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Economical feasibility of prefabricated solutions in healthcare design and construction industry.

P8 report

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MBE Graduation Laboratory: Business models for robots in construction

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Content

Foreword

For almost five years, healthcare design and construction sector is in my focus.
I started my experience in this field from design proposal of health-improving and rehabilitation center in Moscow which was my master thesis in Moscow Architectural Institute (MArchI) in 2012. After graduation I also worked as an architect in large architectural bureau which is specialized in design and construction of healthcare and resort facilities. Healthcare architectural typology is one of the most complicated ones because it deals with great number of technical and technological issues, which dictate the final spatial and design solutions in many ways. Moreover, technical regulations and demands in this type of buildings are one of the strictest ones based on the core functions and nature of the process. To find a rational balance between technology and architectural aesthetics in healthcare is a great challenge for architect.

In 2013 I started my MSc Architecture program in Politecnico di Milano in order to extend my architectural vision and to get European experience and understanding of the profession of architect. Because of the fact that I already had experience in the healthcare sector at that time, I chose the topic of healthcare as my graduation subject in Milan. There is a special department in Politecnico di Milano dedicated to design problems of healthcare facilities. The head of the department, professor Stefano Capolongo, was my supervisor of the graduation project which was dedicated to modular and prefabricated solutions in healthcare design. The main focus of my thesis was to design spatial solutions for general hospital where all functions and departments can be arranged into modular and prefab scheme by using the same span of the structural grid. Questions of modularity, transportability of the modules to the construction site, universality of the layout which allows to put different functions within the same module were the main ones in my research. In order to test my hypothesis and findings I designed renovation project for the real general hospital in one of the Russian provincial cities. The idea behind this step was to test possibility to extend existing healthcare facilities in a modular and prefabricated way which allows to minimize interruptions in the daily activities of the hospital while being under renovation, reduces time schedule for the renovation project in construction phase and increases the quality of the complete work based on in-factory production and assembly process.

The focus of my Milan project was mainly on spatial and technological aspects of modular healthcare design. Since I am particularly interested in medical design and construction sector, as I already mentioned, I decided to continue my research in this field while working on my graduation project in TU Delft on Management In the Built Environment Master program in order to understand the entire process of modular construction not only from architectural, but also from managerial, technological, logistic and financial points of view. The main question of this research is whether modular solutions in hospital construction more economically feasible than traditional on-site construction methods, considering the entire life cycle process of the hospital building? By answering this question, I will understand and evaluate financial, managerial and logistical aspects of hospital construction, which will give me the complete picture of effectiveness of modular construction in hospitals.

I would like to say thank you to my mentors, Peter de Jong and Ruben Vrijhoef, who supported me along this year and organized a number of interviews with the set of experts who helped me to get the picture of processes in modular construction. Special appreciation to all experts and specialists, who kindly agreed to meet and answer to my questions. All their interviews can be found in appendixes of this report. Special thank you to my family who supports me in my career and helps me to get the things I am working on.

Chapter 1.

SUMMARY OF THE RESEARCH.

1.1. Selection of the research topic.

The reason behind my application for MBE program of TU Delft was to understand the management aspects of building development. I have an experience in architecture, and based on it I understood that development and management skills and practices are highly important in modern construction process. I think that ideally, this program should be taken by practicing architect after 4 - 5 years of real practice. In my case, I only have two and a half years of architecture practice. In my case, it is only two and a half years, but even with this experience I can state that it is very useful.

My previous architectural background was partially related with healthcare facilities. I graduated from Moscow Architectural Institute in 2012 with the project of health-improving center. I also worked in big Russian design bureau specialized in hospital design and construction. My Politecnico di Milano master thesis was dedicated to modular general hospital design proposal, and research of most important trends in hospital flexibility, the main paradigm of modern hospital development.

Flexibility in architecture can be viewed as capacity of building to adapt to changing spatial, operational or usage demands whether in a short, medium or long term (Capolongo et al, 2012). Based on this definition, flexibility can be seen as an answer to uncertainty and inability to predict the future. The aim of flexible solutions is to deliver supply which can be adapted, modified or changed in order to meet future needs without demolition of entire structure. Since the life cycle of the standard building is between 70 and 100 years in average, providing flexible design solutions since the moment of creation is a way to extend the use period of the building in a way which meets changing demands (Cor agenaar et al, 2006).

Real estate development process in general, and development of hospital in particular, is a long-term process within changing of economical, technological, political, social and demand-supply ratio situation. Hospital design takes special place while talking about flexibility, since the fact that health care facilities are highly sensible in terms of changing demands because of rapid growth of medical technologies. Hospital has highly technology-oriented environment, which changes rapidly based on supply of new technologies and demand of different user groups of the hospital. Flexibility can be also described as an attempt to match current supply and future demand of the building based on the analysis of future trends, needs and supplies. Figure 1.1 represents 9-step framework of design an accommodation strategy for analysis, design and elaboration of the real estate development project based on comparison of current demands and future supplies.

