supports it, is one of the world's major users of natural resources and therefore needs to promote ways to maximise the efficient use of resources by using fewer raw materials and less energy (Werf, 2021). Modular buildings have been increasingly promoted and used in recent years due to their advantages. If the characteristics of modular buildings can be exploited to increase the circularity of the modular units, then it can be a good way to reduce the input of new building raw materials and energy, and to reduce waste. For project investors, they usually tend to invest in the option with the largest profit. So if investors are to choose more sustainable options, they may need to be given some incentive. The MCI score can also be used as a basis for government subsidies for modular projects with high circularity.

5. Conclusions and Recommendations

5.1. Conclusions

In section 1.2.2, according to the research background and problem definition, the aim of the research is presented：

"To propose a method for circularity measurement based on the characteristics of modular buildings and modular construction."

This research purpose forms the basis of the main research question, which in turn can be divided into five sub-questions. By answering these five research questions, the answer to the main research question can be get and the research aim is met.

5.1.1. Sub-questions

The sub-questions are answered below:

1. **What are the design strategies for implementing circular economy in the building industry?**

This sub-question is treated in section 2.2. To achieve circular economy in building industry, nine design strategies for circular construction are derived from the literature, which are showed below. The first two design strategies occur during the construction phase, while the middle four design strategies occur during the use phase, and the last three design strategies occur during the end-of-life phase of the building.

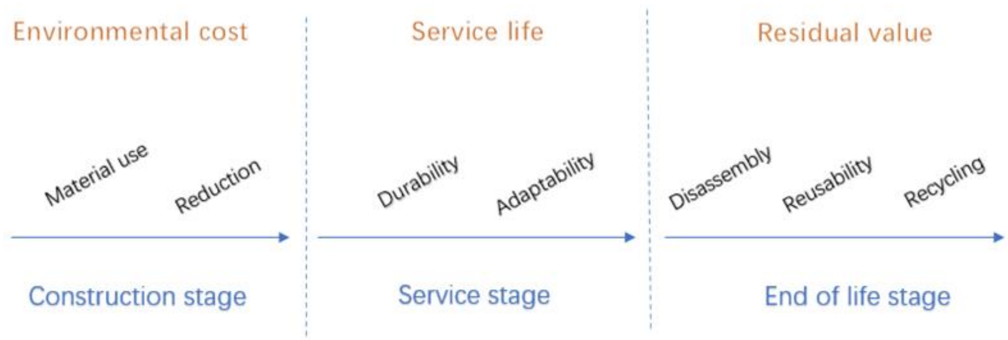


Figure 42. Circular design strategies in different stages of a building.

2. **What are the characteristics of the structure of modular buildings?**

This sub-question is treated in section 2.4. Compared with traditional construction methods, modular buildings have advantages in construction speed and cost. At the same time, the modular building has the characteristics of high standardization and high prefabrication, which makes it have good circular potential. For the structure of the building, it can be divided into core structure, frame structure and self-supporting structure. For the type of modular unit, it can be divided into eight kinds according to its structure and material. As for the connection of the module, it can be divided into intra-module connection, inter-module connection and module to foundation connection according to the scene. The types of connections commonly used in the industry today are summarised and classified.

3. What are the circular design strategies suitable for modular buildings?

This sub-question is treated in section 2.5. By combining the characteristics of modular buildings and from the perspective of reducing the input of materials and resources and reducing waste, four design strategies are selected as suitable for modular buildings, which are design for durability, adaptability, disassembly and reusability. They were the focus strategies of this study.

4. How can the circularity of module units be assessed based on these strategies?

This sub-question is treated in Chapter 3. Structural factors associated with the four circular design strategies were first extracted through the literature and then a questionnaire was conducted to allow respondents to rate the importance of the structural factors under each strategy in order to assign weights to each structure factor. After this, the modular circularity indicator (MCI) can be obtained by the sum of weighted structure factors. This is an indicator for the circularity measurement of modular units in modular construction projects. By analysing and scoring some of the existing modular building projects, it can be known that the MCI scores correspond to reality and to some extent reflect the likelihood of the modules having a second life.

5. What are the economic and environmental impacts of the module's circularity?

This sub-question is treated in Chapter 4. A student housing project in the Netherlands is planned to be built through modular method. By varying the type of modules and connections as well as the load capacity, different modular options can be obtained which have their own MCI scores. Life cycle costing analysis and environmental impact calculations are carried out to investigate the economic and environmental significance of each option. It was found that the MCI does not reflect the economics of the modular units, but rather that a high MCI may lead to an increase in the initial investment in the project. However, there is a positive relationship between MCI and the environmental impact of the modules by relating it to the probability of a second life span.

To achieve circular economy goals in the construction industry, MCI can also be used as an indicator to subsidize highly circular modular buildings to encourage owners to invest in highly sustainable projects. This will allow the modular building industry to move towards more circular projects and reduce the environmental impact of the construction industry.

5.1.2. Main question

The main question of the research reads:

"How can the circularity of module units in a modular construction project be measured from the perspective of structure?"

To answer this question, the Module Circular Indicator (MCI) is designed and proposed. By analysing and scoring the module type, connections and loading capacity of the project, the circularity of a module unit can be presented numerically. Project owners and designers, especially structural engineers, can use this method to evaluate the circularity of modular projects from four circular dimensions. This provides a feasible method for the circularity assessment of modular buildings.

Through case studies, it can be found that projects with high MCI scores cannot bring a better return on investment for investors, but can increase the possibility of modular units being reused to a certain extent, and reduce the environmental impact of the project. If the government wants to encourage investors to invest in more sustainable modular projects, additional subsidies may be required.

5.2. Recommendations

During this research, areas where future studies can take place were found. Firstly, the current economics study is only for a conceptual case study and the various costs used are taken from the literature. However, in the real market the various prices are subject to change at any time, so if subsequent research could be deeply involved in the design, tender or construction process of a modular project, more actual and possibly overlooked cost factors could be documented and obtained.

In this thesis, a linear correspondence is made between MCI and reuse possibilities, as well as some price factors in construction, which is an idealised assumption. In reality the situation will be more complex and subsequent research can analyse these relationships in conjunction with relevant cases to find a more precise relationship between them.

As more and more research and development are carried out on modular construction, more and more module types are emerging, such as those using composite materials, and more and more easy-to-install and dismantle connection methods are being invented. This study only reviews the types of modules and connections that have been commonly used up to now, but in the future more and more new patents will emerge, and the analysis and scoring of these new methods can be used as a complement to the MCI scoring system.

Last but not the least, the study of the circularity of modular construction focuses on its structural perspective. However, in practice, there are many other aspects that affect the circularity and economy of the module, including installations, envelope, fire safety,and foundations. All of which are worthy for future research.

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Appendix A: Sample of questionnaire survey

Introduction:

This questionnaire is part of a study on the circular economy and modular buildings. The aim of the survey is to gain insight into the views of respondents on this topic, to explore the factors that may influence the circularity of modular buildings from the perspective of the building structure and to gauge the importance of these factors. Please answer the questions below and tick the appropriate boxes. Your help will be vital to our research.

