Life cycle cost (LCC) comparison of a modular building structure with a conventional structure in healthcare

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Abstract

With increasing adoption of modular construction in the residential sector, its adoption in the Dutch healthcare sector is studied. Whilst the initial costs can be higher, this method of construction claims to have cost benefits over conventional construction. These are the benefits of construction speed and residual value at the end of lifespan amongst others. Modular buildings are also often advertised as sustainable, because the credentials gained from lean manufacturing coincide with a selection of sustainability objectives [1]. Healthcare projects have higher requirements and process hurdles, which make construction in healthcare much more complex than in the residential sector. However, in the UK, a study of offsite manufacture and modular volumetric construction methods concluded it to be the cost efficient solution necessary for the NHS, which led to 40 modular hospitals planned to be built until the year 2030 [2]. This means that the benefits and drawbacks of a modular approach must be weighed, and this is done in the Dutch context. A life cycle costing is proposed as the fitting tool of assessment.

Interviews were held with Dutch modular contractors to reveal the capabilities and specifics of building in a modular way and find proof for each cost factor. Experts in healthcare construction were interviewed to determine healthcare project priorities and find out whether these are catered for by modular construction. A live construction project of a hotfloor department was then studied. Several options competed in the tender project and were compared in the case study. By collecting the cost quotes and arguing for the monetary value of the identified cost factors, a life cycle cost calculation was done. Additionally, sustainability was considered by calculating the novel carbon tax. To expand the application of results to other projects, sensitivity studies were carried out for each life cycle cost parameter.

The study found that there is application for modular construction in healthcare in the Netherlands. Facilities, which do not host medical installations, do not differ to the construction used in residential modules. As for facilities such as the studied hotfloor department, larger modules and a lesser degree of finish offsite decreases the competitiveness of this construction approach. However, several evident cost factors were proposed to be considered within a life cycle costing. These were earlier income due to faster construction, a gain due to less interest and the residual value. It was found that these considerations allow for a 49,0% increase on the initial cost of a modular option in comparison to a conventional option. A hypothesis was further proposed, stating that the competitiveness of the modular option depends on three criteria. These include the initial modular option costs being up to 49,0% more expensive; the saving in construction time having a monetary value to the client; and life cycle costing results being used in total cost comparison.

Keywords: *Life cycle, cost, modular, construction, healthcare, volumetric, offsite, value, sensitivity study.*

Preface

During my studies at the University of Bath in the UK and Delft University of Technology in the Netherlands, I found that building engineering is distinct in its consideration of complex and multidisciplinary problems. Covering engineering fundamentals in university lectures, I have devoted my scientific research to broadening my knowledge of building design, life cycle analyses and impact on the environment. This is the basis of my BEng thesis, in which I investigated methods used in the UK demolition industry. For my MSc thesis, I continue with the cost evaluation of life cycle activities in modular construction in the context of Dutch healthcare facilities. The report is the current pinnacle of my scientific study.

Acknowledgements

During my research and the difficult circumstances created by COVID-19, I was hugely supported and motivated by people in my professional and personal environment.

I would like to thank my graduation committee, consisting of Dr. ir. K.C. Terwel, Prof. ir. P.G. Luscuere, Ir. P.H. Ham and Drs. ing. J.L.A. Lans, for providing guidance and constructive feedback with diligence. Their each individual input has been invaluable in making sure that I had all the tools I needed to carry out this study. Additionally, I am grateful for the industry and expert contacts, for their contributions through interviews and company data. I would especially like to thank Drs. ing. J.L.A. Lans, the CEO of Medexs, for all the effort expended for me to follow a live case project.

Furthermore, I would like to thank Ir. P.H. Ham and Joris Welles as well as other university peers, with whom I worked on finding the fitting research theme and topic. Lastly, I want to thank my mother and friends, who encouraged me, showed interest in my work and challenged the applied concepts. They contributed with endless support, for which I am utmost grateful.

Kostas Navardauskas Palaima
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1. INTRODUCTION

1.1. Definition

Prefabricated construction encompasses all building systems built using the repetition of elements, but [3] dissects this into **modular construction** - made of volumetric 3D modules; **planar construction** - made of 2D elements; **hybrid construction** – a mixture of stick, flat and volumetric elements; **cladding panels** – 2D façade elements; **pods** – non-structural 3D modules such as toilets and bathrooms. Figure 1 helps to visualise the elements at the various degrees of off-site manufacture or prefabrication.

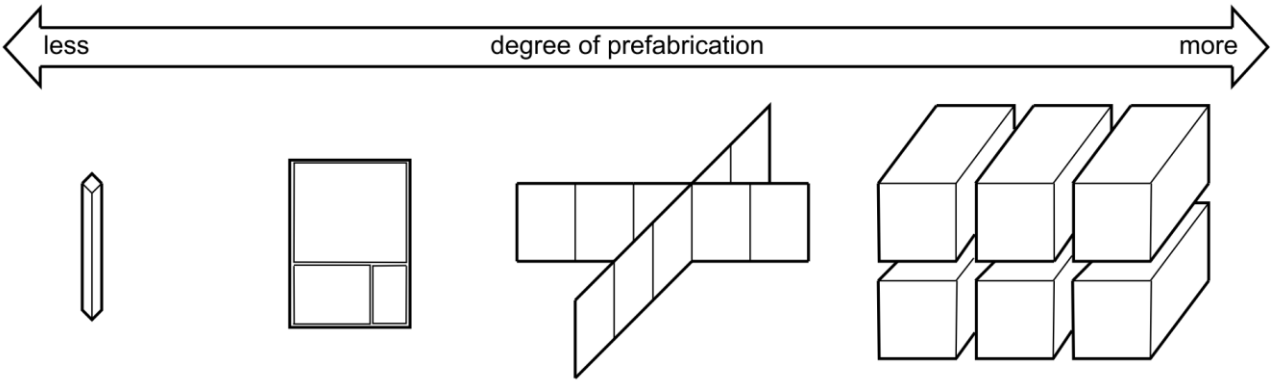

Figure 1: Degree of off-site manufacture [4]

Modules are the structural form with the highest degree of prefabrication. The main distinction of modular construction is that a 3D structure, such as a room, is assembled in the factory. This includes the structural frame, panelling and finishes. Most of the construction work is therefore done in the factory and little assembly is required onsite. Less complex prefabrication systems, such as planar or hybrid, involve the manufacture of individual walls, floors, columns and panels. Unlike with modules, these are assembled onsite.

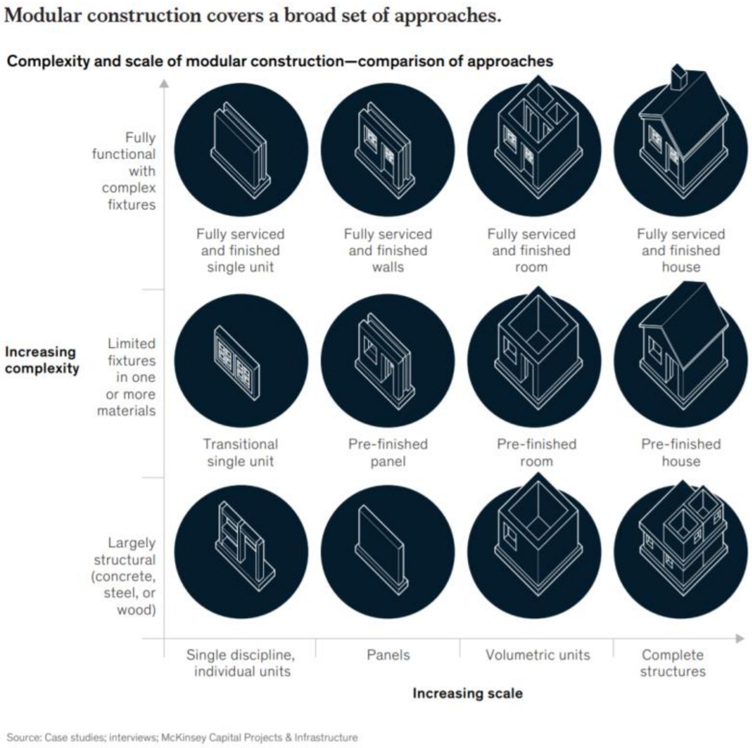

Figure 2: Complexity and scale of modular products [5]

As shown in Figure 2, modular building elements can be evaluated by scale and complexity i.e., level of finish. Scale refers to the overall size of a building part, from columns to wall panels, to rooms, to a complete facility. Whereas the complexity refers to the level of integration of building services, surface finishes and fixtures. A fully equipped 3D volumetric unit has the highest level in both scale and complexity, maximising the benefits of off-site manufacture by scheduling 60 to 70% of work to be carried out in the factory (Figure 3). This can be called a complete building system, and the work on-site considering the modules is delivery only. Figure 3 below, shows the amount of work in the factory for each definition.

	Levels of off-site manufacture (see Table 1.1)			
Parameters	*1. Manufactured components*	*2. Elemental or planar systems*	*3. Modular and mixed-construction systems*	*4. Complete building systems*
Examples of construction technologies	• Timber roof trusses • Precast concrete slabs • Composite cladding panels	• Structural steel frames • Timber framing • Light steel framing • Structurally insulated panels	• Prefabricated plant rooms • Modular lifts and stairs • Modules placed on podium level • Bathroom pods in framed buildings	• Fully modular buildings
Proportion of off-site manufacture (in value terms)	10–15%	15–25%	30–50%	60–70%
Reduction in construction time relative to level 0	10–15%	20–30%	30–40%	50–60%

Figure 3: Proportion of off-site manufacture [3]

The approach of off-site manufacture of building elements is not new. Prefabricated systems and unitised residential homes have been popular at times of economic crises [4]. Most notably, there was a boom in prefabricated construction after WWII and in 1970s, as there was a need for ample affordable housing in Europe. The systems used then could be classed as cladding panel and panelised systems – made of a set of flat elements. Figure 4 shows a panelised system for affordable housing in afterwar UK. Figure 5 shows precast concrete slab and wall construction representative of the Soviet union and eastern Europe in the 1970s. In both examples, speed and cost were the main reasons to apply off-site manufacture and solve housing crises. A further step in complexity – a 3D volumetric unit, such as the steel units in Figure 6, were first manufactured in 1990 [3]. This was possible by employing industrial manufacture concepts borrowed from the aerospace and automotive industries.

Figure 4: Phoenix system of prefabricated post-WWII housing in the UK. Steel frame and panelling [6]

Figure 5: 1970s panelised concrete housing in Moscow [7]

Figure 6: School in South Korea built using structural steel modules [3].

The peaks in construction costs through the years have coincided with the popularity of off-site manufacture. As shown in Figure 7, these costs are currently at an all-time high. Forbes [8] wrote that in 2017, 84% of homes in Sweden were built using prefabricated elements, 20% of homes in Germany, 15% in Japan and lower figures in the US and the UK. In the Netherlands, a calculation in 2018 states that about 10% of new homes have an aspect of off-site manufacturing, which can be considered as prefabrication or modular construction [9]. These numbers show the staggering rise in the uptake of modular building approaches. The reason for this uptake is a plethora of advantages claimed by modular approaches, such as speed, quality, safety and reduction of waste. Additionally, rising labour costs and quality requirements are increasingly making a business case for off-site manufacture. These reasons are why it is believed that modular construction methods are here to stay [5].

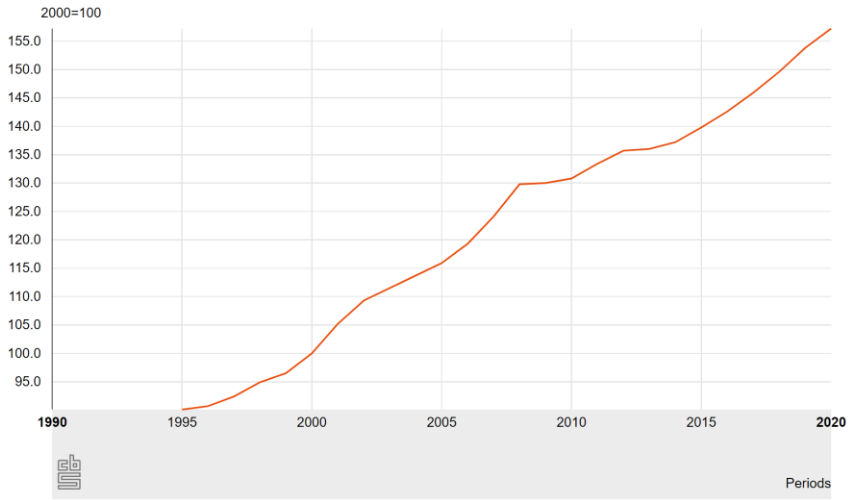

Figure 7: Construction costs of dwellings in the Netherlands [10]

A 2019 report by ABN AMRO [11] states that productivity in the construction sector must go up, because there are two challenges present in the construction industry. The first is the shortage of housing and the second is that all office buildings must reach a minimal energy rating of C by 2023. There are 30 million square meters of offices which must be refurbished to this level. Modular construction can solve the lack of housing in the Netherlands, by raising the number of homes being built each year from 58 000 to 81 000. Modules produced with factory machinery have smaller tolerances and be better isolated. Productivity in the construction industry is low and homes are at 20-year price peak [12], but modular construction can be the change, where 80% of work is carried out in the factory and 20% on site. Work in the factory is not affected by weather, material deliveries can be planned better, processes are standardised and automatised.

The report predicts that 50% of new residential building projects in the Netherlands will use the modular approach in 2030. A high percentage of prefabrication and the use of small modules is said to be a good start, such as in the recent projects of Xavier in Amsterdam Zuidas and the Zalmhaventoren in Rotterdam.

A 2019 Deloitte report on the global construction industry stated the Dutch market should level off after some rapid growth. This is due to strongly increased construction costs. It also points out that new environmental laws are threatening thousands of conventional projects and less so for modular ones. Furthermore, there is a new-found interest in industrialised processes, but willingness to invest in efficiency was stated to be low.

An example of rapid delivery and installation is the construction of Huoshenshan and Leishenshan field hospitals in China, to treat the outbreak of Covid-19. It should be noted here, that a field hospital is a military derived concept where patients are housed for a short time before moving onto a more permanent facility. Therefore, the design and quality of a field hospital should not be mistaken for those of a traditional hospital facility. With this in mind, these modular field hospital projects were developed in an impressive 9 and 12 days respectively, with space for the treatment of 5000 patients [13]. The record project times were achieved with an effective BIM and management system, however, it is clear that the project was dependent on a rapid delivery of 3000 volumetric units.

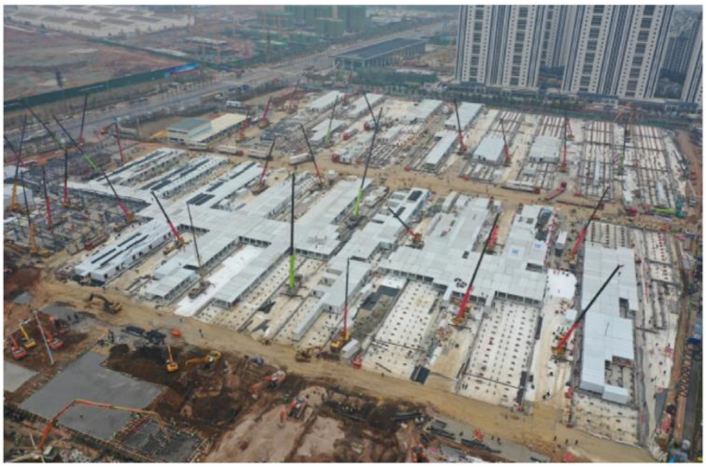

Figure 8: Leishenshan Field Hospital in Wuhan (China) built in 12 days [13]

1.2. Classification

Volumetric modules can be made of different structural materials. Light steel modules are produced from hollow section corners and I-beams between the columns, with thin steel C-sections used for walls and ceiling. Module can also be made of reinforced concrete, casting the floor and walls in one go. Reinforced concrete is normally chosen for its durability and for heightened building security functions. Lastly, timber is used widely in modular construction to different extents of complexity. Simple timber 3D frames are used for residential purposes and engineered timber products allow for larger module spans.

Another important classification of modules is their technical lifespan and function. For example, purpose-built construction temporary site offices are intended to be moved from site to site, they often do not require a foundation and are expected to take a considerable amount of wear and tear on site damage. On the other hand, temporary modular structures can also be designed for a single use. Furthermore, structures can be leased and designed to be easily refurbished and rebuilt in a new location several times during the technical lifespan of the module. Finally, modules can be designed to fit inside a larger structural system, for example attached to the concrete core of a high rise, and this is considered permanent construction. Like with any structure, knowledge of planned lifecycle events is therefore helpful in the design phase.

1.3. Costs

When the initial comparison between a traditional and modular building option is carried out, the calculated design and construction costs are what is initially presented to the client. In general, prefabrication saves on the costs of delivery and installation, but may initially be more expensive [4]. If efficiency is compromised in either stage, the modular alternative may be overpriced. Below, Figure 9 shows how modular construction costs are different and must incorporate non-modular or custom components, personnel costs in the factory and on-site, and factory overheads, aside from the conventional cost divisions.

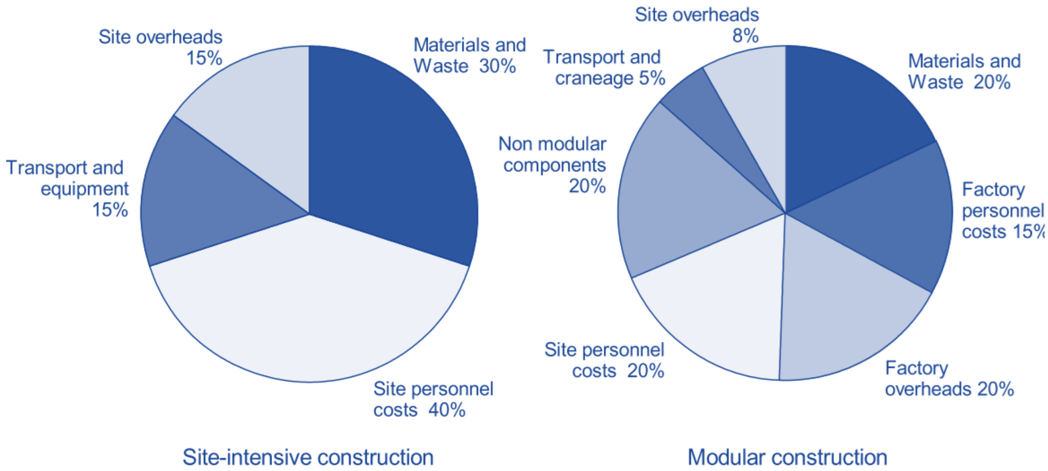

Figure 9: Divisions of traditional and modular construction cost [14]

For a full cost comparison, it is necessary to consider the value of benefits from the modular project. Some of the things to consider are design and production cost (normally 10% higher [14]); transport and installation cost; benefits of speed, such as a faster start-up & less interest paid; the proportion of off-site manufacture; and the efficiencies gained through off-site manufacture. It is roughly estimated that the modular design premium could be up to 10% and still have a financial case due to the benefits [14].

1.4. Sustainability and Carbon tax

The efficiency, quality and disassembly characteristics of modular building is often used as a reason to advertise modularity as a sustainable solution. Sustainability requirements in project tenders are normally included either with the goal of self-promotion or are a required by a government agency. This is in addition to the tax imposed by the European Emissions Trading System (EU ETS), which is a Europe-wide policy instrument for the regulation of emissions. A fixed about of emission allowances are distributed, which are decreased each year at the rate of 2.2% to 0 in 2057. They are tradeable between companies which include oil refineries, steelworks, aluminium, cement, paper and glass producers.

Similarly, the Dutch government has passed the Industry Carbon Tax Act [15] (Wet CO_2-heffing industrie) specifying a CO2 levy in the beginning of 2021. The Dutch carbon tax was enforced to reach the goal of emission reduction of 49% by 2030, from the base year of 1990. The collaboration of the two tax systems are complex, with companies which are affected by the EU ETS system omitted from a portion of the CO2 levy. The varying EU ETS allowance price as well as the rate of increase of the CO2 levy are variables which can change due to the market or changes in policy. However, Figure 10 shows the tax and respective increases for each year in the Netherlands as prognosed by PWC. The reduction factor in the figure represents the reducing emission rights in industry, and the total tax is modelled considering this factor.

Price path and reduction factor development in accordance with the bill

Year	2021	2022	2023	2024	2025	2026
Price path	€30	€40.56	€51.12	€61.68	€72.24	€82.80
Reduction factor	1.2	1.14	1.09	1.03	0.97	0.92

Year	2027	2028	2029	after 2030
Price path	€93.36	€103.92	€114.48	€125.04
Reduction factor	0.86	0.80	0.74	0.69

Figure 10: Carbon tax per year per ton of CO_2 in the Netherlands [16]

This gives the needed cost estimate of sustainability. It already affects steel and cement plants, and may be adopted broader to include transportation and buildings. This has already been done in Germany [17]. Calculating the embodied carbon and thus the carbon tax of modular and conventional structures can give a clear sustainability value, which can be compared. It also allows to make insights into what proportion of the project cost carbon tax will be and what impact reducing embodied carbon can make on total cost.

1.5. Life Cycle Cost Analysis

Even though modular construction can have higher initial cost, costs are recuperated later. Therefore, how can one know what the total value of the modular option is compared to the traditional? A common way to undertake a comparative study of costs is to carry out a life cycle costing. Life cycle costing analysis is the consideration of all costs and gains of owning an asset. This includes the procurement, construction, use, maintenance and decommissioning stages. The lifecycle costs can be grouped into several groups: initial costs (purchase, acquisition, tender and construction), fuel costs (energy in-use), operation costs (maintenance and repair), end-of-life costs (residual value, demolition, deconstruction, resale), financial (loan interest payments) and non-monetary. A lifecycle costing therefore requires a good understanding of the lifespan scenario of the facility in order to propose a trustworthy total cost estimate. Software and excel-based LCC tools (e.g. SimaPro, CRAVEzero) are available on the market and facilitate the process, but software is criticised for the lack of traceability. Traceability of data and a clear cost estimate methodology are the most important limitations of such a study.

Below are examples of life cycle costing applied in research:

- A Belgian study [18] applies LCC to find the best option for the transformation of 352 residences. Varying extents and functionality of refurbishments was compared. The study found that it was cheaper to refurbish the facility instead of new construction, insulation should be applied from within, and that additional functionality should be added to selected residences only, where a change of layout and refurbishment is expected in the future.
- A Czech LCC study [19] compared the renovation to a new construction option of an office building. Recommends carrying out LCC as part of feasibility studies, because the results are significant for the small effort required.
- A Canadian study [20] used LCC for a conversion of a shipping container into a unit. 3700kg of steel is saved from being recycled and a cheap, 3000 CAD, module frame is delivered. This is compared to the environmental footprint and life cycle cost of a traditional timber home. A sensitivity analysis is carried out to calculate the results for varying amounts of recycling and reuse of the structures.

2. METHODOLOGY

The research questions of this thesis are in the context of growing interest in and use of modular structures. From market studies [5][11], it is reasonable to expect that a modular option will increasingly be present in tender competitions. As a poorly understood method of construction, with a different project schedule and construction approach, modular construction must be better studied. It is of interest to reveal the industry practices, costs and compare the costs of a modular option against a conventional option.

2.1. Aim

The aim of the study is to compare life cycle costs of a modular building structure with a conventional structure in the healthcare context. It is intended to provide information to future clients, faced with these tender options, on how to carry out an in-depth comparison by considering life cycle costs and evaluating added value. Sustainability is part of the comparison, as an additional cost through the newly introduced carbon tax. The results are to be used to make a hypothesis on the cost-benefit of modular construction projects and determine their competitiveness in healthcare projects.

2.2. Research question

The main research question is - How do life cycle costs of a modular building structure compare to a conventional structure in a healthcare context?

2.3. Sub-questions

Sub-Question 1: What is the typical project scope, process and context of modular construction in the Netherlands?

One of the advantages of modular buildings is that they are constructed quicker. Off-site manufacture allows for work to be carried out at in the factory and on-site at the same time. This allows for shorter project schedules and shorter construction time on-site. It is unknown whether this, and other modular project considerations, are globally advantageous or whether they present new obstacles. With a plethora of modular systems available on the market, the industry does not advertise the disadvantages of modular construction and only presents opportunities. First-hand sources are very useful to solve these unknowns.

Secondly, modular construction is region specific. This is because building products have to comply with local building codes and many preferences are region specific too. The factors are material and labour costs, allowed road transport widths, building regulations and presence of specialists. In Figure 11 below, some differences are shown in the world map. The US and Canada have a long tradition of timber studwork building and therefore their modular construction consists of timber construction of residential properties. Russia on the other hand, has a tradition of concrete block buildings, of which the efficiency and quality is increased by casting the floor and walls of modules in one go. Japan, South Korea, the UK and Scandinavia are advanced advocates of mixed modular construction approaches, with expertise in high-rise modular construction. It is critical for this piece of research to determine the specifics of offered building systems in the Netherlands and describe project processes locally.

Figure 11: Modular construction in the world

Objectives:

- O1.1. Carry out a literature review on the advantages and disadvantages of modular construction.
- O1.2. Carry out a literature review to explain how modules are designed and manufactured and breakdown module and project costs.
- O1.3. Interview Dutch modular construction companies to find out about the possibilities and limitations of offered systems in the Netherlands.
- O1.4. Use the interview information to describe the steps of a modular project schedule.
- O1.5. Summarise the costs and financial options offered by construction companies in the Netherlands.
- O1.6. Use the literature review and interview information to identify the main risks in a modular project.
- O1.7. Identify any available methods of risk management in modular construction and state what checks can be done.

Sub-Question 2: How to measure the value of benefits of modular construction in healthcare context?

Modular construction methods claim to have additional benefits. Every project has its own unique brief and context, which means that the magnitude of the benefits varies. To varying proportion, speed, quality, safety and sustainability may play a role in opting for a modular option. How should one know which benefits and of what magnitude will be secured in the project? An accurate evaluation of the value of benefits is important, but there is no set way of approaching this. Case studies were done in literature (e.g. [21][22]) on the value of a specific benefit, but more can be done to determine the total cost-benefit.

Furthermore, there are studies of barriers in the adoption of the modular approach [23]. An example is that clients and designers may not risk considering or opting for a modular option, because analysing a modular project and its risks is difficult. However, if the economy trends continue, there will only be an increasing number of off-site manufacture companies, with more solutions. This means that a structured approach is necessary for the client and design team, to collect, inspect and compare information to be able to make a comprehensive comparison between modular and non-modular alternatives. The comparison must include lifecycle costs and consider some healthcare functionality requirements. There is no comprehensive study in literature, which would phenomenologically explain the comparison process and parameter impact on the life cycle costing of modular structures.

Furthermore, the building sector accounts for approximately 40% of annual energy consumption and up to 30% of all energy related greenhouse gas emissions [24]. This is a substantial use of resources, with the sector ahead of transportation and heavy industry. It is a major challenge in Europe and the world, to mitigate climate change by reducing the amounts of energy and resources used in the building sector. Improvements can be made through specifying the construction of higher quality buildings and leaner building processes.

Modular buildings are often advertised as sustainable, because the credentials gained from lean manufacturing coincide with a selection of sustainability objectives [1]. To evaluate the benefits, a calculation of emitted and embodied carbon can be carried out to calculate the carbon tax. The point of interest is the scope of the calculation and the list of activities which should be included. Other benefits derived from functionality, maintenance, rebuilding possibilities, can also be considered. Therefore, it is important to answer the following research question – what activities must be considered in a sustainability evaluation of modular structures and how do their results compare with conventional construction?

Objectives:

- O2.1. Using the literature review and interviews from industry, show how quantified benefits translate to cost.
- O2.2. Using the interviews from industry propose which non-quantified cost considerations are to be translated to cost and provide reason for the estimates.
- O2.3. Using the literature review and interviews from industry explain how sustainability can be translated to cost.
- O2.4. Carry out an interview with a hospital facility manager on the priorities in healthcare projects and how they differ to residential projects. Present project information of similar past healthcare projects.

Sub-Question 3: How to carry out a life cycle costing of a healthcare facility project?

To compare the project costs of modular and conventional options, their main life cycle activities have to be considered. A large portion of cost and energy in a building is expended during its operational stage, however, as far as the structure of the building is concerned, the important stages are design, construction and decommissioning. Including these in a life cycle cost analysis is vital to determine the real value of the structure over its lifespan. Applying life cycle costing can reveal hidden costs past the initial construction costs, and therefore affect tender competitions for client benefit. It can also motivate designers to think in a more circular way, to decrease lifespan cost. However, the industry maintains the practice of choosing the winning project according to initial costs, because a life cycle costing requires effort and rigour to produce a trusted result. The approach is relatively simple and with correct scoping of the LCC the effort required is small, providing the opportunity to choose more competitive and sustainable projects.

A Korean study rated the frequency, effect and severity of cost increasing factors in modular construction [25]. It identified inaccurate cost estimation as the third most cost-increasing factor in modular construction out of 49 factors, with the lack of design professionals and experts coming in first and second. The study also split these into controllable and uncontrollable factors, and inaccurate cost estimation is the controllable factor with the larger impact. This means that a better understanding of the cost make-up and tools such as life cycle costing can make a big difference.

A modular building structure can be used for residential and utility building uses such as offices, schools and hospitals. Offices and schools are similar to residential buildings in terms of constructability. Healthcare projects have higher requirements for quality and function in comparison to other building typologies. The 'hotfloor' departments in hospitals host expensive medical equipment and the facility is installation-heavy.

Installations represent 35% of the building costs [26]. This is a challenge in planning for and prefabrication of hospitals in modular form.

Because of this, faster delivery, adaptability and quality of the facility are parameters weighted differently to office or residential spaces. In the UK, a study of offsite prefabrication and modular volumetric construction methods concluded it to be the cost efficient solution necessary for the NHS [2]. Therefore, the UK is planning to build or extend 40 hospitals with modular construction methods until 2030. Looking ahead, how fitting and competitive is modular construction in the Dutch market? How do the costs compare in the Netherlands and is it worth to build hospitals in a modular way?

Objectives:

- O3.1. Using literature review, explain how a life cycle costing must be scoped and carried out. Reason which activities must be considered in the costing of a healthcare facility.
- O3.2. Using a case study project, find out what was considered in the project selection and set up a life cycle costing which represents the case.
- O3.3. Carry out the life cycle costing of the case study healthcare facility and discuss the results.

Sub-Question 4: Which and how do parameters influence the life cycle costing?

A case study can be very beneficial in describing a real project and its specific problems. However, [27] states that it is not possible to deduce conclusions from case studies - this is true in solely quantitative research with statistically derived results. In qualitative research, however, the aim is to establish a hypothesis, theory or framework which applies to the studied case. Further case studies can then confirm or discard the hypothesis.

The life cycle costing can be adjusted to provide additional benefit by proposing a hypothesis. Similar healthcare projects will have different values for the parameters in the life cycle costing and in turn, different results. Furthermore, carbon taxing may increase or decrease with respect to its initial proposal. Therefore, a sensitivity study of the LCC parameters can be carried out to show the possible outcomes of the project under different conditions. Running such a study can help the client's decision making in e. g. whether it is worth to extend the lifespan of the asset, and what effect choosing a less carbon intensive building structure has on total costs.

Objectives:

- O4.1. Discuss which life cycle cost parameters are important for the studied case and propose several life cycle costing scenarios.
- O4.2. Vary life cycle cost parameters to find the boundaries for modular construction in healthcare. Derive under what conditions modular construction is a viable construction method.
- O4.3. Calculate the carbon tax for each tender option and determine how the tax affects construction costs. Calculate the effect of reducing embodied carbon of the structure.

2.4. Methods

This piece of research is both qualitative and quantitative in nature. Qualitative methods were a literature review and interviews with the modular construction industry to collect information on processes and qualities of modular construction. Interviews were also held with experts of healthcare facilities. An in-depth case study was then carried out and a quantitative approach was used in a life cycle cost analysis related to the case study. Sensitivity studies of LCC parameters were carried out to show how each parameter impacts LCC results and what this means for the competitiveness of modular construction in the healthcare sector.

2.5. Scope, Limitations and Outcomes

The scope of the study is the modular industry in the Netherlands, as the industry development largely varies from country to country. This means that construction cost data, the interviewed companies and persons and the case study are based in the Netherlands. The study encompasses the building structure comparison between volumetric units and their conventional alternative in a healthcare project. During initial research, solely steel units were found to be used in healthcare projects in the Netherlands. Therefore, the study is focused on steel module design and cost. Anything beyond the structural skeleton of the building is not considered. It is only possible to consider the structure in isolation, given that it is interchangeable with no effect on other parts and functions of the building. In a strive to objectively evaluate modular structures, it is aimed to discuss wider disadvantages as well as benefits of off-site manufacture in healthcare.

The LCC study is focussed on a conventional lifecycle costing of a healthcare facility which is a defined as the real costs experienced by the client. Only the most important cashflow items are considered in the LCC to communicate the ease and benefit of this method. As it is important for construction research to tackle sustainability, carbon taxing is used as a monetary expression of sustainability when comparing project options. It must be noted, that the study is focused on a cost analysis and an environmental analysis is outside its scope. For the outcomes of the study, it was intended to explain the required cost considerations in an LCC, how to gather information and assess it. Sensitivity studies were carried out to specify the effects on the cost comparison of each cost item consideration in isolation.

The results of the study are limited to the Dutch industry and the healthcare context. The case study results are unique and cannot be used to prognose the performance of modular construction in other hotfloor projects. The sensitivity study results allow to make generalisations on the cost performance of steel units used in healthcare projects in the Netherlands.

CHAPTER 3

Modular Construction

In this chapter, it is aimed to gather information on the specifics of modular construction. The advantages, disadvantages and the build-up of steel modules are first presented through a literature review. Several interviews were carried out with contractors of modular structures in the Netherlands and the results are discussed in themes. The key interview takeaways are summarised at the end of the chapter. The full interview transcripts can be found in Appendix A.

3. MODULAR CONSTRUCTION

Objectives covered

- O1.1. Carry out a literature review on the advantages and disadvantages of modular construction.
- O1.2. Carry out a literature review to explain how steel modules are designed and manufactured and breakdown module and project costs.
- O1.3. Interview Dutch modular construction companies to find out about the possibilities and limitations of offered systems in the Netherlands.
- O1.4. Summarise the costs and financial options offered by construction companies in the Netherlands.
- O1.5. Use the interview information to describe the steps of a modular project schedule.
- O1.6. Use the literature review and interview information to identify the main risks in a modular project.
- O1.7. Identify any available methods of risk management in modular construction and state what checks can be done.

3.1. Advantages and disadvantages

The advantages claimed by modular construction methods are primarily an increase in speed of procurement and construction, and an increase in quality control and safety [3], [21], [28], [29]. Construction projects have general limitations on speed, independent of construction method chosen. Complying with regulations and sourcing of permits is an essential job. Considering the construction method on isolation, speed, as a quantifiable measure, is easily compared between modular and conventional construction (Figure 12). Several stages in modular projects can be carried out simultaneously, with groundworks and foundations being done on-site, whilst modules are manufactured off-site. Modules are also fitted with building installations off-site. These factors can have a substantial impact on the overall project duration.

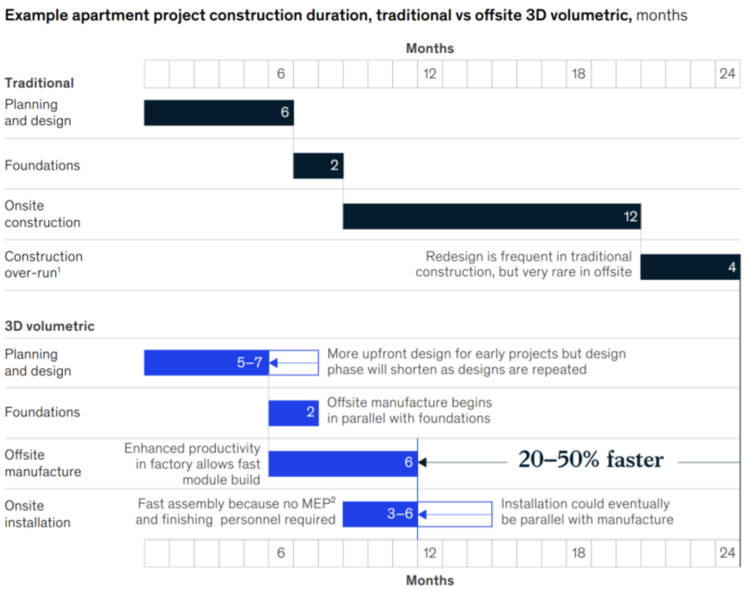

Figure 12: Comparison of project duration, traditional with 3D volumetric construction [5]

As for quality control, the pre delivery tests that take place in the factory allow less space for error and less rework [28]. [5] states that in one instance, the quality of a modular solution minimised the required energy use of the planned facility by 25%. Speculatively, this is due to improved airtightness of modules, tested and brought up to requirement in the factory, which is noted in other studies [3].

Further benefits include on-time deliveries to site; less work and disruption on site, less waste and fewer transport movements [14]. In a study of a twenty-five storey modular residential building in Wolverhampton (UK) it was found that 7.5 modules were installed per day, construction time was reduced by 40%, site personnel was reduced by 50%, site waste was reduced by 95% and deliveries to site were 60% less [3]. Efforts have also been made to research and quantify consequential benefits of modular construction by carrying out comparative studies [30]–[33]. One of these benefits is a lower carbon footprint due to leaner processes.

This explains why modular projects score highly in sustainability assessments [30], [34]. The construction is typically lightweight or lighter than the traditional alternative due to lean practices [34], [35]. For foundations, this normally means a reduction in complexity and some cost savings [5][36]. Furthermore, modular unit structures can fundamentally be disassembled or deconstructed. Units can be moved, replaced and reused, utilising the structure of the unit until the end of its technical lifespan. . These benefits are difficult to quantify as it is speculatory what will happen in the future and what changes will be needed. However, a qualitative assessment and estimate of the added value in the Dutch market, can help to overcome knowledge barriers in the adoption of modular construction [23].