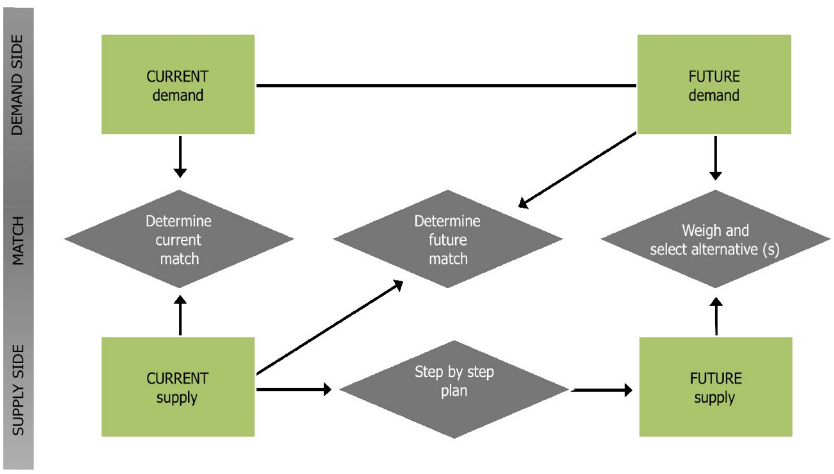


Figure 1.1. Analysis of demand and supply (Source: De Jonge, 2016)

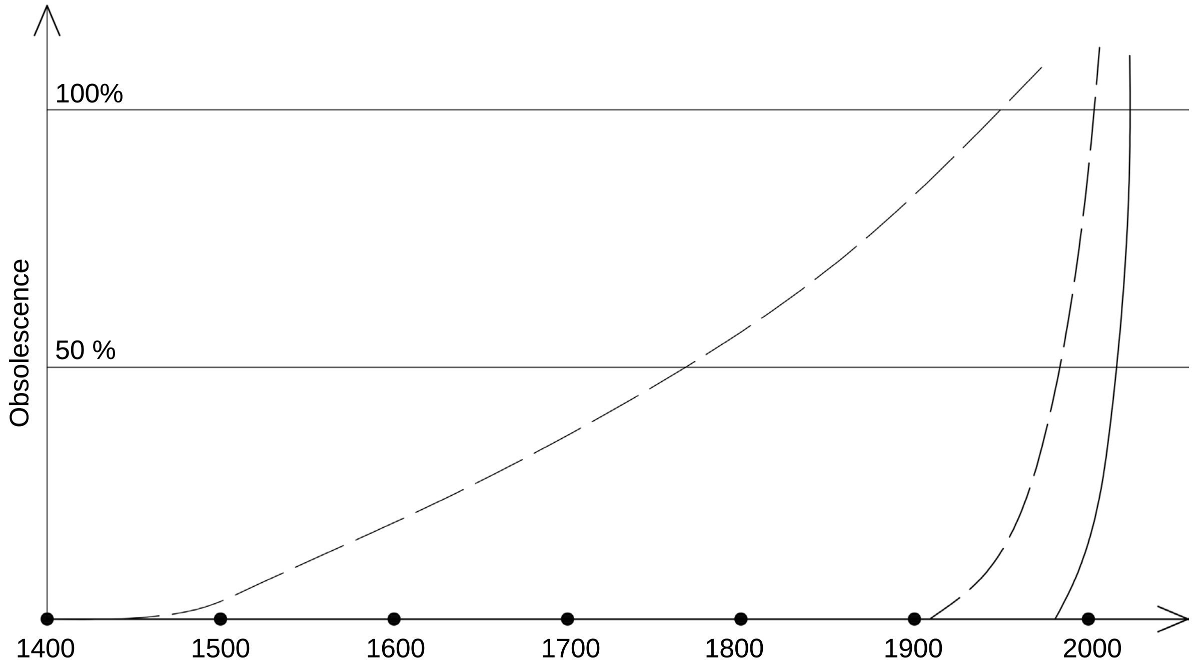


Figure 1.2. Periods of use of healthcare facilities (Source: Capolongo et al, 2012)

Based on rapid changes of health care technologies which need to be implemented in hospitals in order to improve the level of treatment and care, which is, after all, the most important indicator of its effectiveness, hospital can be considered as one of the building typologies with the highest demand for flexibility. Figure 1.2 illustrates the reduce of lifespan of use of health care facilities in retrospective from medieval times till nowadays.

Due to rapid development of medical technologies in the last decades the period of use of health care facilities reduced significantly, as it shown in figure 2. We can conclude that the current supply and future demand of modern healthcare facilities are in conflict with each other. Flexibility in this case is a tool to get and to consider future demand while design the hospital today. Next paragraph will discover different aspects of flexibility, their interact with each other and their contribution to overall flexibility of the hospital.

Flexibility of design. Flexibility of use

Another approach of describing flexibility can be explained as possibility for different users to organize and to reorganize their activities freely and according to their own timeframe, without encountering excessive constraints in the structuring of the space and in the installed plant (such as dimensions, distribution, performances, etc.) (Capolongo, 2012). In this light it is possible to add that flexibility allows different users to change and to organize their own layout within the building without disturbing the timeline and layout of other users.