1. **What is your profession? Please tick the following options.**
   ☐ Engineer
   ☐ Architect
   ☐ BIM Manager/Engineer
   ☐ Manufacturer/Supplier
   ☐ Academic/Researcher
   ☐ Project Manager
   ☐ Client
   ☐ Contractor
   ☐ Worker
   ☐ Quantity Surveyor
   ☐ Other, please specify:

2. **What institute do you work for?**
   ☐ Consultancy
   ☐ Government Sector
   ☐ Academic/Research Institute
   ☐ Manufacturing/Supply Company
   ☐ Construction Company
   ☐ Developer
   ☐ Architectural Firm
   ☐ Engineering Firm
   ☐ Other, please specify:

3. **How many years of experience do you have in the construction industry?**
   ☐ 1-5 years
   ☐ 5-10 years
   ☐ 10-15 years
   ☐ 15-20 years
   ☐ More than 20 years

4. **How many modular construction (also known as prefabricated prefinished volumetric construction or modular integrated construction) projects have you been involved in?**
   ☐ 0

☐ 1-3
☐ 3-7
☐ 7-10
☐ More than 10

5. **Have much do you know about circular construction?**
☐ Never heard of
☐ Have heard of
☐ Informed
☐ Very well informed

6. **What is your opinion on circular construction (multiple choices)?**
☐ Difficult to achieve
☐ No need to worry about this for now
☐ Not that important
☐ Not sure
☐ Might be useful
☐ Generally necessary
☐ Very necessary
☐ Other, please specify:

7. **Listed below are some factors that can affect the circularity of modular buildings, please rate them on a scale of 1 to 5 according to their importance. 1 (very insignificant), 2 (insignificant), 3 (moderately significant), 4 (significant) and 5 (very significant).**

Sufficient load-bearing capacity of the modular structure.
☐1 ☐2 ☐3 ☐4 ☐5

Robust and durable module-to-module connections.
☐1 ☐2 ☐3 ☐4 ☐5

Easy disassembled connections between modules.
☐1 ☐2 ☐3 ☐4 ☐5

Module-to-module connections that can be easily reused after disassembly.
☐1 ☐2 ☐3 ☐4 ☐5

Robust and durable connections of structural elements within modules (e.g., between beams, columns and load-bearing walls).
☐1 ☐2 ☐3 ☐4 ☐5

Easy disassembled connections of structural elements within modules.
☐1 ☐2 ☐3 ☐4 ☐5

Connection of structural elements within modules that can be easily reused after disassembly.

☐1 ☐2 ☐3 ☐4 ☐5

Robust and durable connections between foundation and modules.

☐1 ☐2 ☐3 ☐4 ☐5

Easy disassembled connections between foundation and modules.

☐1 ☐2 ☐3 ☐4 ☐5

Module-to-foundation connections that can be easily reused after disassembly.

☐1 ☐2 ☐3 ☐4 ☐5

Good openness of the modules to adapt to different needs.

☐1 ☐2 ☐3 ☐4 ☐5

Modules are easily removed from the building.

☐1 ☐2 ☐3 ☐4 ☐5

Robust and durable structure of modules.

☐1 ☐2 ☐3 ☐4 ☐5

The removed modular units are easy to reinstall and reuse.

☐1 ☐2 ☐3 ☐4 ☐5

Easy disassembled structure of the building.

☐1 ☐2 ☐3 ☐4 ☐5

An adaptable building structure that allows for retrofitting, changing building scale and relocation.

☐1 ☐2 ☐3 ☐4 ☐5

8. **In addition to the factors mentioned above, are there any other structural factors that you think should be added? If so, how should they be scored?**

Appendix B: Structure calculation

Below are the calculations
The calculation process for the module structure is shown below. These calculations are used to design the beam and column dimensions of the module to determine the material usage for different options. Section B.1. is an overview of the structural analysis, describing the dimensions of the modules and the various loads that the modules are subjected to. Section B.2. shows the structural analysis of the steel module, that is, option 1 A/B and option 2 A/B. Section B.3. shows the structural analysis of the timing module, that is, option 3 A/B. In this study, the methods of hand calculation and modelling analysis were used for structural calculation. Oasys GAS is used as a professional software for structural analysis, mainly for some structural elements with complex forces that are difficult to calculate by hand. Figure B1 below takes option 1A as an example, showing the name and position of each structure element.

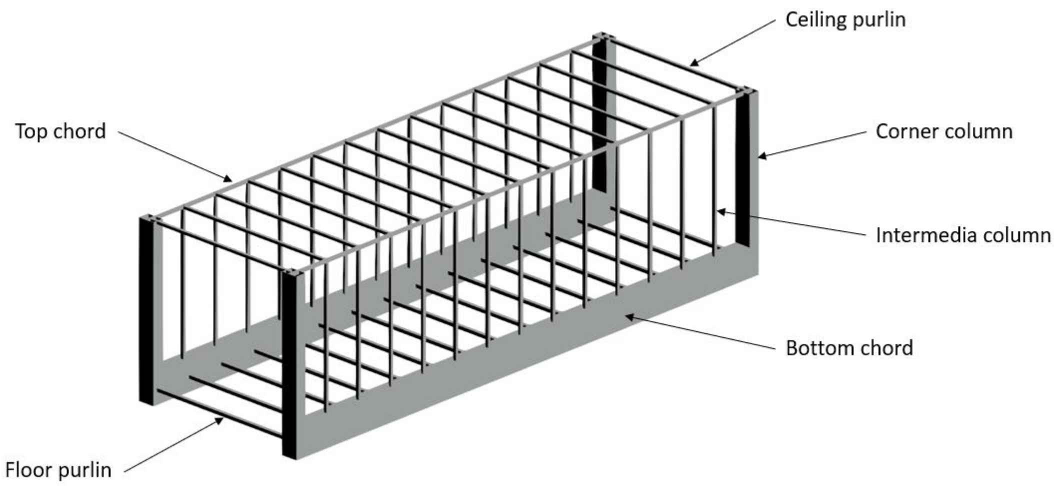

Figure B1. Structural schema of the module

B.1. Overview

Module properties type A		
Module length	L	9.8 m
Module width	W	3 m
Module height	H	3 m
Number of intermedia columns	n_{inter}	13
Number of ceiling purlins	$n_{ceiling}$	15
Number of floor purlins	n_{floor}	15

Module properties type B		
Module length	L	6.7 m

Module width	W	3 m
Module height	H	3 m
Number of intermedia columns	n_{inter}	9
Number of ceiling purlins	$n_{ceiling}$	11
Number of floor purlins	n_{floor}	11

Load		
Permanent floor load	G_k	2 kN/m^2
Variable floor load	Q_k	1.75 kN/m^2
Interior wall load	G_{wall}	0.5 kN/m^2
Façade load	G_{facade}	0.5 kN/m^2
Ceiling load	$G_{ceiling}$	0.5 kN/m^2
Service	$G_{service}$	0.3 kN/m^2
Construction load	$G_{construct}$	1 kN/m^2
Characteristic ceilingr load (SLS)	$G_k + Q_k$	
	$Q_{k,ceiling}$	1.8 kN/m^2
Design ceiling load (ULS)	$1.35 \times G_k + 1.5 \times Q_k$	
	$Q_{d, floor}$	2.58 kN/m^2
Characteristic floor load (SLS)	$G_k + Q_k$	
	$Q_{k, floor}$	3.75 kN/m^2
Design floor load (ULS)	$1.35 \times G_k + 1.5 \times Q_k$	
	$Q_{d, floor}$	5.33 kN/m^2

B.2. Steel module

Steel module is used in option 1 and 2. For module type A and B, due to different force conditions, their bottom chords and corner columns will have different section dimensions.