Lastly, modular projects require many design decisions to be finalised before any manufacture or construction starts. A frequent issue in construction, particularly with large projects, is that they tend to run over the set time schedule and budget. Factors of cost uncertainty, client decisions, extent of preparation and delays are responsible for this [37]. Modular design is only possible with a high extent of preparation and the standardisation of building products allows for a more tangible cost estimate. It is likely that choosing modular construction will lessen the risk of overruns.

Due to limitations of modular building, which are discussed next, a modular design can benefit from the right project context. In Figure 13 below, repeatability, unit size and value density are specified as a simple rating scheme for each building type. Repeatability is a very important factor, which allows efficiency of scale in the manufacture of identical units. Unit size is a design specification, however, large modules may cost more to manufacture and transport. Value density signifies how expensive a module is, and the figure shows that for hotels and hospitals, this factor is high. The fitting and testing of installations and finishes in a controlled environment may prove very advantageous for these building types. This shows that for each building typology, an approach must be defined to maximise the benefits of modular construction.

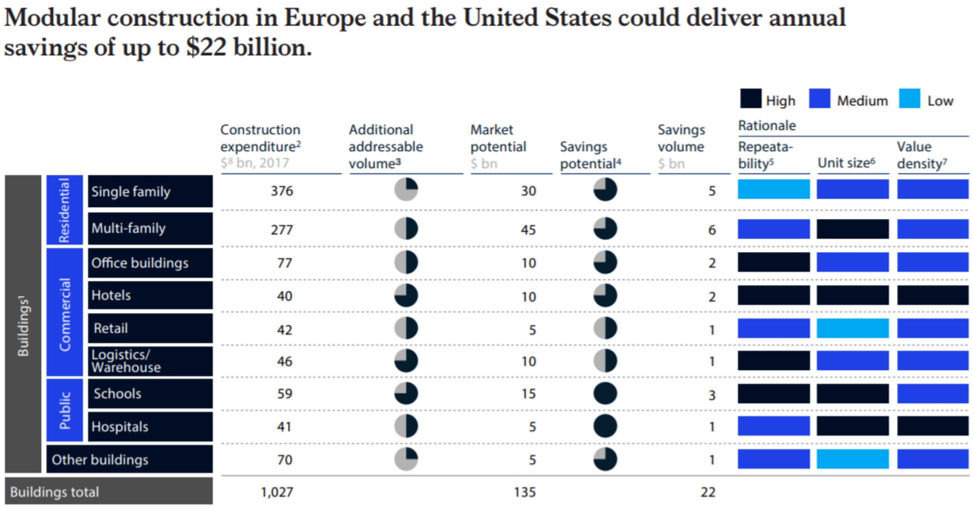

Figure 13: Potential of modular construction for different building typologies [5]

It follows, that modular construction in units is ideal for both small and large, repetitive and rectangular building structures. Apartment blocks, schools and offices where a single chosen architectural grid is followed may be the most suited for modular designs and high level of finish can be achieved off-site if custom solutions are kept to a minimum (Figure 13). It follows that curves are to be avoided, and structurally complex solutions are done more efficiently using other systems. Examples of difficulties in the design are staircases, lift shafts, cantilever structures and atria. Unlike to popular belief, modular structures do not have to carry an industrial aesthetic and a level of custom solutions and façade options can make the building appealing without compromising on efficiency. 3D units are most appropriate when focusing on maximum cost efficiency, with design limitations that follow. Whereas 2D panels are more suited for designs that require more flexibility.

Building with a certain modular system also has related disadvantages. One of them is the investment of time upfront, in the detailed planning of the building. This is unhelpful because design decisions must be finalised early in the project, and it is expensive to incorporate changes down the line. A limited amount of design options may be available [38]. This is particularly true for the 3D units. 2D planar element construction is more flexible, but in turn takes less benefit of off-site manufacture. A client knowledgeable about this construction approach can minimise the risks associated to expectations and modifications of the project.

Transportation by road is a project defining limitation [39]. 3D units are large and unlike panelised products, cannot be stacked. Units placed on lorries must comply with certain dimensions. Methods to maximise module size are using a low deck lorry or acquiring permits for loads of large dimensions. Oversized loads and permitting should be avoided, because it is costly, time-consuming and can hinder the efficiency of on-time deliveries to site.

Modular project costs can vary from traditional proposals. In a developed, competitive market of modular structures, manufacturing efficiencies could lower project costs by 20% [5]. However, the modular market is still developing, and developing differently in each national market. For the time being, costs are expected to be high in comparison. The key question that should be asked when considering the costs of a modular project is - what is the value of the benefits from modular and what is the premium that must be paid for it?

Project tenders can be specified more favourably towards traditional construction methods, therefore ‘clients must make a presumption for offsite’ construction [40]. Otherwise, projects may have too much custom work or no design options for a modular designer to be interested in. The compromises and advantages of using a modular approach are then not considered, which hinders the uptake of modular building. The forms and volumes may not be designed with modularity in mind either.

From an engineering point of view, attention has to be paid to the tolerances of systems and their interfaces, which are largely dependent on the type of connections used [41]. Tall or wide structures need other structures to support the units and produce acceptable displacements at extremities. Therefore, large and complex projects may prove a cost-efficiency challenge for the unitised approach. Modular structures additionally suffer from fire resistance and robustness issues [41].

To summarise, a large part of the stated disadvantages are related to project risks. These are risks present in design variation, choosing the optimal level of off-site manufacture and applying the right modelling and production methods.

Risk category	Risk factor	Explanation	Notation
General risk factors	Economic condition	Economic boom in terms of construction GDP contribution, which affects both construction cost and productivity	EC
	Political & social condition	Change of government policies, change of political support due to change in political environment, and worker strike etc.	PSC
	Construction planning	Project planning for construction	CP
	Construction coordination & control	Project coordination and control during construction	CCC
	Change in design or scope of work	Change of project design or scope	CDS
In-plant risk factors	Drawings supply time	Supply time of shop drawings to plant	DST
	Drawings quality	Errors and clarity of shop drawings	DQ
	Material supply time	Material supply on time to plant	MST
	Material quality	Quality and type of material	MQ
	Labour availability	Labour quantity available for plant	LA
	Labour skills	Skills and experiences of labour	LS
	Fabrication equipment condition	Production line condition in factory	FEC
Onsite risk factors	Temperature	Temperature degree, which affects the productivity of onsite construction, especially in winter	T
	Wind speed	Wind speed, which affects the productivity of onsite erection, and can cause construction cancellations	WS
	Site condition	Ground condition and neighbourhood environment	SC
	Construction equipment condition	Heavy equipment (mainly crane) condition for lifting and installation	CEC

Figure 14: Risk factors in modular construction [42]

A big part of the evaluation of benefits is risk management. As shown in Figure 14, there are risks stemming from prejudice, design and construction, both off-site and on-site. A rigorous risk assessment can help to minimise changes to the budget and time schedule.

3.2. Types of steel modules

To understand modular construction, it is important to discuss the specifications of units and the breakdown of the costs of each activity. This first part of the literature study is based on the information from Professor Robert Lawson from the University of Surrey, who has written a book in 2014 and several articles on modular construction [3], [14], [43], [44]. Up to date, his research is the most comprehensive overview of modular design and cost.

From a structural point of view, the main difference in the design of modules is whether the walls or corner columns are carrying the load. Corner supported units have open sides, which can be connected to form larger rooms. The wall bearing modules are more economical. The layout of space is the deciding factor for which module type is has more advantages. Additionally, there are non-load carrying modules called ‘pods’. Pods are commonly used for bathrooms and other installation-heavy spaces and are inserted into structural units.

Figure 15 (left): Wall bearing module. Kingspan Steel Building Solutions [3]

Figure 16 (right): Corner bearing module. Kingspan Steel Building Solutions [3]

Wall bearing modules (Figure 15) are dependent on the compression resistance of the U-section beams in the wall panels. Resistance can be increased by doubling them up or using a thicker plate profile. Corners can either be made of U-sections or angle sections. The corner columns are used for lifting and for attaching modules to each other, however, the majority of vertical loads are still carried through the walls. Stability is provided with X-bracing in the walls or diaphragm action of panels fixed to the profiles. The advantage of this unit type is light the light stell construction, which is cheap and easy to handle. These units are limited in their stacked height – maximum 4 stories.

The common sections used in corner supported modules (Figure 16) are SHS profiles or angles for the corners, and I-beams spanning in-between. The depth of the beams increases with the span. Floor hight is therefore an important consideration when sizing this type of module. Intermediate posts along the span reduce the beam depth. The main advantage of this type of unit, is that the sides of the module are open, and modules can be connected to create uninterrupted floor space. However, in comparison to wall supported modules, these units lack stability due to the flexible connections between corner posts and beams. Bracing must be installed in addition, and it is commonly located around staircases. The height of 4 to 8 stories can be achieved, and 15 stories with support structures such as concrete cores or additional bracing.

Another variation of this type of unit is an open-ended module (Figure 17). Instead of separate corner posts, a welded steel frame is installed on the short end of the unit. This allows for ceiling to floor windows to be installed and, structurally, the welded frame can provide lateral resistance to the unit.

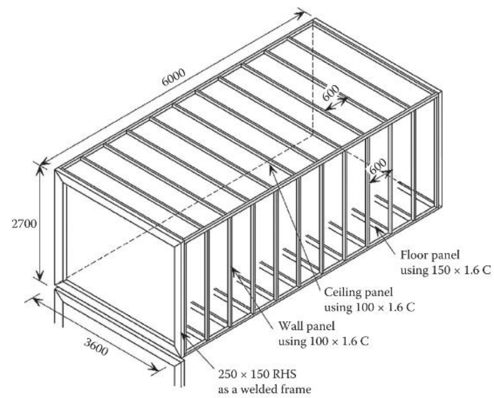

Figure 17: Open-ended module sketch [3]

The type of units is chosen according to the function and layout of the building. Wall supported units are suited for a large variation of accommodation arrangements, hotels, offices and hospital wards. Corner supported or open-sided modules are required for uses where large or flexible floor space is necessary. This is the case for open-spaced offices, retail, education and healthcare applications. Steel units are in general not suited for industrial application and high security uses such as prisons.

3.3. Module build-up

Steel modules are built using an industrial building method of light steel framing. This building method has been derived from timber framing [45]. Cold-formed thin light gauge steel U-profiles of 1-3mm in thickness make up a load bearing structure and are characterised by their versatility and light weight. The units travel on a conveyor belt or mobile platform, where each trade has its workstation: welding, studwork and installations (Figure 18).

Figure 18: Legal & General's UK factory lines

Literature states that light steel framing systems can fulfil high functional requirements [45]. Serviceability criteria always govern units with long spans. It also states that gypsum board fixed to the steel studs is effective in stabilising low to medium height residential buildings. Special steel studs with longitudinal incisions to stop thermal bridging are used at the facades. Several layers of plasterboard are often required to achieve the fire resistance required. The light steelwork is used in the floor, walls and ceiling of a steel unit. Corner post are thick hot-rolled steel profiles.

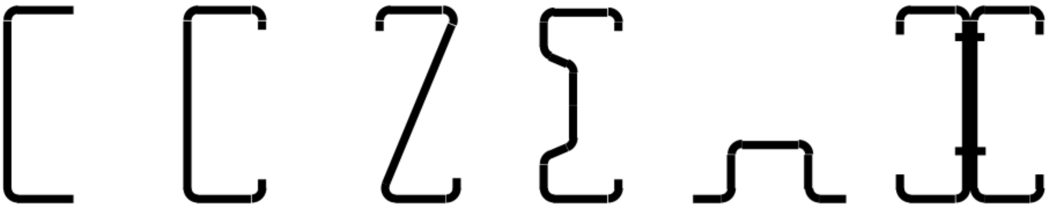

Figure 19: Common light steel profiles used in modular construction [4]

The dimensions of a building module are influenced by the architectural grid which varies according to function. The dimensions also depend on the building form, road transport allowances, alignment with the façade and optimisation of wall and floor thicknesses to maximise useable floorspace. A common grid is a 300mm spacing. Therefore, it is reasonable to aim for a 3m to 3.6m wide, 2.4m to 4m tall and 6m to 12m long module [3]. It is difficult to provide required spaces with smaller dimensions, whereas larger dimensions mean more costly manufacture and transport. The typical weight of such a module when it is fully outfitted is 5 to 8 tonnes [3].

Furthermore, transportability has to be considered. In the EU, Directive (EU) 2015/719 sets out the maximum dimensions and weights of road transport. 4m tall, 2,55m wide and 12m long is a standard European lorry. There are variations and exceptions on larger dimensions per country. Wider lorries are allowed, for example, for the carrying of cars and containers. This means that depending on the dimensions of a building module that must be brought to site, a permit may have to be acquired, adding to the cost.

3.4. Interviews with industry

The modular construction industry differs per region due to differences in regulation and market developments. The research done in the UK, Sweden, South Korea and the US, where the majority of knowledge on modular buildings stems from, can be applied to countries where modular methods are evolving. It is important to find out what procedures take place, what are the costs and the limitations in the specific location of the Netherlands.

Interview Rationale

It was chosen to hold interviews because there is a small amount of volumetric modular manufacturers of permanent buildings in the Netherlands. Using surveys would have been inadequate, as it was expected to receive complex and phenomenological answers, and surveys are best for large sampling and straight forward questions. Interview questions were fixed, supplied to the interviewee in advance, and open-ended in order to investigate what topics matter to the respondent. Using semi-structured interviews also allowed the respondents to mention as much relevant information as possible, making their particular case for or against a proposition. The opinion of manufacturers on the procedures, risks and costs was paramount. Structured interviews would have not allowed the interviewee to explain further on what they found important and unstructured interviewees would have easily turned into a promotion for the company, in addition making it difficult to compare responses.

The interviews included questions on modular buildings, design of modular healthcare facilities and costs. Initially, questions on the environmental assessment of modular structures were also included, but through a narrowing of the study aims, these answers were disregarded. Follow-up answers on costs and life cycle costing were sourced from the interviewees through email. Questions on modular design and healthcare projects consisted of qualitative discussion on context and challenges. Questions on cost focused on actual costs of products and labour as well as financing options. The list of questions, and interview transcriptions can be found in Appendix A.

Interview List

Table 1: Interview list

Company	Contact Person	Experience	Date	Accepted?
Finch Buildings	Reno Mol	Chief Operating Officer with 1 year of experience at the company.	23/02/2021	Discarded
Dutch Cabin Group (DCG)	Angelo de Vries	Technical Advisor/Tender specialist with 8 years of experience at the company.	01/03/2021	Accepted
Jan Snel Daiwa House Group	Jorrit Janmaat and Sam Nederend.	Jorrit Janmaat – Account manager in Healthcare. 4 years at the company. Sam Nederend – Junior Project Manager in Sustainability. 1 year at the company.	03/03/2021	Accepted

Neptunus	Danny Verhaeg	Project Manager. 27 years at the company	10/03/2021	Discarded
Ursem Modulaire Bouwsystemen	Boaz de Boer	Head of Commerce. 22 years at the company.	08/07/2021	Accepted

Companies were contacted with an introductory email or phone call explaining the research topic and what would be discussed in the interview. Interview questions before the interview were provided if requested. Interview requests were sent out to 12 companies, that claimed to design or sell modular buildings in the Netherlands. Companies were found by checking europages.nl which has over 3 million companies listed, for keywords 'modular construction', 'modulaire bouw' and 'unitbouw'. Out of the found companies, 12 were contacted, 6 responded to my request and 5 interviews were organised. Video and audio recordings were made of the interviews. A few companies were discarded due to being out of scope, which was stated in research methodology.

Analysis

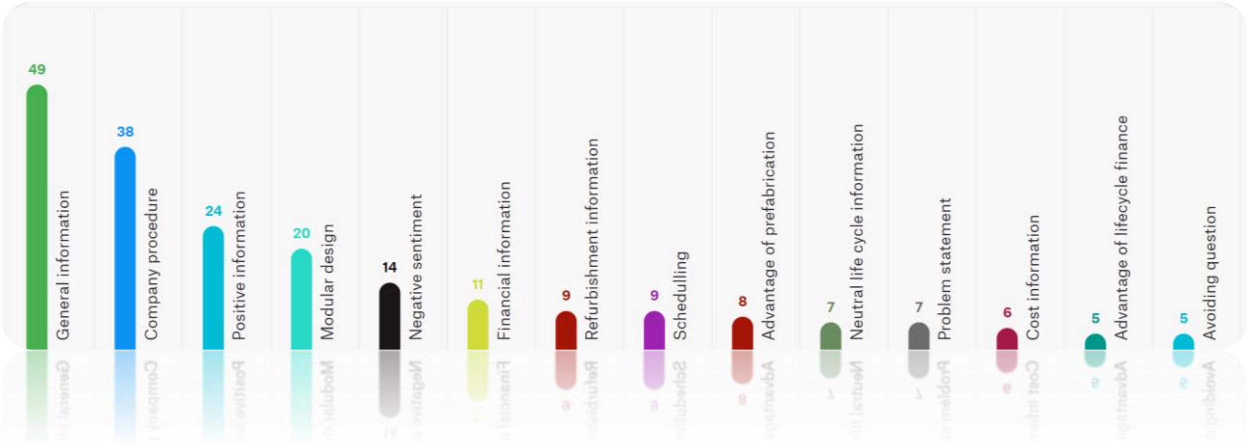

Figure 20: Atlas.ti codes used in interview analysis

Atlas.ti was used to apply codes (Figure 20) to phrases and sentences in the interview analysis. This allows to isolate a single topic and see the responses in particular themes. Codes were created to sort the interview data as well as identify sentiment statements. The codes were condensed into themes, which are presented below. The results contain paraphrased answers of the correspondents. The transcriptions were confirmed by the interviewees. Manufacturer information was gathered during the interviews and a summary is provided below.

Table 2: Manufacturer information

	Dutch Cabin Group B. V. (DCG)	**Jan Snel Daiwa House Group B.V.**	**Ursem Modulaire Bouwsystemen B. V.**
Description	The company offers a selection of services, with a big choice of modules for rent. Permanent building projects range from student residences to hospitals. Comprises brand names: Primakabin, Wagenbouw, Cabin Concurrent, E.Rent Raumsysteme, Direct Bouw, Hamburg Verhuur. The company is under the Finnish	The company builds for a wide range of functions. Housing, offices, education, industry and healthcare.	The company focuses on modular residential and hotel projects. The company also produces bathroom pods for non-modular projects.

	company Adapteo.		
Systems offered	DirectSysteem (for semi-permanent and permanent units), ElementenBouw (for temporary buildings), WMO Units (home extension units with a healthcare orientation).	MOVIX and Modular Units. MOVIX is the use of floor cassettes and ceiling cassettes, wall elements (all flat products) and columns (stick product) and can be called a hybrid system.	Unit system of concrete floor and steel structure for up to 23 storeys. A Cross Laminated Timber (CLT) system for 2 storeys.
System height	2 storeys self supporting, 5 stories with wind bracing	16 stories with concrete core and steel bracing	Ursem can go to 23 storeys, for which a concrete core is required. There are some braces in modules. Non high-rise structures are 5-6 stories with steel bracing and no core.
Unit production capacity	-	5000 units	2000 units per shift, 4000 with two shifts.
Unit cost (euro)	5000 (Only the structure)	13000 (Only the structure)	45 000 – 50 000 project cost per unit. This includes the complete unit price, foundations and all labour.
Max dimensions	Max unit is 3.6m, 10m long and 3.5m tall.	MOVIX system for 7.5m spans, otherwise custom up to 20m. Project specific sizes of Units.	14.5m max length, max cassette dimensions 14.5*4m.
Buy back	Yes	Yes	Yes
Leasing	Yes	Yes	No
Amount of employees in manufacture	40 permanent (interview)	200-300 (this includes workers on site)	40 permanent, can scale up to 120
Revenue	20.8 mil. Euro in 2019 [1]	Jan Snel B.V. 142 mil. Euro in 2020 [2]	6 mil. Euro [3]
Kvk report extra information	In the 2019 report, DCG has a commitment to buy back modules for the worth of €191.200 euro in less than one year, €1.587.200 euro in one to five years and €650.000 euro in over five years' time. In addition to these obligations, the group has the right to buy back some 78 units for an	The company has access to credit guarantees of €85 million through the group. Additionally €5 million bank insurance. The company is committed to buy back modules worth €10.000 in less than one year, €16.000 in one to five	In one project, Ursem has a commitment to buy back units for the cost of €1.000.000 after 10 years.

[1] Kvk 2019 Dutch Cabin Group B.V.
[2] Kvk 2020 Jan Snel B.V.
[3] Kvk 2019 Ursem B.V.

	amount of €250.000. If they do not make use of this, they are obliged to transfer the units to the customer. The option and the obligation both have a term of less than five years.	years, and €38.000 in over five years.	

The Kvk reports show that all companies have agreements to buy back modules. This is good proof that the residual value of modular construction is being utilised. A kvk or company yearly financial datasheet is a simple check of financial commitments of the contractor which the clients can do.

Interview Results

3.4.1. Modular design

Requested to comment on the different definitions of prefabricated and modular structures, the interviewees responded that both are prefabricated products but the main difference was the definition of 2D and 3D products - flatpack elements and volumetric structures. With volumetric elements 80% of the labour is done in the factory, leaving 20% to be done on site. A lot more work is left to be done on site if opting for flatpack. With flatpack, there is less transport and elements can be easily stacked, but there is more assembly onsite. Traditional companies are including more prefabrication methods in construction to increase construction speed, and they may advertise this as modular construction.

> "Modular construction is the use of prefabricated 3D units" (Jan Snel)

Modular methods are suitable for projects of rectangular floorplan, such as schools. Unsuitable project are stadiums and skyscrapers, projects with curves. Repetition of a decided upon module size is key, making a 100 units of the same dimension or a couple different unit types yields the greatest efficiency of scale. Lifts and staircases can be integrated within the structure of a module or installed separately. Non-modular parts of the project must be minimised as much as possible and make up 10% or less of the project. Good module design is also a balance between material use in construction and energy efficiency of the building in use.

Modular buildings are designed in a modular grid. The plans are based on module sizes, not on the use of space. The stability must be also considered at the start. Several modules can be joined to form a single space such as an apartment. A usual social housing apartment for example is made of two modules, each being 3.8m wide and 11m long. The manufacturer, in addition, must decide on the level of finish, whether to aim to complete the module inside the warehouse or to manufacture the main elements and do the finishes onsite.

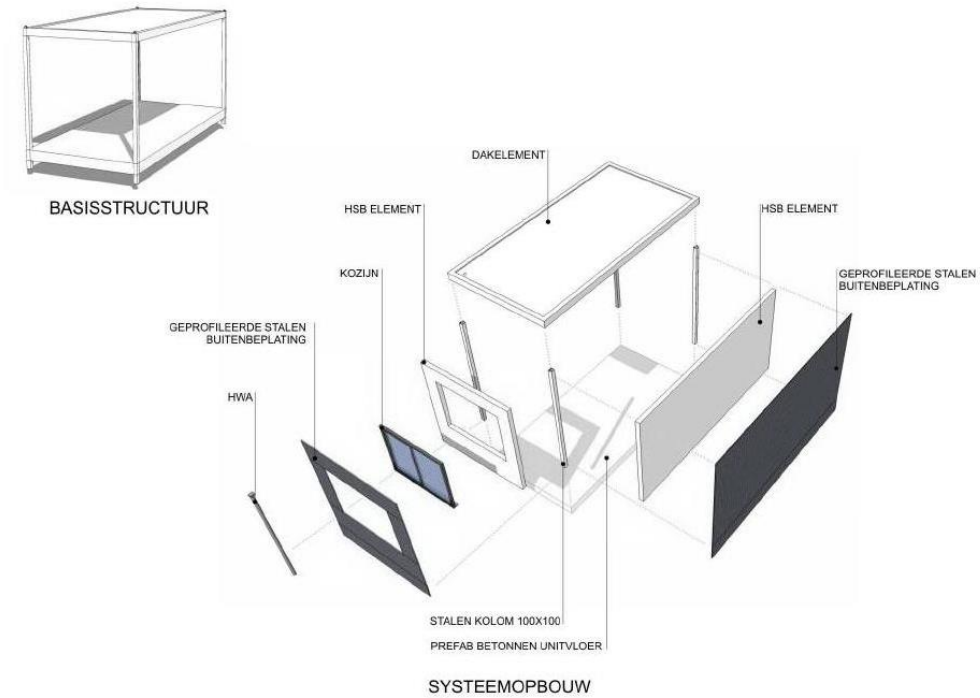

Figure 21: DCG provided system build up in Dutch

"The project must be started with the manufacturer, otherwise time is wasted"
(Jan Snel)

Modular systems are designed to fit with normal building code, structural and fire regulations. This is done so that the modular structure could be compared to a conventional structure and no further verification would be necessary. Fire protection can be provided for the standard 60 mins. However, 120 mins of fire proofing is 8 gypsum boards, which is a lot of extra material and lost floorspace.

Modular steel buildings are light, which requires smaller foundations in comparison to conventional concrete buildings. When it comes to the weight of structures and building foundations, the respondents agreed that it is standard to build heavy concrete buildings in the Netherlands, therefore, modular steel construction is a lighter alternative. When compared to a traditional steel structure however, the difference in weight is insignificant. An advantage of adding some weight to a modular structure was also noted, extra mass is beneficial thermal storage in summer and winter. Therefore, the floor cassette can be a steel frame or a concrete slab. A concrete floor cassette is a beam around the perimeter with a thin concrete slab spanning the middle. This is more efficient than a solid concrete slab. The DCG respondent stated the technical lifespan of a steel module is 50 years.

3.4.2. Healthcare

The Jan Snel contact stated the UK is far ahead in the modular design of healthcare facilities. Germany believes in concrete structures and modular structures are therefore less adopted. The Netherlands is at the starting point or a bit further. Not many hospitals are constructed in a modular way, most of the work is in extending existing hospitals with modules, 5000 m2 of additional floorspace, for example. There are not many new hospitals built in the Netherlands, around 1 a year.

“For healthcare projects, installations have to be put in on site. In residential modules everything is installed in the factory, and so the efficiency is improved.” (Ursem)

With respect to the modular design of healthcare facilities, more work is done on site. For example, the air treatment plant for operation rooms contains loose parts and cables, which are assembled on site. Medical equipment is also installed onsite once the structure is in place, through an open side wall. Ursem confirms this saying the competitiveness of this construction method decreases, as less work can be done in the factory. The respondents recommend that the manufacturer is included in the design process from the very start, and this is imperative for healthcare projects, with an example given for the Wilhelmina Kinderziekenhuis in Utrecht, where the client spent 200 000 euro to remake plans in a modular way, since the permits were already sourced.

The reason for not building all hospitals in a modular way was put down to the fact that it is a small circle of companies working in the healthcare sector and they try to keep it so. This may explain why architects design hospitals in a non-modular way. A big problem is that there are a lot of hospitals from the 70s, built with a lot of concrete, which is now a problem. The unused space must be paid for and you can’t adjust it. Some healthcare installations in a modular project have to be put in on site, which lowers project efficiency.

3.4.3. Project procedure and schedule

When it is agreed to start project design, the client is provided with the project cost and the availability of the manufacturer. A project schedule is put together and a slot in the factory schedule is reserved. The project manager must take care so the two schedules work in conjunction and that project delays do not have significant effect on the factory schedule. The client must make sure that the permits and financing is present at the right time, but it was highlighted, that clients are usually late. If the permits and procurement are fixed, then the production capacity and managing the production effectively is the focus to deliver to budget and on time. At the same time the order is put in, the subcontractors are notified with standard delivery orders and obligations. The delivery date is guaranteed because of tight factory schedules, experience and a ‘no nonsense’ mentality. Furthermore, there are fines, which are agreed for every day spent past the agreed project delivery date. These are agreed at the beginning and DCG stated the fine can be up to 250 euro per day per module. The project schedule is normally 30-40% faster than a conventional project.

Healthcare clients work with an architect first and then a modular manufacturer is consulted. Most of the decisions are already made by then. The manufacturer could advise about modular sizes and dimensions if they were asked earlier. The experience in building in modular is free for the client, if they ask for the manufacturer’s input. But the architect often has his plans finalised, which costs extra time, engineering and money, to then build in modular methods.

Companies offer a mix of financing options to clients. These include short term renting, long term leases, buy-back options, residual value guarantees, moving the structure to another location after a certain amount of time. Depending on the strategy of the company, some of these services are within the scope of the company, profitable and therefore advertised to clients. Other services are possible but do not bring profit and are only arranged in special cases where it may be necessary to win the tender. Recommendations on calculating saved revenue are given to the client because the modular option, in most cases, is more expensive. The time saved through faster construction allows for revenue streams. The client must do this calculation themselves.

It is agreed by the respondents that there is more control over a modular project because of the intense design and engineering phase in the beginning, when the majority of decisions are made. The respondents all agreed that the same supply chain delivery delays apply to modular and conventional construction, and that it is a rare occurrence. Some construction products purchased for modules are custom-made by subcontractors. COVID was given as an example reason for slowing down deliveries, but it did not cause project delays. Furthermore, once a project is agreed, it is very uncommon for a client to request a significant change which would affect the manufacture. The change would also incur a large additional cost. DCG added that the use of a BDB (Bureau Documentatie Bouwwezen) index helps with material price increases. If the project starts a few months later, the BDB index can be applied and increase the contract price by a percentage.

When asked about what is presented to the client to convince them to opt for modular construction, Jan Snel contact said owning their own truck fleet helps with on time deliveries. The DCG respondent opposed saying that owning the truck fleet does not have anything to do with being on time or budget. Ursem pointed out, that a reason for choosing modular offsite manufacture is given as a tight site in a dense urban area. In such a case, on-time deliveries with finished modules are preferred as there is no space to store materials.

3.4.4. Costs and financial options

Module

For DCG, a standard unit is 3x3x6 m, consisting of a concrete floor, four steel columns, a roof, without outer walls, and it costs about 5000 euro. Jan Snel estimates a module of 3x3x6 m, made of concrete and steel without finishes, costs roughly 13 000, excluding engineering, VAT and transport. A standard module is not used for operation rooms and healthcare. The cost depends completely on the function of the module/building (OR/offices/low care). Ursem noted that the work on site should not be undervalued. Installing foundations and the modules is expensive. The project costs per module amount to 45 000 - 50 000 euro. This is inclusive of all construction costs and refers to student housing.

The height of the building affects the cost of the project. Ursem gave an example project in Amsterdam of 350 student homes, the module cost is 60 to 70% if the project is 5 stories, but this percentage decreases if a core is required to go to 16 storeys. Jan Snel agreed that depending on the scale and type of the project, the modules cost 25, 35 or 50% of the total price.

> "The modular option is most of the time not cheaper than the traditional. Therefore the client is encouraged to calculate the extra revenue that is gained through faster construction." (Ursem)

Ursem says the work in the warehouse is repetitive and easier than the work onsite, where there are different complex tasks to do. The team that lifts and installs modules are highly trained experienced specialists, which makes their hours more expensive. Furthermore, the manager of the department and the machinery is expensive.

Transport and lifting

Ursem specified transport and lifting to be 2000 to 2500 euro per unit, depending on the crane size. DCG said that when putting the request to their transport partner, the size also determines whether one or two units can be put on a single truck and that 450 euro for the transport of a single unit is a reasonable price. Jan Snel said transport truck costs 500 euro per 150km for a module of a total height of 3.1 metre. A module of 4 metre height needs a special deep platform truck (dieplader) and costs approx. 800 euro. A mobile crane can cost 1000 euro per day up to 30 000 and more, depending on the project and the location. DCG said two factors help determine the heaviness of the crane – the number of units that have to be lifted and the distance from the truck to the placing position. A normal crane is a 70 to 90 tonne crane which costs about 90 euro per hour and two employees handle the units. For the transport of modules, a width of 3.6 m is allowed in the daytime and 4 m at night. A 4 metre wide module requires a permit to be transported during the day.

Displacing of buildings s discouraged. It is expensive and requires a lot of labour. When reusing the structure, the foundations and work on site still have to be done. Modules have to be disconnected, lifted, transport, lifted and installed. If a company wants to build a project, rent it out for 5 years and then move it to a new location, the foundations must be done again and this doesn't make financial sense. It is more sensible to just build on the permanent site in the first place.

Lifecycle

Ursem presented an interesting case when discussing the lifecycle of modular projects. This project is a 12 year lease, with a guaranteed residual value after that time period. This is needed to get the funding from the bank in the form of a loan, with the assurance that the property will hit this target value. After 20 years, a traditional property will have some value, but what is the value of a temporary building that is removed after some time? The guarantee from the manufacturer is necessary to have the project feasible for the client. Without it, funding is not possible. The value guarantee given after 12 years is 30-40% of the initial investment. 10 years is the minimum for a project to be in a temporary location. If you plan for 5 years only it is not financially feasible.

> "The two financial advantages is less interest and more revenue due to the saved time." (Ursem)

DCG buys back modules and the cost depends on the size of the project. The price is 30-40% after 5 years, 20% after 10 years and up to 10% after 20 years. They can lease for 30 to 45 euro per unit per week, depending on the size, duration and type of units. Jan Snel buys back units after 5, 10, 15 years. The percentage depends on what kind of structure and module size it is. It can be up to 15%. Leasing is an option too with an interest of 6%. Ursem can take the modules back for free after 20 years of use, but does not strive to buy back modules. The building still has value, but this only covers the disassembly and transport back. DCG agreed that demolition costs money, so taking away modules for free is a service too.

There is an issue associated with these guarantees. If the guarantee provided by the manufacturer is later checked after 5 or 10 years in a re-evaluation, and the value is not as expected, this is a problem for every party. It is not clear if the manufacturer or designer would take any responsibility in this case.

3.4.5. Project risks

Some of the project risks mentioned in the interviews are associated with the client and general stigma about modular construction. Clients were said to be responsible for delays due to not receiving permits in time. Van Ursem manufactures 600 modules instead of 2000 because of this. Delays of half a year are not an exception. The main problem is not the amount of modules that can be made, but rather having a continuous flow of projects which to put modules in. The biggest problem in modular construction is when the factory thinks it has production but then stands empty. Reservations in the factory schedule are precise and if there is a project delay, there is no production in the factory for the delayed period. Ursem also manufactures traditional buildings and scheduling is less affected by late permits or late financing as there is no production that has to be queued in the factory.

> "We normally have time over because clients don't live up to the agreement to the schedule." (Ursem)

A stigma to modular construction was stated as the perception of modular buildings as temporary, such as container buildings, but that is not a good representation of what is available on the market. Financial people must also be convinced on the costs and that there is no trickery. People have to see the modular manufacture process. Clients are used to the traditional way of building, which means that if they see a foundation being laid, they think that something can be changed on the roof, but that's the wrong idea. The client is told a hundred times, but most of the time they don't understand. Another example is not involving the manufacturer from the beginning - an architect for the Wilhelmina kinderzienkenhuis got permits for his traditional drawings, and had to spend extra 200 000 euro to convert it into a modular design. The manufacturer must be involved from the start.

Further stigma with modular construction is related to the unknowns to modularity. This may discourage building healthcare projects in modular. A client will look away from modular techniques, if they don't want a rectangular building of if they don't know enough about modular construction. There are also differences by country. Jan Snel said modular construction must be incentivised, similarly to electric cars. People have been designing in traditional methods for years, so it is difficult to change.

The construction industry is developing slowly. Traditional companies are moving over to prefab products such as prefab walls and ceilings and they may call it modular. Effectively it is flat prefab products to increase construction speed. It is not modular and they can't offer a completely outfitted unit. Jan Snel said that traditional companies started this 5 years ago, but it has been available for over 60 years.

> The next crisis, according to the government, will be the climate and it is on the agenda. This product is therefore more used. You see it more with housing, because we need millions of new houses for the next 10 years. Please do it in prefabrication. But for hospitals, there are no sounds at the moment. (Jan Snel)

3.4.6. Client recommendations

In the interviews, client expectations and responsibilities were covered extensively. The information concerning the client perspective is summarised here.

Responsibilities

The interviewees made clear the importance of client awareness of the differences and responsibilities in taking on a project with largely offsite manufacture. Changes are not possible starting from very early on. The client must have the required permits ahead of time, because once the manufacture order is in, it largely cannot be changed or halted. This may surprise clients used to traditional project schedules and requires the client to be more decisive in the design stage.

Clients should also be aware of the actions of the government. The Dutch government is incentivising circularity in construction, but is therefore not directly promoting offsite construction. If it was to promote offsite manufacture, this would likely disrupt the industry. It would cause some players to be expelled from the industry. A governmental accreditation system to promote offsite construction in the UK is summarised in Appendix B. Without direct governmental support, the client must carry out checks to gain confidence in the ability of the contractor to fulfil the project. It is paramount, that the manufacturer has enough capital available for manufacture processes and project risks. The clients can then gain from using mixed financing options offered by contractors, such as leasing and buyback agreements. For projects with a lifespan of less than 20 years, these options should be considered.

When it comes to sustainability, carbon taxation of construction products was said to affect the dynamics of the construction industry in the upcoming years. However, the client does not have to take any action associated with this tax as it is incurred internally. It is planned, that the industry will self-route towards minimising carbon dioxide intense materials and processes. Furthermore, if environmental credentials are not considered, displacing a modular structure to another location is only about 30% cheaper than building new. This value is probably not big enough for displacement to be regularly considered, taking into account associated risks. Therefore, the client must be aware that it is unlikely to be financially sensible to move a modular building.

Risk management

The accreditation system for offsite construction discussed in Appendix B is focused on testing the durability and in turn the ability of an innovative construction method to store value. From the interviews, it is evident that modular building products on the Dutch market are created to fit the building code, but may require additional engineering proof for complex projects. It is likely that if a building system does comply with the building code, it is tested at the TNO, the organisation for applied scientific research in the Netherlands. The client should contact the modular manufacturer and enquire about their system, find out the limitations of the system and what tests, if any, provide confidence that the system is safe and durable.

