Modular construction

A post occupancy evaluation informed design to increase the uptake of modular multi-storey student accommodations

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ABSTRACT

Currently the housing market in the Netherlands faces two major challenges. The first challenge is to build one million extra homes before 2030. The building sector cannot keep up with this enormous number of houses that need to be built as they currently build only around 70.000 houses each year (cbs, 2021). The second challenge is the goal of the EU to transition to a climate-neutral society before 2050 (European Union, 2020). Modular building techniques can help solve the housing shortage by increasing the building efficiency and through the decreased need of skilled labour. It can help with reducing the environmental impact of the building sector, because it has many sustainability benefits such as: reduced construction waste, reduced material-use for onsite construction and reusability of the building components. In this research, modular construction will be researched with the focus on finding the current performance of modular student accommodations and proposing solutions for increasing its performance through designing a standard module. This will be done by using the following main question: “What is the current performance of modular multistorey student accommodations in the Netherlands and how can this performance be increased?” For this research an explorative research type will be used, because in this research the performance of modular construction will be explored together with a possible solution to increase this performance. To do this the research method of case study will be used, which expresses itself in the form of in dept interviews and a project case study.

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1. INTRODUCTION

Personal motivation

When I was looking at videos of the Tesla factory and how they were trying to increase productivity with the use of a giga press and automation, I thought why isn't this used more in the building sector. In my opinion when efficiency is increased, the cost of buildings can be decreased and more buildings can be produced, which will help with the rapidly increasing housing prices and the housing shortage. Furthermore, when less materials have to be used for the construction of buildings, the construction process will have less environmental impact, which is a real issue as well. To achieve this industrialisation of the buildings sector just like the Tesla factory, I found the topic of modular construction. When I started looking into modular construction, I discovered the SUM team, which has found a solution to make renovation of tenant flats feasible by renovating them using modular construction. This was so interesting to me that I joined them as construction coordinator for their prototype, to experience the advantages and disadvantages of modular construction in practice and to use this knowledge for my research to modular construction.

Problems

Currently the housing market in the Netherlands faces two major challenges. The first challenge is to build one million extra homes before 2030, to facilitate the population growth that is caused by immigrants, refugees and population increase through birth (CBS, 2020). In 2020 the government of the Netherlands reported that there was a shortage of 331.000 houses (Rijksoverheid, 2020). Besides population growth this shortage is caused by increasing needs due to increased economic welfare, reduced cohabitation, increasing environmental quality norms and increased urbanisation (Delrue, 1969). The building sector cannot keep up with this enormous number of houses that need to be built as they currently build only around 70.000 houses each year (cbs, 2021). They cannot keep up with the housing demand due to: insufficient building plots, labour shortages, building material shortages, an inefficient building process and a lack of political will. The second challenge is the goal of the EU to transition to a climate-neutral society before 2050 (European Union, 2020). Recently the building sector (and many other sectors) were hit hard by the restrictions that were imposed on building projects, due to the stricter nitrogen and PFAS policy (Schouten, 2020). Many projects that had applied for an environmental permit, were denied due to the lack of room that was available for producing nitrogen. This production of nitrogen damages the environment and is unhealthy for people and therefore should be reduced (RIVM, 2020).

How could modularity contribute to solve these problems

According to a report from ABN Amro (2019), modular building techniques can help solve the housing shortage by increasing the building efficiency and through the decreased need of skilled labour. They also state that unmet housing demand and the relative scarcity and cost of construction labour are the main drivers for modular construction to gain traction. Despite that, 83% of the contractors in the Netherlands experience labour shortages (cobouw, 2021) in combination with the apparent housing shortage, only less than 10% of the houses in the Netherlands are being built using modular construction (ABN Amro, 2019). This indicates that there is a real opportunity for the building sector to increase its efficiency through modular construction. The advice from the advice-committee about the nitrogen problems was to reduce the nitrogen production in the building sector though modular-, energy neutral-, circular- and nature inclusive building techniques (Schouten, 2020). Modularity was proposed to decrease the nitrogen production, because it has many sustainability benefits such as: reduced construction waste, reduced material use for onsite construction and reusability of the building components (Paliwal, Choi, Bristow, Chatfield, & Lee, 2021). These sustainability benefits are becoming more and more important as the demand for materials increases drastically, leading to a shortage of materials and price increases (Rijksoverheid, 2021). Companies that anticipate these changes and successfully adopt modular building techniques are better prepared for a future, in which regulations will most likely become more and more strict as the climate goal of 2050 approaches.

Modular construction

Modularity ranges from 1D single elements to 3D volumetric modules that come fully fitted out and ready for assembly on site. Modular construction and prefabrication are often mistakenly used interchangeably as they are both produced offsite and assembled onsite. There is however a difference, because modular construction adds a form of standardisation, which makes industrialisation possible. This research will focus on 3D volumetric modules, because they are the most efficient form of modular construction (Thai, Ngo, & Uy, 2020).

What has been researched
In recent years there have been many papers that looked into the topic of modular construction, because of the potential efficiency increase and positive environmental effect that it has on the construction sector. For example many papers have looked into the advantages of modular construction and found increased construction speed, cost reduction, increased building quality, safer construction process, less waste, reduced transportation, reusability and less noise pollution to be the main advantages (McKinsey, 2019) (Paliwal, Choi, Bristow, Chatfield, & Lee, 2021) (Said, Ali, & Alshehri, 2014) (Lawson, Ogden, & Bergin, 2012) (Thai, Ngo, & Uy, 2020). Other papers looked into the barriers of modular construction and found lack of collaboration, higher building cost, higher upfront cost, misconceptions about modular building, high initial capital to start a modular factory, distance from the factory to the site, transportation, design guidelines and the lack of manufacturers to be the main barriers (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019) (Hsu, Aurisicchio, & Angeloudis, 2019) (Sun, et al., 2020) (Wilson, 2019). Furthermore, research has been done to materials used in modular construction (Lawson, Ogden, & Goodier, 2014) (Liew, Chua, & Dai, 2019), sustainability of modular construction (Lacovidou, Purnell, Tsavdaridis, & Poologanathan, 2021) and the technology behind modular construction (Hou, et al., 2020) (Mills, Grove, & Egan, 2015). Because the uptake of modular construction is still relatively low, knowledge about the barriers and advantages of modular construction and solutions to increase the performance of modular construction are of great importance for the mass adoption of modular construction.

What is still missing in this research
As can be seen in the previous paragraph, the barriers and advantages of modular construction have been thoroughly researched. However, these studies focussed on specific fields in a specific country or they looked at advantages and barriers for modular construction in general. The building sector is strongly local, which means that what is seen in the US as a barrier or advantage can be different in the Netherlands, therefore it is important to find barriers and advantages specific for the Netherlands. Also, the building function is important to specify when researching the barriers and advantages. This is so important, because 3D modular construction is more suited for building types with a lot of repetition and the possibility of preinstalled infill, which differs per building function. Therefore, the difference in building function can have a big impact on the advantages and barriers of modular construction as well. Despite all these studies to the barriers and advantages of modular construction, very little research has been done to find the barriers and advantages of modular student accommodations that are specific to the Netherlands. Furthermore, there is practically no research that has gathered all information about modular construction and used it to design a standard modular unit that can be widely used across multiple projects. This is however very important because in order to increase the uptake of modular construction with all its advantages, people need a design that combines the information from literature and the information that is in the market. This was the result of a survey from the National Institute of Building Sciences (2018) in which they asked different stakeholders what would help with increasing the utilization of off-site construction. This need can also be seen, as for example DUWO is already building modular buildings for quite some time, but they don't have an optimized standard module yet, which could greatly reduce cost, preparation time and chance for failure (M. Jaarsma, personal communication, January 11, 2022). Therefore, this research will contribute to the knowledge base by making a standard module for student accommodations that is based on literature and information from professional stakeholders.

Graduation research
Despite the many advantages of modular construction, the building sector still heavily relies on traditional construction methods, involving timber formwork, scaffolding and in-situ concreting (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). In order to find out how to give modular construction a boost so that it will be more widely adopted, the barriers and advantages will need to be researched and in combination with market information transferred into a design. Therefore, the aim of this paper is to find barriers and advantages for the application of 3D modular construction (through a performance measurement), specific for multistorey student accommodation in the Netherlands, and finding solutions for these barriers through making a design for a standard module. The following main question will be used: "What is the current performance of modular multistorey student accommodations in the Netherlands and how can this performance be increased?"

This research will specifically focus on modular student accommodations in the Netherlands. Student accommodations are ideal for modular construction due to the great level of repeatability that is possible and the room sizes that are compatible with transportation and manufacturing requirements (Lawson, Ogden, & Bergin, 2012). Despite this, only an estimated 30% of the student accommodations that have been built in the past 5 years use modular construction (M. Jaarsma, personal communication, January 11, 2022). Of course, this is already a lot higher than the average of 10% for all buildings in the Netherlands, but it should be more considering the advantages of modular construction and that this function is highly suitable for modular construction. Just like the housing shortage in the Netherlands there is also a student housing shortage, which is estimated at around 26.500 rooms (Rijksoverheid, 2021). Furthermore, the challenge of transitioning to a climate-neutral society before 2050 is applicable to student accommodations as well. These challenges in combination with the suitability of student accommodations for modular construction make student accommodations a great subject for studying how to increase the performance of modular multistorey student accommodations.

To know how to increase the performance of modular buildings, first the current performance needs to be determined. To do this case study projects will be used which include both traditional and modular buildings. The modular buildings will be compared with the traditional building in order to determine the performance of the modular buildings. The buildings that will be used for this case study will all have multiple storeys and will be situated in the Netherlands. These case study projects will be gotten from the Dutch student housing association DUWO at a later moment in time. When the current performance is determined, solutions for solving the issues that come up will be found through a design-based method. This design-based method will consist out of designing a standard module for student accommodations, which is going to be used by DUWO. This is a good tool for finding solutions for the issues, because the researched information can immediately be applied to the design of a module. This will probably make sure that new problems will come up, which normally would not have been found and this will also eliminate combinations of information that are not possible. Furthermore, the design will help with interviews as there is something to talk about, which will give the interviewee something to talk about outside of the prepared questions.

This research will be structured in the following way. First, the term modular construction is going to be defined, which will give more focus to the research. In the second step, a literature review of all barriers and advantages of modular construction is going to be conducted in order to have a better understanding of the barriers and advantages of modular construction in general. The third step is going to measure the current state of modular buildings that have been built by DUWO, which will be compared against the expectations that DUWO has of modular construction. This will result in the performance of modular construction of student accommodations, which will point out some aspects that can be improved. In the last step, solutions will be proposed for the identified needed improvements from step three through conducting interviews with experienced stakeholders in the field of modularity.