B.2.1. Ceiling purlin

Beam properties (40 x 40 RHS)		
Span	L	3 m
Depth	h	40 mm
Width	b	40 mm
Thickness	t	3.6 mm
Weight	W	4.00 kg/m
Area	A	510 mm^2
Second moment of y axis	I_y	11.1 cm^4
Plastic modulus of y axis	$W_{pl,y}$	6880 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Steel grade		S275
Class		1

Forces		
Distributed load (ULS)	q	1.81 kN/m
Distributed load (SLS)	q	1.26 kN/m
Design bending moment (ULS)	$M_d = q \times L^2 / 12$	
	1.36 kNm	

Bending	
Bending resistance	$M_{y,Rd} = W_{pl,y} \times f_y$
	1.89 kNm
UC	$UC = M_d / M_{y,Rd}$
	0.72

Deflection	
Maximum deflection	$w_{max} = (q \times L^4) / (384 \times E \times I)$
	11.4 mm
Allowable deflection	$w_{allow} = L / 250$
	12 mm
UC	$UC = w_{max} / w_{allow}$
	0.95

B.2.2. Floor purlin

Beam properties (60 x 60 RHS)		
Span	L	3 m
Depth	h	60 mm
Width	b	60 mm
Thickness	t	3 mm
Weight	W	5.29 kg/m
Area	A	674 mm^2
Second moment of y axis	I_y	36.2 cm^4
Plastic modulus of y axis	$W_{y,pl}$	14300 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Steel grade		S275

Forces		
Distributed load (ULS)	q	3.73 kN/m^2
Distributed load (SLS)	q	2.63 kN/m
Design bending moment (ULS)	$M_d = q \times L^2 / 12$	
	M_d	2.80 kNm

Bending	
Bending resistance	$M_{y,Rd} = W_{pl,y} \times f_y$
	3.93 kNm
UC	$UC = M_d / M_{y,Rd}$
	0.71

Deflection	
Maximum deflection	$w_{max} = (q \times L^4) / (384 \times E \times I)$
	7.30 mm
Allowable deflection	$w_{allow} = L / 250$
	12 mm
UC	$UC = w_{max} / w_{allow}$
	0.61

B.2.3. Top chord

Column properties (40 x 40 RHS)		
Length	L	3 m
Depth	h	40 mm
Width	b	40 mm
Thickness	t	3 mm
Weight	W	3.00 kg/m
Area	A	382 mm^2

Second moment of y axis	I_y	8.8 cm^4
Plastic modulus of y axis	W_y	5310 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Steel grade		S275
Cross-section classification		Class 1

Forces		
Compression force from wind	N_w	3.27 kN

Compression		
Stress	$\sigma_{c,d} = N_w / A$	
	$\sigma_{c,d}$	8.56 MPa
UC	$UC = \sigma_{c.d} / f_{y.d}$	
	0.03	

Buckling under compression		
Buckling length	L_{cr}	300 mm
Elastic critical force	$(\pi^2 \times E \times I)/(L_{cr}^2)$	
	N_{cr}	372.2 kN
Slenderness	$\lambda = \sqrt{(A \times f_y / N_{cr})}$	
	λ	0.53
Buckling curve	a	
Imperfection factor	α	0.21
Factor	$\Phi = 0.5 \times [1 + \alpha \times (\lambda - 0.2) + \lambda^2]$	
	Φ	0.68
Reduction factor	$1 / [\Phi + \sqrt{(\Phi^2 - \lambda^2)}]$	
	χ	0.91
Partial factor	γ_{M1}	1.0
Design buckling resistance	$N_{b,Rd} = \chi \times A \times f_y / \gamma_{M1}$	
	$N_{b,Rd}$	96.04 kN
UC	$UC = N_w / N_{b,Rd}$	
	0.03	

B.2.4. Bottom chord for module type A

Beam properties (400 x 300 RHS)		
Span	L	9.8 m
Depth	h	400 mm
Width	b	300 mm
Thickness	t	14.2 mm
Weight	W	148.37 kg/m
Area	A	18900 mm^2

Second moment of y axis	I_y	4.30E+04 cm^4
Plastic modulus of y axis	$W_{y,el}$	2.58E+06 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Shear modulus	G_k	81000 N/mm^2
Steel grade		S275

Forces		
Imposed point load (intermedia column + floor purlin)	F	45.89 kN/m^2

Elem	Case	Stress Calc. Basis	Pos	A [N/mm²]	Sy [N/mm²]	Sz [N/mm²]	By +ve z [N/mm²]	By -ve z [N/mm²]	Bz +ve y [N/mm²]	Bz -ve y [N/mm²]	C1 [N/mm²]	C2 [N/mm²]
Maxima												
1	A1		1	**0.0**	0.0	-27.62	243.0	-243.1	0.0	0.0	243.0	-243.1
1	A1		1	0.0	**0.0**	-27.62	243.0	-243.1	0.0	0.0	243.0	-243.1
14	A1		14	0.0	0.0	**27.62**	145.8	-145.8	0.0	0.0	145.8	-145.8
1	A1		1	0.0	0.0	-27.62	**243.0**	-243.1	0.0	0.0	243.0	-243.1
7	A1		8	0.0	0.0	-2.124	-123.4	**123.4**	0.0	0.0	123.4	-123.4
1	A1		1	0.0	0.0	-27.62	243.0	-243.1	**0.0**	0.0	243.0	-243.1
1	A1		1	0.0	0.0	-27.62	243.0	-243.1	0.0	**0.0**	243.0	-243.1
1	A1		1	0.0	0.0	-27.62	243.0	-243.1	0.0	0.0	**243.0**	-243.1

Beam stress analysis by Oasys GSA

Bending	
Maixmum stress	243.1 MPa
UC	0.88

Elem	Case	Pos	Ux [mm]	Uy [mm]	Uz [mm]	|U| [mm]	Rxx [rad]	Ryy [rad]	Rzz [rad]	|R| [rad]
Maxima										
1	A1	1	**0.0**	0.0	0.0	0.0	0.0	402.3E-6	0.0	402.3E-6
1	A1	1	0.0	**0.0**	0.0	0.0	0.0	402.3E-6	0.0	402.3E-6
1	A1	1	0.0	0.0	**0.0**	0.0	0.0	402.3E-6	0.0	402.3E-6
7	A1	8	0.0	0.0	-19.39	**19.39**	0.0	30.94E-6	0.0	30.94E-6
1	A1	1	0.0	0.0	0.0	0.0	**0.0**	402.3E-6	0.0	402.3E-6
3	A1	4	0.0	0.0	-9.029	9.029	0.0	**0.006037**	0.0	0.006037
1	A1	1	0.0	0.0	0.0	0.0	0.0	402.3E-6	**0.0**	402.3E-6
3	A1	4	0.0	0.0	-9.029	9.029	0.0	0.006037	0.0	**0.006037**

Beam displacement analysis by Oasys GSA

Deflection under ULS		
Maximum deflection	w_{max}	19.39 mm
Allowable deflection	$w_{allow} = L / 250$	
	w_{allow}	39.2 mm
UC	$UC = w_{max} / w_{allow}$	
	0.50	

B.2.5. Bottom chord for module type B

Beam properties (300 x 200 RHS)		
Span	L	6.7 m
Depth	h	300 mm
Width	b	200 mm
Thickness	t	14.2 mm
Weight	W	103.62 kg/m
Area	A	13200 mm^2
Second moment of y axis	I_y	1.58E+04 cm^4
Section modulus of y axis	$W_{y,el}$	1.30E+06 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Shear modulus	G_k	81000 N/mm^2
Steel grade		S275

Forces		
Imposed point load (intermedia column + floor purlin)	F	45.89 kN/m^2

Elem	Case	Stress Calc. Basis	Pos	A [N/mm^2]	Sy [N/mm^2]	Sz [N/mm^2]	By +ve z [N/mm^2]	By -ve z [N/mm^2]	Bz +ve y [N/mm^2]	Bz -ve y [N/mm^2]	C1 [N/mm^2]	C2 [N/mm^2]
Maxima												
1	A1		11	**0.0**	0.0	-26.07	240.4	-240.4	0.0	0.0	240.4	-240.4
1	A1		11	0.0	**0.0**	-26.07	240.4	-240.4	0.0	0.0	240.4	-240.4
10	A1		5	0.0	0.0	**26.07**	109.3	-109.3	0.0	0.0	109.3	-109.3
1	A1		11	0.0	0.0	-26.07	**240.4**	-240.4	0.0	0.0	240.4	-240.4
5	A1		2	0.0	0.0	-2.897	-123.8	**123.8**	0.0	0.0	123.8	-123.8
1	A1		11	0.0	0.0	-26.07	240.4	-240.4	**0.0**	0.0	240.4	-240.4
1	A1		11	0.0	0.0	-26.07	240.4	-240.4	0.0	**0.0**	240.4	-240.4
1	A1		11	0.0	0.0	-26.07	240.4	-240.4	0.0	0.0	**240.4**	-240.4