Achieving high level of flexibility requires a lot of design effort on earlier stages of design process. The wide analysis of future needs of the building and demands of its users currently and in the future is needed in order to get flexible spatial layout. One of the main approaches to reach flexibility is standardization of dimensions of different spaces and prefabrication production of elements to construct these spaces. Possibility to change the spatial layout of the space based on predefined number of prefabricated elements is an effective way to reach high level of flexibility. The continuity to use flexibility from design phase to use and operational phase is highly important in this situation. Space designed with needs for flexibility in mind can be than easily adapted for other needs without costly refurbishment or demolition of the building. Basically, there are three transformation cycles exist.

- Daily / weekly usage transformation cycles

This cycle offers possibility to use the same place during the day or the week for different purposes. For example, consultancy room can be used for its primary function during the week and for office or meeting room during the weekend. This strategy can reduce the demand for office spaces and consultancy rooms in the hospital by careful management of working timetable and exchanging spaces and user flows.

- Medium usage transformation cycles

These cycles refer to seasonal or medium time changes in spatial layout based on natural insolation, amount of sun light and other seasonal or cyclical factors in the work of the hospital

- Long usage transformation cycles

This transformation cycle is similar to daily one, but the change of the function of the space takes long-term charcter. For example, practitioner room can be changed to office or surgery room for a long time without costly refurbishement of the space by using identical prefbrication elements which are common for the entire hospital building (Capolongo, 2012).

Types and levels of flexibility

Flexibility in general and flexibility of hospital in particular can be structured by levels and types of flexibility. There are 3 types of flexibility:

Constant surface flexibility

Variable surface flexibility

Operational flexibility

Constant surface flexibility includes the possibilities to change and to adapt the existing facilities (rooms, units or buildings) to the user needs within the boundaries of the building, which means that the initial floor area is constant. Variable surface flexibility, on the other hand, means that the initial floor area can be increased (or decreased) by adding additional parts to the existing building. These parts can be modular cantilevers which are hanging to the facade and increasing the floor area of the unit, or entire segment of the building which can be added to it in a modular or prefabricated way. The possibility of this type of flexibility should be designed in advance in order not to disturb the daily activities of entire hospital. The third type, operational flexibility, is meaning to adapt one or another unit (or indidual room, or entire building) according to user's needs and demands as well as flexibile operational and technical services and easy access to them. Figure 3 illustrates all three flexibility types.

In addition to three types there are four levels of flexibility in hospital design (Capolongo, 2012). The first level is individual room, which can be adaptable to the user's needs. The second one is functional unit, which can be combined from the set of individual rooms and be able to accomodate any hospital department. Third one is a building level, in which different hospital departments can be accomodated in one building; they can be changed based on current demand or even converted into another function, such as offices or housing. Finally, the fourth level is a hospital complex level, which is combined from identical buildings and accomodates the entire hospital. Due to rapid changes in healthcare technologies the function of total complex can be changed from hospital to housing or office functions in case of proper applicability of flexibility concepts on the previous levels.

The result of my Milan master thesis was an extension of general hospital in one of the Russian cities. The hospital was designed in a fully modular way. The head of the department, professor Stefa-no Capolongo, was my supervisor of the graduation project which was dedicated to modular and pre-fabricated solutions in healthcare design. The main focus of my thesis was to design spatial solutions for general hospital where all functions and departments can be arranged into modular and prefab scheme by using the same span of the structural grid. Questions of modularity, transportability of the modules to the construction site, universality of the layout which allows to put different functions within the same module were the main ones in my research. In order to test my hypothesis and findings I designed renovation project for the real general hospital in one of the Russian provincial cities. The idea behind this step was to test possibility to extend existing healthcare facilities in a modular and prefabricated way which allows to minimize interruptions in the daily activities of the hospital while being under renovation, reduces time schedule for the renovation project in construction phase and increases the quality of the complete work based on in-factory production and assembly process. Next page demonstrates the final design proposal of my master thesis in Politecnico di Milano.

The focus of my Milan project was mainly on spatial and technological aspects of modular healthcare design. Since I am particularly interested in medical design and construction sector, as I already mentioned, I decided to continue my research in this field while working on my graduation project in TU Delft on Management In the Built Environment Master program in order to understand the entire process of modular construction not only from architectural, but also from managerial, technological, logistic and financial points of view.

1.2. Research questions

Modularity is relatively popular trend within architectural community nowadays. Housing, hotels, hospitals, etc are designed in a modular way. The actual feasibility of such solutions, however, does not taken into account in majority of the cases. Usefulness of hospital modularity was explained in details above, but its feasibility is a good question for the research. That is why the research topic of financial feasibility of modular hospital construction was chosen for my graduation project in TU Delft. By doing such a research, I am going to round up the topic of modularity in hospital development not only from design point of view, which was done by me in Milan, but from financial and logistical one as well. The main research question of this project is

To which extent are prefab solutions in healthcare design and construction processes are more economically feasible than traditional methods?

In order to explain this statement, three sub-questions were formulated. They are

1) To what extent is prefab used in current situation in healthcare sector?

2) To what extent is enlarging the amount of prefab elements feasible considering the design and construction process?

3) Which parts of the healthcare facilities are mostly suitable for implementation prefab solutions in a cost-effective way?