2. LITERATURE RESEARCH

2.1 MODULARITY

Table 1: Definitions

Modern method of construction	Broad term for many innovations in the construction industry in general, most of which are offsite technologies. They include modular building, prefabrication, offsite-production, offsite manufacturing and industrialized building. (Rahman, 2014)
Onsite construction	Traditional stick-built construction and in-situ construction that is done on the construction site (Temel & Kahraman, 2018).
Offsite construction	Offsite construction in its broadest terms is the manufacturing of many traditional construction materials away from the construction site, such as bricks, beams, sheets, etc (Gibb A. , 1999). On the other end of the spectrum, it can be the prefabrication of a whole building.
Prefabrication	A form of offsite construction, whereby building parts are generally manufactured in a specialised facility, by combining materials which form a part of the final installation (Gibb A. , 1999).
Modular construction	A form of offsite construction, whereby building elements are prefabricated with the added dimension of interchangeability and standardization to it. This makes mass production possible while allowing a broad variety of products to be made by combining a limited number of building elements (Temel & Kahraman, 2018).
Volumetric	Modules that enclose usable space (Gibb A. , 1999).
Non-volumetric	Modules that do not enclose usable space (Gibb A. , 1999)
Design for manufacture and assembly (DfMA)	Prefab/modular construction

The term modular construction is often used in combination with offsite construction or prefabrication. These three terms can be categorized as Modern Method of Construction (MMC). This MMC focusses on off-site construction techniques which increase efficiency, quality and sustainability. In the paragraphs that follow the definition of modular construction will be elaborately discussed.

To get an idea of what modularity means it is important to look at what the dictionary says about the term modular. According to Cambridge Dictionary (n.d.) modular is defined as “consisting of separate parts that, when combined, form a complete whole”. Merriam-webster (n.d.) defines it as “constructed with standardized units or dimensions for flexibility and variety in use” and Dictionary.com (n.d.) defines it as “composed of standardized units or sections for easy construction or flexible arrangement”. Based on these definitions can be said that modularity involves (1) separate parts and (2) standardization.

The term modular can be used in many different disciplines such as: biology, automotive, computer science and building sector. Therefore, it is important to search in literature what is specifically meant with modularity in the building sector. According to Thai, Ngo & Uy (2020) modularity in construction is closely related to prefabrication, whereby building components are fabricated in a factory and transported to a construction site for installation. They divide prefabrication in three categories, which are: 1D single element, 2D panelised system and 3D volumetric system. This doesn’t mean that modular construction and prefabrication are the same concept as is often illustrated in research papers (Lacovidou et al. (2021). These papers describe modular construction as volumetric units that are fitted out in a factory offsite and are used as structural elements of the building (Lawson, Ogden, & Goodier, 2014) (Said, Ali, & Alshehri, 2014). This definition however has no difference with the definition of prefabrication (table 1), and therefore will not be used in this research. A different definition has been established by Temel & Kahraman (2018) who indicate that modular construction uses prefabrication, but that it adds the dimension of standardization and interchangeability to it. This has many advantages over prefabrication such as: flexibility and the ability to handle the uniqueness of buildings and mass production. This is achieved by combining a limited number of standardized modules into a broad variety of different building designs. In this research the following definition for modular construction will be used: “modular construction involves producing standardized modules of a structure in an offsite factory, after which they are assembled onsite" (McKinsey, 2019). What is still unclear from this definition are the terms modules and standardisation. First the term module will be examined and after that standardization.

Gosling et al. (2016) defined a module as a construction unit that is part of a wider system, which can be integrated through pre-planned interfaces. This unit however can have different levels that vary in measurements, which are according to Gosling et al. (2016) building, elements, components and sub-components. These different levels can be used for both offsite and onsite construction. Examples and definitions of these different levels can be seen in table 2.
Jan Delrue (1969) has done research to the industrialisation of the building sector by designing a modular measurement system. In this research he defines multiple levels of building modules that can be used to make the building process more industrialised and thus more efficient. In contrast to Gosling who defined only 4 levels of building modules, he determined 12 different levels, of which 7 could be used to industrialise the building sector (table 3). Both researchers saw that modularization involves breaking up a system into parts that follow standardized interfaces, rules and specifications (Gosling et al., 2016). The difference between these two researchers is that Jan Delrue made a more specific overview of the parts that a building can be broken up into and Gosling stayed more general. In this research the focus will be specific to entire student studio's that will be modularized, which in turn again are assembled using lower-level modules. Gosling did not make a distinction between modules that enclose multiple spaces and modules that only enclose one space, as he defined both as "elements". Jan Delrue made a differentiation between the two with the terms building cells and building sector cells. Because this research is specific to student studio's, that involve multiple rooms (bathroom, kitchen, living room), it is important to be able to make a differentiation between modules that enclose a single room or multiple rooms. Therefore, the terminology of Jan Delrue will be used in this research. Both researchers defined different levels which can be divided in volumetric and non-volumetric modules (figure 1), which can again be divided in 1D,2D and 3D (da Rocha & Kemmer, 2018). With 3D volumetric modules, up to 95% of the work can be done in the factory, which reduces the assembly time on site (Thai, Ngo, & Uy, 2020). With 2D non-volumetric modules 75% of the work is done in the factory, but still quite a bit of assembly is needed on the construction site (Thai, Ngo, & Uy, 2020). 1D non-volumetric modules can be pre-cut or pre-fabricated in a factory, but most of the assembly work has to happen onsite. If more work is done offsite, more benefits of offsite construction can be achieved. This means that 3D volumetric modules are the most efficient form of modular construction. It has however some disadvantages, which are: size limits due to transportation and low possibility of customization. Also, 2D non-volumetric modules offer far more flexibility than 3D volumetric modules. To fully achieve the benefits of each system, the two systems can be combined into a hybrid version (McKinsey, 2019) (Thai, Ngo, & Uy, 2020), which probably will be used in this research.

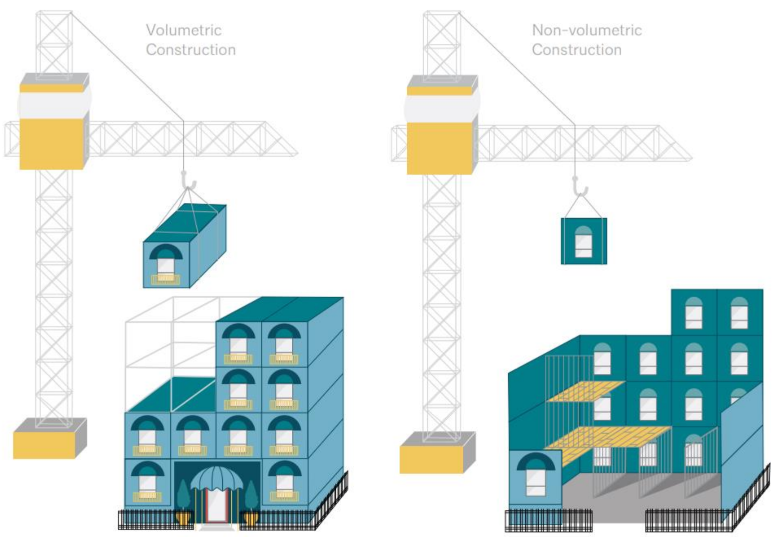


Figure 1: Volumetric and Non-volumetric construction (Wilson, 2019)

Table 2: Different module levels adapted from Gosling et al. (2016)

Level		Definition			Example
4	Building	Entire building is modularized and transported to the site.	Volumetric	3D	Complete house
3	Elements	Large repeatable segments that repeat across a development: they have a structure and can stand alone, and can be the main chunks of which a project is composed. They are connected to a specific function.	Volumetric	3D	Bedroom, bathroom, toilet
2	Components	Fully or partially finished building elements that form part of larger structural elements assembled on site	Non-volumetric	2D	Wall, floor and roof
1	Sub-components	Lowest level, likely to be used by other areas within a building, eighter at the component or element level.	Non-volumetric	1D	Beams and pillars

Table 3: Different module levels adapted from Delrue (1969)

Level		Definition		Example
0	Raw materials	Natural or artificial material that doesn't have a form that has a relation with the to be formed building material.	1D	Iron ore, wood, gravel, cement
1	Building materials	1. Small building materials that due to repetition form building elements 2. Building materials that does not yet have definitive dimensions 3. Building materials that do not have a set length and width, but have a set thickness	1D	Bricks Extrusion profile Wooden sheets
2	Components	At least two dimensions are in relation to a functional or technical activity. The components have a set shape and they determine an activity and not the shape of a room. They are suitable for standardisation.	1D	Doors, kitchen, windows, bath Radiator
3	Elements	Two dimensions determine the shape of a room, third dimension is determined functionally or technologically	2D	Wall
4	Sub-elements	One dimension is related to the room, other two dimensions are determined on lower level (technological or functional)	2D	Ytong
5	Building segments	At least one dimension is determined by the sector and other dimensions are functional or technologically determined. Building segments can realise a building structure and close it off. An entire building cannot consist solely out of building segments.	2D	Beam, tt-floorsegment
6	Building cells	Made through the assembly of building elements. The three dimensions of building cells determine the shape of a room.	3D	Shower cell, sleeping room, kitchen
7	Building sector cells	The three-dimensional building sector cells are the highest possible form of a producible building part. The structure should be independent from the infill or the sector.	3D	3d volumetric unit
8	Building	A whole building that cannot be constructed offsite, due to transportation issues.	3D	

2.2 STUDENT ACCOMMODATION

According to Rijksoverheid (2021), the total amount of students in the year 20-21 that were classified as higher educated (HBO and WO) was 756.900 students. Of these students, 51% lives in student accommodations and 49% still lives with their parents. This amounts to a total of 387.300 student rooms in the Netherland, of which 46% is provided by private parties and 41% is provided by student housing associations. Of these rooms, 52% is a room with shared facilities which averages 17 square meters, 21% is a single room apartment with 24 square meters and 27% is a multiple room apartment that has an average of 69 square meters. On a national level, there is a student accommodation shortage of 26.500 rooms (Rijksoverheid, 2021). Modular construction is very suitable for the construction of student accommodations due to the cellular-type building structure that involves a lot of repetition and where the module size is compatible with the manufacturing and transportation requirements (Lawson, Ogden, & Bergin, 2012). This shows in in the fact that the total share of modular construction is a lot lower (10%) than the share of modular construction in student accommodations (40%) of the past 5 years (M. Jaarsma, personal communication, January 11, 2022). Modular student accommodations started as temporary buildings that would be removed after a few years, but now modular construction is slowly maturing and more and more permanent modular buildings are being built. Figure 2 shows all modular student accommodations of DUWO, in which clearly can be seen that modular construction is moving from temporary constructions to more permanent buildings and that the frequency is increasing. Also, can be seen that for permanent buildings mostly concrete and steel is used or a combination between steel and wood. Also, due to the cellular-type building structure, nearly all modular buildings that have been made by DUWO are made using 3D modular construction.