Beam stress analysis by Oasys GSA

Bending	
Maixmum stress	240.4 MPa
UC	0.87

Elem	Case	Pos	Ux [mm]	Uy [mm]	Uz [mm]	|U| [mm]	Rxx [rad]	Ryy [rad]	Rzz [rad]	|R| [rad]
Maxima										
1	A1	11	**0.0**	0.0	0.0	0.0	0.0	369.7E-6	0.0	369.7E-6
1	A1	11	0.0	**0.0**	0.0	0.0	0.0	369.7E-6	0.0	369.7E-6
1	A1	11	0.0	0.0	**0.0**	0.0	0.0	369.7E-6	0.0	369.7E-6
5	A1	2	0.0	0.0	-12.04	**12.04**	0.0	41.07E-6	0.0	41.07E-6
1	A1	11	0.0	0.0	0.0	0.0	**0.0**	369.7E-6	0.0	369.7E-6
2	A1	10	0.0	0.0	-5.090	5.090	0.0	**0.005493**	0.0	0.005493
1	A1	11	0.0	0.0	0.0	0.0	0.0	369.7E-6	**0.0**	369.7E-6
2	A1	10	0.0	0.0	-5.090	5.090	0.0	0.005493	0.0	**0.005493**

Beam displacement analysis by Oasys GSA

Deflection under ULS		
Maximum deflection	w_{max}	12.04 mm
Allowable deflection	$w_{allow} = L / 250$	
	w_{allow}	26.8 mm
UC	$UC = w_{max} / w_{allow}$	
	0.45	

B.2.6. Intermedia column

Column properties (40 x 40 RHS)		
Length	L	3 m
Depth	h	40 mm
Width	b	40 mm
Thickness	t	3 mm
Weight	W	3.00 kg/m
Area	A	382 mm^2
Second moment of y axis	I_y	8.8 cm^4
Plastic modulus of y axis	W_y	5310 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Steel grade		S275
Cross-section classification		Class 1

Forces		
Design compressive force (ceiling purlin + interior wall + façade + top chord)	$N_{c,d}$	17.43 kN
Wind load	q_w	1.22 kN/m^2
Design bending moment	M_d	0.91 kNm

Compression		
Stress	$\sigma_{c,d} = N_{c,d} / A$	
	$\sigma_{c,d}$	45.63 MPa
UC	$UC = \sigma_{c.d} / f_{y.d}$	
	0.17	

Bending	
Bending resistance	$M_{y,Rd} = W_{pl,y} \times f_y$
	1.46 kNm
UC	$UC = M_d / M_{y,Rd}$
	0.62

Buckling under bending and compression

Buckling length	L_{cr}	2100 mm
Elastic critical force	$(\pi^2 \times E \times I)/(L_{cr}^2)$	
	N_{cr}	41.36 kN
Slenderness	$\lambda = \sqrt{(A \times f_y / N_{cr})}$	
	λ	1.59
Buckling curve	a	
Imperfection factor	α	0.21
Factor	$\Phi = 0.5 \times [1 + \alpha \times (\lambda - 0.2) + \lambda^2]$	
	Φ	1.92
Reduction factor	$1 / [\Phi + \sqrt{(\Phi^2 - \lambda^2)}]$	
	χ	0.34
Partial factor	γ_{M1}	1.0
Design buckling resistance	$N_{b,Rd} = \chi \times A \times f_y / \gamma_{M1}$	
	$N_{b,Rd}$	35.2 kN
UC	$UC = N_{c,d} / N_{b,Rd} + M_d / M_{y,rd}$	
	0.50	

B.2.7. Corner column for module type A

Column properties (300 x 100 RHS)		
Length	L	3 m
Depth	h	300 mm
Width	b	100 mm
Thickness	t	6.3 mm
Weight	W	37.99 kg/m
Area	A	4840 mm^2
Second moment of y axis	I_y	5111 cm^4
Second moment of z axis	I_z	890 cm^4
Section modulus of z axis	W_z	199000 mm^3
Young's modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2
Shear modulus	G_k	81000 N/mm^2
Steel grade		S275
Cross-section classification		Class 1

Forces		
Design compressive force (upper column + ceiling purlin + interior wall + top chord + facade)	$N_{c,d}$	974.07 kN
Wind load	q_w	2.18 kN/m
Design bending moment	M_d	1.64 kNm

Bending

Stress	$\sigma_{m.d} = M_d / W_z$	
	$\sigma_{m.d}$	8.24
UC	$UC = \sigma_{m.d} / f_{m.d}$	
	0.03	

Compression		
Stress	$\sigma_{c,d} = N_{c,d} / A$	
	$\sigma_{c,d}$	201.25 MPa
UC	$UC = \sigma_{c.d} / f_{y.d}$	
	0.73	

Buckling under bending and compression		
Buckling length	L_{cr}	2100 mm
Elastic critical force	$(\pi^2 \times E \times I)/(L_{cr}^2)$	
	N_{cr}	4182.59 kN
Slenderness	$\lambda = \sqrt{(A \times f_y / N_{cr})}$	
	λ	0.56
Buckling curve	a	
Imperfection factor	α	0.21
Factor	$\Phi = 0.5 \times [1 + \alpha \times (\lambda - 0.2) + \lambda^2]$	
	Φ	0.70
Reduction factor	$1 / [\Phi + \sqrt{(\Phi^2 - \lambda^2)}]$	
	χ	0.90
Partial factor	γ_{M1}	1.0
Design buckling resistance	$N_{b,Rd} = \chi \times A \times f_y / \gamma_{M1}$	
	$N_{b,Rd}$	1202.02 kN
UC	$UC = N_{c,d} / N_{b,Rd} + M_d / M_{y,rd}$	
	0.84	

B.2.8. Corner column for module type B

Column properties (200 x 120 RHS)		
Length	L	3 m
Depth	h	200 mm
Width	b	120 mm
Thickness	t	5 mm
Weight	W	24.10 kg/m
Area	A	3070 mm^2
Second moment of y axis	I_y	1685 cm^4
Second moment of z axis	I_z	762 cm^4
Section modulus of z axis	W_z	144000 mm^3
Young’s modulus	E	210000 N/mm^2
Design yield stress	$f_{y;d}$	275 N/mm^2

Shear modulus	G_k	81000 N/mm^2
Steel grade		S275
Cross-section classification		Class 1

Forces		
Design compressive force (upper column + ceiling purlin + interior wall + top chord + facade)	$N_{c,d}$	679.65 kN
Wind load	q_w	2.18 kN/m^2
Design bending moment	M_d	1.64 kNm

Bending		
Stress	$\sigma_{m.d} = M_d / W_z$	
	$\sigma_{m.d}$	11.39
UC	UC $=\sigma_{m.d} / f_{m.d}$	
	0.04	

Compression		
Stress	$\sigma_{c,d} = N_{c,d} / A$	
	$\sigma_{c,d}$	221.38 MPa
UC	UC $=\sigma_{c.d} / f_{y.d}$	
	0.81	

Buckling		
Buckling length	L_{cr}	2100 mm
Elastic critical force	$(\pi^2 \times E \times I)/(L_{cr}^2)$	
	N_{cr}	3581.05 kN
Slenderness	$\lambda = \sqrt{(A \times f_y / N_{cr})}$	
	λ	0.49
Buckling curve	a	
Imperfection factor	α	0.21
Factor	$\Phi = 0.5 \times [1 + \alpha \times (\lambda - 0.2) + \lambda^2]$	
	Φ	0.65
Reduction factor	$1 / [\Phi + \sqrt{(\Phi^2 - \lambda^2)}]$	
	χ	0.93
Partial factor	γ_{M1}	1.0
Design buckling resistance	$N_{b,Rd} = \chi \times A \times f_y / \gamma_{M1}$	
	$N_{b,Rd}$	784.05 kN
UC	UC $= N_{c,d} / N_{b,Rd} + M_d / M_{y,rd}$	
	0.91	

B.3. Timber module

Timber module is used in option 3. For module type A and B, due to different force conditions, their bottom chords and corner columns will have different section dimensions.