1.3. Strategies to answer research questions

There are two main research strategies were chosen to answer these research questions. The first one is literature survey and deep literature analysis in order to understand the nature of modules' production process, its special characteristic features and all accompanied story. This gives an understanding of modular system limitations, nature of manufacturing process, probable financial and technical benefits and limitations of the modular construction. Second strategy is related to empirical part of the research, when all information gathered in the first phase are applied to financial feasibility analysis of one standard module with dimensions mostly used in modular construction. The set of parameters of the module will be analyzed in three main phases - design, construction and maintenance. These parameters include the main aspects of module life cycle in all three phases.

Each parameter will be compared to the similar one in conventional construction in order to check possible savings of modular or conventional construction method in particular aspect of construction process. The results of this comparison will be summarized and presented in final table where the possible benefits of modular construction will be presented. In order to verify the reliability of these results the external experts will be asked whether they are close to reality. The conclusions regarding feasibility of modular construction in hospitals will be explained in conclusion and reflection chapter.

1.4. Theoretical phase of the research. Literature review.

The literature survey phase was represented in all details in P2 report. This chapter will briefly summarize the results of literature survey and explain theoretical findings which became a basis for empirical part of the research.

Lean management and circular economy are main components of modular production.

The concept and philosophy of lean management is one of the most important ones in modular construction. Two main important points are placed here. First one is mass production philosophy which allows to produce factory-based manufactured product with all benefits accompanied by production flow and conveyor assembly technologies. These benefits are quality control along the entire building life cycle, independence from weather conditions, fixed and predictable production time, interchange of the components of the module between different design products, economy of scale principles. Second one is highly customizable layout of the produced modules which can be changed based on pre-designed layout and finishing schemes of the module. Together, these two concepts provide highly flexible, customized and at the same time mass product based on the scalable economy.

Second benefit which comes out from lean management concept is maintenance of the modular building during entire life cycle. Modular manufacturer provides a warranty for his final product and takes all maintenance costs along the warranty period. Since modular producer usually has all required certificates for his modular components, he can maintain the building on the scheduled basis with the special crew who knows all aspects of the particular object. Figure 1.3 represents warranty system provided by Secisui Heim Japanese modular producer.

Figure 1.3. Warranty system of Secisui Heim (source: wwwsecisuiheim.com)

Third outcome of lean management concept incorporated into modular production process is recycling of materials and components (source: Bock, T., Linner, T., Robotic Industrialization, 2015). Factory-based and oriented manufacturing process allows to re-use and re-cycle up to 95 % of materials and components used in modular construction. This fact comes from fixed and controlled production flow, detailed design phase of the project and knowing of all the elements required for the assembly of the module. Re-use and re-cycle of the majority of materials used in modular production allows to implement new types of modules in production without inventing any new details and parts since the same components can be used in new versions.

Moreover, recycled materials can be sold to external parties and make a profit for a modular company (Mark van den Ven interview, appendix x). Probably the most important factor related with lean management in modular construction is great reduction of the waste produced by construction industry. According to Arup, 40 % of global waste is produced by construction industry.(Arup, Circular economy in the built environment report, 2016).Modular construction almost eliminates this problem based on re-cycling process implemented in modular production. Factory-based construction environment controls and counts all materials which are in and out in production process. This makes modular production clean and really sustainable construction method. Figure 1.4 below shows this concept realized in Secisui Heim factories in Japan.

Figure 1.4. Sekisui Heim Reuse System House (source: http://www.sekisuichemical.com, 2016)

Fourth aspect of lean management related with reduction of waste and saving resources is extension of module's life-cycle by factory inspection and refurbishment process. Figure 1.4 above describes refurbishment process in Secisui Heim. After being used modules are sent back to the factory for detailed inspection and possible refurbishment which takes place based on pre-designed layouts with Interchangeable elements. Factory-based quality inspection makes further use reliable and safe-ly. By applying this practice modules can be in stock for 30 years and even more (Mark van de Ven interview, appendix 15). Refurbishment process done in this way, again, reduces the amount of waste and makes re-development and installations of the modules on site quick, clean and safely process.

Factory production chain in modular construction. Japan case study.

Japan modular housing industry was selected as a case study for the literature survey based on high level of development of this technology in the country. Conveyor-based manufacture process, TAKT time and production flow, Just-In-Time concept and many other modern principles of factory produced buildings were invented and used in Japan (Bock, T., Linner, T., Robotic Industrialization, 2015). The large number of Japanese modular factories were studied during literature survey. The character and nature of different production layouts were identified. The two main of them are static and linear ones. The first one is organized around the module, when different components are added to the frame by crew while module is in place. Second one is based on conveyor layout, when module is moved long the conveyor strip and different components are settled to it.

Static factory layout is mainly used in a small scale factories while linear one is usual for large scale factories. Figure 1.5 below shows typical linear organisation of modular factory.

Combination of mass industry and economy of scale with individual and customized product is gained by organization of factory layout. The same conveyor production line can make different products. Mark van den Ven states that each production automated line of De Meuuw can produce up to 3 different modules at the same time (Mark van de Ven interview, appendix 15).