Modulaire Projecten:

Cplxno	Cplxnaam	Vestiging	Type	Bwjr	Eploitatiehorizon	Einde Expl	WoZ	VHE's
1117	Leeghwaterstraat / Feldmanweg	Delft	Spacebox	2003	Tijdelijk	2016	123	123
1117	Leeghwaterstraat / Feldmanweg	Delft	Prefab Cabin	2003	Tijdelijk	2016	100	100
3201	Verlengde Wassenaarseweg	Oegstgeest	3d mkw (COA)	2005	Tijdelijk	2013	136	544
4605	TT Melaniaweg	Amsterdam	Prefab Cabin	2004	Tijdelijk	2018	77	77
4605	MS Oslofjordweg	Amsterdam	Prefab Cabin	2005	Tijdelijk	2019	303	303
4618	Stavangerweg	Amsterdam	3d mkw (COA)	2006	Tijdelijk	2015	96	380
4620	Zuiderzeeweg 30-40	Amsterdam	3d mkw (COA)	2006	Tijdelijk, nu permanent	2025	51	204
1129	Leeghwaterstraat West	Delft	Ursem m1	2009	Permanent		150	186
2490	Stamkartstraat (LUCTH)	Den Haag	Prefab Cabin	2010	Tijdelijk, nu permanent		122	122
3265	Hildebrandpad	Leiden	Ursum m2	2011	Permanent		504	504
4724	Uilenstede Oost 2	Amstelveen	Ursum m2	2014	Permanent		233	233
4646	Darlingstraat (Spinoza Campus)	Amsterdam	Prefab Cabin	2015	Tijdelijk	2030	550	550
4643	Dennerodepad (Spinoza Campus)	Amsterdam	Prefab Cabin	2012	Tijdelijk	2027	700	700
X-it	Laan van Spartaan	Amsterdam	Ursum m3	2018	Permanent		347	347
2000	Waldorpstraat	Den Haag	Ursum m3	2023	Permanent		408	408
1143	TU Midden-Noord (veld 2, B vd Polweg)	Delft	Jan Snel	2023	Permanent		136	136
4000	Wisselweg	Almere	Ursum m3	2023	Permanent		400	408

Kenmerken

Prefab Cabin (Plegt Vos)	Betonnen vloer met stalen frame. Look & stapeltechniek van zeecontainers. Maatvoering cfm BB
3d mkw (COA)	Woningen voor 4 studenten opgebouwd uit 2d of 3d HSB (diverse fabrikanten, meeste 3D Ursem)
Ursem m1	Betonnen vloer met HSB opbouw, in stalen draagconstuctie
Ursem m2	Betonnen vloer met HSB opbouw in stalen frame, koud gestapeld tot 8 lagen, daarboven frame
Ursem m3	Betonnen vloer met betonnen schijven, koud gestapeld tot 20 lagen

Figure 2: Modular projects built by DUWO

2.3 CURRENT PERFORMANCE OF MODULAR CONSTRUCTION

As described in the previous paragraph modular construction is gradually being used more often. In the past there have however been some reports that modular construction lacks performance. A google search and post occupancy evaluations show that overheating of the building has been an issue, due to a lack of cooling systems (Woo, 2017). Furthermore, fire safety has also been a challenge, due to the connections of modules that are difficult to make fireproof and to keep the possibility of disassembly (M. Jaarsma, personal communication, January 11, 2022). Lastly the structural safety of modular buildings has been questioned when the 22-storey prefabricated Ronan Point block collapse in 1968 in East London. This is however a long time ago and modular buildings have proven to be very safe and reliable even in earthquake-prone regions (Mills, Grove, & Egan, 2015). All these performance issues that were mentioned were focussed on the physical performance of the building. In the next part the performance expectations by stakeholders will be elaborated upon. Gibb and Isack (2003) have done research to find the expectations of different stakeholders when it comes to pre-assembly. This study is however quite old and pre-assembly does not only involve modular construction as it also looks at pre-fabrication in general. They found that stakeholders expected the following benefits of pre-assembly: time reduction, increased quality, decreased cost for repeat-order clients, increased productivity, fewer people on-site. A survey from the National Institute of Building Sciences (2018) confirmed these positive expectations of modular construction. Next to the expected advantages, Gibb and Isack found that stakeholders expected the following disadvantages of pre-assembly: possibility of late deliveries, possibility that it is more expensive, poor supply base, lack of customer focus throughout the supply chain, supply chain not able to respond to the challenges offered and high required volume. The survey from the National Institute of Building Sciences (2018) also found that issues with the supply chain and transportation are expected disadvantages, but they add the need for a clear program requirement, the construction culture and no possibility of late design changes to the expected disadvantages.

2.4 INCREASING PERFORMANCE

In order to achieve the most out of modular construction, repetition of components and thus standardisation should be implemented in buildings well beyond individual large projects (McKinsey, 2019b.). The question however is, to what extent should standardisation be implemented in the manufacturing of the modules? Delrue (1969) made a differentiation between open industrialisation and closed industrialisation for the building sector. With open industrialisation, he meant the use of standardised components with which a gamma of different buildings and building functions can be constructed. To achieve this, a common measurement system is of great importance together with common connections and quality. With measurement system, an addition of a standard size is meant, for example with prefab concrete floors it is common to use 900mm as a standard size, which produces 5600, 6500,7400 etc. When this kind of standardisation would be possible to realize, manufacturers can have a very large market reach, which allows them to specialise and achieve economies of scale. This has the advantage of lowered production cost and due to pre-order manufacturing the market cycle risk is reduced. With closed industrialisation, a manufactured component should as well be standardized in measurement system, connection and quality, but this standardisation will be specific for a building function. The aim should be to reach open industrialisation in the building sector, because with this broad form of standardisation, more advantages of modular construction can be achieved, which will move more stakeholders to use modular construction. Most of the advantages of modular construction come from economies of scale, which reduces cost and increases efficiency through spreading of fixed cost, specialisation, low inventory ratio and more effective use of buildings and machinery (Besanko, Dranove, Shanley, & Schaefer, 2007). To achieve this, the mindset of the construction industry should shift from a focus on unique one-of-a-kind project to a more standardized approach (Aapaoja & Haapasalo, 2014). This doesn't mean that all buildings will be the same, but that a number of standard modules can be mixed and matched to build custom designs. This is also called mass customization, which combines the flexibility and personalization of custom-made products with the low unit cost of mass production.

In order to design for mass production, flexibility should be incorporated in the 3D modules, because this will ensure the interchangeability of modules and a longer building lifetime. The building lifetime can be split in two kinds, which is technical and functional building lifetime (Delrue, 1969). The technical lifetime is how long the building can physically stand and be used, which ranges between 50 and 100 years. The technical lifetime of a building depends on the used building materials and de quality of the construction. The functional lifetime however is much shorter, and depending on the function ranges between 5 and 20 years. The functional lifetime is the time that the infill of a building is useful. For dwellings this functional lifetime is the same as the duration of a specific family situation, which is about 20 years. As can be seen, technical and functional lifetime are not the same in length, which means that before a building has to be demolished due to technical failure it already becomes obsolete, because the building use has changed. Flexibility in a building can be defined as the ability to change the infill without making changes to the structure of the building (Delrue, 1969). Therefore, to solve the problem of different technological and functional lifetimes, the infill of a building should be made flexible. In the book "de dragers en de mensen" J. Habraken separates a building in two categories, which are the support and the infill (Havik & Teerds, n.d.). With the support of the building, he means the communal spaces (entrances, corridors, stairwells, meeting spaces, facade), which are the job of the architect to design so that people will cherish them. The infill are the private spaces of the building users, which he thinks should not be designed in detail by the architect, but the architect should provide a framework/context in which the users can define the infill. Through this way of thinking he introduces the separation of control and the time dimension into the design. This time dimension is important, because people and building-use (functional lifetime) change over time and therefore the infill should be designed with optimal flexibility in mind (Havik & Teerds, n.d.). This concept can be applied to modular construction, by making a most basic 3D volumetric module that only uses structural elements. This module should be corner-post bearing and not wall-bearing, meaning that the module will transfer lateral loads through horizontal beams into the corner columns. This way the module consists only out of columns and beams which ensures maximum flexibility. This basic module should act as a framework in which 2D standardized non-volumetric modules can be placed according to the need of the client. Geraedts (2008) identified four key performance indicators (KPI's) for flexibility, which are: partitionability, adaptability, extendibility and multifunctionality. These four KPI's are achieved through the above-described 3D volumetric module, because the building made from these modules can be adapted by adding or subtracting modules, which makes it possible to easily change the function of the building. This shows that a building using 3D volumetric modules can be flexible, custom designed and efficient to produce. In this research I will try to apply this way of incorporating flexibility in the design that will be made.