B.3.1. Ceiling purlin

Beam properties (GL32h)		
Span	L	3 m
Spacing	d	0.7m
Depth	H	120 mm
Width	b	55 mm
Area	A	6600 mm^2
Weight	W	3.102 kg/m
Second moment of y axis	I_y	792 cm^4
Second moment of z axis	I_z	166.38 cm^4
Torsional second moment of area	I_t	9.58E+06 mm^4
Section modulus	W_y	1.32E+5 mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Shear strength	$f_{v,k}$	3.8 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	1.1
Deformation factor	K_{def}	0.60
Combination factor	ψ_2	0.30

Design value		
Bending strength	$f_{m,d}$	16.90 N/mm^2
Shear strength	$f_{v,d}$	2.01 N/mm^2

Forces		
Imposed load (ceiling + service)	G_k	0.8 kN/m^2
Variable load (construction)	Q_k	1 kN/m^2
Combination load (ceiling + service + construction)	p_d	2.58 kN/m^2
Design distributed load	q	1.81 kN/m

Design shear load	$V_d = q \times L / 2$
	2.72 kN
Design bending moment	$M_d = q \times L^2 / 8$
	2.04 kNm

Bending	
Bending stress	$\sigma_{m,d} = M_d / W_y$
	15.45 MPa
UC	$\sigma_{m,d} / f_{m,d}$
	0.91

Shear	
Shear stress	$\tau_d = V_d / A$
	0.41 MPa
UC	$\tau_d / f_{v,d}$
	0.20

Lateral torsional buckling	
Effective buckling length	$L_{eff} = 0.9 \times L$
	2.7 m
Critical bending stress	$\sigma_{m,crit} = \pi \times \sqrt{} (E_{0.05} \times I_z \times G_{0.05} \times I_t) / (L_{eff} \times W_y)$
	97.68 MPa
Relative slenderness	$\lambda_{rel,m} = \sqrt{} (f_{m,k} / \sigma_{m,crit})$
	0.42
Critical factor	$K_{crit} = 1$ for $\lambda_{rel,m} < 0.75$
	1
UC	$UC = \sigma_{m,d} / (K_{crit} \times f_{m,d})$
	0.91

Deflection	
Instant deflection permanent	$u_{inst,G} = 5 \times G_k \times d \times L^4 / (384 \times E \times I)$
	5.44 mm
Instant deflection variable	$u_{inst,Q} = 5 \times Q_k \times d \times L^4 / (384 \times E \times I)$
	6.80 mm
Final deflection permanent	$u_{fin,G} = u_{inst,G} \times (1 + k_{def})$
	8.71 mm
Final deflection variable	$u_{fin,Q} = u_{inst,Q} \times (1 + \psi_2 \times k_{def})$
	8.03 mm
Total deflection	$u_{tot} = u_{fin,G} + u_{fin,Q}$
	16.74 mm
Allowable deflection	$u_{allow} = L / 250$
	29.2 mm
UC	$UC = u_{tot} / u_{allow}$

	0.57

B.3.2. Floor purlin

Beam properties (GL32h)		
Span	L	3 m
Spacing	d	0.7m
Depth	H	180 mm
Width	b	55 mm
Area	A	9900 mm^2
Weight	W	4.65 kg/m
Second moment of y axis	I_y	2673 cm^4
Second moment of z axis	I_z	249.56 cm^4
Torsional second moment of area	I_t	2.92E+07 mm^4
Section modulus	W_y	2.97E+5 mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Shear strength	$f_{v,k}$	3.8 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	1.1
Deformation factor	K_{def}	0.60
Combination factor	ψ_2	0.30

Design value		
Bending strength	$f_{m,d}$	16.90 N/mm^2
Shear strength	$f_{v,d}$	2.01 N/mm^2

Forces		
Imposed load	G_k	2 kN/m^2
Variable load	Q_k	1.75 kN/m^2
Combination load	p_d	5.33 kN/m^2
Design distributed load	q	3.73 kN/m
Design shear load	$V_d = q \times L / 2$	
	5.60 kN	
Design bending moment	$M_d = q \times L^2 / 8$	
	4.20 kNm	

Bending	
Bending stress	$\sigma_{m,d} = M_d / W_y$
	14.14 MPa
UC	$\sigma_{m,d} / f_{m,d}$
	0.84

Shear	
Shear stress	$\tau_d = V_d / A$
	0.56 MPa
UC	$\tau_d / f_{v,d}$
	0.28

Lateral torsional buckling	
Effective buckling length	$L_{eff} = 0.9 \times L$
	2.7 m
Critical bending stress	$\sigma_{m,crit} = \pi \times \sqrt{} (E_{0.05} \times I_z \times G_{0.05} \times I_t) / (L_{eff} \times W_y)$
	92.85 MPa
Relative slenderness	$\lambda_{rel,m} = \sqrt{} (f_{m,k} / \sigma_{m,crit})$
	0.43
Critical factor	$K_{crit} = 1$ for $\lambda_{rel,m} < 0.75$
	1
UC	$UC = \sigma_{m,d} / (K_{crit} \times f_{m,d})$
	0.84

Deflection	
Instant deflection permanent	$u_{inst,G} = 5 \times G_k \times l \times L^4 / (384 \times E \times I)$
	4.03 mm
Instant deflection variable	$u_{inst,Q} = 5 \times Q_k \times l \times L^4 / (384 \times E \times I)$
	3.53 mm
Final deflection permanent	$u_{fin,G} = u_{inst,G} \times (1 + k_{def})$
	6.45 mm
Final deflection variable	$u_{fin,Q} = u_{inst,Q} \times (1 + \psi_2 \times k_{def})$
	4.16 mm
Total deflection	$u_{tot} = u_{fin,G} + u_{fin,Q}$
	10.61 mm
Allowable deflection	$u_{allow} = L / 250$
	29.2 mm
UC	$UC = u_{tot} / u_{allow}$
	0.36

B.3.3. Top chord

Beam properties (GL32h)

Span	L	3 m
Spacing	d	0.7 m
Depth	H	110 mm
Width	b	110 mm
Area	A	12100 mm^2
Weight	W	5.69 kg/m
Second moment of y axis	I_y	1220.08 cm^4
Second moment of z axis	I_z	1220.08 cm^4
Torsional second moment of area	I_t	2.44E+07 mm^4
Section modulus of y axis	W_y	2.22E+5 mm^3
Section modulus of z axis	W_z	2.22E+5mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Compressive strength	$f_{c,k}$	29 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	1.1
Deformation factor	K_{def}	0.60

Design value		
Bending strength	$f_{m,d}$	16.90 N/mm^2
Compressive strength	$f_{c,d}$	15.31 N/mm^2

Forces		
Compression force from wind	N_w	3.27 kN

Compression	
Bending stress	$\sigma_{c,d} = N_{c,d} / A$
	0.27 MPa
UC	$\sigma_{c,d} / f_{c,d}$
	0.02