Once a basic understanding of the modular system is gained, the manufacturer credentials must be checked. Past projects remain the best source of proof. The client must make sure that the manufacturer has built structures of similar dimension, function, cost and to the expected quality. This requires the client to be knowledgeable of both their own needs and what can be delivered with modular methods, which may be challenging for inexperienced clients. A discussion must also be held with the manufacturer about risk management techniques used during the project. Considerations must be the planning of budget and time frame, availability of factory slots and workforce.

To reiterate, given the large investments required in setting up a modular contracting business, financial indicators are very important. The modular contractor is essentially a traditional contractor which also owns and runs an industrial factory. Checking the business' revenue, assets and liquidity is essential to trust the manufacturer with the order.

Costs to consider

A tender choice based on the initial quote of construction costs is most common. Tender options that include certain benefits can be chosen if the cost-benefit analysis exposes additional value gained over cost. Cost-benefit analyses inadvertently take time, require knowledge and considerations can be questionable. It follows, that in a project with added value, it is best for the contractor to provide proof of the extra value. However, from what has been found, this may not be the best approach for modular construction options.

Modular proposals in the Netherlands are likely to cost more than traditional ones. They have additional project value and inherent salvage value in the structural components. The main additional value is faster construction, which allows for the asset to start generating revenue sooner and for less interest to be paid. This can realistically only be calculated by the client themselves.

Inherent value in the structure is the ease of deconstruction and reuse, which results in a residual value higher than that of a traditional structure. Carrying out a life cycle costing of a modular structural skeleton against a traditional one is the most straightforward way to weigh the benefits against costs. Initial cost comparisons are an oversimplification, as resource costs incurred during the lifecycle and the decommissioning of a facility have significant effect on lifespan costs. Life cycle costing, common in other industries, is an effective tool when the comparison scope is well defined and each considered activity is reasoned. For modular construction, the undeniable activities to consider are:

- Construction cost
- Gains due to earlier opening of facility
- Gains due to lower interest
- Operational cost
- Residual value
- Deconstruction cost

Other activities to be considered when relevant are:

- Environmental cost
- Maintenance and Refurbishment cost

3.5. Summary of interview results

These are the subjective comments of the researcher, derived from interview analysis.

Design

- Modular building systems are designed to fit with current building regulations to drop or minimise additional requirements, to bring down cost.
- The more complete a module is offsite, the higher cost efficiency is achieved. 80% to 90% of offsite work is aimed for in a project.
- Transport is a restriction to modular design and transport costs can be significant. Maximising module floor area is a design priority, whilst transporting distance is not significant.
- Fire resistance requirements diminishes cost-effectiveness and reduces useable space. 120min of fire resistance requires 8 gypsum boards for example. This also adds significantly to the weight and cost of the module.

Healthcare

- A small amount of companies have experience in building for healthcare. This may present as an additional hurdle to a modular contractor.
- Modular structures present two disadvantages in healthcare. The first is an inefficiency in trying to replicate the specialist's plans with a modular structure. This can only be overcome if the modular contractor is part of the design team, which is unlikely to happen in the healthcare context, as projects are complex, with many parties already involved. The second disadvantage is an inefficiency in construction as many installations and all medical machinery have to be put in onsite. This elevates the cost of the fully modular method.
- Designing out risk in healthcare projects may be one of the reasons why clients would avoid novel construction methods.

Life cycle and Cost

- A simple standardised life cycle tool that the client could use to collect the required data is necessary. The contractor does not carry a life cycle costing for the client, because it is their finances. On the other hand, the client may find it difficult to trust life cycle costing if there isn't a clear example case given, where the life cycle costing shows concrete cost savings.
- Ursem revealed that the manufacturer must provide confidence that their product will endure its lifespan. Discussing a per case confidence provision to the bank/lender with clients and investors is disconcerting.
- Jan Snel says they have a tight factory schedule. Conversely, a tight factory schedule is riskier since a project delay is more likely to affect other bookings.
- Conversely to the literature review, work on site is more costly per work hour than in the factory.
- 50% of the costs in a low-rise modular steel project are associated with the manufacture and handling of units. The other 50% is site preparation, foundations and non-modular work. Building taller structures, the module cost portion decreases.
- Residual value of a modular project is due to the units only. Therefore, the cost of displacing a structure is high because new traditional foundations are laid each time.
- Maintenance and refurbishment does not differ in cost for modular versus traditional facilities.
- Clients with projects of less than 20 years, may want to consider leasing and buyback arrangements, which also saves trouble in decommissioning the facility.

Chapter conclusion

The interviews have revealed the most important considerations for modular projects in the Netherlands. Maximising the floorspace of a single module is very important. Allowable transportation dimensions and permits are the main restrictions. Furthermore, the more complete a module is made offsite, the greater its cost efficiency. This is because work onsite is more expensive than within the factory.

For construction in healthcare, the interviews have revealed that there are two main hurdles. Firstly, project efficiency is lowered, because more work has to be done onsite for healthcare projects. Secondly, a big hurdle is reproducing the architect's drawings in a modular format. Without including the modular contractor from the beginning of the project, the resulting design may present problems for a modular redesign. With a limited number of contractors which work in healthcare and a generally stricter risk management, a healthcare client may have prejudices against considering a novel construction method.

This chapter provided valuable life cycle information which was included in the life cycle costing case study in Chapter 5.

CHAPTER 4

Valuation of cost factors

This part of the study is aimed at stating the cost factors which make up the total cost of the modular project, and how these differ with the costs in traditional building. This is to allow for a detailed comparison of construction methods according to cost. This includes real quantified costs such as materials and labour and other factors which can affect cost, such as quality, speed, safety and waste. In relation to the costs/benefits discussed in this chapter, a healthcare facility expert is interviewed to discuss priorities for construction in healthcare.

4. VALUATION OF COST FACTORS

Objectives covered

- O2.1. Using the literature review and interviews from industry, show how quantified benefits translate to cost.
- O2.2. Using the interviews from industry propose which non-quantified cost considerations are to be translated to cost and provide reason for the estimates.
- O2.3. Using the literature review and interviews from industry explain how sustainability can be translated to cost.
- O2.4. Carry out an interview with a hospital facility manager on the priorities in healthcare projects and how they differ to residential projects. Present project information of similar past healthcare projects.

4.1. Quantified costs

4.1.1. Material cost

The specific focus of this study is steel modules. As discussed earlier, both hot rolled steel and cold formed steel is commonly used in the construction of such modules. [14] says that material cost is about 20% of project cost. And [5] explains further that material costs depend on many factors, and these are not strictly more or less than traditional construction. Higher tolerances in the factory require higher specification material, which can drive up costs. Furthermore, to keep the module transportable, extra material is used. Structural members may have to be duplicated and extra boarding applied to provide enough rigidity during transport and lifting. Therefore, this report states that materials can have a cost effect in the range from -10% to +15%. The same report gives a suggestion that it is possible to reduce material cost by 20% when compared to traditional methods. This is to be achieved through process factors of direct procurement, delivery optimisation and economies of scale. Leaner manufacture can also save up to an additional 10% of material cost.

The price of hot rolled steel in May of 2021 in Western Europe was 1095 € [46] per metric tonne, however, the price fluctuates quite rapidly considering the low of 325 € in November of 2020. Considering that a module can weigh about 10 tonnes [3] it is of interest to find out what proportion of this is steel and what costs follow. A study on the repurposing of shipping containers into residential property provides some information on this, stating that a standard used container is 3700kg of steel with a cost of 2000 € [20]. This is rather low, and should be assumed higher for newly manufactured modules.

Another way to approach this, is to estimate the total cost by collecting the prices of each steel component. In May of 2021, in the Netherlands, a 100x100x4 SHS profile cost 19 €/m, IPE200 profile cost 29 €/m and a cold formed U-profile 50x80x50x3 cost 7 €/m without VAT [47]. Using these values to estimate the cost of steel of the module (with an assumed width of 3 metres) shown in Figure 22, the cost comes to around 2000 euro for the steel pieces. Additionally, the manufacture of connections has to be accounted for. We will come back to these values later, when the total project cost is considered.

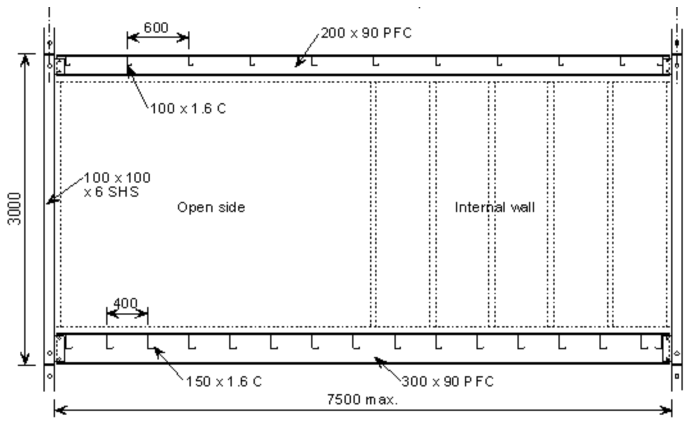

Figure 22: Elevation of a corner supported module showing structural members. [48]

4.1.2. Manufacture cost

When considering manufacture cost, the comprehensive book by R. Lawson states that factory, manufacturing and material costs of units amount to 50%-60% of the project cost [3]. Owning and running a in industrial factory is expensive. An article [14] states that unit construction costs 220Eur /m2, which for a 25m2 module is 5 500Eur for the manufacturing work.

4.1.3. Design cost

There is no data present on this value other than a rough estimate of a 10% increase on design costs for modular construction [14]**.** Articles strongly agree to the notion that more design time is spent in modular construction making the design decisions upfront [5], [28]. In a traditional build, design can carry on even slightly after the start of construction, whereas for modular manufacture, the design and manufacture process has to be fully completed to proceed onto manufacturing and assembly on site. It is suggested that time savings can be made with the creation of design libraries of past projects.

A Canadian study on the optimisation of module configuration says that manufacturers do not identify the cost of connections separate to the cost of modules [49]. Connection and a cost-efficient configuration of modules depends on the connection, transport and lifting cost. The findings state that reducing the number of connections is a good cost saving measure.

4.1.4. Transport and lifting cost

An article reviewing the costs of multiple case studies states that transport of one unit costs 720 euro for an average 320km distance, independent of the dimensions of the module [14]. A crane that can install 6 to 8 modules a day costs 2200 euro a day to rent. Lifting and transport accounts for 40 euro/m2 or 4% of total construction cost. These values are taken from projects in the UK in 2009. Furthermore, site preliminaries which is management, storage, facilities and equipment, is less because of less site supervision and site personnel. The preliminaries make up 5% of the project cost.

4.1.5. Labour cost

Labour cost in modular construction is split into the work by craftspeople offsite and onsite. Even though less workers are required in offsite manufacture, they are highly skilled and subsequently are paid higher wages [23],[42]. This means that labour cost savings from more offsite work can be trivial. In another article, this difference between the traditional and modular methods is 5%, which is in fact not trivial, but small [14]. In reference back to Figure 9, labour costs are the largest proportion of the total project cost at 35% for modular and 40% for traditional projects.

4.1.6. Total project cost

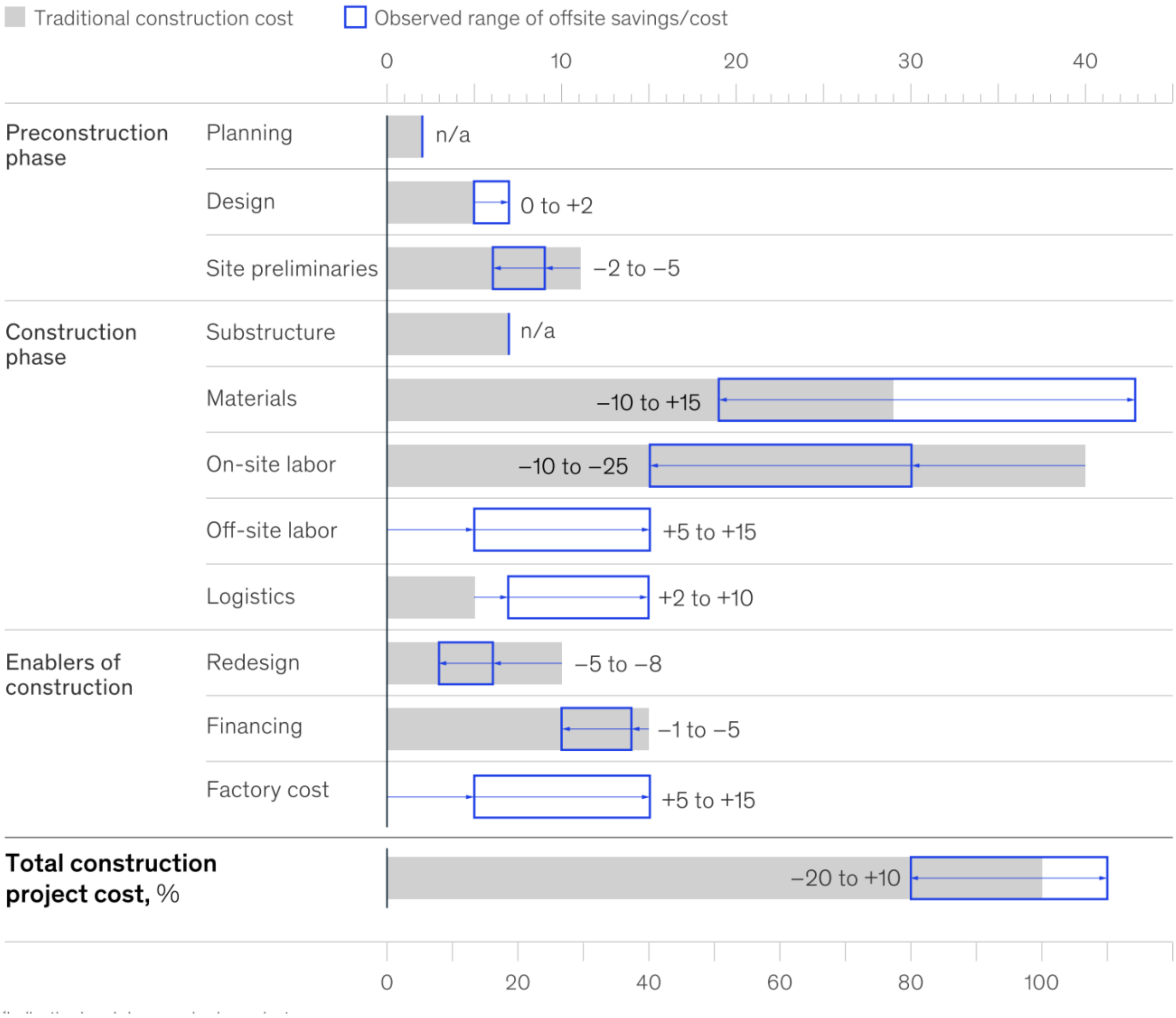

Figure 23: Modular construction cost savings per category [5]

The report by McKinsey consultancy provides a figure which is a good overview of total project costs (Figure 23). The figure shows, that planning and substructure design and construction is unaffected by the construction method chosen. A decline in cost is seen for site preliminaries, onsite labour, redesign and financing. An increase is present in design costs and logistics, with new costs appearing in offsite labour and factory costs. Design costs are argued to slightly decrease by another source [14], therefore there is no consensus and the cost depends per case. Similarly, material cost varies in relation to efficiencies of manufacture. A range of -20% to +10% for the modular alternative is given as a conclusion on the whole project initial cost.

It may seem confusing at this point that costs of logistics are higher even though less transport movement is assumed. The cost of module transport is high, however, due to their volume and weight. An efficient schedule of delivering modules is important to minimise these costs. Furthermore, coping with a change at a late date in construction is difficult in modular construction, but what the report considers under ‘redesign’ is the lack of rework necessary due to higher quality manufacture, as well as that with standardised building parts, small scale rework is easier.

Considering financing costs, lending rates for modular projects are currently high, because the industry is not well understood. The claim for lower financing costs here is determined by a future assumption of solid research & development of the technology, many example projects and economies of scale. Therefore, faster projects can lower financial costs.

Based on the mentioned articles and McKinsey report, these are the known rough costs per a single 3*3*7m steel module:

- 2000 euro on materials
- 4600 euro on manufacturing
- 10% for design (1090 euro)
- 720 euro for transport to site (300km)
- 300 euro for lifting
- 20% for onsite labour (2180 euro)

This is a total of 10890 euro per module. The costs are compared to the steel module costs found in the case study later in this report. These can be found in Appendix D and act as a check to the quote provided by the modular manufacturer.

4.1.7. Project evaluation

Worldwide

A UK case study lays out a summary of what cost savings are made with modular construction [14]:

- Client financial savings 3 to 6%
- Design fees reduction 2 to 3%
- Rework reduction 1 to 2%
- Site preliminaries 5 to 7%

This brings the total savings to 11-20% when compared to traditional construction. The author states that a modular project can therefore be up to 10% more expensive and still be cheaper, when counting the benefits. The article lacks a comprehensive breakdown of all costs and there are very few sources, which calls these values into question.

A residential building case study in the US was carried out to compare a traditional and modular alternatives [50]. It found that modular was 11% cheaper, but states that this is not large enough to outweigh other considerations, such as limitations of modular design. The article also broke down the costs of the two projects. The modular option was more expensive in construction equipment, steel framing structure and roofing categories. The modular option was significantly (>10%) cheaper than the conventional option in indirect costs, masonry work, carpentry, installation of doors and windows and interior finishes.

A Canadian study compared panelised and modular residential construction [51]. The study found that total costs per square foot were 11% lower for modular construction. This is the same as found in other literature from North America [50][5][51]. The market is said to be well established and competitive. In cases when a modular project is more expensive, it is due to the costs of initial planning and set up, transport and lifting procedures.

Netherlands

In the Netherlands, the tallest modular unit construction with 16 stories tall is the Fizz Spartaan residential project in Amsterdam West [52]. 361 student residences were built for the contracted cost of 17 mil. Euro. This equates to a construction cost of 47 000 euro per apartment/unit. The manufacturer of modules was van Ursem. This project is a common example of the application of modular construction in student residences and 'starter' residences in the Netherlands, helping to decrease the housing shortage [53].

A masters student studied this project in 2020 with a focus on project delivery methods [54]. This piece of research documented the decision making that took place. Interviews held with parties revealed that life cycle costing was not considered at all, and only the initial asset cost was being considered. Another point made by the correspondents was that, in the future, the clients must decide whether they want to use a modular approach from the beginning, and if so, work closely with the chosen manufacturer on the preliminary design.

4.2. Non-quantified cost considerations

Non-quantifiable benefits of modular construction are speed, quality, safety, less waste, relocation and reuse possibility as well as a higher residual value.

4.2.1. Speed

Article [14] says that increased construction speed has three effects: smaller interest charges by the client (2-3% saving), income generated from activity during the saved time, less disturbance to the surroundings or business. Additionally, it is said that savings on foundations can be significant, when compared to a concrete frame.

From the client's point of view, a faster completion of the project means that the asset can be operable sooner and profit can be collected for this time. If the new asset is to replace another, the difference between the operating costs of the old and the new can be compared. Asset generated income can be calculated for the saved time between project options. This can represent the cost benefit of the increase in construction speed.

The National Audit Office in the UK provide their results of a study in 2005 on industrialised building. It ambiguously states that savings shown in Figure 24 are achieved. Earlier rent, shorter borrowing period, less snagging (re-work after completion) and less on-site inspection are the stated benefits from largest to smallest. At the same time, it says that traditional techniques are cheaper and 'the time savings available do not currently provide a compelling financial reason to switch production' [55].

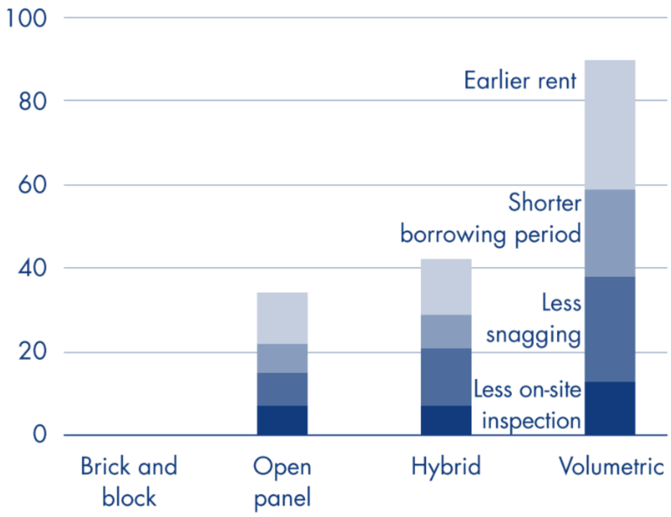

Figure 24: Financial benefit of industrialised techniques in the UK residential sector, GBP/m²[55]

More generally, [56] states that time schedules for projects are created by either timing each activity and being efficient in sourcing or by having a deadline set by the client. The latter requires the ability to quickly source work and material when needed. Past experience is the biggest factor on time scheduling, rather than best practice. The researcher uses the Bromilow Time Cost (BTC) model which corelates construction duration and cost. The paper states that scheduling errors decrease with longer duration projects, whereas cost errors are the same independent of project scale.

4.2.2. Quality

A report by Ramboll Group, lists quality as the second advantage of modular construction, and this follows from the introductions to the topic of other reports [57]. Controversially, a report which carried out a questionnaire of contractors on the barriers of adoption of modular construction in the UK found that one of the barriers is the lack of quality [39]. Another researcher agrees that there are barriers stemming from traditional construction practices, such as lack of responsibility to quality, resistance to radical changes and a lack of interest in improvement [35].

A Turkish study on assessing the airtightness of container homes [58] found that airtightness was poor, with an ACH_{50} range of 9 to 25 where 7.5 is the aim for residential buildings. No relation between airtightness and function of the module was found. Details were provided on how the detail design can be improved to improve airtightness and thermal bridging at junctions. The study also worked out that improving airtightness from high to moderate, does not have a significant impact on energy use.

Furthermore, [3] and [39] speaks of lesser amount of snagging i.e. rework costs due to improved quality, but little proof is given. Lastly, one article [3], due to a very comprehensive overview of the full process, speaks of a comparably easier refurbishment of steel modules, but no data exists.

To summarise, modular construction does not benefit from higher quality of produce, but rather better quality control. High quality can therefore be achieved if it is specified. Only with a high quality and airtightness specification can energy savings be achieved in the use of the structure. Data is lacking to support any improvement in rework and refurbishment.

4.2.3. Safety

[34] states that modular construction eliminates or reduces the main safety hazards of excessive force, poor posture, getting hit, and in general reduces working hours which reduce risk. In the US in 2002 there injuries cost a total of 11.5 billion USD, with 40% of this value due to fatalities [59]. In this article, plumbing, heating and air-conditioning installation was ranked as the highest cost per injury, followed by residential construction. For the Netherlands, Centraal Bureau voor de Statistiek states that in 2020, 3.4% of construction workers had a work-related accident, 26% more than in non-construction industry. This is proof that having more control over manufacture processes in the factory, will reduce costs when comparing to intensive onsite construction. This cost saving, as a factor of the labour force cost, is part of the manufacturer's finances and is not a direct cost to the client.

4.2.4. Waste

About 20% of construction materials are wasted combining all stages of production in traditional construction, and 95% less waste is produced in modular construction [3]. Therefore, a large saving is made in this respect, but it is offset by the previously mentioned higher quality material used and an associated higher labour cost.

4.3. Sustainability in modular construction

Sustainability in modular construction is often approached from the perspective of a light structure and lean manufacture [35], [34]. These are the drivers for low embodied carbon. Additionally, modules can be relocated and a case for multiple reuses of the module and its steel structure [35], [60]. As for steel modules, literature states that 50% of steel in Europe comes from steel scrap and the rate of steel recycling is over 90% [14].

4.3.1. Embodied Carbon

A comparative PhD study of a modular home in the US found that the modular option was 38% lower in carbon emission when the production factory was at optimum production [61]. One of the significant findings of this research was that electricity used in manufacture was significant and constant. This means that if a suboptimum number of modules are being manufactured in the factory, the factory still uses the same amount of electricity. Therefore, functioning at optimum occupancy reduces carbon emissions per module. Sizing plants to be smaller and more efficient with energy is recommended. An interesting idea of moving factories is proposed, where a factory uses local material and builds for projects in the region and is later moved to another region. Another study similarly found that greenhouse gasses were 40% higher for conventional construction and reinforces the previously stated study on the high use of electricity in manufacture [62].

4.3.2. Reuse

An Australian case study of a modular building, compared reuse practices to recycling using a Life Cycle Analysis (LCA) which is an environmental assessment of emissions [60]. It found that designing for deconstruction and reuse can save up to 88% of global warming potential. The author additionally states that some materials such as concrete are down-cycled into inferior products.

Another LCA study compared conventional concrete construction with modular steel construction and modular timber construction [63]. It found that steel construction was 50.7% lighter as shown in Figure 25, but embodied energy was about 50% higher than the base concrete structure. However, 81.3% of the embodied energy could be saved, if the main steel structure was reused. The article concludes that it should be aimed to maximise reuse, as this lessens landfilling, virgin material extraction and manufacturing.

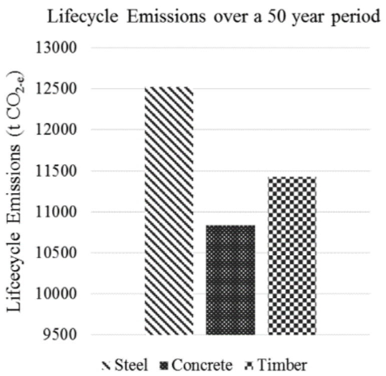

Figure 25: Lifecycle greenhouse gas production of a building over 50 years [63]

A Swiss study on a reconfigurable modular panel, slab and column system made a great case for reuse [64]. In Figure 26, the reasons for demolition of buildings are shown. Structural damage and related issues account for about 13% of choices made to demolish. The largest choice, over 60%, is due to a change in land use. The ability to relocate a structure can therefore save 60% of buildings from being demolished and continue until the end of the functional lifespan. The author concludes that reuse and use of low carbon material are the most important recommendations to designers.

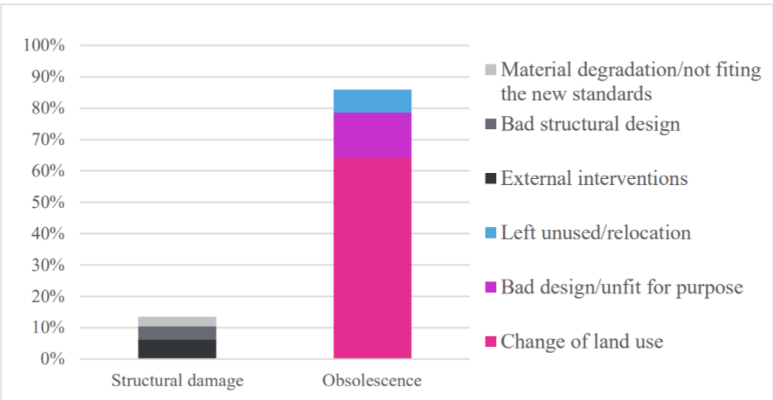

Figure 26: Reasons for demolition from studied 193 buildings [64]

A US study investigated the demolition of an energy inefficient facility [65]. A replacement with an energy-efficient modular facility was proposed and the payback period was calculated in sustainability terms. The greenhouse gas payback period was 6,5 years and the total ecological impact payback period was 11 years.

Although this is an attractive result, the author got to these figures by offsetting carbon with photovoltaic generation. Buildings and energy generation are two separate sectors, both of which require decarbonising. Therefore, one cannot be used to offset the other, which makes these payback results rather trivial.

4.3.3. Lifecycle and refurbishment

The Dutch government has set goals for 2050 - to have the construction industry practice circular methods. Their agenda state the word circularity, without implying a specific construction method. For example, products must have material passports and Life Cycle Assessments (LCA). Traditional companies struggle with this, but it is more straight-forward with a modular structure. In the interviews with industry, DCG specified that for a full refurbishment, the modules are brought back to the factory. Jan Snel carries out refurbishment of its modules. Van Ursem does not refurbish its modules.

Even though there is not much maintenance needed for modular construction because of its simple construction, the maintenance costs of a traditional building and a modular building are comparable. DCG said that the customer performs their own maintenance and refurbishment, because they employ their own maintenance and refurbishment service. Ursem agreed that there is not much difference in refurbishment and maintenance of modular buildings. For example in student residences, an access to each residences' installations is built to facilitate frequent maintenance. That is the same design choice in both modular or traditional.

Jan Snel stated that hospital design is outside the scope of the modular manufacturer. Architecture firms specialising in healthcare must make a design in modular form. If a change in purpose needs to occur in 10 or 20 years it is very easy to change walls in a cost efficient way. There are no concrete walls and therefore less noise and dust, only disassembly. Ursem agreed that the big difference is that there are no solid concrete walls and the sides and roof of the module are gypsum. They can be taken off and fitted again. For example, Ikazia ziekenhuis has 18 modules placed and they have been refurbished 5 times already.

Jan Snel clients sometimes request changes in the modular offices that manufacturers rent out. The refurbishing happens on site and the waste is taken back to the factory to recycle. The modules are not brought back into the factory. DCG disassembles modules after a period of rent and any waste is recycled on site. Another process of separation takes place offsite. Some work must take place on site – for example taking disassembling the roof structure, so that the modules can be accessed. Ursem shared knowledge of displacing buildings to new locations. But what is prominent for clients is the scenarios of adaptability in the future, for example combining apartments into larger ones. Reconfiguring spaces for different uses. Therefore, possible scenarios are provided to the client.

4.3.4. Displacement

Ursem provided the most information on the displacement of buildings. It stated that every time that the building is moved to another location, a new foundation has to be built. This is an expensive process due to double the amount of labour, transport and lifting. There is a saving in the relocation of a building, but it is at around 30%, with the largest saving made on the environment. When moving the building to another location, you have the investment of the material for the module. It does not have to be manufactured again. But the new site requires preparation, and for most cases over 50% of the project has to be done again.

4.4. Priorities for healthcare facilities

4.4.1. Healthcare facility design in the Netherlands

There is a handful of building typologies in the healthcare sector. In an increasing order of complexity, these are long-term care facilities, hospices, clinics, hospitals and laboratories, to name the main ones. These facilities cater for a selection of functions which can be broken up into four functional groups [66]:

Office
- Consultation rooms
- Intake
- Outtake
- Commercial
- Community
- Staff rooms

Hotel
- Children care
- Grownup care
- Physiotherapy
- Bed storage

Hotfloor
- Urgency centre (ER, Ambulance hall)
- Medical logistics centre
- Intensive/diagnostics centre (ICUs)
- Operation rooms

Factory
- Laboratory
- Heating/Cooling and Ventilation Management spaces
- Kitchen
- Washing

Figure 27: Functional hospital divisions [67]

University and general hospitals have departments specialised in all four functions, therefore large hospitals are architecturally complicated. Office and hotel function departments differ little to commercial office spaces in terms of construction and building installations. The hotfloor and factory functions have specific requirements. A hotfloor department is the heart of the hospital and hosts all intensive medical services, such as emergencies, intensive care, operations, testing and preparation of medicine. A factory department takes care of the back-end of these services and provides technical spaces, laboratories, food preparation and washing rooms. These spaces have strict requirements for air quality, temperature and sterile working conditions. Specific building installations are required as well as the space for them. This means that in terms of structure, a taller and longer spanning module must be used in comparison to office and hotel function modules. Medical specialists and contractors provide installation systems for these spaces separately from other departments, which can be equipped by general contractors.

4.4.2. Flexibility

The typology of hospitals in the Netherlands has been evolving over time from simple T and H letter floorplans, to the Breitfuß model in 1960s and comb structures in the 1970s. As a facility, hospitals undergo a lot of changes throughout their lifespan, and these changes are driven by changes in demography, patient preferences (individual wards instead of shared), medical-technological improvements and automation.

To maintain effective use of hospital real estate, the hospital must not have more square metres than necessary and use shared workspaces where possible [68]. The required architectural flexibility is described in literature as **initial** (the ability to change functions as late as possible in the design), **conversion** (the ability to convert function for as low cost as possible), **elastic** (initial and conversion flexibility where nothing has to be converted to change functionality), and **volume** (the ability to carry out construction works or conversions without affecting the processes of the overall building) [69]. [68] states that flexibility must be guaranteed for at least 40 years. Therefore, the building structure is often oversized, especially in parts that are not easily interchangeable, such as operating theatres and intensive care units.

In practice, this means that no installations are mounted into dividing walls so that these can be moved to combine or separate rooms and departments. Installations for a certain function are installed in neighbouring departments in case the department has to expand. It can then do so without any construction work. Furthermore, modularity is common in installations, finishes and fixed inventory, in order to easily replace these.

Flexibility is important spatially as well as in terms of installations. Installation flexibility can be broken down into categories of central function (e.g. generation), distribution, end element and regulation [69]. Even though this is outside the scope of this research, installation requirements may require consideration from the structural contractor. An example of this is concrete core activation. Core activation is effective in controlling the inside climate and is low in energy usage. If it is opted for, it has to be designed early, and it is unknown whether such functionality is cost-effective to manufacture into the floor cassette of a module. A climate ceiling might be proposed instead. Installations are therefore vital to consider in the global design of the healthcare facility as they make up 35% of building costs [26]. A further consideration is the lifespan of chosen installations and inventory, and its relation to other components. Below are the expected lifespans in healthcare facilities stated in NEN 2632:

- Structure – 50 years
- Building installations – 15-20 years
- User installations – 10-15 years
- Fixed inventory – 10 years
- Loose inventory – 10 years
- Finishes – 5-10 years

4.4.3. Interview with healthcare project manager

To understand what a client looks for in a healthcare project, an interview was held with a project manager and technical building services engineer Ronald van Lier from the Reinier de Graaf hospital in Delft. These are the paraphrased interview results.

Design

Hospitals in the Netherlands are designed by consulting employees and patients. It is paramount that the facility meets the demands of its users, and a modular structure can limit design choices. Modular design can apply to the manufacture of patient rooms, offices and kitchens. However, it can be inefficient when a module is too big for one room and too small to build two. Radio therapy bunkers, for example, are completely concrete rooms, which may be difficult to manufacture in a modular way if working with a modular steel manufacturer. A problem with steel modular construction in hospitals is the allowable vibration, for which a heavier construction is preferable. Furthermore, the interviewee thought that modular construction is reliable and fast, and it is growing due to a lack of construction workers.

From the healthcare client's side, the decision to go modular should be taken initially. That is an essential problem for healthcare design, since the design team is highly likely to not include any particular contractor. Involving a modular designer at a later stage increases costs.

Maintenance

Installations and their maintenance have a significant role to play in an energy intense facility such as a hospital. In order to future-proof a hospital, it is practised to overdesign each department in terms of installations. General hospitals also consider the demographic trends in the region when choosing what to specialise in or what provision of services to increase. For example, a department is designed to have the same installations in the walls and ceilings as the departments nearby and vice versa. Therefore, if a department must expand due to increasing demand, it can do that at the expense of a neighbouring department. No construction work has to take place. Construction work must only take place if a department is permanently changing function.

It is not uncommon to see renovation work at a hospital every 5 years due to a change of treatments and advancing equipment. Ronald pointed out that plaster wall and cementitious products are hard to recycle, so using recycled non-cementitious materials is effective in decreasing work and carbon emissions. It is also important to consider the lifespan of each product, however hospital lifespans are decreasing.

Finances

The interviewee expressed that mortgage contracts are very important for hospitals. The profits are tightly related to the interest that you pay on the mortgage. Having lower risk operation means that less interest has to be paid. Having gas systems in a hospital is an example of operational risk. Furthermore, carbon tax can be a big risk for the hospital if they increase at a fast rate, this is where the benefit of electrifying all systems and increasing insulation must be considered.

Sustainability

The interviewee said that government rules and regulations are an obstacle to efficient design of hospitals. The example given was that the efficiency of a hospital building is measured in energy used per square metre. This is misleading, because for the five-year-old Reinier de Graaf hospital this number is high. Yet when comparing energy used versus the service provided – it's low in comparison to other Dutch hospitals. The same goes for airtightness and heat transfer regulations for hospital facades. More stringent requirements, mean that larger installations are required to ventilate the facility, and get rid of excess heat from technical plant. Therefore, these regulations are a constraint instead of a hallmark for efficiency.

Additionally, the hospital's concern is hygiene and patient safety, and environmental concerns are after these. It is effectively impossible for a hospital to become carbon neutral. The main goal in terms of sustainability of healthcare facilities is transitioning from gas to electrical systems.

Chapter conclusion

This chapter listed the cost factors which make up the total cost of a modular project. This included the real quantified costs such as material and labour, and non-quantified cost considerations such as quality and speed. The costs and their key differences to conventional construction were identified by using literature and interview data. Sustainability claims of modular construction were also discussed. In relation to the non-quantified costs/benefits discussed in this chapter, a healthcare facilities expert was interviewed to find the considerations of building for healthcare and find whether the specifics of modular construction is advantageous in healthcare.

It was found that costs in modular construction are larger for logistics (transport and lifting), with offsite work as well as factory operation being new costs. The costs are smaller than conventional construction for onsite labour, redesign and financing. For other cost considerations, speed, quality and safety are thought to be major improvements of this construction method. Speed allows for income to be generated earlier. Quality is improved which is a consideration for airtightness standards and it may benefit a healthcare project. An improvement in safety is associated with installations being mounted and tested offsite, as well as a safer work environment requiring less excessive force.

The literature review and expert interview revealed that there are limits to where a modular structure can be used in a healthcare setting. There are obstacles in terms of spatial arrangements and facility requirements such as for radio therapy bunkers. Furthermore, vibration in steel structures and therefore in modular steel structures is an issue. Lastly, the interviewer stated that there is limited opportunity to involve a modular contractor early in the design procedure.

CHAPTER 5

Life cycle costing

In this chapter, life cycle costing (LCC) is carried out for a studied case. Firstly, the principles and required formulas for life cycle costing are explained. Several measures used to evaluate the results of the LCC are presented. The case study project is introduced with information from the consultant of the client, and the costing approach is elaborated. Scenarios are created to represent the base case, which was considered by the client, and other cases with additional life cycle items. Case study results are presented for each scenario, with and without the inclusion of inflation. The comparison of the modular design option to the conventional one is the primary focus.