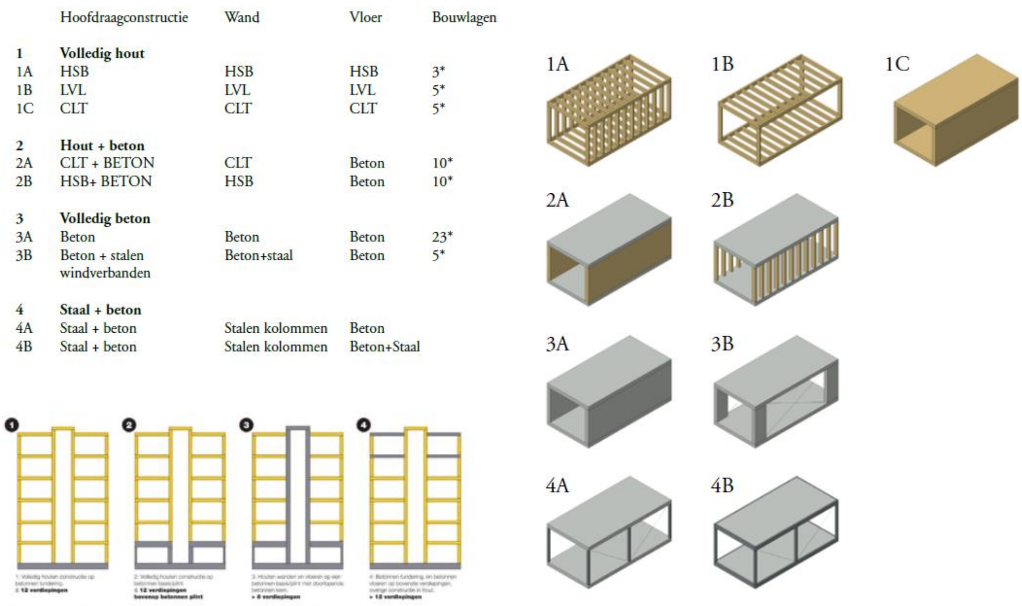
2.5 MODULE LIFESPAN

Next, it is important to look at the use-time of the modules. 3D volumetric units can range from permanent to temporary in use case. 3D volumetric modules have been used regularly to construct temporary buildings, due to the possibility of easy reuse and the quick assembly time on site. These modules can be used for all kinds of building functions, to temporarily fill the need for shelter until something more permanent is built. These temporary buildings are suitable for a shorter time period such as months or a few years. Because they are of temporary nature, the modules don't need to adhere to all building rules that are defined in the bouwbesluit, but have separate rules with lower standards. According to the bouwbesluit a temporary building is a building that will be in one place for maximum of 15 years (Rijksoverheid, n.d.). Because these buildings can easily be relocated or extended, they are not fastened to a foundation. This together with the short use time can be seen as the main criteria to differentiate permanent and temporary construction. Because the temporary modules need to be reused in different locations and for different functions, the modules are very much standardized in the sense that aesthetic aspects are turned down to a minimum (D. Kosterman, personal communication, October 18, 2021). The next step in use-time is semi-permanent modules, which are usually used for a few years up to the maximum of 15 years that is defined in the bouwbesluit. With these modules a more custom design is possible such as differentiating in sizes and finishes, but the general detailing will be the same. The last step in the use-time spectrum is the permanent modules. These permanent modules adhere to the requirements of a permanent building, which make that they can provide a higher acoustic, thermal and visual comfort as well as better air quality. Also, more design variations can be made due to the expected long use-time and thus longer time to get returns on the building. For this research a combination between semi-permanent and permanent modules will be used. From the semi-permanent modules, the standardisation aspect will be used, which is beneficial for the efficiency of the construction process, however the high comfort standards that are defined in the bouwbesluit will be used from the permanent modules. This is very important, because in order for modular buildings to be attractive, they have to perform the same or better than traditional buildings. Furthermore, the modules will have to be able to be used permanently and therefore they will have to be attached to a permanent foundation.

2.6 MULTI-STOREY

The material that can be used for the 3D volumetric basic module depends mostly on the height of the building (Thai, Ngo, & Uy, 2020). This means that wood, steel or concrete can be used. Material choices have impact on the reusability, cost, transportation, environmental impact etc. For example, concrete weight more than wood and the weight of the module has great impact on the transportation cost, because the cost of the tower crane can increase by up to 60% if the module weighs more than 20 tonnes (McKinsey, 2019). Therefore, it is important to specify that this research will look at multi-storey student accommodations with at least five floors. Furthermore, with tall buildings comes a lot of repeatability, which is favourable for modular construction. To maximize flexibility, the structure of the module should be made as slender as possible (Liew, Chua, & Dai, 2019). Therefore, wood is not a good option because of its very low vertical and horizontal loading capacity. Concrete has a very high vertical loading capacity, but a low horizontal loading capacity, which also makes it not suitable for the basic module. Steel is a better option, because it has a high strength-to-weight ratio and a good vertical and horizontal loading capacity. This means that beams and columns can be made very slender. The problem however with steel is that it is not fire-resistant or sound proof, like concrete. To combine the advantages of both steel and concrete it is possible to use a steel-concrete composite (SCC) structural system that combines the use of concrete and steel (Liew, Chua, & Dai, 2019). This system is flexible, adaptable and has the capacity for dismantling and reuse (Ahmed & Tsavdaridis, 2019). To make sure the building has good acoustics, the floors that are in the modules should be made from concrete. In figure 3 an overview can be seen of all possible materials of which a module can be made, including their height restrictions.

In order to deal with lateral forces, depending on the hight of the building a pre-made core can ensure the stability of the building (Mills, Grove, & Egan, 2015). The modules should be connected to the core and they should be connected among themselves. This connection system should facilitate disassembly, so that the individual modules can be reused at the end of the building life. For building that are not higher than six storeys, the modules can be designed as self-stable, which means that they will be able to withstand lateral forces and no stability core is needed. Furthermore, to make sure the building is structurally safe, all modules need to be able to resist vertical loading over the full height of the building.



	Hoofddraagconstructie	Wand	Vloer	Bouwlagen
1	**Volledig hout**			
1A	HSB	HSB	HSB	3*
1B	LVL	LVL	LVL	5*
1C	CLT	CLT	CLT	5*
2	**Hout + beton**			
2A	CLT + BETON	CLT	Beton	10*
2B	HSB+ BETON	HSB	Beton	10*
3	**Volledig beton**			
3A	Beton	Beton	Beton	23*
3B	Beton + stalen windverbanden	Beton+staal	Beton	5*
4	**Staal + beton**			
4A	Staal + beton	Stalen kolommen	Beton	
4B	Staal + beton	Stalen kolommen	Beton+Staal	

Figure 3: Overview of different material combinations in modules adapted from Studio9dots

2.7 ADVANTAGES OF MODULAR CONSTRUCTION

Now that the definition of modular construction is clear it is important to look at the incentives for implementing modular construction:

1. Based on an interview that was conducted with the modular manufacturer JanSnel (annex 1) and literature review, the main incentive for building owners/investors/developers is the increased revenue that can be achieved due to shorter construction time. With 3D modular construction, the lead time of a construction project can be reduced by up to 50% due to the possibility of fast-tracking (Said, Ali, & Alshehri, 2014) (McKinsey, 2019). This means that parts of the building can be worked on simultaneously such as the foundation and the 3D modules, which shortens the lead time of the construction. Because of this reduced construction time, the building will be sooner ready for the owner to rent out or use themselves. This means that the owner can sooner start earning rent money from the project, which can add up to be a significant sum on a project that would normally take two years to construct.
2. Another incentive that has been growing in significance in the past several years is the sustainability aspect of modular construction. 3D modular construction provides the ability of relatively easy reuse of modules and materials (Thai, Ngo, & Uy, 2020). Currently the construction industry is responsible for the consumption of about 40-60% of the total raw materials (Paliwal, Choi, Bristow, Chatfield, & Lee, 2021), which can be greatly reduced in the future when reusing modular buildings. Another advantage of reusability is reduced lifecycle cost of a building due to the ability to sell building parts when the building is at its end of life. This easy reuse is possible because no wet connections are needed for the connection of the modules, which makes it possible to disassemble the building and retrieve the modules. The possibility to disassemble a building also gives the opportunity to easily, quickly and inexpensively accommodate change (Slaughter, 2011). This way a building that has become obsolete can be changed to fit another function that is needed more. This can improve the value of the building for the owner and reduce disruption and downtime for the occupants. Also, due to modular construction, construction waste can be reduced by up to 70% (Lawson, Ogden, & Bergin, 2012). Because waste has a high environmental impact and construction processes are responsible for 30-40% of all waste generation, modular construction can make a real difference. This waste is reduced because of the possibility of reuse, which enables disassembly of buildings instead of demolition and because precise ordering is possible in the factory. The reusability aspect of modular construction will become more and more important as we come closer to 2050 at which point the construction of buildings needs to be a 100% circular (European Union, 2020).
3. The last big incentive for using modular construction is the reduced need of traditional trade labour (Pan & Hon, 2020) (Lawson, Ogden, & Goodier, 2014). Currently 83% of the contractors in the Netherlands experience labour shortages (cobouw, 2021). This is caused by the fact that more construction workers leave than join. A cause of this is that people these days rather do a less labour-intensive job and don't like to work outside in different kind of weather conditions. Modular construction can solve this by offering a nice indoor work environment. Also, because standardization of the production process is possible, less skilled workers can be used in the construction process of the 3D modules. This means that a different pool of people can be accessed that normally would not want or be able to join the construction sector (McKinsey, 2019). Onsite assembly of the modules requires significantly less workers than would have been needed for traditional construction. This together with the increased efficiency and less downtime that can be achieved in the factory will ensure that less construction workers are needed for the construction of a modular building than for a traditional building (McKinsey, 2019). On top of this, automation is possible in the factory, which means that robots can do the heavy or repetitive jobs. This is not yet implemented in many factories, because manufacturers don't feel secure for their return on investment due to the low levels of adoption of modular construction (Lacovidou et al. (2021). Once adoption of modular construction increases more manufacturers will invest in robotic systems that reduce the need for manual labour and can decrease the price of modular construction (Mckinsey, 2018). An added advantage of automation is that robots can do the heavy physical works while the worker only needs to assist the robot and help it when it gets stuck, which is good for the health of the worker (Mckinsey, 2018).
4. According to McKinsey (2019) cost savings can be as much as 24% using volumetric modules and 17% using panelised systems compared to traditional building. However, Sun et al. (2020) found that due to the increased capital cost and the immature modular market that the cost of a modular building is higher than that of a conventional building. The possibility of construction cost saving is mainly

achievable (at this time) for buildings that have the highest proportion of labour-intensive activities and the greatest levels of repeatability. This means cost savings cannot always be realized and depend on the country and building function.

5. Another positive side effect is the increased building quality, which can have a significant impact on the performance of the building resulting in reduced energy use (McKinsey, 2019). This is possible due to the tighter tolerances of joints that can be achieved in a factory, resulting in better air tightness and thus better thermal performance (Lawson, Ogden, & Bergin, 2012). Also, the acoustic quality of the building is greatly improved due to the double layer construction (Lawson, Ogden, & Bergin, 2012).
6. Furthermore, modular construction offers a safer construction process, due to the construction process mostly taking place in the secure environment of a factory, which reduces the risk of construction accidents (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). Also, the safety on the construction site is increased because less hoists are needed, which reduces the chance of something falling on pedestrians as well as on construction workers (McKinsey, 2019).
7. Due to modular construction delivery vehicle visits can be reduced by up to 70% (Lawson, Ogden, & Bergin, 2012). This is because the bulk of the deliveries are moved to the factory, where each visit can be used to deliver more material than could be delivered to the construction site. According to modular manufacturer van Wijnen (2020), up to 49% less lorries are needed to bring materials to the construction site when using modular construction. This is very beneficial for inner-city building sites, as there is less disturbance for traffic and neighbouring properties when there are less lorries going to the construction site.
8. In combination with the reduced disturbance of less transportation, neighbouring buildings are not affected as much when using modular construction, due to reduced noise and disruptions coupled with a shorter construction time (Lawson, Ogden, & Bergin, 2012).