Buckling		
Radius of gyration of y axis	i_y	31.75 mm
Radius of gyration of z axis	i_z	31.75 mm
Slenderness of y axis	λ_y	94.48
Slenderness of z axis	λ_z	94.48
Relative slenderness	$\lambda_{rel,y} = \lambda_y \times \sqrt{} (f_{c,k} / E_{0.05}) / \pi$	

	$\lambda_{rel,y}$	1.54
	$\lambda_{re\ l,z}$	1.54
Straightness factor	β_c	0.10
Buckling factor	$K_y = 0.5 \times (1 + \beta_c \times (\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2)$	
	k_y	1.74
	k_z	1.74
Critical factor	$K_{c,y} = 1 / (k_y + \sqrt{(k_y^2 - \lambda_{rel,y}^2)})$	
	$K_{c,y}$	0.39
	$K_{c,z}$	0.39
UC	$UC = \sigma_{c,d} / (k_{c,y} \times f_{c,d})$	
	0.05	

B.3.4. Bottom chord for module type A

Beam properties (GL32h)		
Span	L	3 m
Spacing	d	0.7m
Depth	H	900 mm
Width	b	300 mm
Area	A	270000 mm^2
Weight	W	126.9 kg/m
Second moment of y axis	I_y	1.82E+06 cm^4
Second moment of z axis	I_z	2.03E+05 cm^4
Torsional second moment of area	I_t	2.02E+10 mm^4
Section modulus	W_y	4.05E+7 mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Shear strength	$f_{v,k}$	3.8 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	0.96
Deformation factor	K_{def}	0.60

Design value		
Bending strength	$f_{m,d}$	14.75 N/mm^2
Shear strength	$f_{v,d}$	1.75 N/mm^2

Forces

Imposed point load (intermedia column + floor purlin)	F	52.82 kN/m^2

Elem	Case	Stress Calc. Basis	Pos	A [N/mm^2]	Sy [N/mm^2]	Sz [N/mm^2]	By +ve z [N/mm^2]	By -ve z [N/mm^2]	Bz +ve y [N/mm^2]	Bz -ve y [N/mm^2]	C1 [N/mm^2]	C2 [N/mm^2]
Maxima												
1	A1		1	**0.0**	0.0	-1.502	14.60	-14.60	0.0	0.0	14.60	-14.60
1	A1		1	0.0	**0.0**	-1.502	14.60	-14.60	0.0	0.0	14.60	-14.60
14	A1		14	0.0	0.0	**1.502**	8.763	-8.763	0.0	0.0	8.763	-8.763
1	A1		1	0.0	0.0	-1.502	**14.60**	-14.60	0.0	0.0	14.60	-14.60
7	A1		8	0.0	0.0	-0.1156	-7.415	**7.415**	0.0	0.0	7.415	-7.415
1	A1		1	0.0	0.0	-1.502	14.60	-14.60	**0.0**	0.0	14.60	-14.60
1	A1		1	0.0	0.0	-1.502	14.60	-14.60	0.0	**0.0**	14.60	-14.60
1	A1		1	0.0	0.0	-1.502	14.60	-14.60	0.0	0.0	**14.60**	-14.60

Beam stress analysis by Oasys GSA

Shear	
Maixmum stress	1.50 MPa
UC	0.86

Bending	
Maixmum stress	14.60 MPa
UC	0.99

Elem	Case	Pos	Ux [mm]	Uy [mm]	Uz [mm]	|U| [mm]	Rxx [rad]	Ryy [rad]	Rzz [rad]	|R| [rad]
Maxima										
1	A1	1	**0.0**	0.0	0.0	0.0	0.0	0.001767	0.0	0.001767
1	A1	1	0.0	**0.0**	0.0	0.0	0.0	0.001767	0.0	0.001767
1	A1	1	0.0	0.0	**0.0**	0.0	0.0	0.001767	0.0	0.001767
7	A1	8	0.0	0.0	-11.81	**11.81**	0.0	135.9E-6	0.0	135.9E-6
1	A1	1	0.0	0.0	0.0	0.0	**0.0**	0.001767	0.0	0.001767
2	A1	3	0.0	0.0	-3.998	3.998	0.0	**0.003536**	0.0	0.003536
1	A1	1	0.0	0.0	0.0	0.0	0.0	0.001767	**0.0**	0.001767
2	A1	3	0.0	0.0	-3.998	3.998	0.0	0.003536	0.0	**0.003536**

Beam displacement analysis by Oasys GSA

Lateral torsional buckling	
Effective buckling length	L_{eff} = 0.9 x L
	8.82 m
Critical bending stress	$\sigma_{m,crit} = \pi \times \sqrt{(E_{0.05} \times I_z \times G_{0.05} \times I_t)} / (L_{eff} \times W_y)$
	156.28 MPa
Relative slenderness	$\lambda_{rel,m} = \sqrt{(f_{m,k} / \sigma_{m,crit})}$
	0.33
Critical factor	K_{crit} = 1 for $\lambda_{rel,m} < 0.75$
	1

UC	UC =$\sigma_{m,d}$ / (K_{crit} x $f_{m,d}$)	
	0.99	

Deflection		
Maximum deflection	w_{max}	11.81 mm
Allowable deflection	w_{allow} = L / 250	
	w_{allow}	39.2 mm
UC	UC = w_{max} / w_{allow}	
	0.30	

B.3.5. Bottom chord for module type B

Beam properties (GL32h)		
Span	L	3 m
Spacing	d	0.7m
Depth	H	650 mm
Width	b	300 mm
Area	A	195000 mm^2
Weight	W	91.65 kg/m
Second moment of y axis	I_y	6.87E+05 cm^4
Second moment of z axis	I_z	1.46E+05 cm^4
Torsional second moment of area	I_t	8.33E+9 mm^4
Section modulus	W_y	2.11E+7 mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Shear strength	$f_{v,k}$	3.8 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	0.99
Deformation factor	K_{def}	0.60

Design value		
Bending strength	$f_{m,d}$	15.21 N/mm^2
Shear strength	$f_{v,d}$	1.81 N/mm^2

Forces		
Imposed point load (intermedia column + floor purlin)	F	52.82 kN/m^2

Elem	Case	Stress Calc. Basis	Pos	A [N/mm²]	Sy [N/mm²]	Sz [N/mm²]	By +ve z [N/mm²]	By -ve z [N/mm²]	Bz +ve y [N/mm²]	Bz -ve y [N/mm²]	C1 [N/mm²]	C2 [N/mm²]
Maxima												
1	A1		11	**0.0**	0.0	-1.463	13.82	-13.82	0.0	0.0	13.82	-13.82
1	A1		11	0.0	**0.0**	-1.463	13.82	-13.82	0.0	0.0	13.82	-13.82
10	A1		5	0.0	0.0	**1.463**	6.282	-6.282	0.0	0.0	6.282	-6.282
1	A1		11	0.0	0.0	-1.463	**13.82**	-13.82	0.0	0.0	13.82	-13.82
5	A1		2	0.0	0.0	-0.1625	-7.120	**7.120**	0.0	0.0	7.120	-7.120
1	A1		11	0.0	0.0	-1.463	13.82	-13.82	**0.0**	0.0	13.82	-13.82
1	A1		11	0.0	0.0	-1.463	13.82	-13.82	0.0	**0.0**	13.82	-13.82
1	A1		11	0.0	0.0	-1.463	13.82	-13.82	0.0	0.0	**13.82**	-13.82

Beam stress analysis by Oasys GSA

Shear	
Maixmum stress	1.46 MPa
UC	0.81

Bending	
Maixmum stress	13.82 MPa
UC	0.91

Lateral torsional buckling	
Effective buckling length	L_{eff} = 0.9 x L
	6.03 m
Critical bending stress	$\sigma_{m,crit} = \pi \times \sqrt{} (E_{0.05} \times I_z \times G_{0.05} \times I_t) / (L_{eff} \times W_y)$
	238.85 MPa
Relative slenderness	$\lambda_{rel,m} = \sqrt{} (f_{m,k} / \sigma_{m,crit})$
	0.27
Critical factor	K_{crit} = 1 for $\lambda_{rel,m} < 0.75$
	1
UC	UC $= \sigma_{m,d} / (K_{crit} \times f_{m,d})$
	0.91