5. LIFE CYCLE COSTING

Objectives covered

- O3.1. Using literature review, explain how a life cycle costing must be scoped and carried out. Reason which activities must be considered in the costing of a healthcare facility.
- O3.2. Using a case study project, find out what was considered in the project selection and set up a life cycle costing which represents the case.
- O3.3. Carry out the life cycle costing of the case study healthcare facility and discuss the results.

5.1. Life cycle costing

Life cycle costing (LCC) is an effective method to assess and compare assets, and provides techniques for long-term engineering and economic analyses [70]. As a decision-making tool, LCC helps to identify the main cost drivers and highlights differences between alternatives. To a large extent, LCC has no fixed methodology, but the standard considerations for buildings are described by ISO 15686-5. An LCC must, above all, state a clear project scope, objectives and a functional unit.

The product life cycle must be defined with a list of costs incurred during each phase. A comprehensive LCC includes accounting elements of present value of future cashflow, discount rate, inflation and loan interest. This allows not to fall into the pitfall of judging a book by its cover i.e. initial cost, but have a better estimate of the true value of the asset through time.

The phases in the lifespan of a building asset are design, construction, operation and maintenance, renewal and disposal [70]. During these phases, two types of costs are incurred, single and annually recurring. Single costs are costs that are incurred one time or less often that every 12 months. For buildings these are the majority of costs, such as new construction or a large repair. Annually recurring costs are expected to be similar month to month and the same yearly, this includes energy, water use and frequent repairs. These costs can be summed up into single annual costs for simplicity.

Generally, a beneficial LCC study must consider [70]:

- A range of alternative solutions
- The cost drivers for each alternative
- The time period for which the asset will be required
- The level and frequency of usage
- The maintenance and/or operating arrangements and costs
- Quantification of future cash flows
- Quantification of risk

An LCC study comes with the following limitations. The results of the study are an estimated asset cost and therefore the validity of its results is only as valid as the inputs. This means that errors in accuracy cannot be measured by statistical means [70]. A comprehensive sensitivity analysis is recommended in this piece of literature, to be carried out instead. Large amounts of data, which may be difficult to source, are required to produce a trustworthy result. The lack of a fixed procedure and the effort required to create confidence in the result is the main reason discouraging companies from adoption of such analysis [71].

5.1.1. Formulas

The LCC, as defined by the ISO code [72] and shown in Figure 28 is the sum of the following costs for modular construction: Planning Costs + Design and Construction Costs + Operating Costs + Maintenance Costs + Disposal Costs – Residual/Salvage Value. Whole life cost (WLC) is the term used for calculations which include incomes, benefits or positive cashflows to the client. Figure 29 provides a visual model of cost magnitude and when they occur.

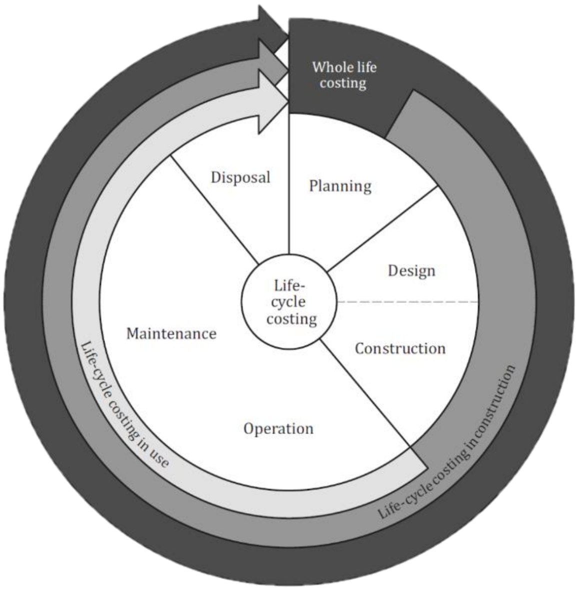

Figure 28: ISO defined costing definitions [72]

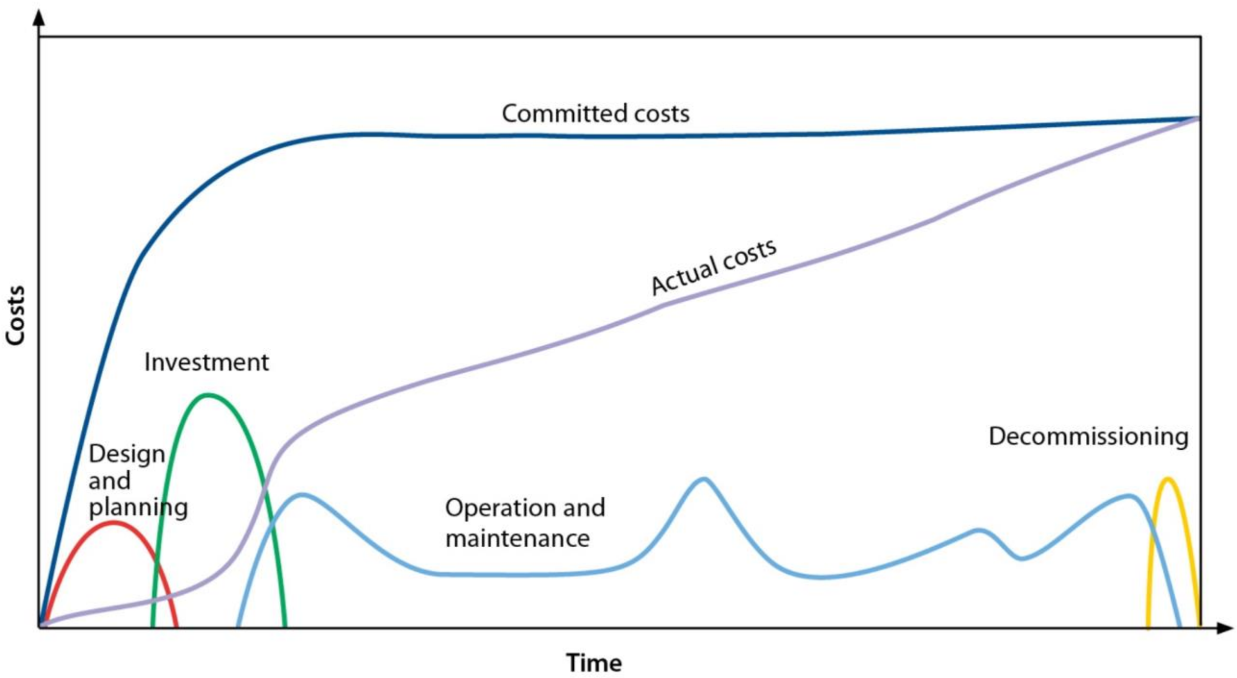

Figure 29: Life cycle costs

The LCC result can be expressed in Present Value (PV) or Net Present Value (NPV) in euro. NPV is equal to PV of gains minus PV of costs. The value of money in the future is lower due to effects of general inflation, specific asset escalation and risks. Generally, a stable investment generates a stable income on investment and in comparison, money that is not invested is losing value over time. This is a key accounting principle in LCC. The decline in value is expressed by using a discounting formula, which contains the discount rate.

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

where Fn is the future value at the end of period n, n is the year, d is the discount rate. (Adapted from [73]*)*

The discount rate is the sum of interest rate and estimated value of investment risk. For example, if a company pays 5% interest on its debt, this is the base discount rate. The investment risks evaluated by the company increase this percentage. Literature [74] states that the interest rate of a stable long-term investment yield in the market should be chosen to calculate PV for LCC calculations. This means that your investment action will be worthwhile when compared to keeping the money in a bank.

Not all future costs may be known. However, if the present cost of an item is know, and the rate of yearly increase rate is know, the future cost can be calculated using the formula below. The rate of increase is a called an escalation rate. Depending on the case, this rate can be taken to be the rate of general inflation or a specific rate related to the asset.

$$Cost_n = Cost_0(1+e)^n \tag{2}$$

where $Cost_0$ is the regular payment, n is the number of years, d is discount rate and e is the escalation rate. (Adapted from [73]*)*

Public projects in the Netherlands are analysed with real discount rates of 3% to 5%, and the recommended value is 4,5% [75]. 'Real' signifies that inflation has been omitted from this rate, a rate which includes inflation is called 'Nominal'. All rates and costs can be expressed in their real or nominal values (see formula below), but consistency in using either type of values must be maintained. Both the private and public sector can additionally raise the percentage due to risk considerations. A higher rate discourages long-term investment.

$$REAL = \frac{1 + NOMINAL}{1 + INFLATION} - 1 \tag{3}$$

Netherlands Bureau for Economic Policy Analysis put this value at 5.5% for the pricing of roads in 2015 (2.5% as a real discount rate and 3% due to risk evaluation) [76]. This is reasonable compared to discount rates used in other studies: 4% [77] and 6% [20].

As discussed earlier, the escalation rate is asset associated inflation, which is affected by inflation, supply-demand and technological factors. The GDP deflator measure is another term for this rate and it is the result of nominal national GDP over real GDP in a given year. As shown in Figure 30, the rate in the Netherlands in 2019 was 3%, whereas average inflation in 2019 was 2,6%. The GDP deflator will be used as the escalation rate in further calculations.

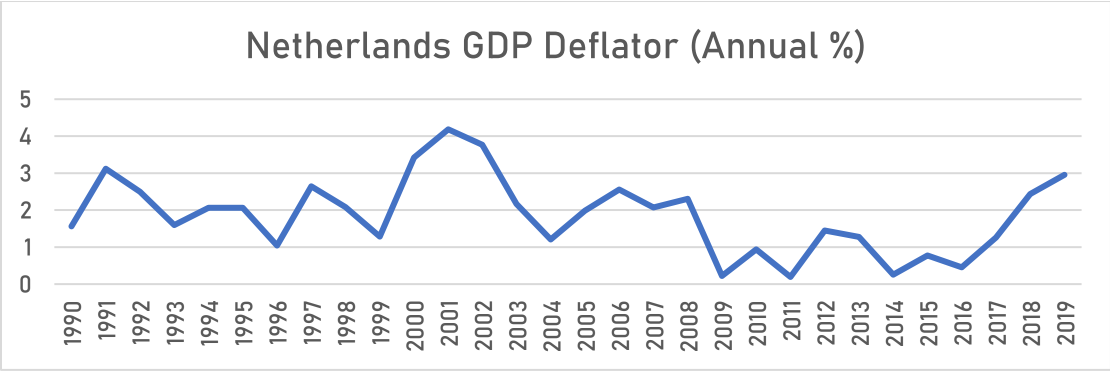

Figure 30: Netherlands GDP Deflator [78]

5.1.2. LCC Measures

LCC can be used to calculate several measures. To calculate the Net Present Value (NPV) the formulas presented above are used to discount every future cash inflow and outflow to Euros today. Another approach of comparing investment opportunity is calculating the Internal Rate of Return (IRR), which estimates the profitability of an investment using a percentage rather than Euro. To calculate the IRR, the NPV must be set to zero, and the resulting discount rate is the rate of return on investment. A limitation of solely carrying out an IRR calculation to compare different investments is that the discount rate, which differs per project and per year, is not considered [74]. The same can be said about the NPV calculation, which only includes the initial discount rate.

NPV and IRR calculations are popular in practice due to their simplicity, but their limitations can be overcome by using the Modified Internal Rate of Return measure [79]. MIRR recognises that positive cashflows are reinvested and therefore includes the loan interest rate and reinvestment rate in the calculation.

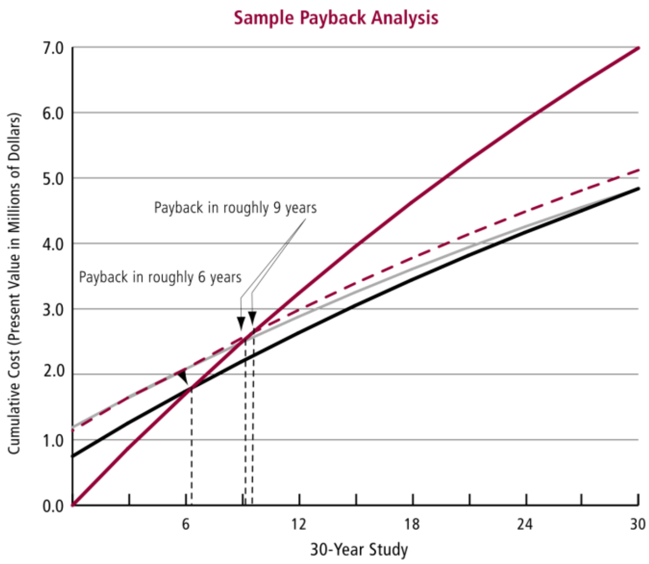

Figure 31: Example Payback Period results graph [73]

Another used metric in investment decisions is the Payback Period. This is a simple summation of the cash inflows and outflows, resulting in an amount of years in which the investment is paid back. The main limitation of this approach is disregarding the time value of money, inflation and effects of irregular cash flow. To overcome this, the Discounted Payback Period can be calculated as part of the NPV calculation. The period is found when the sum of discounted inflows is larger than the sum of discounted outflows. Figure 31 shows a Payback Period calculation when options are compared to a defined base case.

5.1.3. Activities to consider in a healthcare project

Each possible lifespan activity in a healthcare facility is listed below, with an explanation of how the cashflow item must be included in the LCC. It is also mentioned, where the values must be sourced from.

- **Design, construction and financing costs**

These costs can be referred to as initial costs, which can be sourced from a direct quote from a designer, contractor and bank. It is vital, that all quotes accurately describes the project at hand, the level of finish required, transport, labour, project management costs etc. In a life cycle costing, the initial costs are the easiest to source, therefore, the costs should be checked exhaustively and any issues brought up with the contractor. This is the first and most important cashflow item.

There is a lot of choice for financing options for a healthcare facility. Bank loans, government loans and subsidies, co-financing mechanisms are a few possibilities. Considering differences between these financial agreements is beyond the scope of this research. Financing is not part of a life cycle costing and must be treated separately.

- **Operational, maintenance and replacement costs**

Options in tender projects can end up having significant differences in operational cost, sometimes larger than the initial construction cost, when the total life span is considered. This is dependent on building envelope properties of thermal insulation and airtightness, and the energy use of building installations, such as heating, cooling and ventilation. Modelling thermal performance and energy usage is common and the yearly utility cost must be included in the lifecycle costing of the facility.

There may be cases in the construction industry, when different designs require to consider different maintenance schedules due to, for example, different installation or material lifespans. However, in healthcare projects, maintenance considerations have to be made by the medical contractor, responsible for medical systems and finishes. This lifecycle cost is specialism related and can be compared to other options in isolation from the structure of the facility. When studying the structure of the facility, and in the calculation of LCC, these costs shall be omitted.

- **Decommissioning costs**

Decommissioning costs are demolition or deconstruction costs, depending on which method is chosen. Modular structures are inherently easier to disassemble and take away from site, but there is a choice to make for conventional structures. A structural concrete or steel building can be demolished using hydraulic hammers and shears. This is the most affordable option, as these structures are cast together or have a large amount of connections and bolts. Deconstruction, on the other hand, is based on trying to salvage and disassemble as much of the structure as possible. Depending on the structure this can be quite costly, but the salvaged members may have resale value. Deconstruction also requires that the structural members have limited damage and deformation. The quotes for both demolition and deconstruction of a structure can be enquired from demolition contractors. These values are included as the last item in an LCC.

- **Residual value**

The residual value is the value that the structure retains at the end of its planned lifespan. This is the case for some prefabricated and all modular systems. As discussed earlier, the manufacturer can guarantee a residual value of the structure. The residual value may or may not include the cost of disassembly. The manufacturer can guarantee a residual value of the structure at the end of its lifespan in order for the client to apply for a loan. Depending on the manufacturer, the company can also agree on buying back the modules for below their residual value. These values are included as the last item in an LCC.

- **Gains due to faster construction**

Faster project fruition means that facilities can open sooner and start generating revenue. This is project and client specific. The value of the saved construction time can be calculated as the monthly revenue and profit of the facility in operation. Alternatively, the value can be expressed as the rent that would be spent on such a property if the client was a tenant.

Modular projects take a shorter time due to overlapping the work done offsite and onsite, this means that less interest is accumulated. If the time saving is as large as when comparing conventional and modular projects, this sum can be of advantage, especially, if the interest rate is high. Both of these gains are to be considered at the start of a whole-life cost calculation.

- **Carbon taxation**

Depending on the design and use of material for the structural skeleton of the structure, a certain amount of carbon is embodied in the structure. Carbon can be expressed in euros due to carbon taxing and this can be included in the life cycle costing. With the EU distributing less carbon emission passes every year, the cost of emitting carbon rises steadily, which will have a direct impact on the cost of building materials. Considering a less carbon intensive material, such as timber, may be an effective way of reducing construction costs in the future. Carbon tax should not be considered separately to an LCC, because it is included in the price of the material. The tax can be used to accordingly inflate future prices.

5.2. Case study

There are few opportunities for researchers to take part and carry out studies during live project tenders. An opportunity arose for the researcher to take part in a healthcare project, where options of conventional and modular construction methods were proposed. A live case to compare design options and apply life cycle costing to model the real cost of the property through its planned lifespan is of interest to every party in the construction industry. A modular project option is likely to be increasingly available and correctly evaluating its costs is essential.

As modular building options become more widely available, they remain useless to the clients who compare design and construction costs only. A modular proposal is considerably different to a traditional build when considering costs over its lifespan. The benefits brought to a project by using modules manufactured offsite must be given a monetary value to effectively compare the options.

The case study looks at the structural skeleton of a hotfloor department. The proposed tender options are fully interchangeable building structures for the designed hotfloor department. Since only the structure of the building is considered, and not the facility itself, operational and maintenance costs are not considered. Only costs and benefits due to the structure are considered. As the study is based on cost, the functional unit is the euro.

The case study data was gathered through cooperation with Medexs – a healthcare specialist in operation rooms, clean rooms and laboratories. The researcher and Medexs had no conflict of interest in the following tender competition, and Medexs was ready to work with any winning contractor.

5.2.1. Project

The case study project is the construction of a new hotfloor department as an extension to an existing hospital – Antonius Ziekenhuis in Sneek. It also includes renovation works within the existing facility, but the case study is focused on the new free-standing department with a connection to the main hospital building. The facility is 3 storeys with a total floor area of 1938m^2 (646m^2 per storey). The hotfloor contains 5 new operation rooms. The planned lifespan of the facility is 15 years. Figure 32 shows the new hotfloor department of rectangular shape.

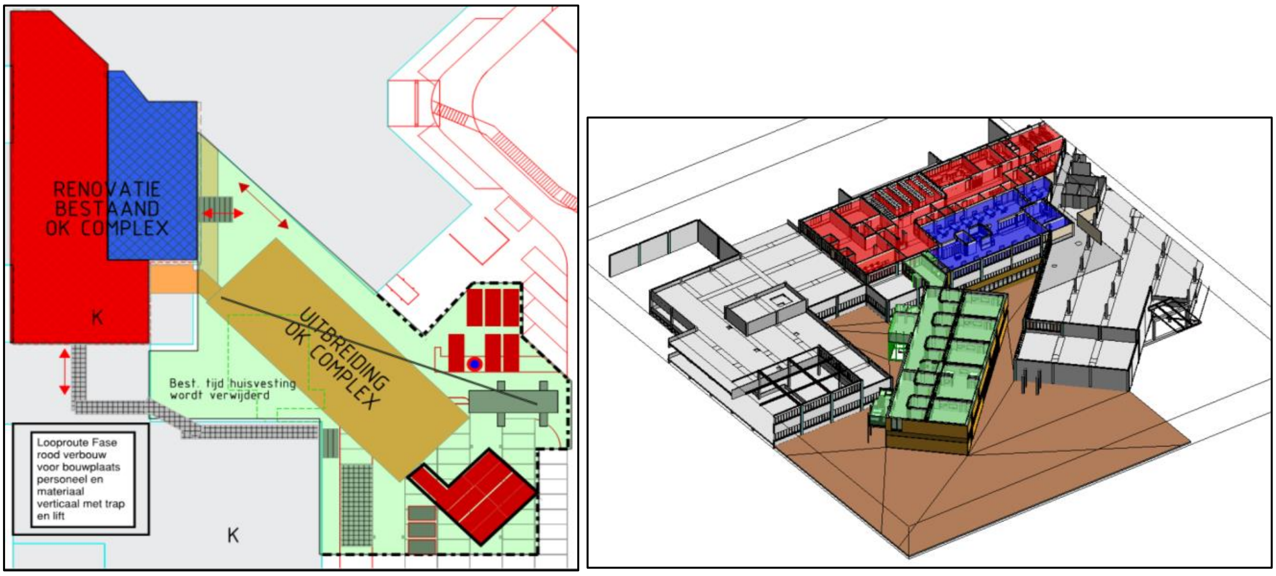

Figure 32: Plan and perspective view of the extension of the OK complex

The client worked with a design team, which included an architect, project consultant, installations Consultant, and project management to put together a tender brief for general contractors. The hotfloor department is meant to replace the operation rooms within the main hospital building and continue operating until the closure of the hospital in 10-15 years. The consultant and company information is anonymised.

5.2.2. Options

In the tender competition, 4 options were presented, shown in Table 3. The client ordered an external consultant, to calculate the guidance construction costs of the facility in conventional reinforced concrete element construction. This guidance option is useful for research, because the consulting company did not compete in the tender and therefore could provide very trustworthy costs in relation to the market.

Table 3: Quotes of total construction and the structural skeleton in isolation

	Consultant (Conventional)	Company A (Conventional)	Company B (Hybrid)	Company C (Module)
Total	1 078 000 €	1 520 251 €	1 171 460 €	2 514 285 €
Skeleton	539 553 €	311 953 €	634 686 €	949 135 €

Company A provided a reinforced concrete structure with some prefabricated elements such as precast columns and hollow core slabs. However, the provided document was titled ‘calculation’ and it was lacking detail typical to a bill of quantities. The budget omitted costs of construction work and finishes. The hourly rates were given, without the estimated labour cost. This type of document was highly irregular as it mimicked a bill of quantities but wildly underestimated the total project cost due to important omissions. Company A, therefore, resulted in a quote of almost half that of the Consultant. Company A and Consultant structural skeletons are comparable, and it is likely that Company A would match Consultant’s quote if it considered necessary items.

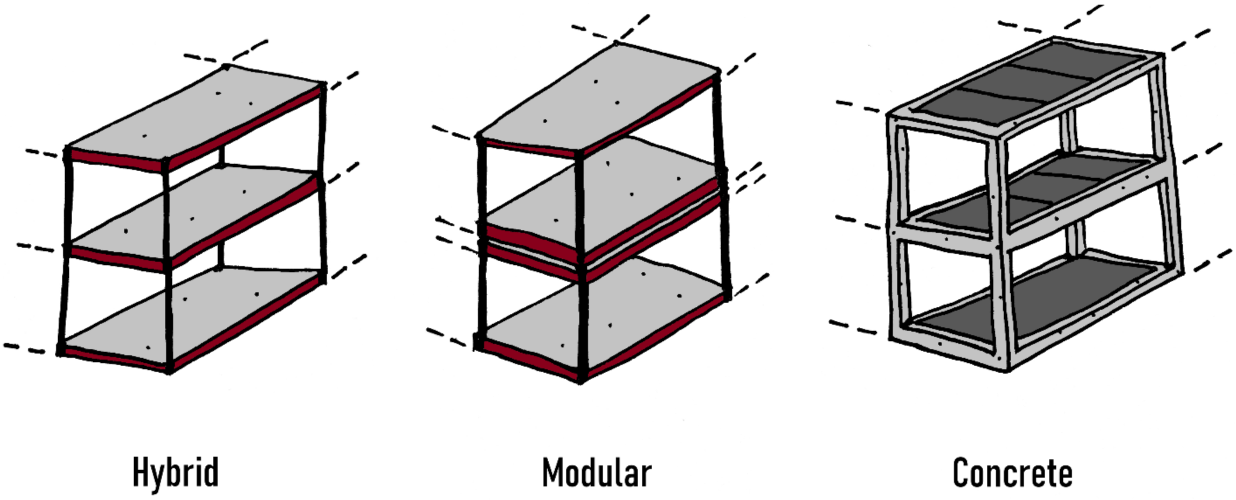

Figure 33: Sketch of proposed options

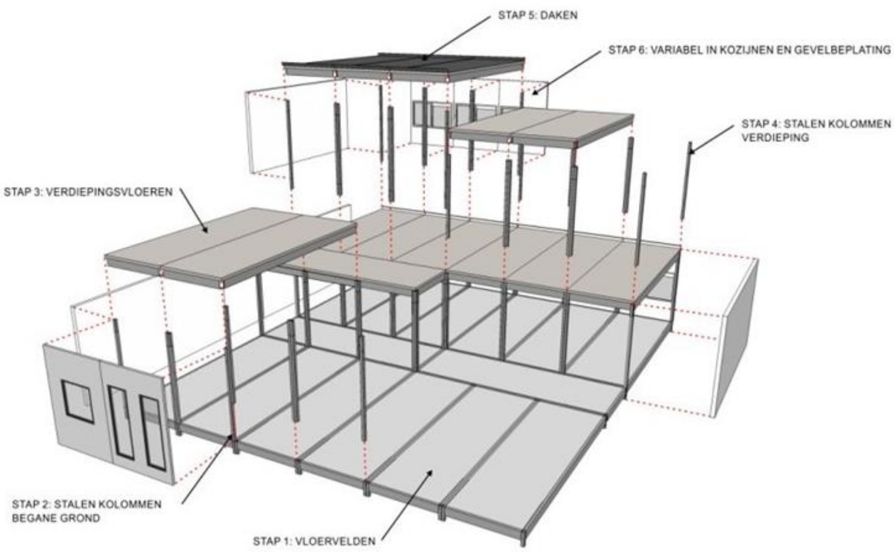

Figure 34: A hybrid construction system

Company B provided Option 3. Option 3 is a building structure, which can be classed as a hybrid construction system (Figure 34). It consists of separate elements, which are columns and floor/ceiling cassettes. This option had a standard bill of quantities provided with it. The document specified that a part of construction, not possible to execute with hybrid or modular would be carried out by Company A. This shows that even for what looks like a facility that is compatible with modular design, a small portion of work has to be carried out by a general contractor.

Company C provided Option 4. There were 102 modules calculated for the department at dimensions of 2,5*7,0-7,5m and 6 modules of 3*5m in plan. The bill of quantities provided with the module option was detailed, providing the full facility, as can be expected from a modular contractor. The cost of this building structure summed up to much higher than the conventional options. Figure 33 shows how the different structural options compare. The modular option doubled up the floor/ceiling cassettes, which is inefficient.

The provided documents were of different level of detail, but they all provided the sizing and costs of the load bearing structure. The life cycle costing was carried out for the structural skeleton in isolation, therefore only these costs were considered. For conventional options this included the columns, shear walls, floor slabs and staircases. For hybrid and modular options it included the steel framing, cassette slabs and staircases. The following elements were excluded: facades, partitioning walls, roofing material, lifts, foundations.

5.2.3. Interview with consultant to the client

An interview was carried out with the consultant to the client to find out what was considered when judging the tender options for this project. The contact was Theo Spoelstra from CureConsult, which consulted the client as a project manager. This information was necessary to set up the base case life cycle costing scenario.

It was revealed that the hospital is in a joint venture with other hospitals in the region with plans to build a large new hospital and move its services there. This is expected to take place in 10 years, at which point the current hospital building will be decommissioned. The lifespan of the hotfloor department specified in the tender was 15 years. Therefore, with organisational decisions at play, the lifespans of 5, 10, 15 and 20 years are reasonable for this case. In context of lifespan, the expected lifespan of a hotfloor department is 20 years and a 10–15-year lifespan is given to the installations. If they are well maintained and reliability is secured, they can last up to 20 years in the best case.

New hotfloor departments are not built with the intention to improve the efficiency of the service, but instead to comply to regulation and provide the services required by the insurance companies. There is no competitive gain for the hospital to have more or better operation rooms, as patients will not change hospitals because of this. The competitive aspect can be applied to lower complexity environments such as MRIs and other diagnostics, where having vacancies can attract more patients. Because of this reasoning, the revenue generated by an operating theatre was not calculated. However, it is known from literature that 2/3 of all hospital revenue stems from hotfloor departments [80]. In a comparable project, CureConsult calculated that renting 4 operation rooms for 9 months, which includes transportation and assembly twice, cost 900 000 euro. Most of the cost is made up of transportation and assembly. This is a large cost to the hospital and renting facilities is avoided.

The client did not consider saved construction time in monetary terms, because the old hotfloor department is meant to carry out all the functions until the new one is built. As mentioned before, hospitals try to avoid the situations of shutting down an operation room or having to rent one whilst a new one is getting built. The usual process is that it is expensive to renovate the operation rooms within an old hospital facility, therefore instead, a new department is built with a connection to the main building and the old hotfloor department is downgraded to patient rooms or offices.

An example case was given of a hospital in Zwolle, where considering revenue gain was applicable. Isala klinieken built and moved into a new hospital facility. But it also had an operation centre with high turnover and low complexity surgery in the underused old hospital facility, which had to be kept up to keep this department working. When the modular centre was finished, the old facility could close completely. This is a case where operational cost savings would be made through faster construction of the new department.

Furthermore, loan interest was not considered in the comparison, as currently interest rates for healthcare projects are low. 1.5% was mentioned in our conversation, which is low in comparison to inflation. It was found that the 8-month shorter modular construction offers a few thousand euros of benefit. It was also highlighted that less project management is required on site due to faster construction. A manager in the offsite manufacture takes some of this workload. In total, the same amount is spent of management, but the offsite management is included in the price of the modular option.

In terms of other tender options, a steel frame structure was also considered but was quickly omitted. The steel structure and its detailing presented airtightness issues and this was said to be a common disadvantage of steel structures. The steel also had to be protected from fire, which could done by encasing it with concrete, cement board or fire resistant paint similarly to modular steel units. However, doing this work onsite increases costs.

The interviewed consultant expressed that there is opportunity for modular construction in healthcare and hotfloor context. Due to many changes and updates in a hotfloor department, modules can provide solutions such as switching of modules. This was said to be realistic, but very complex. Usually the hotfloor department is in the centre of a hospital to minimise distance to other departments, and it would have to be moved outward to be accessible to such functionality. So far, there have not been any architectural proposals showcasing such ability.

5.2.4. Calculation set-up

The following values were inputted in the LCC of the case study. Figure 35 below, is a visual representation of the positive and negative cashflows.

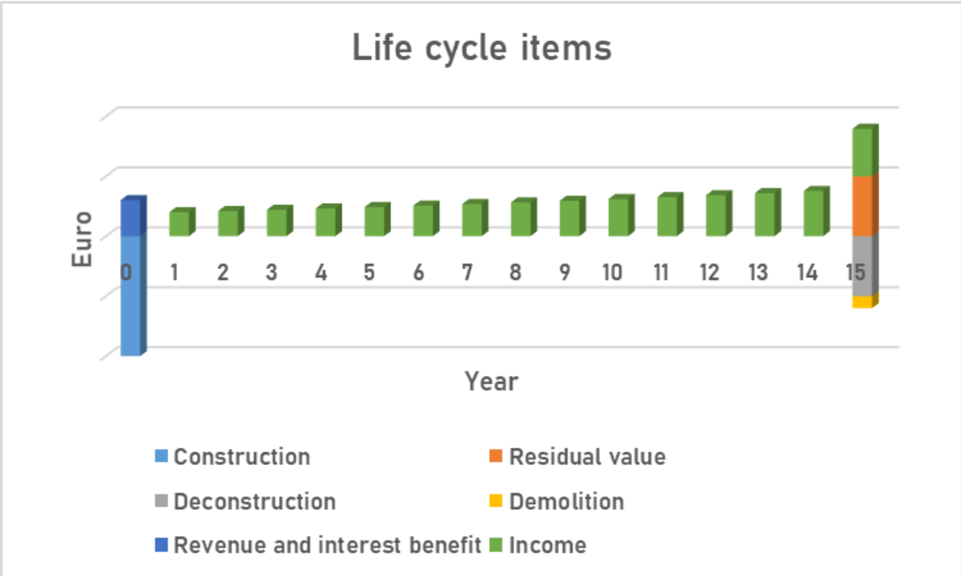

Figure 35: Representation of life cycle items

- **Construction cost.** This is the quoted cost of the structural skeleton, to be placed at the beginning of year 1. As specified earlier, only the cost of load carrying members is considered.
- **Earlier income benefit.** Earlier income is project and client specific. Interest benefit was calculated by calculating the amount of interest cost of 8 months and comparing to the Constultant option, which is representative of the market. Earlier income benefit was calculated by using the example provided by CureConsult for the rent of 4 operation rooms. In that arrangement, the two occurrences of assembly and transport of the modules made up a significant cost, which the researcher assumes to make up 50%. Therefore, the rent of the structure of the modules was assumed to be 20% of the stated value, which leaves the rent of installations and finishes at 30%. This rent of the modular structure translates to 25 000 € for 5 operation rooms per month. For further context, the client specified a fine for running over the planned deadline by a month of 105 000 €.
- **Lesser interest benefit.** Because this study is a comparison, lesser interest for the modular options can be also viewed as an extra cost for the other options. For the purpose of visualisation, it has been added to Figure 35 as a gain at the start of year 1, but in calculation, it is inputted as an extra cost to the other options instead, because they pay this difference in interest. A 1.5% yearly interest rate was stated by the Consultant and so this rate is used to determine the saving.

- **Constant income.** Income is determined by the same calculation as in the previous point. This is in relation to the building structure only and is very little compared to the expected revenue and profit made by the surgical services provided within the hotfloor department. Income is taken as 25 000 € per month.
- **Demolition, deconstruction and disassembly.** These values were taken from contractor quotes. A circular demolition company RGS provided the quotes of 90 000 € for demolition and 70 000 € for the deconstruction of the conventional structures. Disassembly for both the hybrid and module systems was said to cost 255 000 € by their manufacturers.
- **Residual value.** The residual value of Hybrid (100 000 €) and Module (400 000 €) options was guaranteed by Companies B and C at the end of the planned 15-year lifecycle. Industry interviews, covered earlier, revealed that DCG can agree to buy back modules at a decreasing rate, whilst Jan Snel stated that it would buy back modules for up to 15% for up to 15 years. Ursem stated that it would take back modules for free for up to 20 years, but they would, unlike the others, absorb the decommissioning costs. DCG offers more semi-permanent solutions which allow a more competitive residual value estimate for short term. Whereas Jan Snel and Ursem have a hard cap on what they can agree to pay for used modules. Discounting the 100 000€ and 400 000€ values provided by Companies B and C for the hybrid and module systems in 15 years, gives 45 000€ and 179 000€ respectively. This equals 7,1% and 18,9% of the initial cost of the structure. For life cycle costing, Companies B and C discounted residual values were conservatively kept the same for years 5, 10 and 15, and were decreased for year 20 as residual value is assumed to quickly decrease with time. The residual values must equal these percentages of the initial construction cost after being discounted.

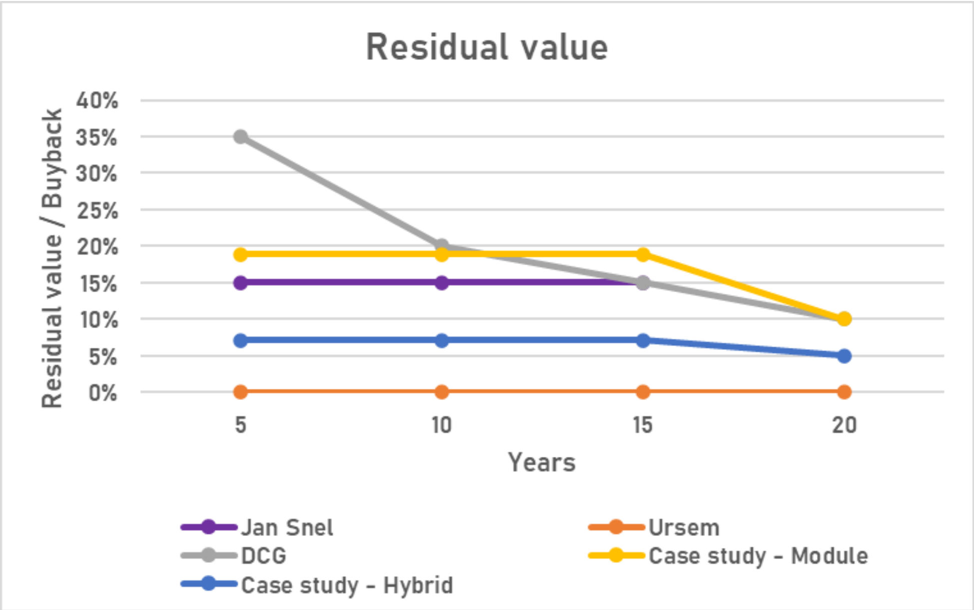

Figure 36: Residual value specified by companies

- **Maintenance and operational costs.** As the study is focused on the load bearing structure of the building, maintenance and operational costs are outside the scope of the calculation. However, if a new calculation is created where the facility in considered with installations, envelope properties and maintenance schedules, these can be added to the current calculation as annually condensed outflows.

The calculation was setup in Excel. Excel has the required NPV(), XIRR() and MIRR() formulas ready to use. These can only be used to calculate the measures for annual cashflow items. In Figure 37 below, the LCC calculation is assembled to model a 15-year lifespan, as per the tender requirement.

All positive and negative cashflow items were imputed at the timestamp at which they are planned to occur and summed to total undiscounted cashflow. Using these cashflow values, the dates of payment and the discount rate, the NPV was found for each year. The cumulative NPV column values can be compared to the initial investment to determine the when the discounted payback period is achieved. This was run for each option.