A remark has to be made that to reach the full extent of these advantages, experience and design for economies of scale are of great importance (McKinsey, 2019b.). This was discovered through a survey that was done in Las Vegas, which shows that there is a big difference between experienced and inexperienced stakeholders when it comes to the perceived and achieved benefits of modular construction (Paliwal, Choi, Bristow, Chatfield, & Lee, 2021). The experienced stakeholders expected to have more advantages from modular construction and also actually achieved these benefits. The inexperienced stakeholders however expected less advantages and also achieved less of the benefits. From this can be concluded that knowledge about, and experience with modular construction is of paramount importance for the success of modular construction. Furthermore, to achieve the full potential of these advantages, the involved stakeholders need to communicate very well and repetition should be implemented well beyond individual large projects (McKinsey, 2019b.).

2.8 BARRIERS THAT HINDER MODULAR CONSTRUCTION

Despite the many advantages that modular construction offers, adoption has been low. This is because the construction industry is unfamiliar and not confident with implementing modular construction due to the following barriers:

1. Lack of collaboration and coordination between the different involved parties (client, architect, contractor, manufacturer) is according to a study done by Sun et al. (2020) the number one barrier for modular construction. Unlike other sectors that accepted innovations very well, the construction sector has historically failed to sustain innovation long enough so that it can harness the benefits of it (Murphy, Perera, & Heaney, 2015). One of the main reasons for this, is the separation of the design and construction stages that is applied in the traditional design-bid-built delivery model. This traditional delivery model is linear, meaning that first the design is made and once the design is finished the contractor is involved, leading to poor communication between stakeholders. Because of this separation, new technology and building methods that are adopted during the design phase struggle to survive during the construction phase. Innovation is an iterative process, which requires a lot of flexibility and good communication. Modular construction using volumetric units is a relatively new innovation in the building sector and therefore requires flexibility and good communication in the building process. This makes that the traditional delivery model is not suitable for the construction of modular buildings (Wilson, 2019). Better delivery models for modular construction are design/build and integrated project delivery (Wilson, 2019). These delivery methods ensure collaboration and trust through involving the contractor and manufacturer early in the design phase. This will make the design a lot more efficient, as the manufacturer and contractor can give feedback on the design, explain constraints imposed by the module production and give guidance throughout the process. This also allows for real costing to be performed early on in the process so that the design can be steered to be within budget.
2. Misconceptions about modular building are a major barrier for the adoption of modular construction (Jiang, Mao, Hou, Wu, & Tan, 2018) (Lacovidou et al. (2021). Modular buildings are considered to be more structurally vulnerable due to collapses of buildings around the world back in the 60s. For example, the 22-storey prefabricated Ronan Point block collapse in 1968 in East London. These accidents made the durability and structural integrity of prefabricated buildings questionable to the public and created a negative public perception of modular construction (Lacovidou et al. (2021). Modular buildings have however proven to be very safe and reliable in earthquake-prone regions (Mills, Grove, & Egan, 2015). Another obstacle to the take up of modular construction is the public perception that modular construction is a cheap, ugly, poor-quality and an industrialized alternative to traditional construction processes (Jellen, 2015). This is however not the case anymore and as indicated in the advantages of modular construction, it provides an even a better-quality building than with traditional building methods. Also based on the interview with modular manufacturer JanSnel (annex 1) there are many possibilities of changing the appearance of a modular building, so that you cannot even see the difference between a modular and a traditional building anymore. These misconceptions make that the majority of the construction firms are not fully aware of the advantages of modular construction (Jiang, Mao, Hou, Wu, & Tan, 2018). This in combination with the lack of social acceptance of modern modular products is a significant challenge. Because of this negative public perception, in recent years modular construction was rebranded to modern method of construction due to the misconceptions about modular construction (Lacovidou et al. (2021).
3. The lack of modular factories is a major barrier. There still are so few modular factories, because very high initial capital (50-100 million (McKinsey, 2019)) is required to set up the manufacturing plant for the production of the modules (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). Due to the still low demand for modular construction, potential new manufacturers are reluctant to put this big of an investment in a modular factory, because they feel insecure about their return on investment (Lacovidou et al. (2021). Because of the low uptake of modular construction and the lack of modular factories, the average distance between the construction site and the factory is quite big. This distance is a barrier, because if the distance is too big the transportation cost will be too much and the project will not be feasible (Paliwal, Choi, Bristow, Chatfield, & Lee, 2021). This transportation is a barrier in itself as well, due to the limited module size that can be transported over the road (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). For the Netherlands transportation without police escort may have a maximum width of 3-meter, height of 4,25 meter and length of 16,5 meter (rdw, 2021). These

size restrictions should be considered when making the design of the building. Due to the just-in-time delivery that is needed on site, close coordination is need among the manufacturing, transportation, management and assembly operations (Hsu, Aurisicchio, & Angeloudis, 2019). This means that it is very important to optimise time-critical logistic systems and to intensively manage them. When the distance between the construction site and the modular factory decreases, so will also the transportation cost and the risk for delay.

4. Unsuitable building plot due to the shape can be a practical barrier (M. Jaarsma, personal communication, November 25, 2021). With 3D modular construction the design freedom is strongly reduced, due to the standardized nature of modular construction. This means that when the building plot has a shape that does not correspond with the form of the module, often the decision is made to not use modular construction. The main reason for this is that developers want to realize as many square meters as possible, which is only possible if the building follows the contours of the building plot.
5. There is a lack of design guidelines for modular construction, which makes it difficult for designers to design the building efficiently for the application of modular construction (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). These design guidelines are of great importance for the success of modular construction, because the design stage determines up to 80% of building costs. For offsite construction to be a success a highly detailed design is needed very early on in the project, the construction process requires different infrastructure and the effect of geometric inaccuracies and installation must be considered. I noticed this myself when building at the SUM team, as we experienced some delays due to building aspects that were not thought of during the design, which you should try to avoid when industrialising the building process. The design team may also need to take on different responsibilities, as the design should take into account the manufacturing process and transportation, which were traditionally considered the responsibility of the contractor. Digital technologies such as BIM are essential to make a detailed design that is a one-to-one copy of the building to be built in order to minimise failure and mistakes at the construction site (Wilson, 2019). To maximize the efficiency of the design, the architects should produce custom designs that use a range of standardized components.
6. Clients and their teams cannot make changes to the building design anymore, without major consequences to the building schedule and budget (Lacovidou et al. (2021). Clients will have to get used to this and see the advantages that this can bring them. Normally design can overlap with construction allowing minor modifications to the design of a building during construction. This is not possible with modular construction, because the design needs to be specified very early on in the building process. Late changes will cost more money and may lead to waste generation (Lacovidou et al. (2021). Encouraging clients and their teams to complete their design decisions early on in the design process increases the viability of modular construction as well as the resource, time and cost efficiency levels. It also reduces construction time, construction cost and gives greater certainty on project delivery.
7. Unwillingness of financial investors to fund prefabricated projects can be an issue (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). These investors are most likely not familiar with modular building, and therefore see more risks for the project to fail. One of these risks is the manufacturer failing to deliver, which creates risks in the project delivery time, budget and quality of the building (Lacovidou et al. (2021). This can be resolved if the manufacturer can provide guarantees that they will deliver on time. Also improved education, communication and experience with modular construction is needed for this barrier to disappear. This in combination with higher upfront cost at the design and prefabrication stage, due to a more detailed design at the beginning of the project is a problem (Jiang, Mao, Hou, Wu, & Tan, 2018).
8. Lack of government support is a barrier for the uptake of modular construction (Sun, et al., 2020). In order to make sure that modularity is being used on large scale and that the most advantages in the field of sustainability are being realised the government should intervene. The government can do this by switching from an incentive policy to mandatory policies, that will force stakeholders to use modular construction. Examples of these mandatory policies are standardizing modular connection systems that enable reuse and interchangeability and setting a minimum amount of modular construction that should be used as is being used in Singapore. For stimulating reusability of modular elements, sector wide agreements should be made about making standards (de Bruijn, 2021).

2.9 TECHNOLOGY

The construction industry is lagging behind when it comes to the use of digital technologies and automation, but slowly but surely it is catching up. This can be seen in the fact that building information modelling (BIM) was considered a specialized tool and now it is widely used in the construction sector (Elghaish, et al., 2020). The construction industry has started to embrace technologies such as virtual reality (VR), augmented reality (AR), mixed reality (MR) and artificial intelligence (AI). Also, the use of drones and 3D printing has become more popular recently. In this section we will discuss what influence these new technologies can have on the uptake of modular construction.

3D printing has been growing in popularity as the technology matures. Many experiments are being done to test if 3D printing could increase building efficiency on site by automating the building process on site. 3D printing has quite a few benefits which include: reduced material transportation and storage, reduced waste, reduced injuries and fatalities on site, time savings and the ability of mass customization (Sakin & Kiroglu, 2017) (EI-Sayegh, Romdhane, & Manjikian, 2020). However, there are currently also many disadvantages to 3D printing, but there is a possibility that these disadvantages could be overcome when the technology matures. Examples of disadvantages are: rough surface quality due to the printing process, design and material limitations, design size limitations due to printer size, high material cost, high initial investment, challenging and expensive transportation of the printer, not possible to print large scale projects, material is to brittle for structural use (EI-Sayegh, Romdhane, & Manjikian, 2020). Another disadvantage is the low level of flexibility that 3D printing provides to a building when in the in-use phase, because the building structure cannot easily be adapted. This means that even though, 3D printing reduces building waste significantly, the demolition waste will be huge when a building becomes redundant or too old, because it will have to be completely demolished instead of disassembled and reused like modular buildings. With the current state of technology modular construction trumps 3D printing, because all the advantages of 3D printing also to some extent apply to modular construction, while 3D printing has a lot more (serious) disadvantages. However, 3D printing could be used in a modular factory to automate the production of long-lead components such as joints. This way modular construction and 3D printing can complement each other.