Elem	Case	Pos	Ux [mm]	Uy [mm]	Uz [mm]	|U| [mm]	Rxx [rad]	Ryy [rad]	Rzz [rad]	|R| [rad]
Maxima										
1	A1	11	**0.0**	0.0	0.0	0.0	0.0	0.001721	0.0	0.001721
1	A1	11	0.0	**0.0**	0.0	0.0	0.0	0.001721	0.0	0.001721
1	A1	11	0.0	0.0	**0.0**	0.0	0.0	0.001721	0.0	0.001721
5	A1	2	0.0	0.0	-7.601	**7.601**	0.0	191.2E-6	0.0	191.2E-6
1	A1	11	0.0	0.0	0.0	0.0	**0.0**	0.001721	0.0	0.001721
2	A1	10	0.0	0.0	-3.851	3.851	0.0	**0.003355**	0.0	0.003355
1	A1	11	0.0	0.0	0.0	0.0	0.0	0.001721	**0.0**	0.001721
2	A1	10	0.0	0.0	-3.851	3.851	0.0	0.003355	0.0	**0.003355**

Beam displacement analysis by Oasys GSA

Deflection		
Maximum deflection	w_{max}	7.60 mm
Allowable deflection	w_{allow} = L / 250	
	w_{allow}	26.8 mm
UC	UC = w_{max} / w_{allow}	
	0.28	

B.3.6. Intermedia column

Beam properties (GL32h)		
Span	L	3 m
Spacing	d	0.7 m
Depth	H	110 mm
Width	b	110 mm
Area	A	12100 mm^2
Weight	W	5.69 kg/m
Second moment of y axis	I_y	1220.08 cm^4
Second moment of z axis	I_z	1220.08 cm^4
Torsional second moment of area	I_t	2.44E+07 mm^4
Section modulus of y axis	W_y	2.22E+5 mm^3
Section modulus of z axis	W_z	2.22E+5mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Compressive strength	$f_{c,k}$	29 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	1.1
Deformation factor	K_{def}	0.60

Design value		
Bending strength	$f_{m,d}$	16.90 N/mm^2
Compressive strength	$f_{v,d}$	15.31 N/mm^2

Forces		
Design compressive load (ceiling purlin load + ceiling purlin weight + interior wall + façade load + top chord weight)	$N_{c,d}$	14.76 kN
Wind load	q_w	2.18 kN/m

Design bending moment	$M_d = q \times L^2 / 8$
	2.45 kNm

Compression	
Bending stress	$\sigma_{c,d} = N_{c,d} / A$
	1.22 MPa
UC	$\sigma_{c,d} / f_{c,d}$
	0.08

Bending	
Bending stress	$\sigma_{m,d} = M_d / W_y$
	11.04 MPa
UC	$\sigma_{m,d} / f_{m,d}$
	0.65

Combined bending and compression	
UC	$(\sigma_{c,d} / f_{c,d})$^2 + $(\sigma_{m,d} / f_{m,d})$
	0.66

Buckling		
Radius of gyration of y axis	i_y	31.75 mm
Radius of gyration of z axis	i_z	31.75 mm
Slenderness of y axis	λ_y	94.48
Slenderness of z axis	λ_z	94.48
Relative slenderness	$\lambda_{rel,y} = \lambda_y \times \sqrt{} (f_{c,k} / E_{0.05}) / \pi$	
	$\lambda_{rel,y}$	1.54
	$\lambda_{re\ l,z}$	1.54
Straightness factor	β_c	0.10
Buckling factor	$K_y = 0.5 \times (1 + \beta_c \times (\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2)$	
	k_y	1.74
	k_z	1.74
Critical factor	$K_{c,y} = 1 / (k_y + \sqrt{} (k_y^2 - \lambda_{rel,y}^2))$	
	$K_{c,y}$	0.39
	$K_{c,z}$	0.39
UC	$UC = \sigma_{c,d} / (k_{c,y} \times f_{c,d}) + \sigma_{m,d} / f_{m,d}$	
	0.86	

B.3.7. Corner column for module type A

Beam properties (GL32h)		
Span	L	3 m
Depth	H	300 mm
Width	b	300 mm

Area	A	9.0E+4 mm^2
Weight	W	42.3 kg/m
Second moment of y axis	I_y	6.75E+04 cm^4
Second moment of z axis	I_z	6.75E+04 cm^4
Torsional second moment of area	I_t	1.35E+09 mm^4
Section modulus of y axis	W_y	4.5E+06 mm^3
Section modulus of z axis	W_z	4.5E+06 mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Compressive strength	$f_{c,k}$	29 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	0.98
Deformation factor	K_{def}	0.60

Design value		
Bending strength	$f_{m,d}$	15.05 N/mm^2
Compressive strength	$f_{v,d}$	13.64 N/mm^2

Forces		
Design compressive load (ceiling purlin load + ceiling purlin weight + interior wall + façade load + top chord weight)	$N_{c,d}$	1092.46 kN
Wind load	q_w	2.18 kN/m
Design bending moment	$M_d = q \times L^2 / 8$	
	2.45 kNm	

Compression	
Bending stress	$\sigma_{c,d} = N_{c,d} / A$
	12.14 MPa
UC	$\sigma_{c,d} / f_{c,d}$
	0.89

Bending	
Bending stress	$\sigma_{m,d} = M_d / W_y$
	0.54 MPa
UC	$\sigma_{m,d} / f_{m,d}$
	0.04

Combined bending and compression	
UC	$(\sigma_{c,d} / f_{c,d})$^2 + $(\sigma_{m,d} / f_{m,d})$
	0.83

Buckling		
Radius of gyration of y axis	i_y	86.60 mm
Radius of gyration of z axis	i_z	86.60 mm
Slenderness of y axis	λ_y	34.64
Slenderness of z axis	λ_z	34.64
Relative slenderness	$\lambda_{rel,y} = \lambda_y \times \sqrt{} (f_{c,k} / E_{0.05}) / \pi$	
	$\lambda_{rel,y}$	0.56
	$\lambda_{re\ l,z}$	0.56
Straightness factor	β_c	0.10
Buckling factor	$K_y = 0.5 \times (1 + \beta_c \times (\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2)$	
	k_y	0.67
	k_z	0.67
Critical factor	$K_{c,y} = 1 / (k_y + \sqrt{} (k_y^2 - \lambda_{rel,y}^2))$	
	$K_{c,y}$	0.96
	$K_{c,z}$	0.96
UC	$UC = \sigma_{c,d} / (k_{c,y} \times f_{c,d}) + \sigma_{m,d} / f_{m,d}$	
	0.96	

B.3.8. Corner column for module type B

Beam properties (GL32h)		
Span	L	3 m
Depth	H	250 mm
Width	b	250 mm
Area	A	6.25E+04 mm^2
Weight	W	29.38 kg/m
Second moment of y axis	I_y	3.26E+4 cm^4
Second moment of z axis	I_z	3.26E+4 cm^4
Torsional second moment of area	I_t	6.51E+08 mm^4
Section modulus of y axis	W_y	2.60E+06 mm^3
Section modulus of z axis	W_z	2.60E+06 mm^3
Mean modulus of elasticity	E_{mean}	13700 N/mm^2
5% modulus of elasticity	$E_{0.05}$	11100 N/mm^2
Mean modulus of shear	G_{mean}	850 N/mm^2
5% modulus of shear	$G_{0.05}$	693.75 N/mm^2
Bending strength	$f_{m,k}$	32 N/mm^2
Compressive strength	$f_{c,k}$	29 N/mm^2