Integration of modern technologies and installations into modular houses and other modular typologies is current trend in Japan modular manufacturing. Toyota Home, Sekisui Heim and other modular producers actively integrate electronic and wireless technologies in their modules in order to make it interactive. Hospital, in this way, is really good candidate for modular construction, based on high level of installations, systems and devices. Patient assistance technologies, remote control of in-patient ward environment, health-checking systems and others - all of them can be integrated into module while designed and produced. This aspect makes factory-based hospital units are extremely suitable.

An important success factor of Japan modular building industry is inclusiveness of great number of industries and suppliers into supply and production process. Figure 1.6 represents circle of companies and industries involved in modular production. Such large cooperation allows to make state of the art products and always attract innovations from different fields. Economy of scale is definitely grows from this cooperation and allows to interchange the elements and technologies between them.

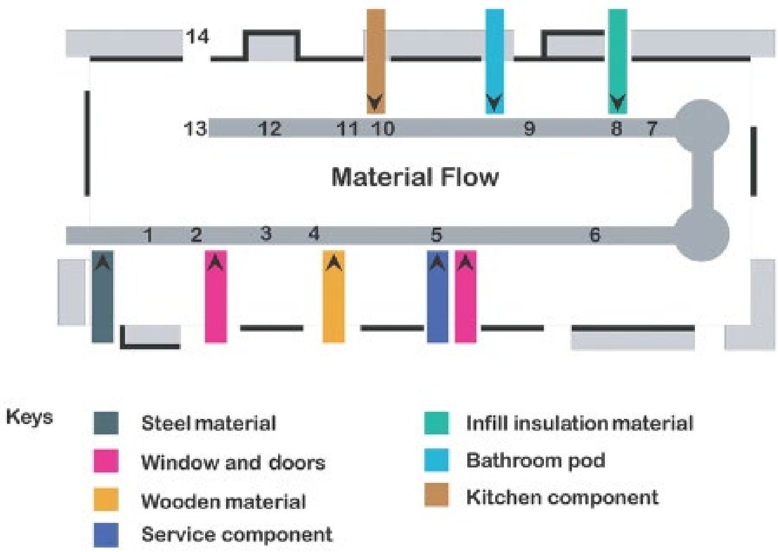


Figure 1.5. Linear (conveyor) organisation of modular factory (source: www.sekisuichemical.com, 2016)

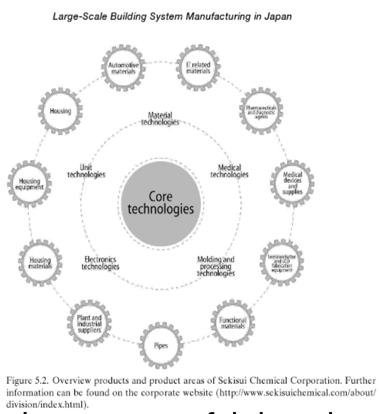


Figure 1.6. Cooperation between prefab housing industry and other industries in Japan (source: Bock, T., Linner, T., Robotic Industrialization, 2015)

1.5. Empirical part of the research.

An empirical part of this research tests all findings of literature survey in application to the standard module used in modular hospital construction. Set of parameters of the module in three phases of its life cycle - design, manufacturing and maintenance - are tested against similar processes done in conventional construction. Based on unavailability of the data some parts of the construction process are not covered by this analysis, while in others educated guess is applied. The data for this analysis is gathered partially from literature sources, partially from the interviews with experts. The results of this research will be represented in this chapter.

1.5.1. Design phase.

The analysis of design process in modular construction figured out 50% savings in cost and 15% savings in time comparing to conventional design process. Time savings are mostly come from using BIM software such as Autodesk Revit and Inventor in design process. It is important to mention that the pre-requisite in this result is that all modular components and layouts are pre-designed in advance. Mark van den Ven, De Meeuw manager, states that his firm can propose quite different layouts and finishings of the module, but all of them are based on set of standard components which are already pore-designed and modeled in Revit (Mark van den Ven interview, 2017, Appendix 15). That is why modular design is mostly about assembly of the modules in final building according to the brief, rather design everything from the ground. It might be possible that the client would be agree on even those modules which are already produced, and there would be no time for design at all. Mark van den Ven says that design phase can take only two-three days. The point here is that De Meeuw makes profit on re-use and recycle of the modules based on their common layout. In case of usual design the company can agree to take module back from the client after the end of use period, which is a significant benefit for him. If the design is unique, De Meeuw would not take it back.

Cost savings are based on minimum participation of external architect in the design process. Modular building companies still consult with an architects, but only for the number of questions, while they elaborate most of design and technological solutions by themselves. This results in 3-4% for design fee from entire construction budget instead of 6-8% in traditional design. Table 1.7 shows these figures.

Parameter	Modular construction	Conventional construction	Savings, %
Time savings	85 % from conventional design	100 %	15 %
Cost savings	3 - 4 % from entire construction budget	6 - 8 % from entire construction budget	50 %

Figure 1.7. Summary of savings in design phase (source: Author, 2017)

1.5.2. Construction phase.

The main difference in construction phase between modular and on-site construction is that in modular variant 85-90% of the process is done in factory, while traditional process goes entirely on construction site. Conventional builders can rise up to 80 m2 per day, while production time of one module with UFA of 30 m2 takes from 20 hours to 2-3 days, depends on the interior finishing. The excavation and foundation works, however, take the same time and cost. Table 1.8 below represents the results of construction part survey.