Calculation ye	15
Discount rate	5%
NPV	2 547 929 €
IRR	40%
MIRR	6%
Loan interest	2%
Reinvestment	0%

Year	Date of Payment	Construction Cost	Benefits and Income	End-of-life Items	Undiscounted Cashflow	Net Present Value (NPV)	Cumulative NPV
0	2021-12-31	- 949 135 €	200 276 €		- 748 859 €	- 748 859 €	- 748 859 €
1	2022-12-31		300 000 €		300 000 €	287 081 €	- 461 778 €
2	2023-12-31		300 000 €		300 000 €	274 719 €	- 187 059 €
3	2024-12-31		300 000 €		300 000 €	262 889 €	75 830 €
4	2025-12-31		300 000 €		300 000 €	251 568 €	327 398 €
5	2026-12-31		300 000 €		300 000 €	240 735 €	568 134 €
6	2027-12-31		300 000 €		300 000 €	230 369 €	798 502 €
7	2028-12-31		300 000 €		300 000 €	220 449 €	1 018 951 €
8	2029-12-31		300 000 €		300 000 €	210 956 €	1 229 907 €
9	2030-12-31		300 000 €		300 000 €	201 871 €	1 431 778 €
10	2031-12-31		300 000 €		300 000 €	193 178 €	1 624 956 €
11	2032-12-31		300 000 €		300 000 €	184 860 €	1 809 816 €
12	2033-12-31		300 000 €		300 000 €	176 899 €	1 986 715 €
13	2034-12-31		300 000 €		300 000 €	169 281 €	2 155 996 €
14	2035-12-31		300 000 €		300 000 €	161 992 €	2 317 988 €
15	2036-12-31		300 000 €	145 000 €	445 000 €	229 941 €	2 547 929 €
16	2037-12-31				- €	- €	2 547 929 €
17	2038-12-31				- €	- €	2 547 929 €
18	2039-12-31				- €	- €	2 547 929 €
19	2040-12-31				- €	- €	2 547 929 €
20	2041-12-31				- €	- €	2 547 929 €
21	2042-12-31				- €	- €	2 547 929 €
22	2043-12-31				- €	- €	2 547 929 €
23	2044-12-31				- €	- €	2 547 929 €
24	2045-12-31				- €	- €	2 547 929 €
25	2046-12-31				- €	- €	2 547 929 €
26	2047-12-31				- €	- €	2 547 929 €
27	2048-12-31				- €	- €	2 547 929 €
28	2049-12-31				- €	- €	2 547 929 €
29	2050-12-31				- €	- €	2 547 929 €
					Total NPV	2 547 929 €	

Figure 37: Example LCC calculation for a 15-year lifespan of the modular option

Scenarios are created to analyse the results step by step. Scenario A is the representation of what was considered by the client in the case study project – the initial costs and the residual value. Scenario B includes the essential end-of- life costs of demolition, deconstruction and disassembly. Scenarios A & B are life cycle costings as defined by the ISO 15686-5. Scenario C includes the latter and the two benefits of earlier income due to faster construction and lesser interest. Scenario D includes the latter with the addition of an estimate of constant yearly income. Scenarios C & D are whole life cost calculations as defined by the ISO 15686-5, because they include external benefits to the client besides costs. As mentioned previously, the modular option is compared to the Consultant option, as the option which best represents market prices. Result sensitivity of the considered cashflow items is discussed in the next chapter.

SCENARIO A – Initial cost and residual value

SCENARIO B – Initial cost, residual value and end-of-life costs

SCENARIO C – Initial cost, residual value, end-of-life costs, earlier income, less interest

SCENARIO D – Initial cost, residual value, end-of-life costs, earlier income, less interest, income

The following assumptions are made in the calculation of each scenario:

- 0% inflation, commonly assumed in public projects. Results can be used to compare options without the uncertainty of inflation rates which change yearly.
- 4,5% real discount rate, as proposed for public projects.
- MIRR variables: 1,5% loan interest (client Consultant interview) and 0% reinvestment rate
- Deconstruction is assumed for the conventional options. Deconstruction of a conventionally built reinforced concrete structure implies using salvaging practises to extract valuable structural members, which can result in a lower cost than demolition.

5.2.5. Results

The results show how each scenario performs in a 15-year LCC (or whole-life cost as per ISO definition in Scenarios C & D). The discussed measures of NPV, IRR, MIRR and Discounted Payback are evaluated.

Table 4: Scenario A, 15 year lifespan

SCENARIO A 15-year LCC	Consultant (Conventional)	Company A (Conventional)	Company B (Hybrid)	Company C (Module)
Initial cost	539 553 €	311 953 €	634 686 €	949 135 €
NPV	-539 553 €	-311 953 €	-583 014 €	-742 447 €
IRR	n/a without a single positive yearly cashflow sum			
MIRR	n/a without a single positive yearly cashflow sum			
Disc. Payback Years	n/a without positive end result			

Table 5: Scenario B, 15 year lifespan

SCENARIO B 15-year LCC	Consultant (Conventional)	Company A (Conventional)	Company B (Hybrid)	Company C (Module)
Initial cost	539 553 €	311 953 €	634 686 €	949 135 €
NPV	-575 723 €	-348 123 €	-714 778 €	-874 211 €
IRR	n/a without a single positive yearly cashflow sum			
MIRR	n/a without a single positive yearly cashflow sum			
Disc. Payback Years	n/a without positive end result			

Table 6: Scenario C, 15 year lifespan

SCENARIO C 15-year WLC	Consultant (Conventional)	Company A (Conventional)	Company B (Hybrid)	Company C (Module)
Initial cost	539 553 €	311 953 €	634 686 €	949 135 €
NPV	-575 999 €	-348 399 €	-514 778 €	-674 211 €
IRR	n/a without a single positive yearly cashflow sum			
MIRR	n/a without a single positive yearly cashflow sum			
Disc. Payback Years	n/a without positive end result			

Table 7: Scenario D, 15 year lifespan

SCENARIO D 15-year WLC	Consultant (Conventional)	Company A (Conventional)	Company B (Hybrid)	Company C (Module)
Initial cost	539 553 €	311 953 €	634 686 €	949 135 €
NPV	2 645 865 €	2 873 465 €	2 707 086 €	2 547 653 €
IRR	55,5%	96,0%	68,9%	39,8%
MIRR	7,5%	9,6%	8,3%	6,5%
Disc. Payback Years	2	2	2	3

5.2.6. Analysis

The IRR, MIRR could not be calculated in the first three scenarios (Table 4, Table 5, Table 6), because the measures require for at least one positive annual cashflow sum to provide a result. Discounted payback period could also not be calculated as income is necessary to swing the balance from negative to positive. The point at which this happens is the payback moment. In Scenario D, Table 7, the IRR and MIRR values tell a similar story to the NPV measure. The discounted payback period results also follow the NPV result and are trivial. Due to the continuity of results, only NPV is analysed.

Table 8: Case study results

15-year NPV	1st	2nd	3rd	4th
Scenario A	Company A	Consultant	Hybrid	Module
Scenario B	Company A	Consultant	Hybrid	Module
Scenario C	Company A	Hybrid	Consultant	Module
Scenario D	Company A	Hybrid	Consultant	Module

In terms of net present value competitiveness, the tender options line up as shown in Table 8. The modular option is last in each considered scenario. A change is noted between the Consultant and Hybrid options, and this shows that the additional considerations in Scenarios C & D are responsible for the NPV increase of the Hybrid option. In these Scenarios, an increase is also noted in the NPV of the Modular option. Figure 38 shows the year by year summation of the NPV for each option. Proportions between the option NPVs are maintained and a slight decrease in gradient is notes throughout the lifespan, due to discounting. The larger change in gradient in the last year is explained by demolition/disassembly costs and residual value.

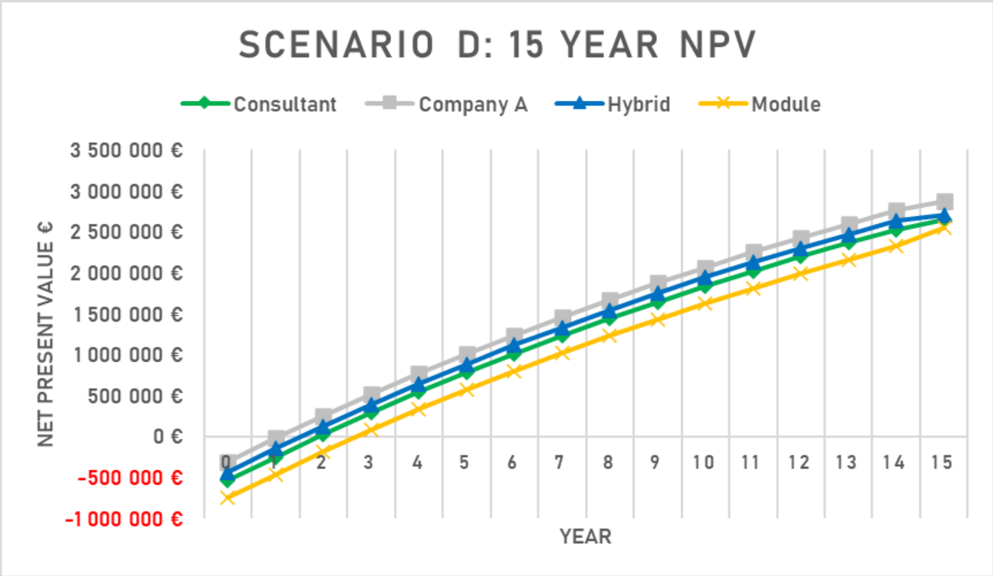

Figure 38: 15 Year NPV for Scenario D

Evaluating the results using the 0% inflation scenario recommended for governmental analyses and the Stanford University inflation and discount rate used for life cycle costing of buildings, Table 9 is generated. These two approaches are interesting for analysis, because by omitting inflation, future fluctuations in inflation are overcome. However, including a conservative inflation rate can give a more realistic result. Organisations normally evaluate the risks they are willing to take and set these rates, but for the simplicity of this research, conservative outcomes are highlighted.

An omission of inflation gives a more conservative result in for Scenario A. For the other Scenarios, the inclusion of inflation gives more stringent results. As this study is focused on using life cycle costing to evaluate the impact of the main life cycle items of modular construction, the latter Scenarios are more important. This means that inflation must be included.

Table 9: Competitive pricing of the modular option, with and without inflation, for Scenario D

No inflation and real discount rate at 4,5%	Competitive modular cost:	Percentage over the cost of the conventional structure:
Scenario A	746 000 €	38,3%
Scenario B	650 000 €	20,5%
Scenario C	852 000 €	57,9%
Scenario D	852 000 €	57,9%
Inflation at 3% and real discount rate at 3,9% [73]		
Scenario A	764 000 €	41,6%
Scenario B	602 000 €	11,6%
Scenario C	804 000 €	49,0%
Scenario D	804 000 €	49,0%

Chapter conclusion

In this chapter, the formulas which make up life cycle costing, and the measures used to evaluate LCC results were discussed. The consultant of the client was interviewed to explain what was considered in the tender procedure of the studied case. An LCC of the case study was then run with several LCC scenarios. The results of the modular option were compared to that of the consulting company.

The case study results were primarily compared on their net present value (NPV) which is the approach used in public projects, where costs are the major cashflows. This contrasts with private investments, where a profit is important. Other life cycle costing measures did not provide further insight. The results showed that the modular option was not competitive to the conventional option under any of the considered scenarios. However, by considering a conservative situation where inflation is included, it was found that the modular option would, in this project tender, be competitive at a cost of 804 000 € or 49% above the cost of the Consultant’s option.

CHAPTER 6

Influence of LCC parameters

This chapter is aimed at variation of life cycle and whole life costing parameters. By varying each parameter in isolation, its impact on the results can be assessed. The standard discount and inflation rate were taken from Stanford University Guidelines for LCC of buildings, 3,9% and 3% respectively. The same scenarios as in the previous case study were calculated. The results were analysed to quantify the effect on NPV of the modular construction option versus the conventional option. Furthermore, the rate of increase or decrease of the NPV was studied.

Carbon taxation was recently introduced to have an ever-increasing impact on the construction industry, incentivising the use of low carbon materials. The amount of embodied carbon was, therefore, calculated for each structure to identify whether, due to carbon tax, the cost of modular construction will decrease in future years. The reduction of embodied carbon using recycled material and cement additives was also suggested, as well as a modular timber option for a broader comparison.

6. INFLUENCE OF LCC PARAMETERS

Objectives covered

- O4.1. Discuss which life cycle cost parameters are important for the studied case and propose several life cycle costing scenarios.
- O4.2. Vary life cycle cost parameters to find the boundaries for modular construction in healthcare. Derive under what conditions modular construction is a viable construction method.
- O4.3. Calculate the carbon tax for each tender option and determine how the tax affects construction costs. Calculate the effect of reducing embodied carbon of the structure.

6.1. Life cycle costing parameters

Lifespan. The lifespan of a property is an important parameter in life cycle costing. A longer lifespan means that monthly and yearly operational and maintenance expenditure become a greater percentage of total costs. End of life cashflow becomes less dominant. Cashflows which are closer to the current day have more importance. Therefore, a shorter lifespan means that the initial and end of life costs and gains increase in importance.

Inflation. Inflation varies yearly and is therefore an uncertainty in life cycle calculations. It can be omitted, calculated only at the start of an NPV calculation or considered for each year using a MIRR calculation. Calculations of public projects or projects which do not focus on the return on investment are commonly NPV focused, omitting inflation and using an advised national discount rate. We have seen this in the case study calculation. However, varying the inflation rate, when inflation is considered, will reveal whether manipulating this parameter changes the NPV of options.

Earlier income benefit. This is the major benefit of modular construction, alongside a lesser interest payment. As these monetary benefits occur at the same time, the results relate to them both. The aim is to find out what impact the uncertainty of pricing this benefit has on the NPV.

Constant income. Considering income in the NPV calculation gives an overall positive end result, which shows the discounted payback period. It also allows the IRR and the more stringent MIRR calculation to produce a result. A large cashflow consideration such as income has the ability to significantly skew results.

Real discount rate. The real discount rate is that from which inflation has been subtracted. There is a variation between studies and the recommended value for public projects is 4,5% [75]. Increasing this rate decreases the value of future cashflows, and the cashflows in the beginning of the lifecycle become more important.

Carbon tax. Carbon tax is affected by time, as each year this tax rises. The less carbon intensive option becomes more competitive each year. The tax can be used as a parameter to identify what effect it has on making a modular structure competitive in the future. However, the modular option must initially have less embodied carbon than the conventional option, for this to have increasing effect over time. Furthermore, by adjusting the amount of embodied carbon of the design, it is possible to tell whether and when more sustainable options will be competitive. This means using recycled steel instead of virgin, or using timber as the main structural material to inadvertently pay a lower carbon tax included in the material cost.

6.2. Sensitivity studies

Life cycle costing scenarios remain the same as in the earlier case study. By assessing the scenarios, it is aimed to find:

- How does the length of the lifespan affect the life cycle costing? It is hypothesised that increasing the lifespan would make hybrid and modules less attractive, due to less a lesser residual value and heavier discounting.
- How much more expensive can the modular option be initially, to still be cheaper than the conventional option over the lifespan?
- What effect does inflation, real discount rate and income have on the calculation?
- Will carbon taxing increase the competitiveness of modular structures in the future?
- What is the impact of reducing embodied carbon in these options, by using less carbon intensive concrete, recycled steel or timber in the tender options?

The assumptions in this calculation are used to produce a realistic business case, and find the impact of parameters considered within an LCC:

- 3% inflation. Stanford university.
- 3,9% real discount rate. Stanford university.
- Deconstruction is assumed for the conventional options. Deconstruction of a conventionally built reinforced concrete structure implies using salvaging practises to extract valuable structural members, which can result in a lower cost than demolition.
- The consultant option is set as the base case, for which the reasons are discussed in the case study. The performance of the modular option is compared to the base case.

6.2.1. Lifespan

For the consideration of this parameter, the total net present value (NPV) is calculated for every lifespan and every tender option. The results show differences in NPV between actual lifespans of the structure and can be used to make decisions such as when to decommission the structure to maximise NPV.

SCENARIO A – Initial cost and residual value

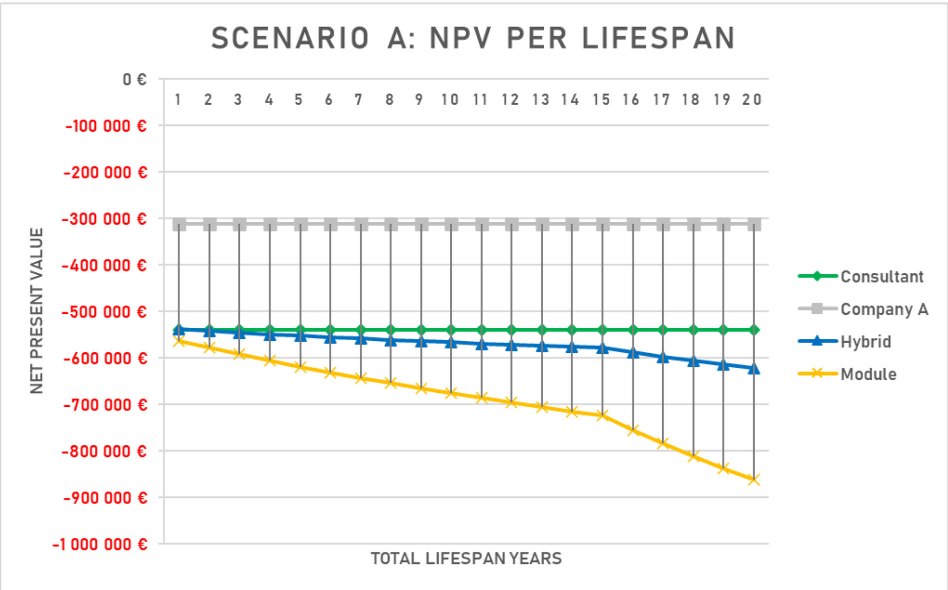

Figure 39: Scenario A

The graph shows that the conventional options (Consultant and Company A) do not change gradient when lifespan is increased, because they only include the initial costs. Hybrid and module options lose NPV with an increasing lifespan. This is because the residual value is discounted more heavily for every additional year. It is also responsible for the slight curvature. The kinks at the 15-year lifespan for the two options are due to an additional decrease in residual value.

For the 15-year lifespan, it is found that the modular option is initially overpriced by 24,2% (Competitive initial costs are 764 000 €). The modular option can be 41,6% more expensive than the conventional option and achieve the same NPV in 15 years.

SCENARIO B – Initial cost, residual value and end-of-life costs

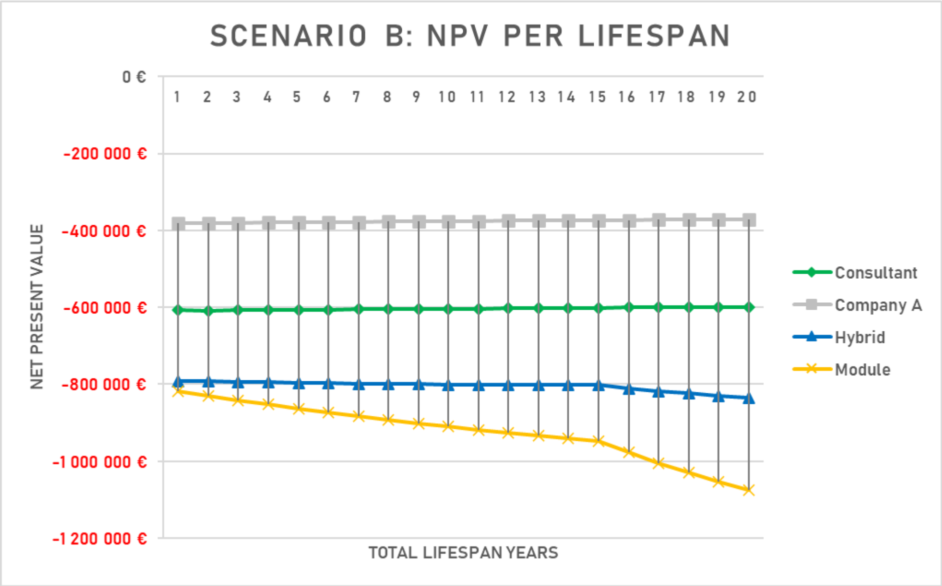

Figure 40: Scenario B

Considering additional disassembly and deconstruction costs for each option, decreases the NPV of hybrid and modular options in comparison to Scenario A. The conventional options (Consultant and Company A) show a slightly increasing gradient, because the expense of deconstruction at the end of the lifespan is decreasing in negative value due to discounting.

At the 15-year lifespan, the modular option is initially overpriced by 57,7% (Competitive initial costs are 602 000 €). The modular option can be 11,6% more expensive than the conventional option and achieve the same NPV in 15 years.

SCENARIO C – Initial cost, residual value, end-of-life costs, earlier income, less interest

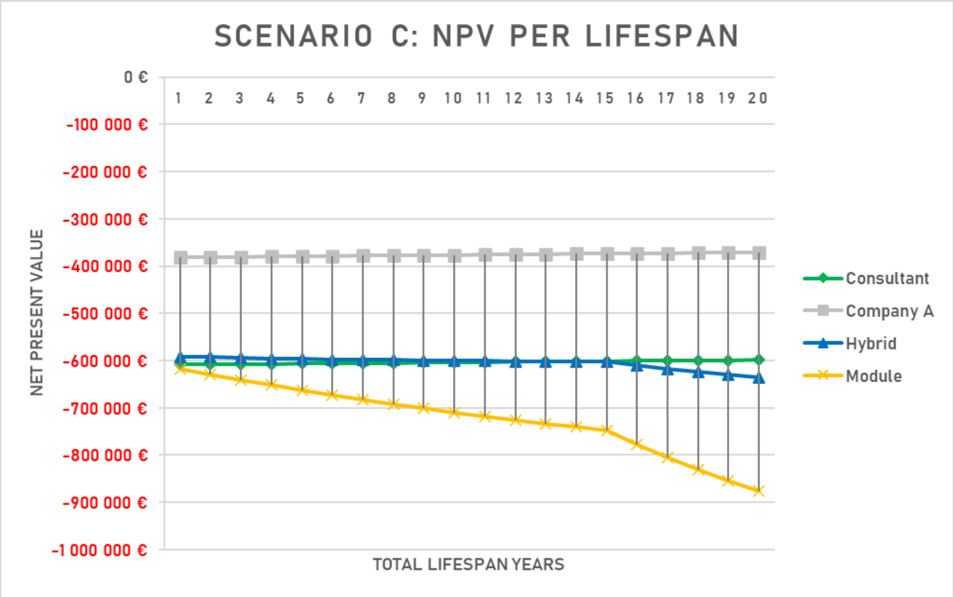

Figure 41: Scenario C

With the addition of earlier income and lesser interest benefits, Scenario C shows an improvement in NPV of hybrid and modular options. The hybrid structure is competitive against the consultant option at the 15-year lifespan.

At the15-year lifespan, the modular option is initially overpriced by 18,1% (Competitive initial costs are 804 000€). The modular option can be 49,0% more expensive than the conventional option and achieve the same NPV in 15 years.

SCENARIO D – Initial cost, residual value, end-of-life costs, earlier income, less interest, income

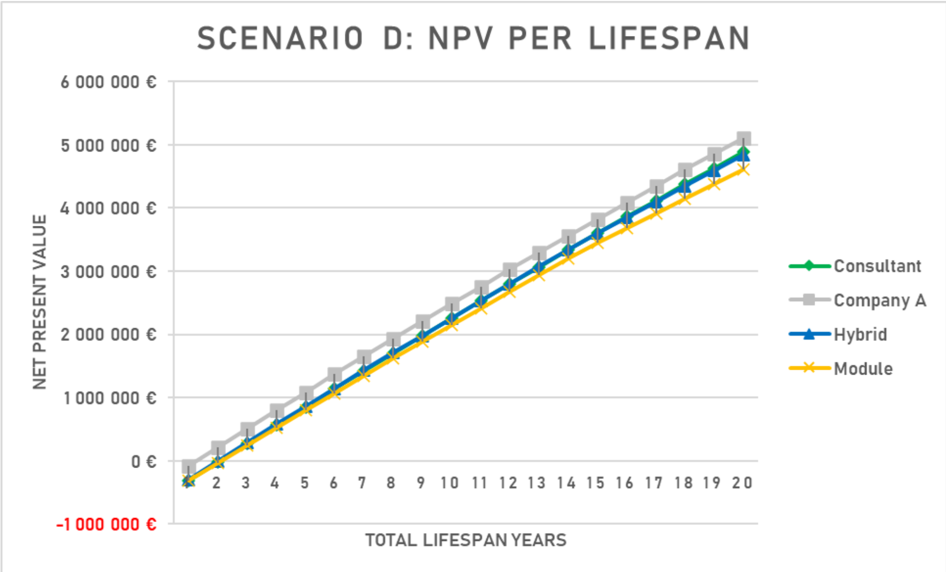

Figure 42: Scenario D

Lastly, a consideration for constant income is made. These results are similar to those of Scenario C. However, the nominal NPV difference between options is decreased due to a large assumed income.

At the15-year lifespan, the modular option is initially overpriced by 18,1% (Competitive initial costs are 804 000€). The modular option can be 49,0% more expensive than the conventional option and achieve the same NPV in 15 years. This is the same result found in Scenario C.

It is found that the modular option is not competitive against the conventional option in any of the considered scenarios. A fixed or decreasing residual value of the modular option creates an unfavourable result for modular structures. With each additional year added to the lifespan, the residual value is further discounted which produces a negative gradient in comparison to the other options.

6.2.2. Inflation

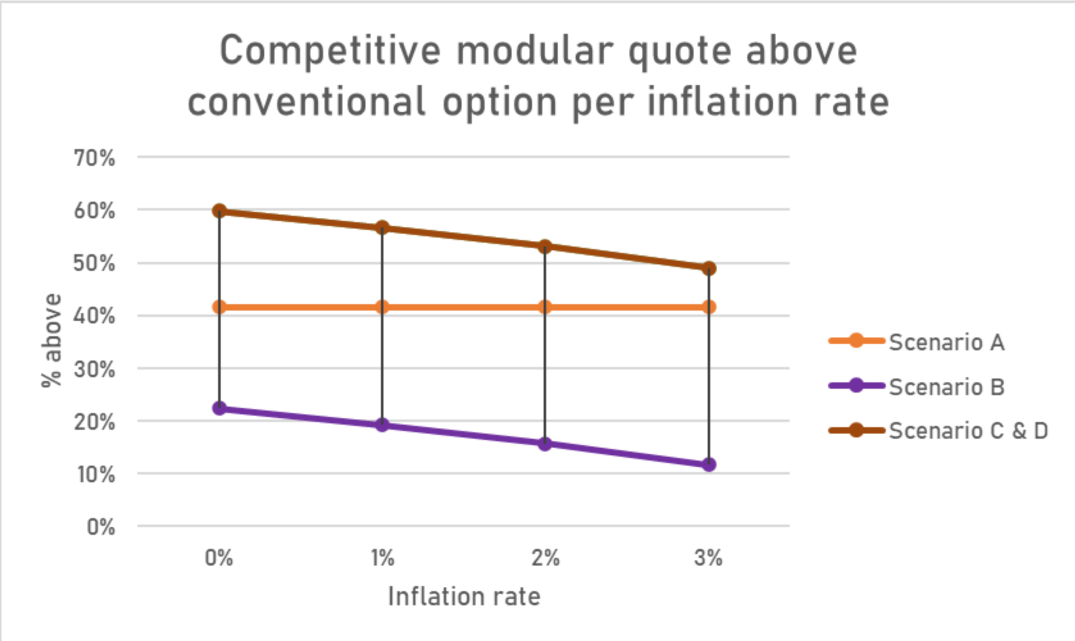

Figure 43: Inflation sensitivity

In the sensitivity study of inflation effects, the inflation rate was varied between 0% and 3% for each LCC scenario. The NPV value of the modular option was matched to that of the conventional option at the 15-year lifespan. The difference in initial cost was recorded.

The results show that considering different inflation rates has no effect in Scenario A and the modular option can be 41,6% more expensive than the conventional option. In Scenario B, the modular option is heavily affected, decreasing from 22,3% at 0% inflation to 11,6% at 3% inflation. In Scenarios C & D, the modular option is equally negatively affected by the increasing inflation rate. This suggests that the additional consideration of income in Scenario D does not have an effect on the results.

6.2.3. Earlier income

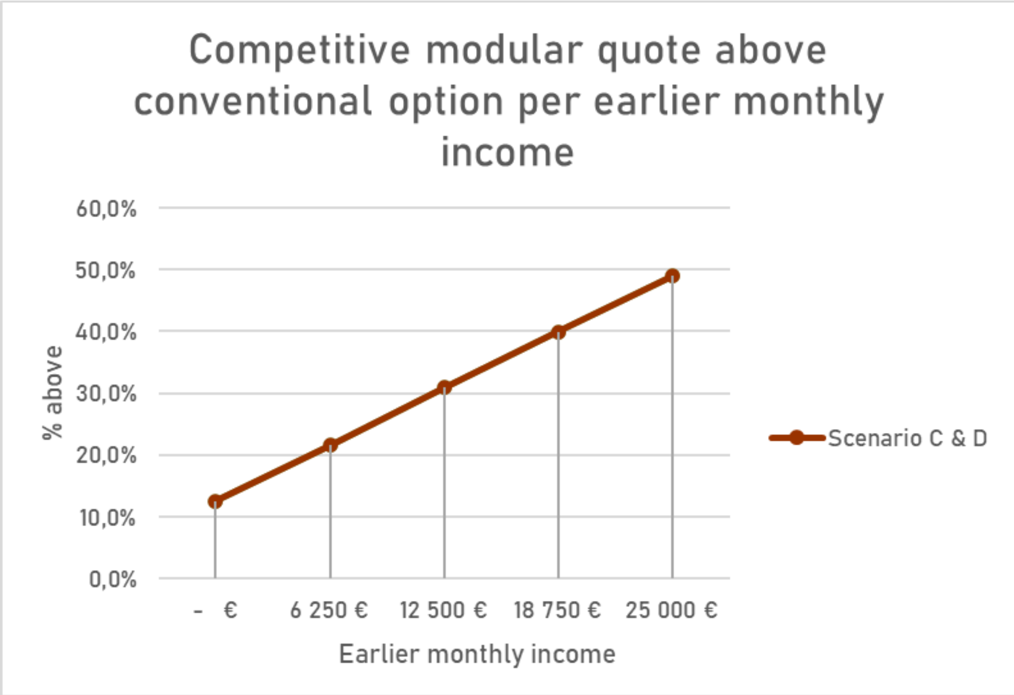

Figure 44: Earlier income

This sensitivity study encompasses earlier income generated due to faster construction. The results show that the increase in this benefit has a significant positive impact for the competitiveness of the modular option. In the case study, the modular option was prognosed to take 8 months shorter to construct than the conventional option. The highest value of 25 000 € is derived from the interview with the consultant to the client, which represents the isolated cost of renting the structural skeleton of a 5-operation-room facility. As renting operation rooms is expensive, this was considered as the maximum value. At maximum earlier income valuation, the modular option can be 49,0% more expensive than the conventional option for Scenario C and D.

6.2.4. Constant income

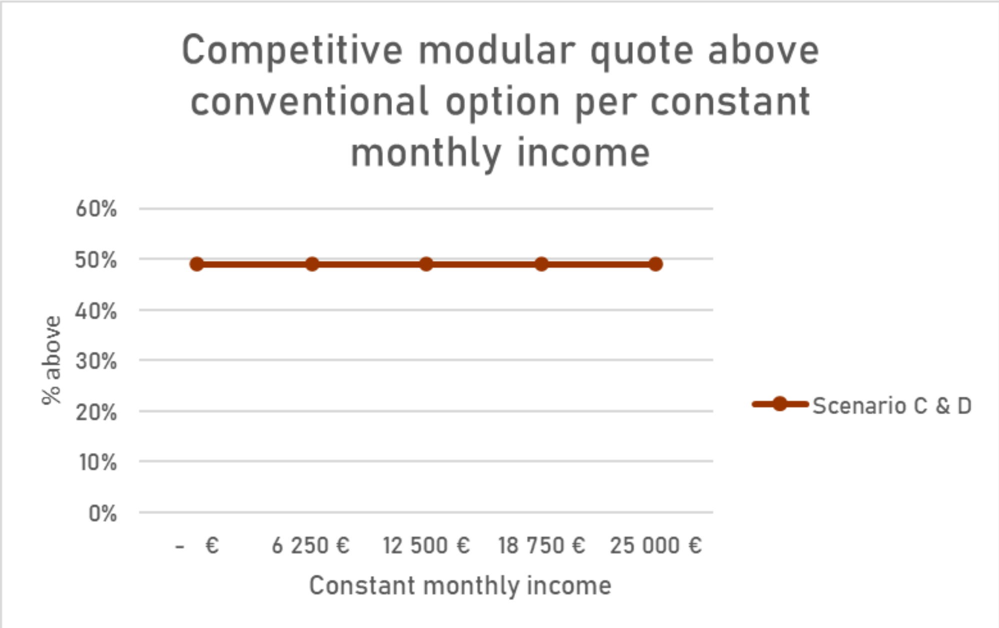

Figure 45: Constant income

A sensitivity study of constant income over the lifespan of the structure confirms what can be expected from earlier results where Scenarios C & D match. Judging from Scenario D, considering constant income does not affect the results. Constant income can be considered if it is necessary to evaluate measures such as IRR, MIRR and Discounted Payback Period. This cashflow item must be escalated by the inflation rate and included in every option. It also means that similar regular constant real cashflow items will have no impact on the NPV. At any monthly income, the modular option is competitive at up to 49,0% more than the conventional option.

6.2.5. Real discount rate

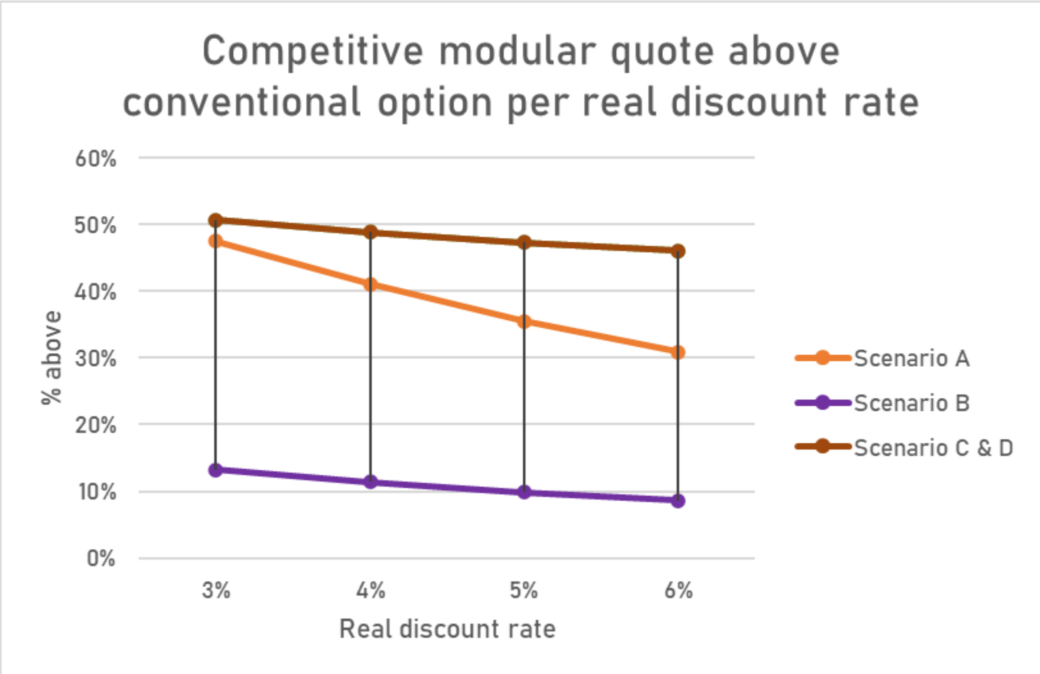

Figure 46: Real discount rate

In the sensitivity study of the discount rate, results show that the real discount rate affects scenarios B, C & D at a comparable rate – increasing the real discount rate lowers the competitive cost of the modular option. These scenarios decrease by 4,6% in Figure 46, when comparing the real discount rates of 3% and 6%. Scenario A shows a larger rate of decline. It decreases by 16,7%. This is due to the increasing discounting of the residual value, which is the only other item considered with initial costs in Scenario A.

The data shows that a smaller discount rate is beneficial for modular construction. It is also clear that considering other end-of-life costs, such as demolition, deconstruction and disassembly (Scenario B) is a necessary first step to life cycle costing. It is dangerous to consider Scenario A, as it can lead to a higher total life cycle cost than expected. Considering other benefits does not further impact the rate of decrease in competitiveness, as long as they are incurred at the start of the life cycle (Scenarios C).

6.3. Embodied carbon and carbon tax

The carbon tax, in its proposed form, is an increase of 10,56 € per year starting at 30 € per ton of CO_2 in 2021. It increases linearly and has a proportional effect on the options through time. This means that if the carbon tax of Option 1 is 20% lower than that of Option 2, in 10 years' time the carbon tax of Option 1 will remain 20% lower. However, the relation of the carbon tax to whole-life or life cycle cost may change.

It is in the interest of carbon taxation to increase the cost of carbon at a faster rate than the escalation rate of the asset. Otherwise, even though the euro amount per ton of carbon may increase each year, the real value of carbon would stagnate. That would halt all the pressure on industry to look for lower embodied carbon alternatives. The current fixed yearly increase achieves this with double-digit yearly percentage increases in the beginning going to a 5% yearly increase in year 2040.

If the modular steel option is lower in embodied carbon than the competition, this competitive advantage will increase in the future. The embodied carbon is calculated for each option using the extensive material

Inventory of Carbon and Energy from the University of Bath [81]. Furthermore, two cases are calculated. The first one is using all virgin material and standard cement mixture. The second is using lower embodied carbon fully recycled steel and concrete with the lowest embodied carbon cement replacements. This is done to check the effect of reasonably decreasing embodied carbon in these options.

A modular timber option is additionally calculated. Timber construction requires less energy and research suggests that carbon taxing increases the competitiveness of timber structures to other structural materials [82]. Timber construction can be built as panelised, hybrid or modular systems with the use of CLT, LVL and Glulam products [83]. However, no research is present on corner supported timber modules, which are necessary in the healthcare context. It is of interest to see how a modular timber option compares to the case study options. Therefore, an equivalent corner supported Glulam module was calculated by translating each steel beam from the steel module into a glue laminated beam of strength GL28h. Beams were checked for flexural strength and columns for compressive strength, for a rough sizing of the timber module. The calculations can be found in Appendix F. Figure 48 is a visualisation of the assessed structures.