Artificial intelligence (AI) can replace a lot of manual labour, which is prone to mistakes. This will save the construction sector a lot of time, which makes the construction process more efficient. In order for offsite construction/modular construction to achieve optimal cost savings and increased efficiency, technology-advanced design approaches should be implemented (Hou, et al., 2020). An example of this technology-advanced design is generating an optimal modular design using augmented intelligence in combination with BIM. Another example is to use a BIM-based information management system that can be used to make the modular units optimal for the clients demands. AI can also contribute to the logistic aspect of modular construction. Because the modules are produced offsite, the transportation workflow from off-site to on-site requires great attention. By using BIM and cloud-based internet of things (IOT), building components can be traced in real time (Hou, et al., 2020). This in combination with advanced VR and AR visualisation techniques enable accurate monitoring of the project schedule, cost and safety which can increase the decision-making quality. Furthermore, AI in combination with machine learning can also be used to identify potential safety hazards and is able to optimize schedules or assign tasks to different construction parties. Despite all these advantages, AI will probably not be used much in the near future because very few industry leaders have the processes, recourses and existing data strategies in place to power the necessary algorithms to usefully implement this technology (Mckinsey, 2018).

2.10 STAKEHOLDERS

The success of a modular construction approach depends on how well information is shared between the parties involved. Therefore, it is key that before the design begins the responsibilities and scope of work for each stakeholder should be defined. This should be done in order to prevent potential gabs or overlaps in scope, with which a scope of work checklist can help.

According to McKinsey (2019) realizing the benefits of modular construction will require different stakeholders to make a series of choices. Developers will have to change their thinking from unique projects and opportunities to a productized way of thinking. To do this they will have to identify the segment in their portfolio where volume and repeatability come into play, which can be assigned as the product core that remains consistent across developments. They also should articulate the right design parameters that balance modularization at scale with the freedom to tailor each project. For successful modularization it will be crucial to build a relationship with the modular supplier, which means that they should aim to transition from operating on a project-by-project basis to forming a strategic partnership with involved stakeholders. In this partnership they should try to optimize for manufacturability and make the right trade-offs among quality, cost savings and time savings to eventually reach a standardized but customizable design. Developers can be the catalyst for the transition to modular construction, as they can determine how and by whom their projects are being realized. Because of this they can also benefit a lot from the advantages of modular construction. The early movers can gain significantly when they pocket the cost savings that modular construction gives, until they have to hand in these savings to clients in order to stay competitive (McKinsey, 2019b.). The first step for developers should be to test fully modular construction on an individual small-scale project in order to gain experience and trust in the supplier. Based on this experience the process can be tweaked to be rolled out and applied to large number of projects. Developers will most likely face many challenges when adopting modular construction, but when modular construction is applied to large scale, the advantages that have been discussed earlier can lead to great benefits for them.
However, social housing organisations such as DUWO don't always develop student housing themselves. They often use turnkey contracts, which means that developments of new student accommodations are not done within the organisation, but are handed over to other developers. They do this because a project is part of a bigger project, because they don't have enough developers inhouse or want to reduce risk (M. Jaarsma, personal communication, November 25, 2021). Due to these turnkey contracts DUWO sometimes has less influence on the choice between modular and traditional construction.

For investors modularity is particularly interesting, because it is an opportunity to set itself apart from other investors (McKinsey, 2019). They will also overtime have the benefit of reduced market risk due to the repeatability and thus reusability of the design aspects, which will provide investors more confidence in the success of the project because it has already been demonstrated to resonate with the market (McKinsey, 2019b.). Because DUWO could also be seen as a long-term investor, these advantages could be beneficial for DUWO.

The level of modularity influences the freedom of the designer. This means that when using 3D volumetric elements, which is a high level of modular construction, the design freedom of an architect is limited. Especially when not only the secondary spaces, such as a shower or toilet cell are modularized, but also the primary spaces, such as bedrooms and kitchens. Because of this, the architect can feel that he loses his control over the entire building design and that his role becomes secondary or purely shape focussed (Delrue, 1969). This is due to the form of standardisation that 3D modular construction entails, which means that many aspects of the building are already determined. Because of this you would think that architects are not so keen on modular buildings, as this takes away a lot of their work. However, in the design meeting for a modular student accommodation (Laan van Kronenburg 7) the architect Studioninedots proposed to find a standard module that can be used for all student accommodations in the future. This to me was quite surprising and will be examined further in p3.

3. RESEARCH QUESTIONS

Main question:
"What is the current performance of modular multistorey student accommodations in the Netherlands and how can this performance be increased?"

Sub questions:

- **What is modular construction?**
  To answer this question, I have to gather information about modular construction through literature research. This is important because modular construction can be interpreted in many ways and has different levels. Therefore, to give focus to this research it is important to specify and choose a specific form of modularity. I already did some research to the definition of modular construction and because of that I know that it will be important to look at modular construction in the building sector specifically and that there are different levels of modular construction. It will also be important to further look at materials, lifetime of the module, production process and standardisation of modules.
- **What are according to literature the advantages and disadvantages of modular construction?**
  To answer this question, I have to look at what advantages and disadvantages have been identified in literature, as a lot of research has already been done to identify these. It is important for the research to know the barriers and advantages that have been identified in literature to be used as background information in the following sub-questions.
- **To what extent can modular construction currently satisfy the expectations of student housing associations in the Netherlands?**
  1. To answer this question, I have to determine the expectations of DUWO. According to Cambridge dictionary expectations are "a feeling or believe that something will or should happen". In relation to DUWO this means that they feel some things (positive and negative) should happen when they make a modular building instead of a traditional one. By determining these expectations, I can also discover why DUWO sometimes chooses to build modular and other times prefers traditional construction. To determine the expectations when building modular I am going to take the following actions:
     - Find and analyse more literature next to the literature that I have already found about expectations of stakeholders for modular construction.
     - Examine two multistorey student accommodations that have been built using traditional construction methods. This way the I can get an overview of the standard which modular construction must follow or surpass. When examining these buildings, I should use the following key performance indicators(kpi): building cost, building speed, maintenance cost, materials used, user satisfaction, utilities cost, waste production, insulation, installations etc.
     - Interview different stakeholders that work at DUWO. By doing this I can get more information about what kpi's are important and which should definitely be included in a modular building, or which can be reduced when building modular.
  2. Furthermore, I will have to research the current state of the modular buildings that have already been made by DUWO. To do this, I will take the following actions:
     - Examine three multistorey student accommodations that have been built using modular construction techniques. These buildings should all have a permanent living status, they should not be older than 10 years and they should at least have five storeys. When examining these buildings, the same kpi's that were used to examine the traditional buildings will be used.
     - Interview stakeholders that were involved in these projects (disciplines within DUWO, architect, manufacturer, municipality, structural engineer). Ask them what went right and what could have been done better. This way it is possible to get to know what the expectations of stakeholders are for modular buildings in the past, now and in the future.
     - Because DUWO has to take their customers in mind, it is good to not only look from the perspective of DUWO, but also to look from the perspective of the students that live in a modular building. To do this, post occupancy evaluations from literature will be used as a basis in combination with structured interviews with students that live in modular student accommodations. (performance categories for residential properties (McGrath & Horton, 2011): thermal comfort, Visual comfort, acoustic comfort, indoor air quality) In literature I

have found two post occupancy evaluations of modular student accommodations which are taken in England and in Australia in the years 2011 and 2016 respectively.

3. With the information from the sections above it will be possible to compare DUWO's expectations of modular building against the current state of modular student accommodations and to see what can be improved. To do this a comparison table will be made in which the kpi's of the modular buildings will be compared against the expectations. This comparison will result in over, under or good performance of the kpi's of the modular building.

- **How can the performance of modular construction for student accommodations in the Netherlands be increased?**

  The previous question gives the performance of modular buildings, which will be used in this question. The goal is to find solutions to improve the underperforming or overperforming kpi's that were found and to come up with a standard module for multistorey student accommodations. When performance of the current modular student accommodations turns out to be good, the focus should be on making modular buildings even more efficient. To do this I am going to do interviews with experienced stakeholders that can provide solutions to increase the performance of modular building. These stakeholders include developers, architects, manufacturers and structural engineers. Once the solutions have been found to increase performance of the modular buildings, these solutions are going to be used when designing a standard module for student accommodations. This standard module will be used for a newbuilt building (Laan van Kronenburg 7, Amstelveen), which means that I will be able to get the assistance of the architect (Studioninedots) that is involved in this project. This project is interesting, because as can be seen in figure 4, the building is situated on a plot in which a traditional- and a modular student accommodation has already been build and this building will not only be modular, but also sustainable.

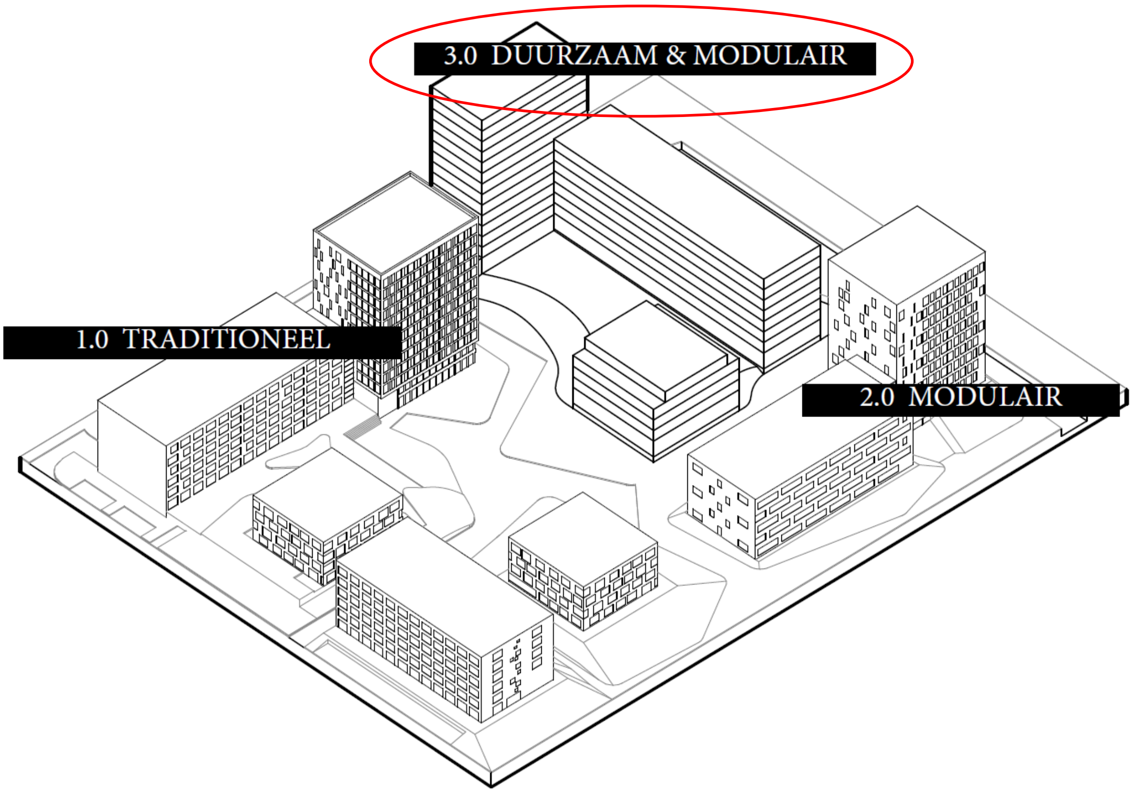


Figure 4: Overview of the project site, adapted from Studioninedots

4. RESEARCH METHOD

Type of study + methods to be used
For this research an explorative research type will be used, because in this research the performance of modular construction will be explored together with a possible solution to increase this performance. To do this the research method of case studies will be used, which expresses itself in the form of in dept interviews and project studies. Furthermore, I will use literature research, field research and design research to gather the data and to design an end product.