Factors		
Partial safety factor	γ_M	1.25
Modification factor	K_{mod}	0.60
Size factor	K_h	1
Deformation factor	K_{def}	0.60

Design value		
Bending strength	$f_{m,d}$	15.36 N/mm^2
Compressive strength	$f_{v,d}$	13.92 N/mm^2

Forces		
Design compressive load (ceiling purlin load + ceiling purlin weight + interior wall + façade load + top chord weight)	$N_{c,d}$	760.84 kN
Wind load	q_w	2.18 kN/m
Design bending moment	$M_d = q \times L^2 / 8$	
	2.45 kNm	

Compression	
Bending stress	$\sigma_{c,d} = N_{c,d} / A$
	12.17 MPa
UC	$\sigma_{c,d} / f_{c,d}$
	0.87

Bending	
Bending stress	$\sigma_{m,d} = M_d / W_y$
	0.94 MPa
UC	$\sigma_{m,d} / f_{m,d}$
	0.06

Combined bending and compression	
UC	$(\sigma_{c,d} / f_{c,d})^2 + (\sigma_{m,d} / f_{m,d})$
	0.83

Buckling		
Radius of gyration of y axis	i_y	72.17 mm
Radius of gyration of z axis	i_z	72.17 mm
Slenderness of y axis	λ_y	41.57
Slenderness of z axis	λ_z	41.57
Relative slenderness	$\lambda_{rel,y} = \lambda_y \times \sqrt{(f_{c,k} / E_{0.05})} / \pi$	
	$\lambda_{rel,y}$	0.68
	$\lambda_{re\ l,z}$	0.68
Straightness factor	β_c	0.10

Buckling factor	$K_y = 0.5 \times (1 + \beta_c \times (\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2)$	
	k_y	0.75
	k_z	0.75
Critical factor	$K_{c,y} = 1 / (k_y + \sqrt{} (k_y^2 - \lambda_{rel,y}^2))$	
	$K_{c,y}$	0.94
	$K_{c,z}$	0.94
UC	$UC = \sigma_{c,d} / (k_{c,y} \times f_{c,d}) + \sigma_{m,d} / f_{m,d}$	
	0.99	

Appendix C: Initial cost of options

The price compositions of each option are shown in the figure below. The price of building materials refers to the price of the European market in April 2022.

	Option 1A	Option 1B	Option 2A	Option 2B	Option 3A	Option 3B	Source
Steel/timber frame	€ 5969.61	€ 3,207.42	€ 5,969.61	€ 3,207.42	€ 5,854.18	€ 3,324.28	MEPS, Timber-online
Gypsum board 16mm*2	€ 1971.07	€ 1,453.25	€ 1,971.07	€ 1,453.25	€ 1,971.07	€ 1,453.25	Debouw-marktshop
Cement bonded board	€ 1026.06	€ 701.49	€ 1,026.06	€ 701.49	€ 1,026.06	€ 701.49	BetonWood
Ribbed decking	€ 650.33	€ 444.61	€ 650.33	€ 444.61	€ 650.33	€ 444.61	Tata Steel
Ribbed cladding	€ 294	€ 200.60	€ 294.00	€ 200.60	€ 293.41	€ 200.60	Cladco
Transportation	€ 500.00	€ 500.00	€ 500.00	€ 500.00	€ 500.00	€ 500.00	(Palaima, 2021)
Lifting	€ 300.00	€ 300.00	€ 300.00	€ 300.00	€ 300.00	€ 300.00	(Palaima, 2021)
Labour	€ 3,031.60	€ 1,981.65	€ 4,294.77	€ 2,807.34	€ 3,011.13	€ 2,002.28	(Bertam et al., 2019)
Manufacturing	€ 6,468.00	€ 4,422.00	€ 6,468.00	€ 4,422.00	€ 6,468.00	€ 4,422.00	(Lawson, 2010)
Total	€ 20,210.67	€ 13,211.03	€ 21,473.84	€ 14,036.72	€ 20,074.17	€ 13,348.50	

	Option 4A	Option 4B	Source
Concrete	€ 1,502.28	€ 1,032.12	Checkatrade
Steel bar	€ 1,694.56	€ 1,157.93	MEPS
Transportation	€ 500.00	€ 500.00	(Palaima, 2021)
Lifting	€ 300.00	€ 300.00	(Palaima, 2021)
Labour	€ 4,484.93	€ 3,176.59	(Bertam et al., 2019)
Manufacturing	€ 6,468.00	€ 4,422.00	(Lawson, 2010)
Total	€ 14,949.77	€ 10,588.65	

Appendix D: Shadow cost of options

The unit shadow cost of different building material can be found from the database by NMD, which are showed below:

Material	Unit price
Steel	€ 0.0353 /kg
Concrete C30/37	€ 40.71 /m^3
Timber GL32h	€ 1.25 /m^3
Gypsum board 16mm	€ 0.384 /m^2
Cement particle board	€ 3.3 /m^2

Therefore, the shadow cost of option1, 2, 3 and 4 are calculated:

	Option 1A	Option 1B	Option 2A	Option 2B	Option 3A	Option 3B
Frame	€ 144.53	€ 77.66	€ 144.53	€ 77.66	€ 10.23	€ 5.81
Gypsum board 16mm*2	€ 81.56	€ 60.13	€ 81.56	€ 60.13	€ 81.56	€ 60.13
Cement bonded board	€ 31.52	€ 6.63	€ 31.52	€ 6.63	€ 31.52	€ 6.63
Ribbed decking	€ 15.88	€ 10.86	€ 15.88	€ 10.86	€ 15.88	€ 10.86
Ribbed cladding	€ 7.16	€ 4.93	€ 7.16	€ 4.93	€ 7.16	€ 4.93
Total	€ 280.65	€ 160.21	€ 280.65	€ 160.21	€ 146.35	€ 88.36

	Option 4A	Option 4B
Concrete	€ 408.02	€ 280.32
Steel bar	€ 50.48	€ 34.49
Total	€ 458.50	€ 314.82

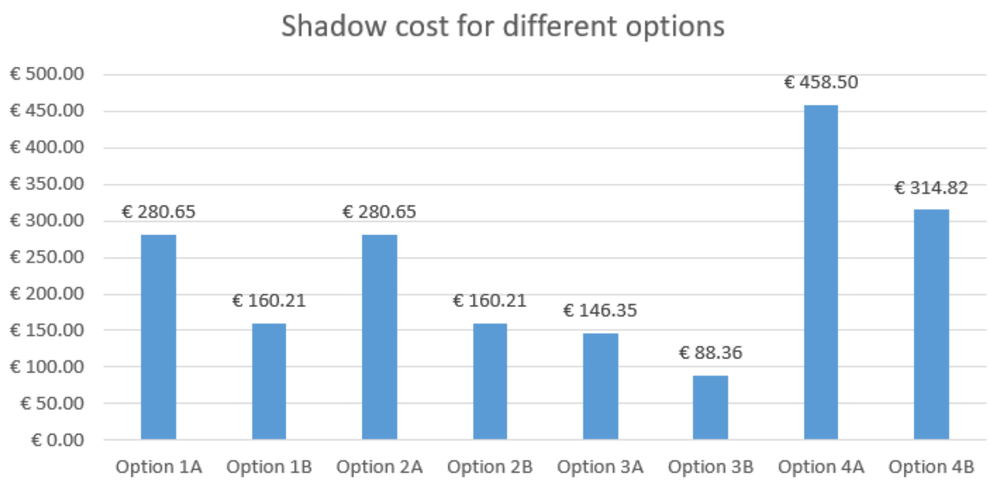

Figure D1. Shadow cost comparison for the options