Parameter	Modular construction	Conventional construction
Cost of foundation works as % from total budget	4%	4%
Amount of m2 constructed per day	180 - 300 m2	Up to 80 m2

Figure 1.8. Summary of savings in construction phase (source: Author, 2017)

1.5.3. Use phase

Use phase deals with annual daily maintenance and refurbishment process. Modular construction gives 0,5% savings in the first one comparing to conventional one. This is mostly based on general contractor who is represented by modular manufacturer himself, as well as on quite controlled production process, which results in computerized maintenance phase with machine-like check-up system. Refurbishment process in modular building takes from 25 to 50% savings in cost, based on pre-designed flexible layout and well known set of components from which the module is built. Possibility to relocate the module to the new site is solely modular opportunity, which costs around 30% of the cost of the module. Table 1.9 below demonstrates these findings.

Parameter	Modular construction	Conventional construction
Annual maintenance costs	1,5 %	2 %
Refurbishment costs	25 - 50 % from conventional one	Highly depends on the case
Relocation costs	4.800 - 6.700 Euro per module	Non applicable

Figure 1.9. Summary of savings in use phase (source: Author, 2017)

1.5.4. Total savings in modular construction.

Table 1.10 below demonstrates summary of the savings indentified in modular construction in design, construction and use phases of building's life cycle.

1.6. Conclusion of the research. Answers to research questions.

1.6.1. To which extent are prefab solutions in healthcare design and construction are more economically feasible than traditional methods?

Time. Modular hospital can be built from the ground. It is a fact confirmed by several experts in this research (see appendixes). The main benefit of modular construction is time required to complete the building. Modular building can be assembled from 2 to 3 times faster comparing to traditional one (see chapter 5, construction phase). This results in fast start of hospital's use phase, which brings not only earlier revenues, but also allows to provide healthcare in limited time period which is quite important for hospital typology. The conclusion is that if time is the critical factor, modular construction is definitely feasible solution.

Phase	Parameter	Modular construction	Conventional construction	Savings, %
Design phase	Costs	50 % from conventional design (3 - 4% of total budget)	6 - 8 % from total budget	50 %
	Time	15 0 ;3 % faster comparing to conventional design *	Depend on the case	15 0 ;3%
Construction phase	Costs	52.900 Euro / module 1800 Euro / m2 *	2500 Euro / m2	28 %
	Time	180 - 300 m2 / day	Up to 80 m2 / day	80 %
Use phase	Costs	2 % / year from construction budget	2 % / year from construction budget	None
Refurbishment phase	Costs	25 - 50 % from conventional construction	Highly depends on the case	25 - 50 %
	Time	Highly depends on the case	Highly depends on the case	depends on the case

* - including VAT (21 %)

Figure 1.10. Summary of savings in modular construction (source: Author, 2017)

Cost. The cost of each construction project is unique based on its circumstances, goals, location and man y other factors. This research compares the main aspects of design, construction and maintenance process for an average module with UFA of 29 square meters and for one square meter in traditional hospital construction. Construction cost of 1 m2 of the module was calculated equal to 1.846 Euro, while construction cost in compared traditional hospital was equal to 2.533 Euro / m2. It results in 27 % of costs savings when modular method is used. It is important to mention, however, that usual marginal cost per square meter in Dutch state hospitals should be less or equal to 2.000 Euro/m2. Since hospital development is primarily governmental activity, this price per square meter can be taken as a constant. In this case, cost savings based on modular construction are equal to 8 - 9 %. Literature research presented in chapter 3 reports savings between 11 and 19 % comparing to conventional construction methods. It is possible to say, then, that these research findings, which gives cost savings in modular variant between 9 and 27 %, are realistic. A very important factor of hospital development cost is medical equipment and installations. Depends on the nature of the hopital, cost of equipment can vary really high. The module considered in this research is an individual in-patient ward. That is why equipment cost for this hospital typology is not the highest among hospital departments. Surgery room or MRI block will have a higher price/m2 based on higher equipment level.

Time, then, is the most important saving factor in modular construction. A lot of hospital extensions, therefore, are ideal situations for modular construction, when construction process should be done in a very limited period of time and without disruption of existing facility.

1.6.2. To what extent is prefab used in current situation in healthcare sector?

Modular construction in healthcare is currently used mainly in extensions of healthcare facilities. This is partially related with regulations which allow to use modular building as temporary structure for several years. Traditional hospital construction mainly uses prefabricated bathroom pods and facade panels. Some recent projects, such as Miami Valley hospital completed in 2012, use internal prefabricated walls with integrated headwall systems for in-patient wards. Another current modular component used in hospital development is MEP installations, pre-assembled in a factory and mounted above the ceiling and in other places on a construction site in a quick way. Modular construction, at the same time, uses fully prefabricated volumetric modules to complete the hospital. Several companies in Netherlands, Germany and Latvia are specialized in modular hospital construction. The choice of construction method, therefore, is depend on the client and particular project circumstances. Modular hospital construction is the most promising and growing sector, right after sub-urban housing, which is growing now. (Mark van de Ven interview, appendix 15).