Figure 47: Corner supported Glulam module (Lehmann Group CH)

The goal of this rough comparison is to see what impact the carbon tax has on initial construction costs and how a fitting timber alternative compares. The limitations include a feasible structural layout of a Glulam module subject to a full structural analysis and a lack of research and examples (Figure 47) of corner supported timber modules. The costs of such a timber module are unknown.

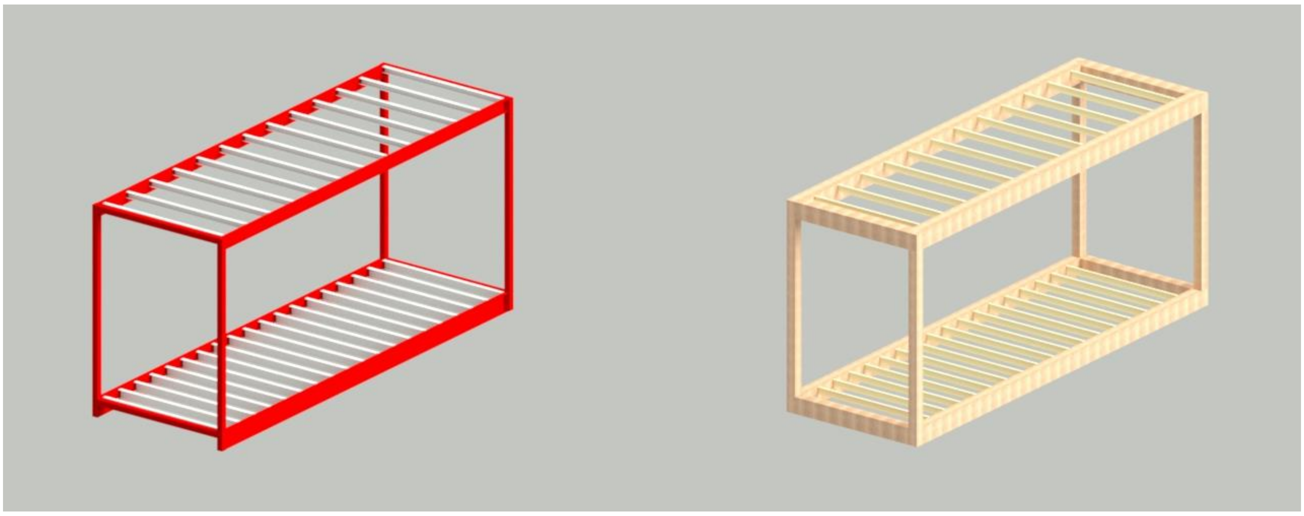

*Figure 48: A steel 2,5*7,5 module and its equivalent module in GL28h timber*

The following assumptions are made for the comparison shown in Figure 48:

- The exact impact on construction product costs due to carbon taxing is a complex prediction outside the scope of this piece of research. Given that steel and cement making industries are directly affected by the EU ETS and the CO2 levy in the Netherlands, it is assumed that it directly impacts the product costs.
- All concrete members have prefabricated elements, meaning that a higher grade of concrete is used (RC40/50).

6.3.1. Results

Standard materials

The first result below is the carbon tax for each project option, using standard materials. The tax is calculated and shown for 20 years ahead. This means that the initial costs of the same tender competition options would be accordingly higher by the specified amount. The result is adjusted for 3% inflation, which allows to compare the amounts directly.

- Structural steel is from a 57% recycled source (EU average)
- Concrete is RC40/50 CEM I
- Timber is GL28h

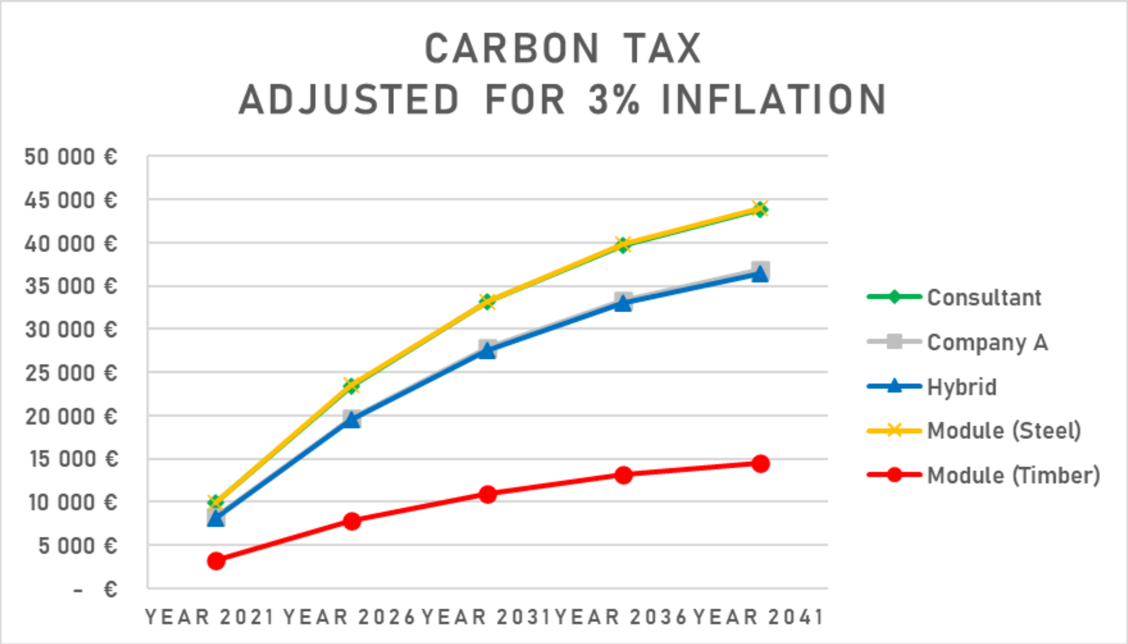

Figure 49: Carbon tax (High carbon)

The results show that the modular steel and conventional consultant options are almost equally affected by the carbon tax. Similarly, the hybrid and conventional option from Company A are equally affected and equate to less tax than the modular steel option. The modular timber option equates to the least carbon tax, and is lower by more than half of every other option.

Low carbon materials

The second result is the carbon tax for each project option, using reasonable low carbon materials. The term 'reasonable' means that the material is known and used in industry.

- Structural steel is from a 100% recycled source
- Concrete is RC40/50 with 50% Blast furnace slag
- Timber is GL28h

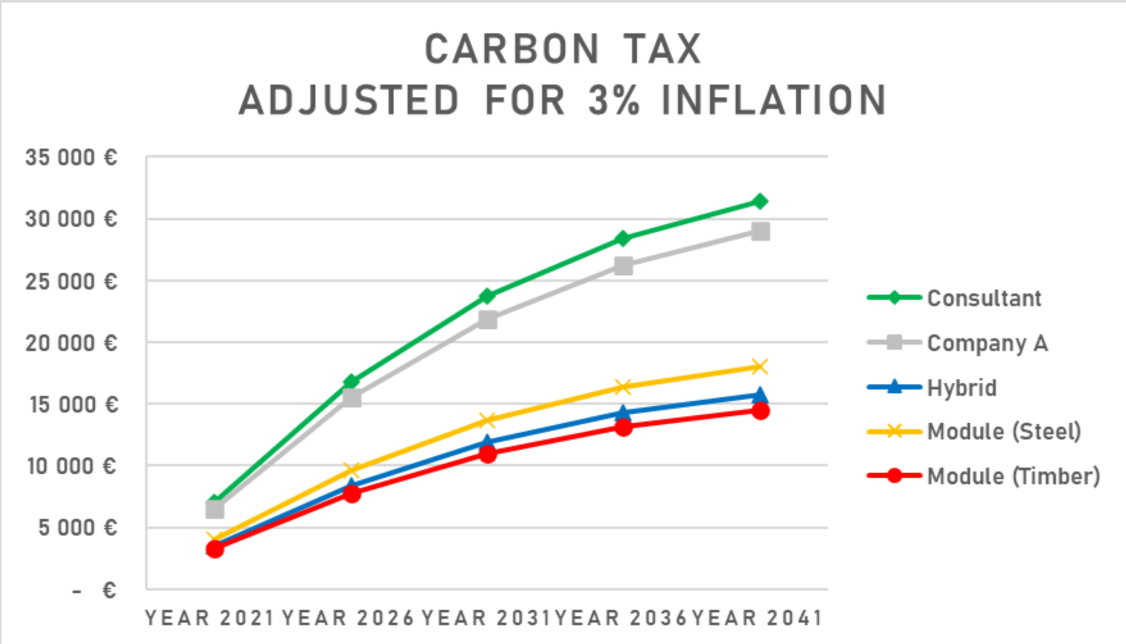

Figure 50: Carbon tax (Low carbon)

This result shows that reasonably reducing embodied carbon lowers carbon tax in conventional options and majorly lowers the tax for modular and hybrid structures. For the tax in year 2041, this is a decrease of 28% for the Consultant option, and a decrease of 59% for the modular steel option. This gives credibility to the fact that steel modular structures can be more sustainable than conventional concrete structures, if reasonably reduced embodied carbon material is used. The modular timber option is still the best performing, with the lowest tax.

Table 10: Carbon tax per option

Year 2021	**Consultant**	**Company A**	**Hybrid**	**Module (Steel)**	**Module (Timber)**
Standard	9 837 €	8 278 €	8 172 €	9 867 €	3 261 €
Low carbon	7 056 €	6 510 €	3 534 €	4 054 €	3 261 €
Year 2041	**Consultant**	**Company A**	**Hybrid**	**Module (Steel)**	**Module (Timber)**
Standard	43 792 €	36 851 €	36 378 €	43 926 €	14 518 €
Low carbon	31 408 €	28 978 €	15 730 €	18 048 €	14 518 €

Looking at year 2021 in Table 10, it can be said that the carbon tax makes up a small proportion of the initial costs, representing 1% of the modular steel option cost (949 135 €) when standard materials are used. In year 2041 this is 4,6%. This means that the impact of the tax over this period of time is significant, and it is worthwhile to transition to the use of low carbon materials in modular construction, as it more than halves the internalised tax.

The difference in tax between the consultant and modular steel options, for the low carbon materials, is 3 000 € in 2021 and 13 000 € in 2041. This is a small advantage for the competitiveness of modular steel over the conventional concrete option. The lesser carbon tax is clearly not enough to make the modular steel option competitive in the studied case, in any considered scenario. Varying the tax rate increases and decreases the tax for all options proportionally. It is unlikely that the carbon tax can be raised so far as to alone have considerable effect on the competitiveness of modular steel units.

Chapter conclusion

In the case study, the modular option is too expensive in every considered scenario. However, the sensitivity studies revealed that the use of life cycle costing (or whole life costing) and inclusion of the several main life cycle items of modular construction, evaluates these considerations to be worth up to 49,0% of the initial cost. This means that a modular option, in the context of building hotfloor departments, can be this much more expensive initially and have the same NPV in 15 years as a conventional option. Earlier revenue or income due to a faster completion of the project is the main contributor to this result. Without it, the conservative Scenario B evaluated the considerations at 11,6%.

Sensitivity studies have also shown that increasing the lifespan generally decreases the competitiveness of modular construction due to the arrangement of lifecycle items. Low inflation and real discount rates are beneficial for a modular option in a life cycle costing. Considering earlier income due to faster construction is of great benefit to the modular option. As for constant income throughout the life cycle, it does not have effect on the proportionality of the results.

Reducing embodied carbon in the modular option has a positive impact on competitiveness. The carbon tax can be decreased up to 59% by opting for low embodied carbon materials. However, in comparison to the conventional concrete structure, the nominal tax difference was not enough to make the modular option competitive in any of the considered case study scenarios. The proposed timber module had the overall lowest embodied carbon. There is no data available on the cost and feasibility of such a structure, therefore its competitiveness is unknown. However, the tax in isolation, differs little between the low carbon modular steel and modular timber options.

The results of these sensitivity studies are limited to healthcare-oriented modules in the Netherlands. This includes modular projects of hotfloor and factory departments, where larger dimension steel modules are used. The modules used for hotel and office functions are comparable to those used in the residential sector. Therefore, although the concepts are broadly similar, the costs and their comparison for hotel and office function modules are outside the scope of this study.

7. CONCLUSION

7.1. Modular construction in healthcare

Interviews with Dutch modular contractors were useful in revealing first-hand knowledge on modular construction. For healthcare projects, two hurdles were identified. First, project efficiency was said to be lower because more work must take place onsite. Installations cannot be pre-mounted and overall finish of the module is low. Secondly, projects are designed by client and architect teams in a conventional manner. The project then must be translated into a modular form. It may be difficult to replicate the initial drawings in modules, whilst aiming for maximum repetition and scale. A solution to this is to include the modular contractor early on in the design process. With less contractor choice in healthcare and a generally stricter focus on risk management, a healthcare client is in general less prone to consider a modular option.

In terms of cost, transport and lifting were noted as very significant costs in modular construction. Fire protection, as is necessary for all steel structures, was also a large part of total costs. Maintenance costs were said to not differ for modular structures. The residual/salvage values are a positive income, but disassembly costs must also be considered. From all listed cost considerations, several essential factors were considered in the case study LCC. These were the most certain and easiest to estimate for given a project – earlier income, less interest and residual value.

The case study did not show signs of modular construction being a viable option at the quoted cost. However, it was found that the strength of modular construction lies in the construction speed and the downfall lies in limited equipping of the module offsite and waste in doubling up the ceilings/floor cassettes. This inefficiency increases with the number of stories. Therefore, projects of up to several storeys, with requirements for fast erection are most suited for the modular approach.

The results stemming from the case study cannot be directly used to predict the life cycle cost of a modular option in another hotfloor project. However, a hypothesis can be proposed to be tested in other case studies, as long as studies have enough relevant attributes and are not unique [84]. The proposed hypothesis is that in tender procedures of similar size, modular construction is viable when:

1. The initial costs are no more than 49,0% above those of the conventional option (and no more than 11,6% when only the initial cost and end-of-life items are considered).
2. A life cycle costing (LCC) or whole life cost (WLC) calculation is carried out to prove the NPV of the modular option. The client accepts an NPV comparison.
3. Construction time is a financially significant consideration to the client, and it equates to direct savings.

Point 1 is derived from assessing the value of cashflow items of the modular option through its lifespan. The benefits of earlier income, lesser interest and high residual value showed, that the modular option can be 49,0% more expensive initially and have the same NPV as the conventional option at the end of the planned lifespan of 15 years. The major cost driver for this result is the earlier income benefit. This benefit can be accurately measured as it occurs at the start of the lifespan. However, this requires the beneficiary to determine the gain which the organisation receives from the facility being finished earlier. This can be the savings made when comparing an old facility with a new one, or the monthly rent of such a facility.

A key difference between steel modules made for the residential sector and those proposed for this hotfloor department is the level of equipment and finishing. It was reiterated by all interviewees – the more work is done offsite in the factory, the more competitive the module is. The hotel and office function departments in the hospital are very similar to residential modules, in that they can be finished in the factory. However, the hotfloor and factory function departments require specialist installations. If this cannot be done in the factory under an agreement between the modular contractor and medical contractor, the modules are installed onsite 'bare'. The work is then continued onsite by the medical contractor. In this case hybrid, panel and stick systems, such as hybrid have an advantage over modules. They carry the benefits of speed, lesser interest and salvage value, whilst being easier to design with, transport and lift. A downside is a marginal amount of extra work required to assemble the hybrid structure.

In the case study, steel modules are compared to a partially prefabricated concrete structure. A steel frame structure was also considered by the client. But it was pointed out, that steel framing presents airtightness issues, which are expensive to amend. This is due to the detailing of the steel structure. Therefore, both steel modules and hybrid are likely to be superior to steel framing in hotfloor projects.

When it comes to environmental considerations, a modular steel structure can lower its cost due to carbon tax by 59% by using lower embodied carbon materials. This is possible by using recycled steel and concrete with cement replacements. A timber module can further decrease carbon tax, however, the feasibility of corner supported timber modules in healthcare projects is unknown.

7.2. Life cycle costing

The life cycle costing of the case study as well as the sensitivity studies that followed, allow for several conclusions of the procedure.

- Residual or salvage value does not affect whole life cost significantly as thought at first sight. It is the last cashflow item and is therefore the most discounted. Furthermore, disassembly cost is not included when talking about residual value. It can offset the benefit of residual value.
- Similarly, the cashflow items in the early years have major impact. Earlier revenue is therefore the most important consideration. This is advantageous, because it can be accurately estimated and does not have a major impact from inflation.
- Even though considering income in a whole life costing does not affect the proportionality of results, it makes for an overall positive NPV result. The measures of IRR, MIRR and discounted payback period can then be determined. Therefore, if these measures are looked for in cases where investment opportunities of different projects are compared to each other, including an assumption for income is useful and does not affect the outcome.
- Residual value and the value listed in buy-back agreements is not the same. Residual value may be needed to get an approval from the bank to receive a loan for the project. A buy-back agreement is made with a particular company, which, depending on its functioning model decides at what proportion to the residual value the buy-back price can be agreed.

7.3. Recommendations for further research

During the study, areas where further research can take place were found. In direct relation to the topic, the case study showed that in many cases the hybrid system, classed as a hybrid form of construction, had a competitive NPV result. From the onset, the hybrid system provides similar advantages to modular construction, at lower cost. However, there is reason to believe that hybrid systems take longer to erect. Further research can look into the differences of hybrid and modular structures and what this means for construction in healthcare.

As access to data is key in research, opportunities in live modular projects should be taken to document the impact of lesser advantages and disadvantages of modular construction. It is expected that modular construction results in less snagging (rework after completion) and less onsite inspection. However, extra material used for transport-readiness of modules is an extra cost. Further case studies with access to a comprehensible amount of data, can test the hypothesis laid out in the conclusion and document lesser understood cost factors.

Judging by durability and functional lifespans of materials, engineered timber could be considered for corner-column supported module construction. Modules built with CLT panels (wall-supported) are available and used in the residential sector. Given that buy-back agreements and residual value valuations were found to extend to 20 years after construction, engineered timber modules have the same potential to be reused and displaced. Further research on life cycle cost, durability and construction methods for engineered timber modules is recommended.

Sustainability focused studies should look into quantifying the reuse, refurbishment and displacement of modules in environmental cost. This study focused on directly incurred costs and did not include environmental considerations. Environmental life cycle assessments (LCA) should be carried out on modular structures and their reuse. Even though it was found that moving modules is very costly and new foundations have to be laid every time, ultimately, reusing or salvaging a structure is a benefit in terms of environmental cost. Such studies are needed to further the circularity of structural elements.

On the same note, further building engineering research should be considered on the topic of modular and reusable foundations. Foundations are responsible for both high cementitious materials use as well as a significant part of the project cost. The reuse of foundation systems, whether a slab, modular shallow foundation or piled foundations would present great potential for modular structures, besides general circularity. The feasibility of such systems and their benefits must be weighed.

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9. Appendices

Appendix A. Interview transcripts

Interview at Jan Snel with Jorrit Janmaat and Sam Nederend on 03/03/2021.

KN: What would you describe as a modular design/modular building? What are the differences to prefabrication?

JJ: We use a lot of prefabrication as I showed before. We want to do as much as possible in the factory and place it in the units if we can, and place it on site. It a bit hard to say. Modular construction is ... you use prefab units.

KN: Where should the focus of a designer be when designing in modular?

JJ: We see of course, that hospitals always start with an architect and at a later point we come in. But then a lot of the thinking work has been done. Most of the time we think, call us a bit earlier, we can advice about modular sizes, about dimensions. We have a lot of experience over the 60 years, which you can use for free, so we like to be in front of the product. Instead of, when the architect has made all of his plans, and says this is it and you have to build it like this. We say we can, with special dimensions, it costs extra money, extra engineering, extra, extra, but we can fix it. We saw this for the tender of three operating theatres in Utrecht for the Wilhelmina kinderziekenhuis, the architect had asked the local government already for the permit, with his drawings, so we had to make several different types to fit it. It cost him probably 200 000 euro extra for a small project and it wasn‘t needed, if he had asked us to join. Everything is possible with modular construction, all sizes and dimensions, but you have to transport it on the road of course. You have to draw the project in a modular way, so if you can start with modular units, then you can see that the architectural plan is drawn in that way. We have to be in front of the project, otherwise they call us and say nice plan, but we do it our own way.

KN: What are the main drivers to design in modular and where are traditional methods superior or significantly more cost-efficient?

JJ: The traditional method I think is only superior for skyscrapers. So we build until 16 levels, which is quite high for the Netherlands. So we have no competitors in that kind of way. If you look at New York and buildings of 400 metres they are not built from units. But I think in Japan or Thailand they do it, so it is possible. We build until 16 levels, but if its asked by the market, we will of course have a look to build higher. And then maybe about expansion [KN: interviewee means span], so this is 7.5m MOVIX, but if you want to build it 15m or 20m without a column, it is possible, but you need a big beam to get those columns out. Stadiums or something that has to be in a round shape or another figure, then the traditional way of building is in advantage. But most housing types, industry, healthcare, leisure, schooling, it‘s all possible in modular constructing, so we see no limits.

KN: What are the typical sizes of modules you produce, how many floors can be self-supporting, what support structures have you used in the past?

JJ: 16 stories. We have some examples of 12 levels. Sometimes we use a concrete core and extra steel bracing, so then we can go up. We are a bit further on the way than other companies, we have a lot of technical knowledge. We have two building systems, MOVIX and units. With MOVIX, the architect is a bit more free to create an expression of the building, a bit more free.

KN: What codes do you use?

JJ: We have a technical department, but I don‘t know myself.

HOSPITALS

KN: Have you undertaken any modular hospital design? What are the main challenges for modular design of hospitals? Why isn't every new hospital built in modular?

JJ: We see differences by country. It has to be pushed sometimes, just like cars which are being more and more electric. We see that a lot of people that are already there for 10, 20, 30 years, thinking traditional. But the new generation and managers and saying why would you do it like this? The level of quality is equal or sometimes higher because we build inside the factory, with no rain, weather conditions. We see them for years and years doing it the same way and now they are bending to teh modular way of thinking. Also for the circularity. If it‘s permanent, maybe someone thinks, let‘s make the hospital smaller or bigger, give it another useage. This is also very easy in a modular way and not the traditional way, and we also see a lot of hospitals from the 70s. They are all built from a lot of concrete and that‘s now a problem. So now they have a hospital of 80 000m2 and he only needs a hospital of 30 000m2 but they have to pay for teh whole 80 000m2 and you can‘t adjust it. That is a big problem. So you see more and more people moving to modular, but they have to see it, like you today, they have to see it to believe it. Some reference projects. It‘s coming but it needs time. It‘s in people‘s nature to think in the traditional way, until they have seen the modular way. It‘s also a small circle of companies working in the healthcare sector and they try to keep it at that point. Those traditional companies are moving to prefab, prefab walls and prefab ceilings. They try to think in a modular way, and they call it modular, but it‘s not modular – it‘s prefab, to make it faster. And you see it with housing, they are nota s far as we are to make it as complete unit as we have. They are just starting over the last 5 years to think about prefabing, which we are doing over 60 years. You need the right kind of employees, timbermen, plumber men, those are less and less popular. There‘s a lot of managers, but we need people who actually do things. So we need robots and then we can do everything in prefab. It‘s a slow process, you see it moving. In the UK, I think it‘s very far. In Germany it‘s a bit tough, they really believe in concrete and they are certain in what they are doing. Every country has its development. The Netherlands is at the starting point or a bit further, we don‘t see a lot of hospitals constructed in a modular way. It‘s quite new, we deliver to hospitals that are existing already, that we are adding modular construction to it. Complete 5000m2 extra. There are not that many new built hospitals built in Holland. Maybe 1 a year. Somebody has to start with it.

The next crisis that will be, the government says, will be the climate and then it will be on the agenda. Now we have COVID of course. But the climate is also a big problem, then this product also becomes more used. You see it more with housing, because we need millions of new houses for the next 10 years, please do it prefab. But for hospitals I don‘t hear any sounds, at this moment. They say, you have to be circular, they don‘t use the word modular, but they use the word circular. That‘s where the traditional companies struggle, because you need a passport of all the materials you use. That‘s quite new for them. In a way also for us, but we can add the passport quite easily. In 2030, you have to be at a certain point, also with energy useage, you also have the 2050 agreements.

KN: How are services routed and connected in your modular buildings? What are the benefits/difficulties?

JJ: For the design of the hospital, we don‘t do it ourselves. We ask prooven hospital architects, to make a design with our modular product. We start from day 1 together with the hospital, architect team and ourselves and then we can create a modular hospital. If people think in 10 or 20 years, and they would like to change the purpose, it‘s very handy the modular way of constructing because you can quite easily change walls in a cost efficient way. Otherwise you have to break down concrete walls, and you have a lot of noise and dust and stuff like that. You just have to disassemble it.

What we do when a building is rented for a certain period. For 1 or 10 years, it doesn‘t matter actually. We just dissassemble it, we have some garbage of course, we recycle that on site into containers, and those containers come back overhere or a contract partner, they make a selection what they can use and what not. We have to, for a certain part, we get the modules back and then there‘s another process of seperation. But sometimes we have to dissassemble the roof on site for example and we have to do a selection already over there.

For refurbishments, sometimes we rent out offices, and the client says that we want to do it another way. We fix everything onsite and we take the garbage back here to recycle it. We don‘t take a certain part, and bring it here, so we do it all on-site. At this point I think it‘s the only right thing to do.

We are also thinking about a way, let‘s say we have an operating theatre, it‘s 3 modules, we have to take it out of the building, place the new modules and take the old ones with us. But then we need modular techniques, that‘s a bit hard at this point. Because some things are done on-site. I want one long cable for example, of 9 metres, instead of 3 cables of 3m.

The air treatment plant for the operation room is loose in a unit, and we add all cables into that unit, and it gets assembled on site. At the last part, they bring in the x-ray and other equipment, and the wall is open. It‘s airtight, a box in a box actually.

ENVIRONMENTAL IMPACT

KN: How would you describe sustainable construction?

SN: For BREEAM you can look at Jorrit, I haven’t done it but I know what it is. LCA is I think a very good about the inside of the materials and what the environmental impacts of the materials is. You have two sides, you have the material side and the energy side. And we mostly look at the material, carbon emitting side, that comes from the LCAs. For most of our products, a k3000 unit, we know what the environmental impact is. From the bouwbesluit Netherlands regulations, how do you say it, its necessary, so we already have it that you need to make an LCA of a new building to see if it’s good. And theyre trying to get it down to 0 in 2050, because that’s when the govenernment said we should have a circular economy. And by 2030 we want to go half way. I would say Jan Snel is very up to date on the development. That’s one part, the other part is the energy useage, which is also important. They have to collide a bit, more isolation is more of materials but also a slash on the useage of energy. It’s trying to find the balance.

BENG, close to energy neutral buildings. I focus on the materials side and energy use side.

KN: Do you have environmental LCA data of your modules?

SN: Are you going to publish it or is it classified? I don’t know if Jan Snel gives out information. Do you have it from the other building companies I wonder? We have quite a big LCA database, and I think we are the front runners in terms of that, because if you ask my colleague Daan, in a round table meeting with realtors, what is the base for modular buildings and circularity. Because the modular building is one thing, and the inside into the materials in another thing. If I can share the information, I don’t know.

KN: I’m looking at the whole picture of easier refurbishments and click in the walls etc.

SN: With measuring it’s always a discussion, it’s one of the most hard things. I think you can look at some different statistics like, your emitting on building site, your emitting in the factory. So you have your standartisation, I think that’s very important. Then you have your transportation, which is heavily reduced, because we get all of the things to our facility, and then it goes in the unit to the building side. Whereas for traditional building you need to get everything to the building site. And the modularity is circular by itself already and mostly standartisation, because it traditional building it’s all… every project is different and we have that also but the building blocks can be standardised. So your production can optimised. It’s an optimised process, and the factory that we have, all year round you work in the same environment. All sorts of things from worker health to concrete hardening. All parts of the production process I think. And also I think, if you look at the two cilinders behind you, [with comparison of material quantities] it shows the embodied carbon from a modular and traditional building.

We use very little concrete, compared to other buildings, but it has the same qualities. You also don't need to demolish it, you can take it apart and put it somewhere else.

KN: CO2 ladder and the GPR?

SN: We are stair 3 and we are looking to get stair 4 soon, in a couple of months. So that is one. GPR I don't know of exactly, I know that we did a project just a few months ago, it's upto the client. It's always possible to do it, but it's not from the government. You need to look both at material and the energy useage, so looking at LCA and BENG, so GPR considers both.

KN: How is refurbishments considered in the LCA?

SN: it's still a discussion point. If we have a unit and we put it in a building and 20 years later it comes back and we put it in a new building, the embodied carbon is still in the unit, so can we call it 0? You can imagine it's strange to calculate the embodied carbon twice for the same building. So it's open discussion in the Netherlands.

Follow-up questions answered through email by Jorrit Janmaat:

1. How many modules can be produced per year in your factories? How many workers work full-time in the manufacture in the factory?

Maybe 5.000 units a year, it depends what you call a module/unit. Maybe 200-300 employees in the factory. But it depends, the employees inside work also outside on the locations

2. What is a good cost estimate of a small module e.g. 3*3*7 metres, with basic finishes for the healthcare sector? What cost percentage of the total project cost is the cost of the modules?

3x3x7 is not a standard module. A standard structure 6x3x3 (not a finished module) of concrete, steel cost roughly 13.000 euro, excluding engineering, VAT, transport, etcetera. But a standard will not be used dor a OR for example. It depends on the scale en type of the project of the modules itself cost 25, 35 or 50 procent of the total price.

3. How much does the transport and the lifting of a module into place cost?

Horizontal transport (truck) cost 500 euro for 150km for a module with a maximum total height of 3.1 meter. A module of 4 meter height needs a special truck (NL=dieplader) and coast approx.. 800 euro. A mobile crane can cost 1000 euro up to 30.000 or much more, depending on the project and the location itself.

4. Is maintenance of modular structures cheaper? How much does it cost to refurbish a module after 10 years?

There is not much maintenance needed for a modular construction. It is after all concrete, steel, wood, insulation and finishing. The cost depends completely on the function of the module/building. OR/CSS/offices/low care/etcetera.

5. Does your company buy back modules after 5, 10, 20 years of use, if so what percentage of the initial price do you pay? Do you lease modules? How much does a 5, 10, 20 year lease cost per year?

We do but back modules after 5,10,15 years. It depends on what kind of structure and module sizes, what the percentage will be. It can be up to 15 percent I think. Lease is just a financial method, so that is also an option. The formula for lease is mostly total cost project / 60 months lease period (for example) * 1,06 interest

6. What evidence do you give to clients that the project will be on time and on budget? (e.g. owning your own truck fleet etc.)

We guarantee the delivery date because of tight factory schedules and experience, and a no nonsense mentality.

By owning (almost) the whole process and prefabrication there a no big interruptions or surprises or interfering weather along the way.

7. What evidence can you give that advantages of speed, quality and less waste, that are normally expected from modular construction, will be achieved for a new project?

Reference projects and fact sheets and explaining the process of course.

8. How do you identify risks in a project and manage them? How extensive is your control in the project? What happens to the project if there's a big change by the client late in the project, the price of steel goes up or a subcontractor doesn't deliver?

If we sign for a project, all the prices are fixed. No additional work will be charged unless the client is changing while the process is on the run. Between signing the project and start prefabrication is a short amount of time, so rising prices has less impact comparing to traditional long term projects.

Interview with Dutch Cabin Group, Angelo de Vries on the 01/03/2021.

KN: How would you describe the difference between modular and prefab? Can you tell me about your products?

AV: The difference is 3D and 2D. Modular is built in a factory, whereas prefab 2D floor and wall elements are built on site. For modular, we work inside and it is less CO2 emission too, because there are less movements to and from the site.

We also buy up the modules from clients at 30-40% after 5 years, 20% after 10 years and up to 10% after 20 years. You have to keep in mind that demolition costs money, so us taking away the modules is a service too. Our units have about a 50 year lifespan.

The allowed module road width by day is 3.6m and by night it is 4m. However, that is more expensive as you need police supervision and the work is at night. If you are building a large project it really adds up. Our max unit is 3.60m wide, 10m long and 3.5m tall.

For fireprotection we make modules 60 min resistant. Fire resistance diminishes the cost-effectiveness of the module and reduces useable space, 120min fire resistance is 8 gypsum boards for example.

KN:What is the focus designing in modular?

AV:One of the rules we have is 90% standard unit construction and 10% custom work. But of course not everyone wants to build in modular, because they either don't want a rectangular building or don't know enough about modular.

KN:What modular systems do you have?

AV:One is called DS system and it is manufactured in the Netherlands. The other one is made in Czechia.

KN:How tall can you build?

AV:2 stories self supporting, 3 stories with windbracing with corner columns of 80mm*80mm and 5 stories with windbracing and larger corner columns of 100mm*100mm

KN:Why aren't more hospitals being built in modular?

AV:There are unknowns to modularity and the other thing is that some don’t want to design in modular due to form or other restrictions.

KN: What can you tell me about LCA?

AV:We are currently working on an LCA of our modules, due to recent changes in regulation.

KN:How does a refurbishment of a module take place?

AV:Two things can happen here. We either bring back the whole structure to our facilities and do a full refurbishment. A project that has just come back to our facility, stood onsite for 15 years. If it is a small renovation, a few walls and doors, then we do that on site. Interestingly, Ikazia ziekenhuis in Rotterdam has 18 modules placed, and they have been fully refurbished 5 times already.

Follow up questions answered through email:

1. How many modules can be produced in your factories per year? How many workers work full time in manufacturing in the factory?

Depends of course always on the applications and the difficulty of the projects, are the schools that are fairly easy to fill in or is it a complex healthcare institution. Do we completely finish the units in the production warehouses or do we largely finish the units on the construction site itself. At the moment we have about 40 permanent employees who work in both production warehouses, we also hire people who help out if necessary. So calling the number of units per year is very difficult, we look more at the turnover that we bring in.

2. What is a good cost estimate for a small module, e.g. 3*3*7 meters, with basic finishes for the healthcare sector? What percentage of the total project costs are the costs of the modules?

3x3x7 meters is not a standard unit model for us, our standard unit has the size of 3x3x6 meters. The above unit, concrete floor, four steel columns and a roof without outer walls costs about € 5000 each.

3. How much does it cost to transport and lift a module into place?

We always request a quote from our transporters for transport costs, we must specify the distance and can two or just one be loaded on the truck, around € 450 each is a reasonable price for the transport of one unit. Lifting, how many units have to be lifted and what is the distance from the truck to the position where the units will be placed, with those two factors you can only determine the weight of the crane, we often have to deal with a 70 or 90 ton crane, costs about € 90 per hour, and then you also need two employees to handle the units, so picking up one unit from the truck and placing it costs about € 90 each, half hour crane needed with two employees.

4. Is maintenance of modular constructions cheaper? How much does it cost to refurbish a module after 10 years?

Maintenance costs of a normal building or modular construction are almost the same, I can't tell you the costs of a module for 10 years, the customers always do that themselves cheaper and faster most customers have their own technical service or there is one at a school janitor who performs maintenance.

5. Does your company buy back modules after 5, 10, 20 years of use, if so what percentage of the initial price do you pay? Are you renting modules? How much does a 5, 10 or 20 year lease cost per year?

If we buy back modules, it always depends on the large project and whether we also want the project back for 5 years, approximately 20 to 30% of the construction costs, rent or lease per unit between 30 to 45 euros per unit per week, depends on the size and duration of the project and type of units

6. What evidence do you provide to clients that the project will be on time and within budget? (e.g. owning your own truck fleet, etc.)

We don't have our own truck fleet, but that has nothing to do with being ready on time or budget.

When we receive a project from a customer, we always have to make a time schedule and often the customer demands a delivery date and if you are later than the delivery date you will have to deal with a fine, which can be up to 250 euros per calendar day (7 days a week).), in addition to a schedule, the project leaders also keep an eye on the budget, which is their responsibility. When a calculator calculates a project, there is a contract price and the contract price also shows the time frame for how long it can take, and we use that data to make a schedule and our project leaders have to monitor those two things to see if things are going well. After delivery, there is always a subsequent calculation and this shows what we have actually spent on the project, simply put what profit we have achieved.

7. What evidence can you provide that the speed, 5000 and less waste benefits normally expected from modular building will be achieved in a new project?

We purchase most materials custom-made, so waste is minimal with us and we also separate our waste into seven waste streams. Speed is right we are at least 30% faster than a traditional contractor.

8. How do you identify and manage risks in a project? How extensive is your control over the project? What happens to the project if there is a major change by the client late in the project, the steel price rises or a subcontractor fails to deliver?

In construction we have to deal with a BDB index, this index also keeps an eye on price increases if we determine a contract price and the project starts a few months later, then we can release the BDB index on it and it may just be that you may increase the contract price by a percentage, see example in the appendix.

With regard to safety we employ a KAM safety officer who writes the construction safety plans himself and also checks on the construction site whether everyone adheres to the rules and adjusts where necessary. In addition, all our employees have followed at least VCA basic training.

Major changes we never encounter the clients on the construction site, during the design we sit down with the customer and the users to coordinate all drawings with each other and we also determine the drawing together as being final, then we go ordering everything and if something has to be changed, this will really cost a lot of money and our customers are not really waiting for that.

When ordering from us, our subcontractors also receive a standard delivery order with a delivery obligation, it almost never happens that they do not deliver, unless the factories are shut down due to corona, for example, which is now the case, we are now also dealing with delivery times that are normal. 6 weeks is now a minimum of 10 weeks, but nobody can do anything about that at the moment, that's called unforeseen and most customers understand this at the moment.

Interview with Heddes, Boaz de Boer on 08/07/2021.