Data collection
The data from the sub-questions will not be gathered fully chronologic from the first question to the last question, but the data will be gathered in batches per sub-question. This means that I will work on all sub-questions simultaneously, which gives the opportunity for information feedback loops. This way it is possible to use new information from one sub-question for another sub-question, which gives more dept of information to the research.

1. **What is modular construction?**
2. **What are according to literature the advantages and disadvantages of modular construction?**
   For the first two sub-questions literature research will be used. This is possible, because a lot of research has already been done to the definition and the advantages and disadvantages of modular construction. Furthermore, this literature research will be complemented with possible information that comes from other sub-questions. These first two sub-questions will form the context on which the following questions will be built.
3. **To what extent can modular construction currently satisfy the expectations of student housing associations in the Netherlands?**
   For the third sub question, semi-structured interviews will be held and project studies will be done to gather the data that is needed. I will analyse 2 traditional student accommodations followed by the 3 modular multistorey student accommodations, which will all be analysed based on the same kpi's. The data that is needed to do these project case studies will be gotten from DUWO in the form of reports, drawings, financial sheets and user complaints. During the interviews, interviewees can give clarification of data that was found with the case studies or provide new information that can be used in the case studies. Before the interviews, an interview protocol will be made in which all the steps of the interview will be described to ensure the maximum amount of information that can be gained from the interviews and nothing will be forgotten. The interviews will be done with stakeholders (DUWO, architect, developer, manufacturer, structural engineer and municipality) that were involved in the 3 modular projects, meaning that I will have to do a maximum of 18 interviews, depending on if there is some overlap between projects and stakeholders. In the interviews I will ask questions about the kpi's that were analysed from the project case studies, which can give new insights to the data that was gathered.
4. **How can the performance of modular construction for student accommodations in the Netherlands be increased?**
   The fourth sub question will consist out of data gathering through interviews and making a proposal for a standard module for multistorey student accommodations. The first step will be to make an initial design based on the information that I already gathered for this P2 report. I will make this initial design in collaboration with Studioninedots (project architect), because they have experience with modular construction. For this initial design, at least the following topics should be included: materials, connections, standardisation, transportation, lifetime, reusability, flexibility. To further improve this initial design, information from the case studies will be used and interviews will be held with professionals in the field of modular construction. From each discipline (DUWO, architect, developer, manufacturer, structural engineer and municipality) that is involved with modular construction, I should do at least two interviews with different people within that discipline. This should give enough information for me to make a proposal for an efficient standardized module and if this doesn't, I can do more interviews with a specific discipline that still lacks information.

Data analysis

1. Project case studies:
   To analyse the gathered data from the project case studies, which include at least 2 traditional student accommodations and 3 modular ones, I will make a comparison table in which all data will be

displayed. With this table I will be able to make an average of the data that was gathered for the traditional and modular buildings.

2. Interviews:
   To analyse the data that is gathered via interviews I will record the interviews and make a summary with the most important findings. I will not fully transcribe the interview as this is not relevant for this research, because I am looking for new insights and I am not going to compare interviews.
3. Project case studies + interview results
   With the data of the project case studies and the complementary data of the interviews it will be possible to compare the modular building with the traditional building. Per kpi I will analyse the performance of the modular building in comparison to the traditional one. This makes it possible to see on which points the modular building is under- or overperforming.

Data plan
The data that will be gathered through the interviews and the project case studies will be used as underlayer on which this research will be based. All data will be made anonymous to some extent, meaning that the name of the specific interviewee will not be included. However, it is important for the reusability of the data to include metadata, and therefore the age, gender, ethnicity, role, company, interview setting and date will be included in the transcripts. To enlarge the data set that researchers can use, the FAIR guiding principles were designed to ensure that all digital resources can be Findable, Accessible, Interoperable and Reusable. To support this, I will include metadata to the transcribed interview and I will ask the interviewees to give consent to further anonymized use of the data in further researches.

Ethical considerations
Before using the data, I will ask the specific organisation or person to whom this data belongs if I am allowed to use it and if the data needs to be anonymized.

5. RESEARCH OUTPUT

The output will be:

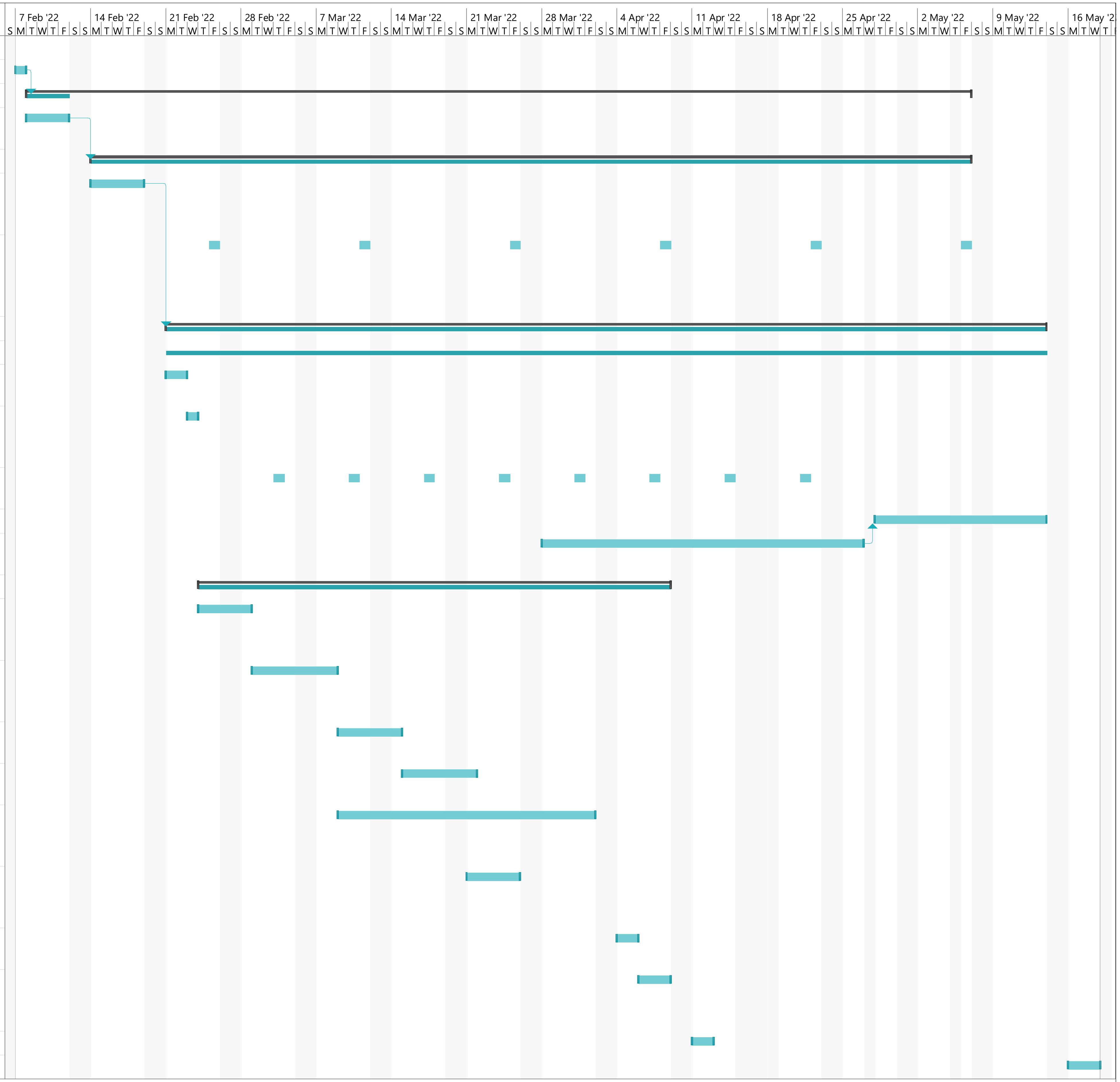
1. **Matrix of the performance of modular multistorey student accommodations.**
   In this matrix the performance of modular multistorey student accommodations can be seen in comparison to traditional student accommodations.
2. **Recommendations on how to improve the performance of modular multistorey student accommodations.**
   These recommendations will be textual and will be grouped according to the kpi's that were used to analyse the existing buildings.
3. **Standard module design for multistorey student accommodations.**
   This design will be mostly textual in which technical specifications of the module will be described, a process plan will be made and recommendations will be made. To complement this, also some technical drawings will be made.

6. PERSONAL STUDY TARGETS

As I explained in the introduction, I am a great fan of Tesla and the innovation, pro-environment and efficiency that they promote. Therefore, the main thing that I want to learn is how modularity can increase efficiency in the construction industry and how modularity can contribute to a more environmentally friendly society. At the same time, I think it is very interesting to learn about how different stakeholders in the construction process look at the change that modular construction can bring and to see if they are open for this change. Furthermore, an added bonus is that through my internship at DUWO, through the interviews and through the SUM project, I will be able to get acquainted with the working field, which will be beneficial for my working career after I hope to graduate in the summer of 2022.