1.6.3. To what extent is enlarging the amount of prefab elements feasible considering the design and construction process?

This research explored fully prefabricated 3d-dimentional modules as the maximum scenario in order to see the possible benefits of off-site construction. Pre-designed layout of hospital departments and, at the same time, possibility to customize them for particular client gives a wide range of prefabrication options. When time is the critical factor and the hospital (or, hospital extension) needs to be completed in a short period of time, fully prefabrication and 3d-dimentional construction is definitely an option, since construction schedule is reduced by 50 % in a modular way. It is important to stress the point that time savings do not result in lower quality, but, to the opposite, provide higher quality control and material savings based on lean management and careful production flow (see part 2.2). It is possible to say, then, that when short construction time schedule together with efficient and quality-controlled construction environment is a goal, fully modular construction is an option. Cost savings from 9 to 27 % comparing to traditional construction is another benefit. It is important to say, however, that even if modular variant is more expensive than conventional method, start of use phase of the hospital is still much earlier, and revenues from hospital activity start to accumulate earlier.

1.6.4. Which parts of the healthcare facilities are mostly suitable for implementation prefab solutions in a cost-effective way?

As it was stated in the report, fully operated hospital can be built from the ground in a modular way. That is why all hospital departments are suitable for modular construction. However, based on the set of interviews and literature review done in this research it is possible to state that those hospital departments which are highly equipped with electronic and special medical devices are the first candidates for modular construction. Surgery rooms, MRI units, intensive care wards - these departments are recomended to build in a modular way in order to test all systems in advance in a factory and then transport them to construction site (Mark van de Ven interview, appendix 15). The benefit of their construction in a modular way is a short time of completion. Based on the actual hospital demand these units can be assembled in the factory in a short way and installed in the hospital quite quickly without any disruption of current facility, which is very important for continuity of hospital operation flow. These modules are ordered as real manufactured products, with high level of quality control and warranty for all electronic systems they contain. This complex warranty is another benefit of such devices. Easier and integrated maintenance provided by modular manufacturer eliminates daily problems and reduces time for maintenance. The cost of maintenance, however, is not lower than in traditional construction (see part 3.1).

Chapter 2.

PROBLEM ANALYSIS AND RESEARCH QUESTIONS. VISUALISATION OF RESEARCH DESIGN AND FINAL PRODUCT.

2.1. Relevance of the research topic and graduation project.

Scientific relevance.

The topic of my graduation project, in a way, is quite practical. In a few words, I am willing to understand does modular solutions in hospital design and construction more economically feasible, or, simply speaking, cheaper, than traditional on-site construction process. Financial savings in modular construction in general, and in hospital development in particular, based on off-site methods, can make it more attractive for construction firms, contractors, developers, and, finally, for the end users. The huge increase of final quality of the completed building, based on inside production and assembly techniques, is another practical benefit of modular construction. Although previously mentioned aspects are quite practical, I believe my graduation project contains scientific relevance as well. One of the main components of modular and off-site construction methods is lean management, or, in other words, reduction of the resources along the life cycle of the building, from design to refurbishment (see part 2.2). Savings in materials, used in construction process, overheads, labour costs, while increasing the quality of the final product, is the crucial goal of modern construction industry
(source: Arup, Circular economy in the built environment report, 2016). In this regard, the famous moto of Miss van der Rohe, "Less is more", becomes realy important and practical by applying modular construction process to construction industry. Circular economy, as the global concept, with lean management as a part of it, is another scientific approach comes from my research (see part 2.1). The resources of our planet are limited, and with growing population of Earth, we need not only use its resources in the most effective and sustainable way, but rather re-use and recycle them in order to not throw away a lot of resources which might be used again. Modular construction, for sure, perfectly matches this global concept of circular economy and can bring added value to development of this philosophy, which becomes one of the main ones in XXI century (source: www.ellenmacarthurfoundation.org). It is important to mention that in this research circular economy is considered as strategy to extend lifecycle of the building by possibility to convert it to other function and to re-use parts of modular building in different locations. Another part of it, re-use and re-cycle of materials, is also important component of circular economy, but this is not in the light of this research.

Societal relevance.

Potential societal relevance of the research lies within the concept of circular economy mentioned in previous paragraph. Since circular economy, and lean management as part of it, has an aim to reduce the waste of resources during the production and life cycle process of the building, implementation and enlargement of modular construction technologies in construction industry might save energy, materials and labor resources, which can be used in other places. That is why this research is addressed to almost all target groups in our society.

Utilisation relevance.

This research aims to show economic benefits of modular construction. That is why, if these benefits will be clearly identified and presented, utilization, or, simply speaking, increase of the percentage of modular construction might take place in construction industry of particular region. Construction companies, developers as well as construction suppliers are direct agents of further implementation of modular construction in general, and in hospital development in particular. Since this research demonstrates organizational processes which take place in factories for modular construction, organizational models for such business can be extracted by entrepreneurs from this research. Overall, demonstration of potentials of modular construction and its benefits in different fields (lean management, circular economy, higher quality, shorter construction period, etc.) will be a trigger for practical implementation of these technologies in construction sector of particular region, with participation of different players.