KN. 0:14

I got in touch with you by writing to Van Ursem. As I saw on your website, but also from some of the projects of student residences that I've been looking at, that you work tightly with Ursem and Heddes, you work together. How does it work? Because Van Ursem, I understand, manufacturer the modules themselves? And you are like a larger contractor that take that in?

BB. 0:56

Yeah, we are the main contractor in the project, and we are shareholder in the Ursem factory. Heddes and Schouten are the main shareholders in Ursem. On that level, we have, of course, our interest in the company as the main contractor to provide the building to the clients. Ursem is the manufacturing of the modules, Schouten is for the MEP and Heddes is the overall delivery of the building.

KN. 1:41

Okay, that's good. So you told me that, that you don't do any hospitals, any health care facilities, right. And that's, that's completely fine for my study, because I'm looking into the lifecycle costs of modular building in the Netherlands. And I want to compare it to traditional construction. So in a case study, I am comparing a project that can be built in as a steel structure, but not in modules. Versus a modular building. That's what I'm focusing on mainly. And it just so happens that the case study is a hospital extension, but it's not about a hospital, it's about the structure. The costs of it should be quite straightforward to estimate, because we're not talking about, the complicated insides of a hospital and the MEP. It's just just a structure comparison because I study structural engineering. Let's start with some of the questions then. Some of them in the beginning, they're general, and then I'll ask you about the costs. So, in the beginning, I would just like to ask you, because I have interviewed some medical staff about hospitals and some hospital facility managers earlier on, because I wanted to find out what the specifics are of a hospital and I saw that there was a big confusion between the words modular and prefab and, and people are using it to either their advantage or I don't know how they want to sound. And for example, this one surgeon, he told me that that particular hospital was modular, that he was only looking from what what he knows. And this meant that some of the medical equipment was in parts or some of the partitions were in parts, but the building of course, he didn't know about that. So what do you think are the differences between prefab and modular? What kind of products are modular when it comes to buildings?

BB. 4:25

Of course, I can only explain it a little bit from our point of view, but we see of course modular is also prefab. We see the difference that in prefab construction, you have, let's say 2D parts, produce them offsite and you connect them onsite.

To a 3D building. In modular, with our construction systems from Ursem, we say that a module is a 3D part of a building, we make the 3D parts ourselves, we construct them into a 3D module, then we transport it and install it. So for us it's two kind of ways, if you do flatpack 2D you can save on transport a lot when you transport it but you have more work onsite.

And if you have modules in the way we do it, you have 80% of the labour in the factory, but of course, building a module in a factory is also prefabricating a part of the building so, I can understand that there is some confusion.

KN. 6:12

Where should when when designing a building or looking for the right option for a certain project or a certain tender where should the designer that the modular designer Where should his or her focus be, what should they evaluate about the tender, whether the tender fits this modularity concept? How do you evaluate a tender?

BB. 6:44

Well, from from our point of view, we have thought of design guidelines with our construction system. And we make if there is let's say a preliminary design of a tender or maybe there's only a schedule or programme then we can make a modular configuration and of course, the design company can also do that. So, they have to design a module and not likely spaces, based on what is the most common module size. In our systems it is flexible, so, you can make a longer or wider module. So, we don't have one size some other companies you have spoken to, they have one size. In our system you have flexibility. So, you can find the right size and then you have to multiply it as much as possible in that size. If you have done that as a designer then the next big step for us is the stability of the building. You saw that we do high rise, so for us stability is step number two. Making a layout with the module size that is multiplied the most times, is more general, and then the next step is making sure you have the stability in order, and then find the good facade solution. And also you have let's say the module which is the more general layout and then maybe you have the staircases you have maybe some of the rooms that is not really fitting to try to fit them. In some buildings we do we also have staircases in a module, then the complete module is integrated, the staircase and elevator is also integrated. We tried to make the not modular parts as small as possible.

KN. 9:20

I understand. You are the first one to mention stability, that's for sure. Because other respondents didn't know much about that. Just because they don't work on such projects, I guess.

BB. 9:38

We have the module system that goes the tallest, up to 23 stories for now.

KN. 9:51

And because it goes up to 23 stories, what different methods of stability are there, what supports, I assume some sort of core or some bracing? What kind of methods?

BB. 10:11

Well, if we go to up to 23 stories, we have a concrete core. And we have some, some braces in the modules, not in every module, but in some. And together with the module itself, we can, we can engineer structurally that it fits. We also have some systems that is not for high rise, it's five-six storeys, and then there is a lot of steel braces for stability. For lower buildings, we don't need a core. And if you go a little bit high rise, then we need to at some point we need the core, because it's a better solution.

KN. 11:01

Another question in this field is when is traditional construction actually superior? When do you make that call? I understand that you try to increase efficiency by reducing the non modular parts in a project to make them as little as possible. But at what point is a project just better to do in a traditional way?

BB. 11:36

Well, most of the times, it's because of the numbers and the repetition. So let's say this is a smaller building. And we can do it really good in, let's say, a fixed modular size. Of course, for us, it's important, but it's more important that the module is maybe at least 100 items, and at least 100, the same. And if it's not the same, only two or three or four types. So if a building fits for that solution, then it is more feasible to do it in a in a modular system. And other other aspects is a logistics of the 23 storey building we are working on now in preparation is in The Hague. And it's near the railway. And there's really a small side. So there is not enough room for all the materials to take them on site and to construct it traditionally, we just bring in the module and it is being installed, because of the smaller size or maybe let's say high density in the city, a small location, then I think people are more interested in trying to find out if modular is a solution.

KN. 13:05

So because of the on time deliveries, you need a much smaller site.

BB. 13:12

Yeah, and also because you have less rotation. Less store a stack on side. So you don't need all the facade element columns, concrete, all the different items, you don't need to stack it on site. In the factory, you connect it to the module and the module is like the stack. The supply on site, you don't need to have it there, you have it on the factory.

KN. 13:51

You mentioned that you can build any kind of specified dimensions, but there must be some sort of extremes. So what are the extremes of your systems and what is kind of the most often size that you see in projects over and over?

BB. 14:13

So in this presentation, we have this conveyor belt system and between the columns we have 14 and a half meters. Concrete slab we use standard is 14 and a half meter and four meters width. The maximum module size in our system is 14.5 metres and 4 metres wide.

KN. 15:08

And four meters width in the Netherlands, just want to check with you, you can transport those with a permit at night?

BB. 15:19

You can transport it by day with a permit. 3.5m you don't need any special transportation, only by four meters you need a special transportation sometimes the facade is also added to the four meters. So, you have four meters maybe 20 or 4 15 and what we see in a lot of designs is that module is like 370, 380 thats the main, the common size. So together social housing 60 - 70 m2 housing, then we have two modules and we connect them to one residence, to one house.

KN. 16:17

And so and the length of these modules would be how much?

BB. 16:22

This is an example of social housing, it is two modules and I think it was three eighty something and a length of 10, 11 metres. Other construction systems, we have a system of 2 stories with only wooden structures, we add a little bit of steel and it was CLT, where the bearing structure is all timber.

KN. 17:40

I see that in all of these the floor cassete is concrete.

BB. 17:46

Yes. We design it our own, the engineer is our own with the steel system we have a little bit of a higher height of 30 centimeters but in the middle we have 12cm, like a concrete beam with a topping. Because it's inefficient to do the whole slab, for the weight of the module.

KN. 18:21

That's true because modules are also good especially in steel and timber because they're quite light. Would you say that you would normally when building in modules, require a smaller foundation? What about in comparison to traditional construction steel structure okay?

BB. 18:47

Well maybe not then. In the Netherlands we are used to build heavy buildings. When you do it in concrete or brick then it is heavier than the module. But if you do really light system in steel and maybe also steel concrete combination floors, then it is I think the same as modular. We have a concrete slab in the modules and I know that some companies don't have that, but we want some weight in the module. For thermal capacity. A really wide module that is of course efficient for the foundation and also for transportation and for lifting. But if you have the energy in your building thermally, in summer and winter, it's better to have some weight.

KN. 19:59

And the last question in this section is, you said there are some guidelines, also that you use for the project, but also what codes do you use when designing in modular? Because I haven't found in the literature that, you know that there would be there's there's no euro code on, let's say, on building in modular.

BB. 20:24

We comply to all building codes there are. Because our systems are designed so that they can be compared with a traditional building.

KN. 21:07

And the stability of, for example, if you go over six stories. The stability of these modules, I don't think that the standard building code has these calculations, do they?

BB. 21:30

We have a team that checks it, and we provide it to the client.

KN. 21:36

Is there any other extras that you have to do? Outside of the code? Extra fire regulations or fire checks?

BB. 21:59

I don't think so. We have chekced that systems comply with structural and fire regulations.

KN. 22:03

At this point I will ask you about, I know that you don't do any hospitals, but just a general question. What do you think, if you were to design, a health care oriented facility? What if you were to build a hospital in modules? What do you think the main difficulties there would be?

BB. 22:54

The reason we don't do healthcare projects, is because we think in most of the healthcare projects, installations have to be put in on site. Because if we do a house in modules, it is possible to put a lot of things in it in the factory. The more complete the module is, the better for the efficiency of the project.

KN. 24:20

So you're saying that, that taking on a hospital project would require more work on site just to connect everything. And you become less competitive then.

BB. 24:34

That's right. We have high end modules and only plug and play onsite. Other companies they have really simple modules with less finishing and high end components, and then you can easily produce them, put them on site. But that's not our business model. We can make the sample module and we can transport it, but in the competition, like you said, we cannot become competitive. We try to do as high end modular systems as possible.

KN. 26:38

Okay, so let's move on to the other questions, then. This is about costs. How many modules can be produced per year in your factories, or per month? And how many workers work onsite in these factories in the manufacture?

BB. 26:58

2000 modules. We don't do that, but it is possible in the factory, and that is one shift, from 8 to 5. So we can do two shifts and make more. The main problem is not the amount of modules we can make, but rather to have the projects where to put the modules in.

KN. 27:58

In my thesis, I also want to cover kind of how to know that a Consultant or a contractor in a modular project, when modular advantages are promised to the client, such as we'll deliver it fast, we'll deliver it may be a bit below the price of the standard project... How can we trust these claims? And how can we check them? That's what they want to find out more about. And capacity is important for these checks. And how many workers are employed in the factory?

BB. 30:07

How many? Normally we have like 40 people. But if the production is more intense, then we can put in more workers, maybe up to 120 for big projects. We have a standard team that makes prefab bathrooms all the time, and if we have modular projects we scale up to 100 to 120 people.

KN. 31:07

And what is a good cost estimate of a small module? For example, three by three meters by seven meters in length?

BB. 31:21

There is a lot of work that has to be done onsite, for example the foundations and everything needs to be connected. So the costs are 45 000, 50 000 euro. And this is not healthcare, it's student housing.

KN. 32:06

That's if you divided the whole project cost into the amount of modules, right? I looked up all of these student houses, in the Cobouw database. And I tried to, you know, source as much information as possible. And when you break down projects by the number of modules that were in them, it is about 50,000. Would you agree with me that, that the manufacture within the factory, its cost, basically is half of the costs of the whole project?

BB. 33:15

It does, but it really depends on the type of project. For instance we have a project in Amsterdam of 350 student housing, if you have the same project 16 stories, and then the same project 5 stories and it's a much more simple building, then I think the percentage of the module will be 60 or 70% of the total costs. But in highrise the percentage will go down, because you need a core etc. And we're talking about a steel structure module.

KN. 34:58

How much does the transport and the lifting of a module cost per module, which you say, and what's the rent of a big crane?

BB. 35:15

We estimate it normally on 2000 to 2500 euro. Depending on the crane.

KN. 35:52

How much are can these cranes lift into place in a day? How many units can be connected?

BB. 36:07

For highrise it's 8, sometimes 10. If it's more easier, not highrise, then 10-12.

KN. 36:27

I'm looking at lifecycle costs. Do you think that the maintenance of modular structures is cheaper in any way? Just because from the design perspective, they are very standardized. So if you had to maintain it, or even maybe in some cases, even taking the whole building apart, refurbishing and putting it together in another place, another building. How do you think that is cheaper than repurposing a traditionally built steel building, even if it's disassemblable.

BB. 37:19

I don't think there's much difference. What we see if the type of projects, for example student housing or hotel, is that there is a lot of design attention to maintenance. You have maybe 200 300 500 rooms in student housing in one complex, so you need an efficient plan of maintenance, and we integrate it in the design. So the pipes are accessible from the corridor. and you don't have to enter the house. In a normal Dutch house, the shaft is not accessible. But in student accommodation the shaft is accessible. If you build that traditionally or modular, you make that same decision.

KN. 38:57

And what if the whole structure has to be refurbished?

BB. 39:00

The big difference is that we have little concrete, so we don't have a lot of stone wall, the walls and the roof of the module are gypsum layers. You can take them off and fit them again.

KN. 0:22

Is this something that you do? Do you get modules back to refurbish them?

BB. 0:35

No we don't do that. We had one project where we had the modules disassembled. And then we took them to a new location and assembled them. We did that. But a lot of clients are interested in... Let's say we have a lot of small houses, lets say 24m2. And we have them all together. Can we make them one 48m2 house? Can we make two, one? So we have scenarios for the clients, what is possible to change.

KN. 2:01

Okay, that's interesting. For this project that you disassembled a building and then moved to another place. Do you know the costs of that? How much that cost? Because that's very interesting and it doesn't happen often.

BB. 2:24

It's quite expensive. Because there's a lot of labor and transportation and lifting et cetera. Of course you have the investment in the material, for the module, we don't have to make it. But the new site has to be prepared. More than 50% you have to do again.

KN. 3:06

Is there a saving?

BB. 3:07

There is a saving. 30% saving I think. I did some information for one company that is temporarily available 5 to 10 years and they want to put in 200 student housing and they want to have a building they can take apart, they want to know what is the initial investment, how much would they save when they move it. But in the Netherlands you have to make the foundation over and over, connecting over and over.

KN. 4:20

Your company doesn't buy back modules, right?

BB.

We can go into a deal with with the take back guarantee. But it's not like we have a lot of modules in our factory.

KN.

What do you mean by the guarantee?

BB. 4:56

So there is one client, who we're building for, a temporary location, the lease is for 12 years. He said can you give a guarantee that you will buy the modules back after 12 years. It's a guarantee that we provide, which gives the client the ability to go to the bank and get funding, with the assurance that the property will have a value. In a permanent building and land location, after 20 years it still has some value. But if you have a temporary building and it is removed, what is the value of the property. It is not in that location. Our aim is not to take the module back, but the guarantee is to have a feasible project for the client.

KN. 6:41

And what kind of guarantee did you give in this project after 12 years?

BB. 6:59

30% or 40% of the initial investment. The financial number to convince your bank for a loan, that's what you need.

KN. 7:20

After that period of time, you may or may not buy that, but that's another deal in the future. You don't lease modules, you don't make deals where after 10 years, we will definitely buy back. Do you have other projects like this where you have to give a guarantee of the value of the projects? Because I am interested in for example, in five years, what kind of a guarantee would you give, and then in 10 years, and then in 20 years?

BB. 8:03

From now we have one project but we are in progress with it, I believe it's for 10 years. What we see is that if you have five years then it's not financially feasible. But the companies that make the project, they rent out the project for five years together with the guarantee of buying it back. And then after 5 years, in a new location, the foundation would have to be done again et cetera, so it's more sensible to just build in the permanent site in the first place.

KN. 9:15

Only after 10 years, it starts to make sense you say. If you said that for that specific project of 12 years, you guaranteed that it would be 30%. Then in 20 years, how much would you say that you could guarantee?

BB. 9:45

Then we would take it back for free. There's not no value, but there's no cost of dissassebly.

KN. 10:09

Another question about this is- this guarantee what if you guaranteed that it has this value. What if someone comes in and rates rates the value of the structure and it's not that value? So where do you stand as the as the one who provided this guarantee?

BB. 10:44

If someone does a valuation after 5 or 10 years. And we still have the guarantee at the end in euro, we don't do percent. Then everybody has a problem of course. Of course the bank does all kinds of evaluations. A lot of people think modular construction is temporary construction like container buildings. And that is not the case. We make permanent buildings in a modular way. We convince the financial people on the cost of construction, we show them around, they come and see, and convince them that there is no trickery.

KN. 11:30

Okay, the last three questions. What evidence to give to clients that the project will be on time and on budget?

BB. 13:09

We don't own our own truck fleet but we have a big transport and lifting partner. We are the main contractor and we always have to deliver on time. Otherwise we get a big penalty. I think the penalty is a big incentive for us to deliver on time. What is important is that you manage your production effectively. Because the way the project is really dynamic and not fixed in time and if you know things are fixed such as permits and procurement, then you need to know for sure you have the production capacity. And that's the main thing we do. We have a project schedule and we a factory schedule. Two schedules that we need to connect. If the project schedule is delayed and we need to know what does it mean for the factory. We are not in production of that module but we need to know it is going to be in the factory period that we already have, because then we can't guarantee the schedule anymore.

KN. 14:47

Is the schedule of the factory occupancy... Is that also provided to the client to show that or is that something you arrange yourself?

BB. 14:59

We provide them with it, because they are in a worry. What about my project? What if I submit my project to your company? Can you guarantee me the production period? We say we can, we make a reservation on capacity, but then you have to provide the permits, or the finance etc. And because they don't do that, they don't do that on time. We have a little bit of a discussion in the production period.

KN. 15:40

Do you often in the scheduling of the occupancy of the factory, do you have, to leave some time over for this kind of occurrences?

BB. 15:52

We have time over because they don't live up to the agreement to the schedule. We think we have production in the factory, but then we have an empty factory. That's the biggest problem, that we have a modular construction. As a company we also have traditional buildings. And the traditional building, if you have an agreement, if you have a permit, if there's money, then you order the piles in the ground and then you start. And then if somebody says I want to start in the summer and there's no permit, you don't start in the summer, you start in autumn or in the winter, there is no problem. But in the factory, it is different. If someone says we start in the summer, we keep the reservation in the factory for the summer for that project, and if the project delays, the factory has a problem, because there's no production for that period.

KN. 17:14

And from experience, how big are delays normally, half a year?

BB. 17:23

Big, yes, that's not an exception. So let me tell you that we can make 2000 modules a year, we make 600 a year on average.

KN. 18:04

What evidence can you give that the advantages of speed, so the faster construction, quality, less waste will be achieved? For example, if the client expects a certain quality, and then you work to deliver that quality and there's a mistake in the end, at the end the module quality is it's not high enough? How would you fix that? How would you convince the client that you will deliver it 40% faster and you will deliver it to that quality?

BB. 18:52

It depends a little bit, because the 40% advantage in time you only have to discuss that at the moment when they choose modular construction. if they choose to go with a modular system. It can be 40%. Maybe we can make the schedule in a traditional way and in a modular way. If the client says okay, I want to do it with modular. Then we just have the schedule in a modular way. We give the 100% schedule, so you don't have to guarantee that it will be 40% faster, you get an agreement on the modular schedule. And the modular schedule, is normally 30-40% faster than a normal project and it really depends on the project. So you have a discussion upfront, because you have to convince the client what is the best way for the project, is it a modular way, maybe combination of the two.

KN. 21:01

Given that it will probably take 30% 40% less time, do you turn that into a monetary value? So that you can earn this much revenue in that time?

BB. 21:18

We do that, because normally, in most cases, it's not really a cheaper. And it's the same, but you have a half year revenue more than the traditional way, and the client needs to take it into account. We cannot do that, because it's not revenue for us, but for them.

KN. 21:51

Are there any other monetary benefits like this?

BB. 21:54

Well the interest of course, the loan for the investment. and then they have less interest, less costs and more revenue. I think the main two financial items.

KN. 22:15

And the last question is, how do you identify the risks in a project, and what's, how extensive is your control in the project and what happens if there's a big change by the client late in the project or the price of this steel or concrete goes up, or subcontractor doesn't deliver some products?

BB. 22:39

Well the extensive control of the project is because in the modular way, we need to make the module in the period where we normally do the foundation. So in the schedule of the engineering in the modular project, we have more intensive engineering in the earlier stage. And we do it really intense. We don't have any mistake on the module. I think it doesn't happen that we make the module wrong. Like in the plan, it fits, there's no deviation there. That means that the client can't change anything, and we tell them a hundred times and they say they understand, but most of the time they don't. Because on site we only foundation works, so they think they can change something on the roof, no problem, and that's the wrong idea that clients have of modular buidling. Of course we can make fitouts, so this is the module and if you want a fit out then it has to comply with the module, the price changes also. So what we do is before we do the agreement we try to secure the suppliers, at the moment if you have the suppliers and the client when you are signing the contract, then you write in the suppliers and contractors in the contract.

KN. 25:23

If a subcontractor doesn't deliver, then you have backups? Or does it just not happen often maybe?

BB. 25:36

In a modular way it doesn't happen more often than in the traditional way. Sometimes in a project we have someone who doesn't deliver, but it's not common because we have partnerships, so they know what is expected from them. If we need 10 plumbers, and we only get 5 then we'll look at our other contacts.

KN. 26:43

One quick question. Within the 50,000 euro, how much is spent on the labor and how much labor cost is incurred in the factory and on site? Because even though there's less work on site, I think, because it's more expensive and the end, the same amount is spent on manufacturing the module and putting it together, in terms of labor force?

BB. 27:46

In the factory we have a lot of repetition. We have to train people to do the same activity a lot of times. So there are less skilled people because they do more repetitive labour. On site it's more difficult there's a lot of explaining, a lot of different activities. If we had a half year project, and someone does a months work, they still need to be trained.

KN. 28:53

Articles say that in a factory, there's more machinery and more work can be done by one person. So therefore, slightly more can be paid to this one person, but he's a lot more efficient at manufacturing. Whereas work on site is just assembling. Can you explain that?

BB. 29:24

I don't know if that's what they mean. But we have, we have a captain for running the department in the factory. The manager of the department, they are expensive, the machinery is expensive and we have items that cannot be done by machinery, but otherwise there's a lot of repetition. And on site you also have supervision and a manager. And the work there is more complex because there are different tasks to do. There is a team that does the installing of the modules. Of course after a while it's the same and the same. They get trained also, but it's more specialised labour. You must put a team that has experience. We don't call 5 handymen to put in our modules.

KN. 31:03

Even though less little work is done on site, they're still there paid more than the people in the factory. So would you say that the labor costs are kind of 50/50 between the factory and the site?

BB. 31:25

I think so, because in the factory, there's a lot of engineering. The people that do that get paid a lot. Production phase is no thinking, just doing.

KN. 31:55

You've answered all the questions. Thanks very much. I will also send you my piece at the end of September hopefully, after that I will be a structural engineer, building engineer, in the Netherlands probably.

BB. 34:40

If you agree, I want to stay in contact. If you are finished in September we can see what we can do.

KN. 34:49

Okay, we'll keep in touch then. Have a good day.

Appendix B. BOPAS interview, example log and procedure

A system of testing, checking and guaranteeing a new construction method or product can decrease the risks of a construction method. From the interview with Ursem, it was found that the manufacturers take it onto themselves to provide guarantees of durability to secure financing of projects. This is an additional hurdle for both the manufacturer and client.

The UK accreditation scheme BOPAS (BuildOffsite Property Assurance Scheme) is a unique scheme that assures prefabricated products and systems including volumetric modular construction since 2008. It was founded due to an increasing nervousness of major mortgage lenders in the UK, which approached the BuildOffsite organisation of manufacturers and BLP (Building LifePlans) insurance to create a scheme which could provide the required confidence in modern construction methods (MMC). Around 100 manufacturers are now fully accredited with BOPAS, since 2016 when interest in such a scheme started to increase. The scheme is looking abroad for markets to branch out and the interviewee confirmed that the Netherlands are considered.

I held a videocall interview with Jeff Maxted, the Director of Technical Consultancy of BLP insurance, on the 29/06/2021. A semi-structured interview format was followed and the results are summarised below. The goal of the interview was to understand why this globally unique accreditation scheme exists and how it functions. Subsequently, it was of interest to ask the interviewee what benefit such a scheme can bring to the construction sector in the Netherlands. The interview was coded using Atlas.ti and the information is presented below.

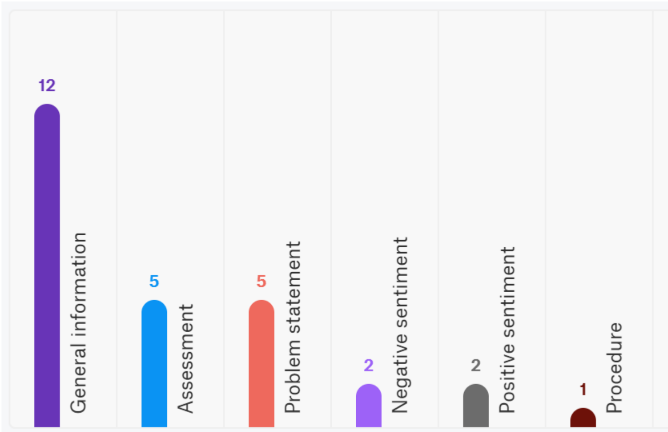


Figure 51: Codes used to group information

BuidOffsite, which is an organisation comprising manufacturers of prefabricated and modular products, put together the BOPAS scheme with two main parties, which are Lloyd's Register and BLP insurance. Lloyd's register has been assessing property such as nuclear power stations and are experienced in regulating processes and their financing. The specialty of BLP insurance is to carry out the durability assessment of materials going into the modules. They provide a warranty based on a durability assessment.

It follows that the scheme consists of two phases. The first one is the factory accreditation with the durability assessment of the system. The considered systems are only those of which the methods are carried out inside a factory, therefore methods also requiring work other than assembly onsite are outside the scope of BOPAS. Lloyd's register works on the second phase, and they provide a company structure overview and check the financial indicators of the company to make sure that they can deliver the service they aim to deliver. This is not an exact science, but best practice is used.

The durability assessment checks whether there is adequate moisture protection internally and externally. Energy efficiency and durability for two mortgage loan terms of a sum of 60 years is required. BLP has a team of engineers, architects and building surveyors, who carry out checks as part of the warranty process. This allows BLP to provide the standard 10 to 12 year warranty, which is an industry standard. They look at the design details and structural and material performance. Associated required testing is carried out by a recognised testing house such as the British Research Establishment (BRE). This is comparable to the Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO) in the Netherlands. There are techniques, such as insulated concrete formwork and thin joint blockwork, which are described as MMC, but these are onsite methods and are not covered by this scheme.

BOPAS:

- BLP 60 years durability assessment
- Lloyd's Register financial assessment
- Web-based database

The largest problem with MMC in the UK is that it is expensive to set up a new factory for modular or panelised systems. If there isn't a pipeline of work going ahead, it becomes very difficult to run the business below factory capacity. Due of tough market conditions, some companies accredited with BOPAS have failed, because there was not enough uptake of their product. Companies that specialised in commercial buildings, schools and factories moved into the residential sector.

The government has shown interest in the scheme as they have tried to promote offsite construction for many years. Funding from the government comes from an organisation called Homes England. They incentivise manufacturers and developers to build affordable housing and they have been promoting offsite technology for some time. The UK government targets to build 300 000 homes a years. This is not possible with traditional construction. The main problems are a labour shortage, which was made worse by Brexit and Covid.

BOPAS is a prerequisite of the offsite sector in the UK, particularly in the residential area. Lenders and investors seek a warranty from either NHBC (National House Building Council) which warrants traditional builds or BOPAS. The results of the BOPAS assessment are presented differently for lenders, developers and manufacturers. Even though the resulting reports are different, crucial information on the durability and an explanation of the construction method is provided to different levels of technical detail. Accreditation is also possible for a variety of processes, such as manufacture, project management, or construction and design. Most participants aim to be fully accredited. BOPAS additionally offers carbon assessments, life cycle assessments against a traditional build, and even though these can add additional value to the project, it is not an integral part of the BOPAS procedure.

To summarise, BOPAS helps to value property to a higher degree of accuracy. It gives confidence about how the innovative method compares to a more traditional method. This is necessary because there isn't long term evidence of durability of 60 or 100 years. The increased confidence affects everyone, the funder or lender, developer and purchaser.

This is a short description of an offered system on the BOPAS website, which gives several design guidelines. These allow to compare different modular systems quickly using simple criteria, and then look further in the BOPAS assessment if that is necessary. Having the system information on public display also carries out a great deal of education, for clients interested in innovative building methods.

The BOPAS process

In the flowcart below, the client is the manufacturer of a prefabricated or modular building product. Assessment quotes are provided to the client by BLP and LR. BLP procedure is explained in Appendix 4 of the BOPAS guidance document. Technical information is requested from the client and a desk study is carried out. A case report is drafted and a site visit is carried out, before granting accreditation. The desk study includes checks based on a reference building. This is detailing, structural calculations, physical and chemical material resistances. LR carries out the gap analysis which determines the 'gap' between where the business is, and where it aims to be. This helps to identify required performance or how far away the business goals are.

The BOPAS website is also a web-based database and point of contact to check that manufacturer information is up to date. It logs a short explanation of the method and design rules and limits which have to be met to build with the system (see example log above). Non-accreditation takes place due to non-documented elements found in a system, repetitive failures (product or system), significant number of minor non-conformities, activities outside of scope and unsafe work practices. An example of website log is below.

The BOPAS representative emphasised that the procedure is not an exact science. The BOPAS guidance document covers a plethora of relevant factors needed for an offsite manufacture led project to be successful. However, the guidance, appendices and online information lack an explanation on how the factors are considered. It would be useful to see where subjective decisions were made and what indicators must be met. In the opinion of the researcher, it is less important to reason the subjectivity of the assessment than to clearly state what indicator values are necessary, so that the systems can be compared against each other. This would increase transparency of the process and give additional confidence that clients are accredited using the same standards and not on a per case basis.

Example accredited technology

Caledonian Modular Steel Framed Modular Volumetric Building System

Primary structure comprises hot rolled steel with light gauge steel external wall infills, floor and ceiling elements erected around a concrete/steel core structure. Approval is based upon a height limitation of 30 modules and standard module dimensions of 5m width, 4.2m height and 18.7 m length.

- Maximum 30 storeys subject to structural analysis.
- Bottom members in contact with foundations/sub-structure must be fully isolated from contact with moisture from the ground or external sources.
- Where lightweight gauge steel framing is used for ground floor construction next to the ground, the ground below the floor must be sealed to prevent moisture entering the void, such as a membrane with 50mm oversite concrete, in accordance with the recommendations of Steel Construction Institute publication P262.
- Where a lightweight gauge steel frame ground floor occurs over a void next to the ground, the void must be cross ventilated to a minimum standard of 1500mm2/linear metre, or 500mm2/m2 of floor area.
- Masonry wall cladding cavities should be minimum 50mm and ventilated.
- Conventional cladding, such as timber cladding, should have a minimum 25mm drained back-cavity, or as required by the cladding manufacturer.
- Rendered external thermal insulation systems and/or insulated brick slip cladding systems applied to steel-framed structures must have a minimum 15mm drained back-cavity. The application of insulated cladding systems should be considered to minimise the risk of water entering the structure at vulnerable junctions, for example window jamb/sill junctions, in accordance with the recommendations of the Steel Construction Institute publication P343.
- Stainless steel fixings, such as channels for masonry retention systems, must be isolated from the galvanised steel to prevent bi-metallic corrosion.

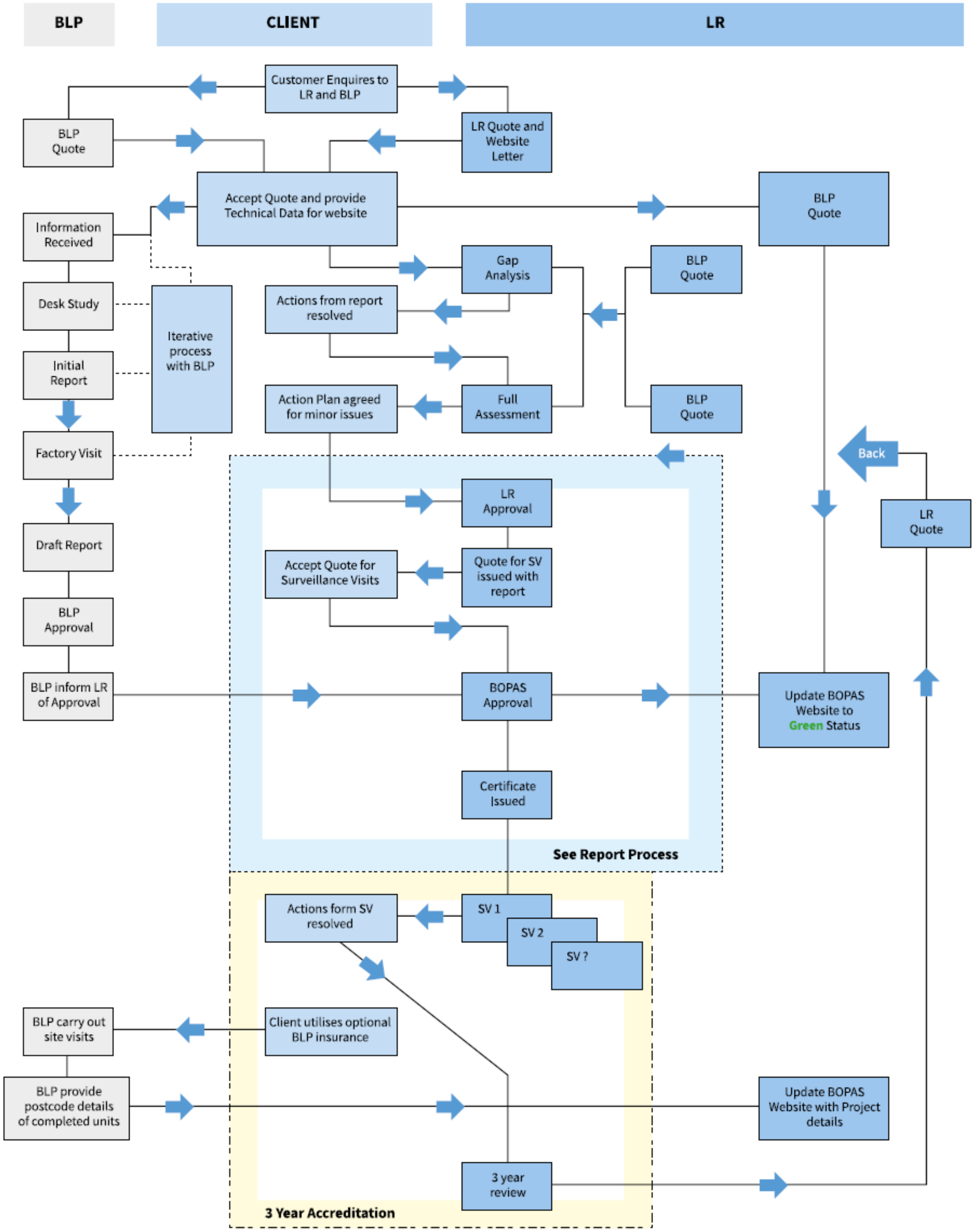


Figure 52: The BOPAS accreditation procedure

Interview transcript. Interview held with Jeff Maxted on the 29/06/2021.

KN. 0:04

How was BOPAS created? And who took the initiative? And how did it all come about?

JM. 0:17

Okay. Yeah, my focus began life back in probably 2008 2007 2008. When the major mortgage lenders in the UK, were beginning to get rather nervous about offsite construction that was beginning to become more common, but it wasn't really there were examples of it being used in, in the UK. And they were nervous about how durable the sort of construction would be, what the impact of any defects would be, and would impact on their lending of mortgages. So they approached build-off-site who are an organization that specializes in promoting offsite construction techniques, to see if they could put together a team that would be able to give them confidence that any system built non traditionally, call it MMC or whatever you like to call it, would be durable for a minimum of 60 years, or two mortgage terms. So build-off-site put together a team comprising two organizations. One is Lloyd's Register, who essentially came out of Lloyd's of London. And they have been assessing sort of shipping, nuclear power stations and the like, for many, many years. And they look at the processes employed by the organizations to ensure that they're consistent. They have proper training, proper quality assurance, to ensure that whatever is produced, when it leaves, the factory is of the same quality and correct quality every time it comes out. And the other party was BLP insurance, who I work for. We're a warranty provider in the UK, and have been since 2004. And our role was to carry out a durability assessment sort of got all the materials going into these modules. Look at how they're put together, how tall they can be built. Do they offer adequate protection from moisture, both internally and externally. And we work very closely with the lenders, the Royal Institute of Chartered Surveyors and valuers to develop the BOPAS process. So it's essentially two phases, there's the factory accreditation and also the durability assessment of the of the systems that are being used. And essentially, they can be two they can be either 2D is a panelized system that's put together on site or a modular volumetric type system. There are techniques that we use in the UK that will be described as a modern methods such as insulated concrete formwork, and thin joint blockquote materials but because the essence of those is, is really site driven, most of the work is carried out on site. They're outside the scope of BOPAS. So we're looking at systems where the majority of it is carried out in a factory environment. So BOPAS, we went through pretrials with different systems when BOPAS launched in 2013. Even back then it was pretty much a cottage industry, there wasn't an awful lot going on in terms of MMC or offsite fabrication, but from about 2016 2017 we're seeing much more in terms of different manufacturers coming through and getting accreditation. And we're now at a point where we've probably got approaching 100 manufacturers who are either fully accredited under BOPAS or are going through the process. So that's a large part of the the off site sector currently being used in the UK. We are looking at systems and manufacturers from abroad as well. So China, Holland, Spain, Turkey, we've looked at systems in lots of different areas.

KN. 5:19

What I'm unsure about is, is what exactly is checked, because the way that I see it with Lloyds and BLP is that someone would have to check the sort of the finances of the company, I assume their financial processes, and then the other side is checking the durability, and the system itself, which I assume is checked by sort of building engineers, or structural engineers.

JM. 6:12

We have a team in BLP, we have a team of engineers, architects, building surveyors, who have been carrying out these sorts of assessments and design checks as part of their warranty process, because we provide a 10 to 12 year warranty for new buildings being built in the UK, as do many other warranty providers. And we've just taken that process that we've used since 2004, to provide a warranty, to look at the off site sector as well. So we, as you say, we look at the designs, the detailing, the structural performance, we're not a test house, we don't do our own testing, but we do ensure that we're testing is required. It is carried out by a recognized testing house such as BRE, or similar.