7. PLANNING

ID	Task Name	Duration	Start	Finish	Predecessors
1					
2	Make document layout	1 day	Mon 7-2-22	Mon 7-2-22	
3	**Researchquestion 1**	**60 days**	**Tue 8-2-22**	**Fri 6-5-22**	**2**
4	Write modular construction definition based on literature	4 days	Tue 8-2-22	Fri 11-2-22	
5	**Researchquestion 2**	**56 days**	**Mon 14-2-22**	**Fri 6-5-22**	**4**
6	Advantages and disadvantages of modular construction from literature	5 days	Mon 14-2-22	Fri 18-2-22	
7	**Update advantages and disadvantages modular definition based on field information**	**47 days**	**Fri 25-2-22**	**Fri 6-5-22**	
14	**Researchquestion 4**	**56 days**	**Mon 21-2-22**	**Fri 13-5-22**	**6**
15	**Standard module design**				
16	Make a basic design based on literature	2 days	Mon 21-2-22	Tue 22-2-22	
17	Discuss design with Studioninedots and implement changes	1 day	Wed 23-2-22	Wed 23-2-22	
18	**Update design based on field information**	**52 days**	**Thu 24-2-22**	**Thu 12-5-22**	
27	Finalise design	11 days	Thu 28-4-22	Fri 13-5-22	28
28	Interviews with experienced stakeholders	20 days	Mon 28-3-22	Tue 26-4-22	
29	**Researchquestion 3**	**32 days**	**Thu 24-2-22**	**Fri 8-4-22**	
30	Gather data of modular and traditional student accommodations	3 days	Thu 24-2-22	Mon 28-2-22	
31	Interview different roles within duwo about their expectations of modular construction	6 days	Tue 1-3-22	Tue 8-3-22	
32	Analyse traditional student accommodations	4 days	Wed 9-3-22	Mon 14-3-22	
33	Analyse modular student accommodations	5 days	Tue 15-3-22	Mon 21-3-22	
34	Interview stakeholders that were involved in the modular projects	18 days	Wed 9-3-22	Fri 1-4-22	
35	POST occupancy evaluation of modular building from the perspective of the user	5 days	Mon 21-3-22	Fri 25-3-22	
36	Compare modular against traditional	2 days	Mon 4-4-22	Tue 5-4-22	
37	Make recommendations on how the performance of modular construction can be increased	3 days	Wed 6-4-22	Fri 8-4-22	
38	P3 presentation	2 days	Mon 11-4-22	Tue 12-4-22	
39	P4 presentatie	3 days	Mon 16-5-22	Wed 18-5-22	



Project: P3 and P4 planning v2
Date: Thu 13-1-22

Task	Summary	Inactive Milestone	Duration-only	Start-only	External Milestone	Manual Progress
Split	Project Summary	Inactive Summary	Manual Summary Rollup	Finish-only	Deadline	Process
Milestone	Inactive Task	Manual Task	Manual Summary	External Tasks	Progress	

8. REFLECTION

I think the course AR3R010 was very good and it helped me with finding my graduation thesis topic, and it helped me formulate the problem, which makes this research relevant. Even though in the beginning I thought it was quite difficult to find the right topic, my main mentor Peter de Jong and my second mentor Herman vande Putte guided me to formulate this research proposal.

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ANNEX 1

Interview met Daan Kosterman over modulariteit

Datum: 18-10-2021
Time: 12.00 – 12.45
Interviewer: Kevin Vader

1. **Wordt volgens u modulair bouwen het bouwen van de toekomst? Zo ja waarom?**
Ja. Modulair bouwen heeft het voordeel dat het in de fabriek tot een hoog niveau afgewerkt kan worden, en doordat er in een gecontroleerde omgeving wordt gebouwd ook nauwkeuriger kan worden gebouwd. Er is minder transport nodig dan met traditionele bouw, omdat er altijd volle vrachtwagens met materialen naar de fabriek kunnen komen. Modulair bouwen heeft ook het voordeel dat industrialisatie mogelijk is, waardoor gebouwen 30-50% sneller gebouwd kunnen worden. Dit is mogelijk voor gebouwen met veel repetitie, wat niet wil zeggen dat alle gebouwen er hetzelfde uit zien. Als gebouwen meer volgens een standaard worden gebouwd, zullen gebouwen nog sneller en goedkoper gemaakt kunnen worden. Een ander voordeel aan 3D modulair bouwen is dat wanneer een gebouw aan het einde is van zijn levensduur of overbodig is geworden, dat de modules gerenoveerd en hergebruikt kunnen worden. Dit zorgt ervoor dat de complete levensduurkosten van modulair bouwen goedkoper zijn dan bij traditionele bouw.
2. **Zijn de bouwkosten lager voor modulaire gebouwen dan in traditionele bouw?**
Met een volledig geïndustrialiseerde productielijn zal modulair bouwen goedkoper worden dan traditionele bouw, voor een bepaald gestandaardiseerd gebouw type. Op dit moment zijn wij vergelijkbaar in prijs met een traditionele bouwer.
3. **Wat zijn de grootste uitdagingen die overwonnen moeten worden om ervoor te zorgen dat modulair bouwen op grote schaal toegepast kan worden?**
Door de hoge initiële kosten van een modulair bouwbedrijf is het moeilijk om zo een bedrijf op te starten. Ook heeft modulair bouwen meer risico, wij weten bijvoorbeeld niet of er in de toekomst meer eisen aan materialen komen waardoor de modules van nu toch niet meer hergebruikt kunnen worden. Voor modulair bouwen moeten beslissingen veel eerder worden genomen dan met traditionele bouw en is het achteraf bijna niet meer mogelijk om aanpassingen door te voeren. Dit vinden opdrachtgevers vaak lastig omdat ze niet gewend zijn om deze beslissingen nu al te moeten nemen. Ook is het voor architecten lastig om te ontwerpen aan de hand regels die voor modulair bouwen gelden, omdat alle modulaire bouwers andere standaarden hanteren. Het is cruciaal dat de modulaire bouwer vroeg wordt meegenomen in het ontwerpproces, zodat ze nog advies kunnen geven. Ook is het een probleem dat het niet zo makkelijk is om de productie uit te breiden van de fabriek, omdat er te weinig personeel beschikbaar is.
4. **Welke soort van modulariteit (2D,3D) is volgens u het meest efficiënt en heeft dus de meeste voordelen?**
Wij zijn gespecialiseerd in 3D modulair bouwen, maar we doen ook wel wat met 2D modulair bouwen. Het een is niet per se beter dan het andere, maar er zit wel verschil in waarvoor ze gebruikt kunnen worden. 3D prefab heeft het voordeel dat het gebouw veel sneller in elkaar gezet kan worden en uit elkaar gehaald kan worden. De materialen die het meest milieubelastend zijn zitten voornamelijk in de “kooi” en deze “kooi” kan in het geval van 3D units makkelijk hergebruikt worden. Er verandert over het algemeen niks aan de constructie het is voornamelijk de in en uitbouw die door de loop van de tijd veranderd. Het

nadeel van 3D modules is dat het transporteren lastig kan zijn door de afmetingen van de modules. Het voordeel van 3D units is ook dat de afwerking van de units al op een heel hoog niveau in de fabriek kan worden gedaan, waarna er op de bouwplaats alleen nog verbindingen moeten worden weggewerkt en installaties moeten worden aangesloten.

5. **Welke mate van standaardisering gebruiken jullie?**
   Het komt vaker voor dat we van een bestaande tekening die gebaseerd is op traditionele bouw een modulair gebouw moeten maken, of dat het efficiënter is om onze units iets groter te maken dan onze standaardmaat omdat de klant er dan meer rendement uit kan halen. We hebben verschillende lijnen, waarvan er een heel standaard is en die gebruikt wordt voor tijdelijke scholen, kantoren, bouwketen. Een andere lijn is wat meer permanent en hiervoor gebruiken we de standaardmaat van 3x6 meter. Deze units zijn semipermanent en worden over het algemeen tussen de 6 maanden en 5 jaar gebruikt, maar soms ook wel 10 jaar. Ook hebben we units voor de wat meer grotere bouw, waarbij je moet denken aan bijvoorbeeld studentenkamers of appartementen. Deze units worden naar permanente eisen neergezet en staan er over het algemeen zo een 15 jaar. Bij deze units blijft de detaillering ongeveer hetzelfde, maar wijken de maten vaak af omdat opdrachtgevers net iets anders willen dan onze standaardmaten. We zijn nu bezig met wat appartementen en studentenwoningen die we willen standaardiseren en deze standaarden aan te gaan houden als uitgangspunt waardoor we verder kunnen industrialiseren. De belangrijkste uitgangspunten waarop je kan industrialiseren zijn constructie en detaillering en daarom is het belangrijk om op dat gebied uniformiteit te creëren. Als er geen standaardisering wordt toegepast kunnen fouten minder goed worden herkend. Opdrachtgevers willen vaak zo snel mogelijk een gebouw hebben, waardoor ze steeds meer geneigd zijn om wat in te leveren op het gebied van creativiteit. Dit wil niet zeggen dat alle gebouwen hetzelfde worden, er is nog veel mogelijk in gevelafwerking en maten van kozijnen.
6. **Hoe wordt er voor de stabiliteit van het gebouw gezorgd?**
   Voor hoogbouw kan worden gewerkt met een traditionele in het werk gestorte stabiliteitskern, maar er zijn ook prefab betonkernen die demontabel zijn. Tot de hoogte van 5-6 verdiepingen is het rendabel om geen kern toe te passen maar ervoor te zorgen dat de 3D units van zichzelf stabiel zijn wat zorgt voor stabiliteit in het gebouw.
7. **Welke soort gebouwen hebben de voorkeur voor modulair bouwen?**
   Een kamer appartementen zoals studentenwoningen zijn ideaal voor modulair bouwen, omdat ze volledig afgewerkt kunnen worden in de fabriek. Ook appartementen kunnen heel goed modulair worden gemaakt en zijn ze niet afhankelijk van de grootte van de modules, omdat modules aan elkaar gekoppeld kunnen worden.
8. **Waar is volgens u nog onderzoek naar nodig, zodat modulair bouwen meer toegepast gaat worden (stakeholders, technologie, logistiek, ontwerp)?**
   In principe moet er op alle gebieden nog onderzoek gedaan worden, omdat modulair bouwen nog vrij nieuw is. Specifiek is het nog nodig om onderzoek te doen naar duurzaamheid van modulair bouwen en dan met name gericht op wat de impact is van het slopen van een traditioneel gebouw in vergelijking met het hergebruiken van een gebouw. Het is dan ook belangrijk om te kijken naar het verschil tussen 2D en 3D modulair. Er is ook nog onderzoek nodig naar restwaarde van gebouwen en dan met name gericht op inzicht krijgen in de hoogte van deze restwaarde, zodat dit ook meegenomen kan worden door banken wanneer zij een lening verschaffen.