KN. 7:18

And then the finances, is that what Lloyd's Register does?

JM. 7:22

Yeah, they do an overview of the company structure and their finances to ensure that they're in a position where they can deliver the service that they're looking to deliver. Sadly, it's not an exact science. And we have seen a number of manufacturers go out of business, purely because there has been a great deal of take up of their systems. And that's one of the biggest problems in the UK is now it can be quite expensive to set up a new factory, and start producing modules or panelized systems. And if there isn't a pipeline of work going ahead, then it becomes very difficult, because if you haven't got that factory running to a capacity, then it can very quickly become a non profitable business. So we've seen a few that have come and gone. Many of them have been startups. A lot of the organizations that we've accredited have been around for some while producing sort of commercial buildings, other schools or factories or other sort of buildings. And they've moved into the residential sector.

KN. 8:47

Have you been in contact with the government? Have they shown interest in such a scheme? Or have they may be even, let's say motivated industry to create such a scheme?

JM. 9:00

Oh, absolutely. The government have been trying to promote offsite construction for many years. Much of the funding is done by an organization called Homes England. And they offer grants to manufacturers and developers to develop land, ideally aimed at the the low cost housing sector to try and promote buildings that are affordable for key workers and younger people. And they have been promoting modular construction. They government have pointed Mark Farmer who's a Consultant to promote offsite technology and he produced a book called 'modernize or die'. I don't know if you've seen a copy of this? I would strongly recommend you can take a look. It's right because you know, the construction sector in this country is very expensive, very unproductive. And we need to move forward with modern methods of construction, to try and deliver the homes that we need. The government had a target of 300,000 homes being built a year. And we were never going to achieve that. With traditional construction. I'm still not certain we're going to get there using traditional and modern methods, that the government is certainly behind moving towards a modern, off site solution to much of our housing needs.

KN. 11:00

Since it's now been around for a while, is there any stats that the scheme has achieved, as in involving a certain amount of companies or, you know, because you've accredited a certain product, that a project has taken place because of that?

JM. 11:31

Well, in truth, BOPAS is almost a prerequisite of the the off site sector now, particularly in the residential area. There are two key requirements that most lenders have, if they're looking to provide funding or lend or provide mortgages on off site schemes using off site techniques. One of which is the NHBC, I don't know if you've come across the NHBC. They are the biggest warranty provider in the UK. They provide warranties for all the major traditional house builders in the UK. And then now beginning to look at off site. Because a lot of their clients looking to go down the route. I mean, one of the major problems we've got is labor. And certainly Brexit and COVID hasn't helped that. So there is a labor shortage in the UK. So offsite techniques are one way of resolving that, that issue. And NHBC provide a form of accreditation for the off site sector. As I spoke at focus, I know lenders will either insist on a system having NHBC or BOPAS accreditation, before they will lend on it. And as I say, we've now got approaching 900 manufacturers that have got BOPAS accreditation, which is a very large part of the sector. And that's growing all the time, we all see new people coming in from abroad and a new companies setting up from within the UK. So it's an integral part of the the off site construction sector.

KN. 13:47

Is there may be document that you have on this that you could share with me? That would that would be very helpful.

JM. 13:58

Yeah, I can show you the BOPAS guidance document that will talk you through what the processes are. I'll send that through to you. It will show you what the technical assessment process looks like. You've looked at the bopet website, presumably?

KN. 14:23

Yeah, that's what the next question is about that. I saw that there was three divisions, I don't know if it's three separate schemes or three angles of it, but basically one for lenders, one for manufacturers and one for developers. So how does that work?

JM. 14:57

It just gives an outline to the various part is as to what the BOPAS process offers. But essentially the main part of BOPAS is it identifies the manufacturers, what their system is, not alone of the type of system it is whether it's volumetric or panelized, the construction techniques and where they are through the, the accreditation process. Ther is a traffic light system. So all organizations when they register a BOPAS start as Amber. And as they achieved the various accreditation points, because they can be accredited for manufacture, project management, construction, and design. And they need to go through those various processes and move from Amber through to green. So once they are all green, then they are fully accredited. Under BOPAS. And so it's very transparent as to where they are in their accreditation process to anybody who's interested in looking at their system and see how, what it is, what it's like, and how far they are down the route to accreditation.

KN. 16:20

I assume that, for example, the structural the durability checks of the system are only in relation to the manufacturer's part, right? Because for developers and for lenders, they would probably only be interested in finances?

JM. 16:51

No they're very much interested in all aspects of the process. They want to ensure that these things are curable. So they're very keen on the durability assessment.

KN. 17:06

Why make the differentiation of the three parts? Why not just have a single assessment?

JM. 17:14

I think it's fair to say people like to look at different things, I think, and you can look at the manufacturer, for example, in their information, they can look at the technology in more detail. And there's a section there for lenders, as you say where they can just get an overview of the systems. I think, to be honest, the website is due for an overview fairly soon, needs updating, and we're beginning to add more things to what we're able to offer manufacturers. Obviously sustainability is a very hot topic at the moment, as I'm sure it is in the Netherlands, and we are able to offer carbon assessments, a lifecycle assessments of how the systems compare with traditional build. It's not an integral part of BOPAS, but it's something we can look at. Manufacturers can take that up if they want to add some value to their offering to the market.

KN. 18:23

And would you say that this scheme helps to value the property more accurately than it would otherwise?

JM. 18:42

Yeah, it does. I mean, it gives them more confidence about how these properties compare with more traditional built forms of construction. And they need that assistance because there isn't the long term evidence there to demonstrate how these buildings are going to perform over 60 or 100 years. And so they do rely on it to a certain extent in terms of the durability of the systems, how they value one next to another is interesting. They may still take a different view between the two but I'm not a valuer. So I don't want to get too deep into that side of things.

KN. 19:31

And then about mainland Europe - what I've read about the markets, products and the modules that different manufacturers offer in Germany and the Netherlands are at the same stage where there are a couple of joint ventures and groups of these modular companies that try to join to their advantage. But there is no accreditation system or any kind of other security other than them showing you their previous projects. So what would you recommend for the market? Should anything be implemented? How do you think the market will develop from from here on? Should the government do something to increase the building of modular homes because the issues are very much alike? There's also a housing crisis and the issues are the same.

JM. 21:46

Yeah, I mean, I think it's incumbent on governments of all countries to try and promote the offsite sector. I think it's, in this country, certainly, there's an awful lot of legislation and standards around quality and durability. From what you're saying there doesn't seem to be that same rigor and requirements in the rest of Europe, and I think to give confidence to these forms of construction, you need to have such accreditation is in place. And it's anything that really gives confidence to funders and lenders and purchasers at the end of the day that those they're buying are going to be durable, and for a long, long, long period. I can put you in touch with some other organizations are here in the UK that might be worth us speaking to if you've got the time. And as you say, there are a number of organizations that are working together to promote the off site, the offsite Alliance and various other bodies that would be able to give you some some more insight.

KN. 23:18

I would first want to have a look at the guidance document. So I can compare with what I know is done in the Netherlands. Thanks very much for your time.

JM. 23:53

Good luck with your appointments.

Appendix C. Hospital project manager interview transcript

Interview with Project manager - technical building services eng. Ronald van Lier.

KN: What does the Reinier de Graaf Groep aim to provide, specialized or general healthcare?

RL: Reinier de Graaf consists of a hospital, laboratory and a few companies that support the hospital, you have to think about sterilization. We have one main building in Delft that's about 60 000m2 and we have a few policlinics, smaller hospitals, where people don't have to travel very far. The main building was delivered in 2015 so it has been operational for about 5 years. We are a training hospital, so we train future doctors. Our goal is not always production but also education. We specialize in women's birth and the elderly and cancer treatments. We do a lot of other things also. We don't do complex heart and lung surgeries. We have an emergency room and we have a part in the building reserved for the huisdoctors.

KN: Given the changes in law in 2008, what is financially important now, for the survival of the hospital.

RL: We are the first hospital in the Netherlands to be built with its own mortgage, so it wasn't subsidized by the government. So if you need to earn back the hospital that you built, the you need to make sure that your mortgage is competitive enough to work as a business. We financed a build within some financial borders, that had an impact on its size. I think we are the highest turn around per square metre in the Netherlands, so it was a very tight build. Your profits is related to the interest that you pay for your mortgage. If you have a high profit or low risk for your finances, you will pay less interest and earn more money. And vice versa. So that's the mechanism that works for financing a hospital.

KN: Since some services are more financially beneficial than others, does it affect your decision making?

RL: No, because every year the game field changes. So if you do a lot of treatment of one subject for one year, you'll get less money per treatment next year. You make certain agreements with health insurers and they make sure that they don't pay enough and that you don't specialize in everything, but that you have a mission for the population around you. Some treatments like cancer treatments are quite expensive. We don't' make the decision if somethings too expensive or not. We look at the future so if you look at the region that we're stationed in, we expect a lot of births in the next couple of years, so you specialize in the birth part.

KN: Which of the laws (Zvw Gzw..) are of interest to you and what should I consider in my thesis?

RL: If you look at my business. I take care of the facilities of the hospital and my no 1 priority is reliability. The reliability of the installations and function are the main goal. Because if I have a reliable installation, I will never loose any production when it fails. That's one of the things that I can tell you, I am not interested in how much we get paid, I am more interested in the reliability and the cost. If I keep my costs down, then it will be a win win situation for everybody. Every decision that I make is based on a risk assessment, it also includes the risks of finances. Are you prepared for an installation that is very reliable or will you pay a bit less and try to deal with it with people or some measurements in emergency situations. We have a continuous risk analysis on every euro that we've spent trying to maintain output and maintain safety for the patients, and still have an operation that is cheaper than everybody else. There's a relationship between the age of a building and the cost that you spend on it. The funny thing is that the building is most expensive when it's first opened. The you have a lot of little problems that need to be solved. Then you have the period where the costs are less, that's the most interesting period. And then you have a period where the installations become older n adless reliable, and you'll have to invest more to maintain your reliability. So we're at the stage where the costs are low, we have a semi-old building, from an installations view. We have a small footprint of costs of installations but it will rise in the coming years because of the installations.

KN: What role does sustainability play in the procurement of a new facility?

RL: That's funny, because I absolutely don't believe in it. Let me explain. I have one of the buildings that if you look at the energy output, is the highest per square meter in the Netherlands. But if you compare the energy for the work we provide, then we have one of the least cost for installations and durability and CO2 output. So you have to design a hospital not by government regulations because there's a problem with the hospital as a whole. I have a hospital that is well insulated. I have triple glazing, you can't open windows, heat pumps to warm and cool the building and ground buffers to store energy for the summer and winter. But if you look at the electricity production cost by medical treatments, then I have a hard time ventilation all the heat out of the building. So there is an ideal situation, for a hospital as a energy dense usage, is being outperformed by the insulation of the building. So it will cost you more to cool and transport that energy than if you have a less well insulated building. So I now have a very high heat production, so I'm going to sell it to the neighborhood. So ill supply excess heat for 400 buildings. That's environmentally sound. But the regulations from the building authorities doesn't take into account that the transport of heat and coolth is more important than the insulation value. So if I produce a lot of heat, I need to get it to a usage that is environmentally friendly. Now I have a neighbor of 400 houses. I can give it to them to make a sustainable environmental impact. So the building regulations are not always the most efficient in such an environment, especially for hospitals, because of the treatments that we do. We will not become CO2 neutral, it's fairly impossible, I have 10 000m2 of solar panels and it only provides 1-2% of my electricity use. So if I want to completely make it sustainable I will never succeed in that. But a nice hospital within a city limit, is that you can use that building for energy buffering . And that's what we do, we have a few buffers, and we collect the heat and coolth and you can provide it when its needed. So that's our view of the environment. We don't use gas for heating, we only use gas for producing hygienic enough steam, because alternatives aren't hygienic enough. So my concern is hygiene and patient safety, and the second concern is the environment.

KN: What changes of function were preprogrammed in the design of the facility in Delft? How easy is conversion between wards?

RL: We designed a hospital with a few things. Our outer skin is also our main construction, so what is done with the outer skin is done quite easily. We don't have to tear anything down or make constructional works. What we also did is we designed every department overrated. So if I have an ICU, that has things like air, electricity, then the department next to it also has it. So you can have a harmonica model, it can breathe. It can borrow room from that other department but it has the same functions and facilities in it. If an ICU is being overwhelmed by patients it can expand within a building without converting anything. If there are less patients it can shrink a little bit. So that is our goal for expanding those departments. What you also see is that the length of a medical treatment is shortening, so that will also provide more space for other treatments that you can do in the same room. We make sure that the facilities are basically all the same, so you've overdone a bit during this time but you can manage the next 20 years without very high turnover costs.

KN: How do you know how much more installations you should install?

RL: That's not a very difficult decision. If you know what the needs are, so you need the staff that uses the rooms to participate… The users had a large part in designing the building. We had a lot of talks before designing. You then have the sense what a department really used to treat the patients. So if you really want to design a hospital you have to listen to the user and design it around it. I had a project manager of a state run hospital in Qatar. They had built 50 hospitals, all the same. They spent 40 billion euros for building the most modern hospitals in Qatar. When they built the first 8 or 10, they stopped the project because there wasn't a doctor that wanted to work there. They were designed form a technical point of view, this is what we think we need. And when the doctors and nurses came in, they said that this is unworkable. The nice thing about participation of users, then you also get a level on which everyone wants to work at in the hospital. We're building a hospital as a skin for the process that will take place there. It doesn't have to be pretty, it doesn't have to be big, but it has to function.

KN: I have looked at the plans of the hospital, and it looks like it is a building structurally designed using prefabricated parts, however, I spoke with prof. Maarten van der Elst and he used the term modular.

RL: It's not the construction, because the construction is relatively low in cost. The installations are modular. We did that on two purposes, first reliability. If you build smaller installations specifically designed for a department. Then if that installation fails, then you only affect for instance 20% of your building and 80% is still operation. You can design in two ways, you can design twice as big, or how we did. We told every engineer that if one installation fails it cannot be more than 75% of maximum output. So if one part fails I have 3 parts left and I can continue with the basic operations. That's the most modular part. As I've told you the outer structure is the construction, so what happens within is kind of flexible. We have designed the rooms that are quite the same, so they can change functions, without tearing it down. But if you have an entire department that needs to change its function then you have to tear it down in the old fashioned way.

KN: Is it interesting to have a modular structure or can everything be efficiently done using modular installations? Can you see any benefits to this?

RL: I hope for the last. I did some builds with hotels with a modular concept. So you take a concrete structure and you shove the rooms in, and they are built in factories. That kind of modularity is the future for building houses. For some parts it applies to hospitals. Our main technical rooms were built in a factory, disassembled and put together on site. So that will drastically reduce your time required to build. If you take the entire hospital, there are some parts that are specialized. For instance, we have radio therapy bunkers, completely made of concrete. Those will be untransportable for modular use. So there will always be parts of a building that cannot be used. But if you look at a patient room, yes that can be constructed. I believe they are building a module hospital in the Hague. The only problem with a module is that it has a certain dimension. And those are too big to build one room and too small to build two. So you have an ineffective use of square meters.

KN: What spaces would fit unit construction?

EL: Patient rooms, offices, kitchens. We have kitchens in each department providing for food, beverages. Some projects choose for one big kitchen, but we have small ones. There are a lot of rooms with the same activity, storage rooms, waste rooms, those kind of things can be built modulary. Only if you look at for instance an operating theatre. Those are also operated modulary, only an entire complex consisting of those is difficult to integrate in a building. But there are certain companies like Jan Snel.

KN: Units are an efficient building form, but during their lifecycle they can be easier to refurbish or they can be even brought back to the factory to be refurbished. Do you see advantages in the use of unit construction?

RL: We started with that, for building of our entire hospital. I had a director who said that we have to pay this for ourselves so I don't care if we have to stack containers, I don't care how ti looks, it just has to be efficient. So we actually calculated that in the beginning, also with prefabricated bathrooms. Only back in the day it was still the most expensive way to build. It's fast and it's reliable, absolutely, you have a good quality that's one of the main advantages. But the costs were incredibly high. What you see now is that people like Medexs specializes in those types of builds and they will, as the cost on site, people and environment and carbon emissions. Those factories will become interesting for putting buildings together. At this moment you see that for temporary buildings, buildings needed for 10 years, buildings that need to inflate/deflate. But with hospitals that's a difficult market, because of the specialized treatments that are taking place, the very heavy backbone in installations usually, we use a lot of electricity, so you need a very reliable power installation. So yeah that is the future, but that future is based not on environmental impact, but on the lack of people that can build buildings. It's an expensive feature to build hospitals in modular now.

KN: Is there a substantial amount of construction that takes place during the lifecycle of a hospital?

RL: What you see in hospitals is if you build a building for 40 years, you will have 3 or 4 renovations during that time. With a hospital it is not uncommon if a renovation happens every 5 years, because of change of process, change of treatment, for instance new diagnostic equipment that we need. In that case the hospital is very volatile. Its' difficult to manage. If you look at the environmental impact of those refurbishments, they can be on one hand be very high, but you also see installations in hospitals that are well over 40 years old, which is environmentally sound on one hand. Usually the power usage is quite high for those installations. Compare it with a Saab, it's a strong car, takes a lot of money to build, has a terrible mileage but it will last you 400 000 km, whereas, sorry for the French, Renault doesn't. What's the most environmentally friendly way of using something, that's quite difficult. You can compare hospitals with Saabs, not the most pretty one, and not the most friendly, but reliable and steady. Ofcourse if an installation uses a lot of energy it has to be replaced, but in construction, for concrete, the carbon is at the beginning of the process not during the process, so that's different.

KN: What kind of work do you procure at a hospital and what are the reasons?

RL: We try to make use of the materials we have, a sink or a door that we can reuse gets reused in our next renovation. Our problem is that I'm trying to devise a way to make renovations circular, what's quite difficult, because if you look for instance at plaster walls, those are quite difficult to reuse. But for instance a door, window or some sanitary equipment we will try to reuse again and again until its very worn down. So basically in every project you are trying to reduce cost and impact by reusing as much material as you can, but not all materials can be reused. If you look at the buildings of the future, they will be constructed from only materials that can be reused. For instance a hospital from wood in the future is probably possible, if you look at it from that point of view.

KN: Maybe we can use less carbon intensive material then?

RL: You always have to consider the lifespan of materials. For example our façade is ceramic, which is intensive to produce but it can be used for 50 years. You take the CO2 cost at the beginning of the material and not during its lifespan.

KN: When does what maintenance work take place and what is the schedule? I want to propose an alternative design made out of units, and see how that would work. I would like to include at what point what works are to take place.

RL: I have a laboratory that needs to be replaced within 5 – 6 – 7 years. So that is an interesting case. It's becoming too old. The nice thing is, I'm currently building a smaller hospital in Voorburg which has the potential to be modular based hospital. It will not replace the building, but it's a nice study, because you have the end result and you can reengineer your design. The nice thing is also that it's a smart building, so it has a lot of technology which can make the hospital user friendly. And in the upcoming future, I have the laboratory that needs to be replaced and it's quite easy to modulate.

KN: Has there already been any replacement of installations since the opening of the hospital?

RL: No not big ones. We just finished an expansion of our operating rooms in Delft. And that has been built on a steel frame, on a parking garage. We also checked that for is it possible for whether it is possible to make that modular. It's a steel frame it doesn't have a lot of concrete construction. The other problem is the amount of vibration that we need to operate, no one tried to do that without concrete, you need weight to try to reduce that. So the next concrete case is the laboratory.

KN: Do you carry out LCAs for renovation works? I assume one was done for the construction of the new facility.

RL: For our new hospital in Voorburg we did that, but it must be on a very small scale. It's more the vision that you have. If you want to become less dependent on power, you need to electrify everything. Then you can manipulate that LCA quite easily. The main problem, that is not very clear what the CO2 taxes will do. But if you design a building, and take into account that there will be CO2 taxes in the upcoming decade, then everything they do in a traditional way, gas, less insulation, then it will become a financial risk for the existence of the hospital. If you take into account that risk and you want to minimize the risk in the future, then those cases are quite easily made, you don't invest in fossil fuels, that's quite easy. But you also need to have a bit of gut, because mostly it’s a bit more expensive, if you don’t use it, but if you take into account that it will become a risk once oil prices go up and taxes have to be paid, then the decision is quite easily made.

KN: Was there an environmental assessment for the RdGG?

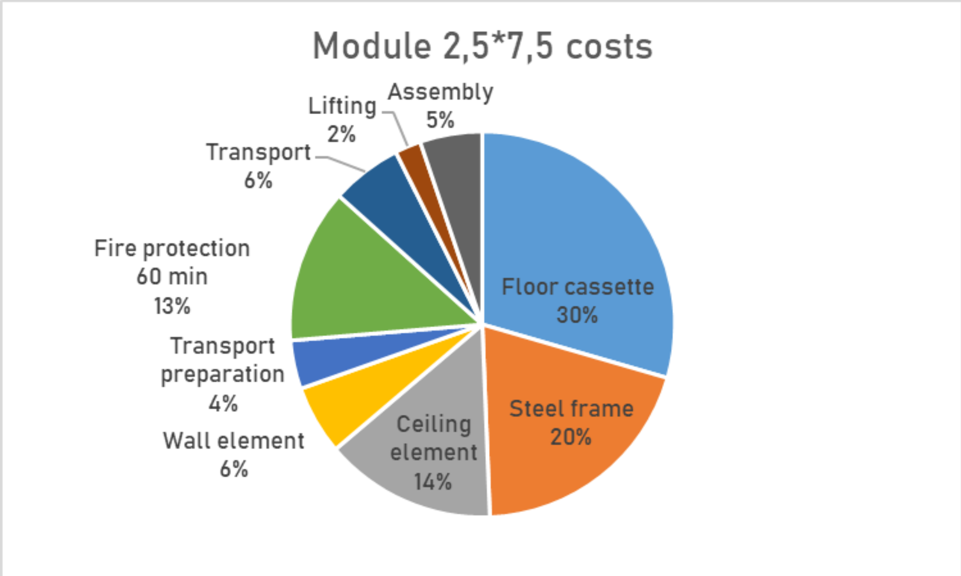
RL: Of course we take in the environmental, and we electrified everything. You have to take into account that this was 10 years ago, at that time it was quite progressive. We still have gas, but it’s mainly used as a back up if anything goes wrong, the little cost that I spend investing on the gas installation is fairly little compared to a days loss if I’m out. For the hospital in Voorburg, as I said, it’s all electric. A friend of mine told me that the impact, the solar panels, heat pumps and those sort of things, you don’t need to consider it, because you take what’s available and affordable at that time. A lot depends of the market, the reliability and how you use it. For instance if you say that you have one central installation and you need it to be reliable, then build two. But you can also have a 100 little installations and they don’t have to be reliable, because if one fails I still have 99 left. The design decision that you make in the beginning, has more impact on the building than something that you use over the next decade for the installations. So I believe that the CO_2 tax, will create pain on the usage side and not on the building side, so if you want to pay a co2 tax and want to do it in a proper way then you have to tax both instances. So if you use concrete instead of wood, then you would probably pay more. If the building is more reliable in a way that it will last for 50-60 years you need to compare that. So concrete isn’t a bad material, it uses a lot of co2 in the beginning but doesn’t use it a lot of co2 at the end of its lifetime. And wood would have to be replaced. So not everything is as clear in the beginning, so it’s quite difficult to make an environmental impact of a building if you don’t take those things into account.

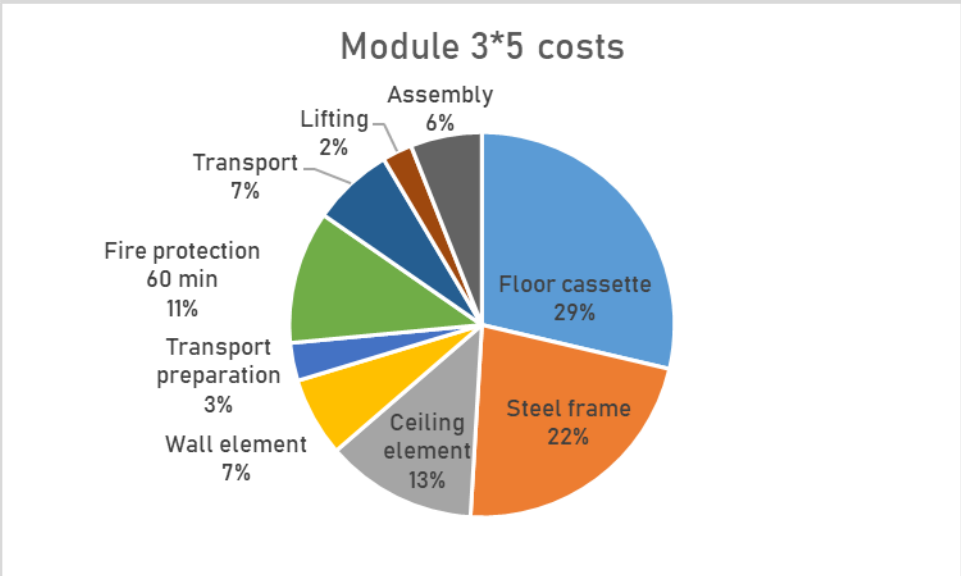
KN: Would you carry out an environmental assessment for the replacement of the laboratoria, and what would you do?

RL: Definitely, first I would completely electrify it. As I said, gas is an operational risk. The amount of materials used in the lab needs to be clean in a certain way and they use a lot of plastics and rubber kind of things, and they are environmentally not very practical. And you use it because you want to survive in 10 years as a hospital. You don’t want it to become a risk, for example if co2 taxation really does take place.

KN: Thank you very much for your answers.

Appendix D. Case study module cost breakdown





Case study module cost breakdown:

Module 3*5		**Module 2,5*7,5**	
Floor cassette	3 334 €	Floor cassette	3 933 €
Steel frame	2 590 €	Steel frame	2 654 €
Ceiling element	1 477 €	Ceiling element	1 925 €
Wall element	773 €	Wall element	773 €
Transport preparation	370 €	Transport preparation	543 €
Fire protection 60 min	1 297 €	Fire protection 60 min	1 729 €
Transport	794 €	Transport	794 €
Lifting	292 €	Lifting	292 €
Assembly	698 €	Assembly	698 €
TOTAL	11 624 €	TOTAL	13 341 €

For comparison, the numbers stated in the McKinsey report:

- 2000 euro on materials
- 4600 euro on manufacturing
- 10% for design (1090 euro)
- 720 euro for transport to site (300km)
- 300 euro for lifting
- 20% for onsite labour (2180 euro)

The costs proposed in the case study are reasonably close to those stated in the report. Lifting and transport costs are very close per module. There are too many unknowns to make any other insights. It can be said, however, that like for steel structures, fire protection is a large cost to the structure.

Appendix E. Sensitivity study data

Inflation

0%

Scenario A: 19,5% less, (764 000 €), which is 41,6% more than conventional (LCC)

Scenario B: 30,5% less, (660 000 €), which is 22,3% more than conventional (LCC)

Scenario C: 9,2% less, (862 000 €), which is 59,8% more than conventional (WLC)

Scenario D: 9,2% less, (862 000 €), which is 59,8% more than conventional (WLC)

1%

Scenario A: 19,5% less, (764 000 €), which is 41,6% more than conventional (LCC)

Scenario B: 32,3% less, (643 000 €), which is 19,2% more than conventional (LCC)

Scenario C: 11,0% less, (845 000 €), which is 56,6% more than conventional (WLC)

Scenario D: 11,0% less, (845 000 €), which is 56,6% more than conventional (WLC)

2%

Scenario A: 19,5% less, (764 000 €), which is 41,6% more than conventional (LCC)

Scenario B: 34,3% less, (624 000 €), which is 15,7% more than conventional (LCC)

Scenario C: 13,0% less, (826 000 €), which is 53,1% more than conventional (WLC)

Scenario D: 13,0% less, (826 000 €), which is 53,1% more than conventional (WLC)

3%

Scenario A: 19,5% less, (764 000 €), which is 41,6% more than conventional (LCC)

Scenario B: 36,6% less, (602 000 €), which is 11,6% more than conventional (LCC)

Scenario C: 15,3% less, (804 000 €), which is 49,0% more than conventional (WLC)

Scenario D: 15,3% less, (804 000 €), which is 49,0% more than conventional (WLC)

Real discount rate

3%

Scenario A: 16,1% less, (796 000 €), which is 47,5% more than conventional (LCC)

Scenario B: 35,6% less, (611 000 €), which is 13,2% more than conventional (LCC)

Scenario C: 14,3% less, (813 000 €), which is 50,7% more than conventional (WLC)

Scenario D: 14,3% less, (813 000 €), which is 50,7% more than conventional (WLC)

4%

Scenario A: 19,8% less, (761 000 €), which is 41,0% more than conventional (LCC)

Scenario B: 36,7% less, (601 000 €), which is 11,4% more than conventional (LCC)

Scenario C: 15,4% less, (803 000 €), which is 48,8% more than conventional (WLC)

Scenario D: 15,4% less, (803 000 €), which is 48,8% more than conventional (WLC)

5%

Scenario A: 23,0% less, (731 000 €), which is 35,5% more than conventional (LCC)

Scenario B: 37,5% less, (593 000 €), which is 9,9% more than conventional (LCC)

Scenario C: 16,2% less, (795 000 €), which is 47,3% more than conventional (WLC)

Scenario D: 16,2% less, (795 000 €), which is 47,3% more than conventional (WLC)

6%

Scenario A: 25,6% less, (706 000 €), which is 30,8% more than conventional (LCC)

Scenario B: 38,3% less, (586 000 €), which is 8,6% more than conventional (LCC)

Scenario C: 17,0% less, (788 000 €), which is 46,0% more than conventional (WLC)

Scenario D: 17,0% less, (788 000 €), which is 46,0% more than conventional (WLC)

Earlier income

No earlier income:

Scenario C: 36,0% less, (607 000 €), which is 11,1% more than conventional (WLC)

Scenario D: 36,0% less, (607 000 €), which is 11,1% more than conventional (WLC)

6250 eur/month:

Scenario C: 30,9% less, (656 000 €), which is 21,6% more than conventional (WLC)

Scenario D: 30,9% less, (656 000 €), which is 21,6% more than conventional (WLC)

12500 eur/month:

Scenario C: 25,6% less, (706 000 €), which is 30,8% more than conventional (WLC)

Scenario D: 25,6% less, (706 000 €), which is 30,8% more than conventional (WLC)

18750 eur/month:

Scenario C: 20,5% less, (755 000 €), which is 39,9% more than conventional (WLC)

Scenario D: 20,5% less, (755 000 €), which is 39,9% more than conventional (WLC)

25000 eur/month:

Scenario C: 15,3% less, (804 000 €), which is 49,0% more than conventional (WLC)

Scenario D: 15,3% less, (804 000 €), which is 49,0% more than conventional (WLC)

Constant income

Only Scenario D:

- No income: 18,1% less, (804 000 €), which is 49,0% more than conventional (WLC)
- 6250 eur/month: 18,1% less, (804 000 €), which is 49,0% more than conventional (WLC)
- 12500 eur/month: 18,1% less, (804 000 €), which is 49,0% more than conventional (WLC)
- 18750 eur/month: 18,1% less, (804 000 €), which is 49,0% more than conventional (WLC)

- 25000 eur/month: 18,1% less, (804 000 €), which is 49,0% more than conventional (WLC)

Appendix F. Timber module approximation

Below are the calculations to find the rough glue laminated timber (GL28H) equivalent of two steel (S355) sections (200*90 PFC and 300*90 PFC) by checking flexural strength. These are the main beams of the ceiling and floor cassettes for the module of 2,5*7,5. The columns were sized using a compression check parallel to the grain. Compression parallel to grain is 24,0N/mm^2. The rough equivalent to a 100*100*5mm SHS columns is a GL28H column of 170mm*170mm.

	A	B	C	D	E	F	G	H	I	J
1	Glulam beam 1 flexural strength check (EN 1995-1-1 :2004)					Glulam beam 2 flexural strength check (EN 1995-1-1 :2004)				
2	Title	Quantity	Formula	Units	Comments	Title	Quantity	Formula	Units	Comments
3	200*90PFC	10,3		kNm	Action	300*90PFC	20,2		kNm	Action
4	GL28H					GL28H				
5	f,m,k	28		N/mm2		f,m,k	28		N/mm2	
6	b	180		mm		b	240		mm	
7	h	280		mm		h	280		mm	
8	L	7500		mm		L	7500		mm	
9	L,eff	6750	=0,9*B8	mm		L,eff	6750	=0,9*G8	mm	
10	Wel,y	2352000	=B6*B7^2/6	mm3		Wel,y	3136000	=G6*G7^2/6	mm3	
11	k,sys	1			(no group action)	k,sys	1			(no group action)
12	k,mod	0,6			(permanent)	k,mod	0,6			(permanent)
13	gamma,m	1,25			(glulam)	gamma,m	1,25			(glulam)
14	k,crit	0,31	=IF(B23<0,75;1;IF(0,75<B23<1,4;1,56-B23*0,75;IF(B23>1,4;1/(B23^2);"oops")))			k,crit	0,46	=IF(G23<0,75;1;IF(0,75<G23<1,4;1,56-G23*0,75;IF(G23>1,4;1/(G23^2);"oops")))		
15	k,h	1,08	=MIN(1,1;(600/B7)^0,1)			k,h	1,08	=MIN(1,1;(600/G7)^0,1)		
16	L,eff/b	37,50	=B9/B6			L,eff/b	28,13	=G9/G6		
17	f,m,y,d	4,50	=B14*B15*B12*B11*B5/B13	N/mm2		f,m,y,d	6,63	=G14*G15*G12*G11*G5/G13	N/mm2	
18	G0,05	638	=B19/16			G0,05	638	=G19/16		
19	E0,05	10200				E0,05	10200			
20	I torsion	2182268	=B7*B6^2/(3+1,8*B6/B7)			I torsion	3550189	=G7*G6^2/(3+1,8*G6/G7)		
21	I z	136080000	=B7*B6^3/12			I z	322560000	=G7*G6^3/12		
22	sigma,m,cri	9	=PI()*SQRT(B19*B21*B18*B20)/(B9*B10)			sigma,m,cri	13	=PI()*SQRT(G19*G21*G18*G20)/(G9*G10)		
23	gamma,rel,	2	=SQRT(B5/B22)			gamma,rel,	1	=SQRT(G5/G22)		
24	Mc,y,Rd	10,6	=B17*B10/10^6	kNm	Resistance	Mc,y,Rd	20,8	=G17*G10/10^6	kNm	Resistance

Appendix G. Comparison of healthcare facility costs in traditional and modular construction

The Cobouw Bouwberichten Database boasts a set of over 400 000 documented projects. This database has been searched to find comparable project costs, floor area, amount of stories, apartments and in some cases number of units. Companies document their projects in brochures, but these values are often not stated.

The database was used to find relevant healthcare projects in the Netherlands, built in a modular or traditional way. Selection limitations were that the project cost was a single number rather than a range, the data was complete and that the project was built as permanent or semi-permanent, meaning for longer than 5 years.

Traditional Construction

Traditional construction **new** hotfloor projects which include operation rooms in the last 10 years, searched for with the keywords 'operatie kamer','OK':

Project	Contractor	Cost	Floorspace (m2)	Year of Completion	Duration in months
Noordwest Ziekenhuis	Haskoning	40 mil. €	28600	2023 expected	14
Slingeland Ziekenhuis	Haskoning	120 mil. €	42000	2025 expected	36
Langeland Ziekenhuis	Sprangers	15 mil. €	10000	2020	22
Medisch Centrum Vechtdal	Dura Vermeer	55 mil. €	20000	2020	21
Bergman Clinics	Goossen Te Pas Bouw	4,5 mil. €	3700	2020	12
OZG Scheemda	Pieters Bouwtechniek	110 mil. €	32000	2018	27
Isalaklinieken	BAM	225 mil. €	108000	2013	44

Traditional construction projects of **renovation and extension** including operation rooms (hotfloors) in the last 10 years, searched for with the keywords 'operatie kamer','OK':

Project	Contractor	Cost	Floorspace (m2)	Year of Completion	Duration in months
Wilhelmina Ziekenhuis Assen	BAM	12 mil. €	3500	2023 expected	26
Maastricht UMC+	Brekelmans	70 mil. €	21000	2017	41
De Honte Ziekenhuis	Sprangers	21 mil. €	42215	2020	17
UMC Groningen	BAM	10 mil. €	7550	2021	17
Laurentius Ziekenhuis Roermond	-	101 mil. €	10300	2018	44
Diakonessenhuis Utrecht	Sweegers & de Bruijn	185 mil. €	2500	2022	43
Bethesda ziekenhuis	Strukton	5 mil. €	300	2019	18

Ziekenhuis Gelderse Vallei	BAM	110 mil. €	1000	2020	30

It is noted, that most projects are below a 6 storey height, which can be carried out in low-rise modular construction. The average cost per square metre for reconstruction projects is 2177 euro. The average cost per square metre for new projects is 5750 euro. The amount of projects and variation in scale does not allow to draw any firm conclusions.

Modular construction

Modular projects in the heathcare sector, keywords ‘modular’, ‘modulair’:

Project	Contractor	Cost	Floorspace (m2)	Year of Completion	Duration in months
Gezondheidscentrum legerplaats in Ermelo	Aannemersbedrijf Dons en Troost	3 142 000 €	1200	2019	9
De Meulenbeek woonzorgcentrum in Ulft	Nezzt/de Meeuw	1 500 000 €	3000	2019	6
Admiraal de Ruyter Ziekenhuis in Goes	Jan Snel	3 000 000 €	2000	2016	4
Haaglanden Medisch centrum met Moeder-Kindcentrum	Wagenbouw BV	3 000 000 €	3000	2021	9
Innersdijk woonzorgcentrum Ter Boer	Wagenbouw BV	2 000 000 €	12000	2011	6
Thema Thorax Erasmus Medisch Centrum Rotterdam	Sprangers bouwbedrijf	6 300 000 €	4200	2014	9

A relative comparison of these modular projects to the conventional projects is not possible. However, it is noted that past modular healthcare projects are relatively small in scale, inexpensive and are built quickly.