2.2. Problem statement and research questions.

As it was already stated in foreword and relevance of the research parts, the main research question and problem statement is:

To which extent are prefab solutions in healthcare design and construction processes are more economically feasible than traditional methods?

In order to explain this statement, three sub-questions were formulated. They are

To what extent is prefab used in current situation in healthcare sector?

To what extent is enlarging the amount of prefab elements feasible considering the design and construction process?

Which parts of the healthcare facilities are mostly suitable for implementation prefab solutions in a cost-effective way?

2.3. Problem analysis.

Flexibility of hospitals as a driver for modular construction.

As it was stated in foreword, I am involved in the research and design of healthcare facilities and, particularly, hospitals, for 5 years already. One of the most important, novel and actual questions of modern hospital design is flexibility (source: Capolongo et al, 2012). Hospitals are quite technologically-sensitive objects, and, consequently, the demand for new installations, new spaces and new facilities as well as changing and reorganization of the current ones is quite high. Figure 1.1 demonstrates the speed of obsolescence of hospitals from medieval time till nowadays (source: Capolongo et al, 2012). Modern medical technologies are developed very fast and require new spatial layout from healthcare facilities. Flexibility definition can be explained as:

Capacity of building to adapt to changing spatial, operational or usage demands whether in a short, medium or long term (Capolongo et al, 2012).

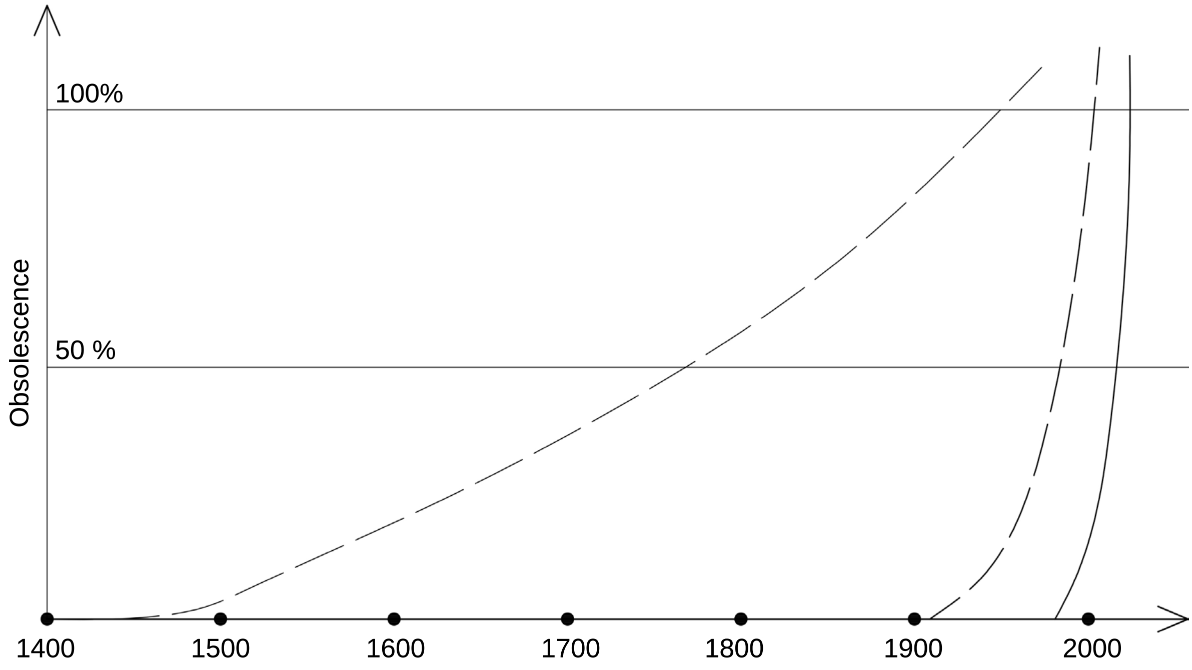


Figure 2.1. Periods of use of healthcare facilities (Source: Capolongo et al, 2012)

Flexibility, then, is a reaction to the problem of quick obsolescence of hospital buildings, and the strategy to overcome it in effective and long-term way.

The concept of flexibility has several types and levels. There are 3 types of hospital flexibility:

- Constant surface flexibility
- Variable surface flexibility
- Operational flexibility

Constant surface flexibility includes the possibilities to change and to adapt the existing facilities (rooms, units or buildings) to the user needs within the boundaries of the building, which means that the initial floor area is constant.
Variable surface flexibility, on the other hand, means that the initial floor area can be increased (or decreased) by adding additional parts to the existing building. These parts can be modular cantilevers which are hanging to the facade and increasing the floor area of the unit, or entire segment of the building which can be added to it in a modular or prefabricated way. The possibility of this type of flexibility should be designed in advance in order not to disturb the daily activities of entire hospital.
Operational flexibility, the third type, is meaning to adapt one or another unit (or indidual room, or entire building) according to user's needs and demands as well as flexibile operational and technical services and easy access to them. Figure 2.2 illustrates all three flexibility types.

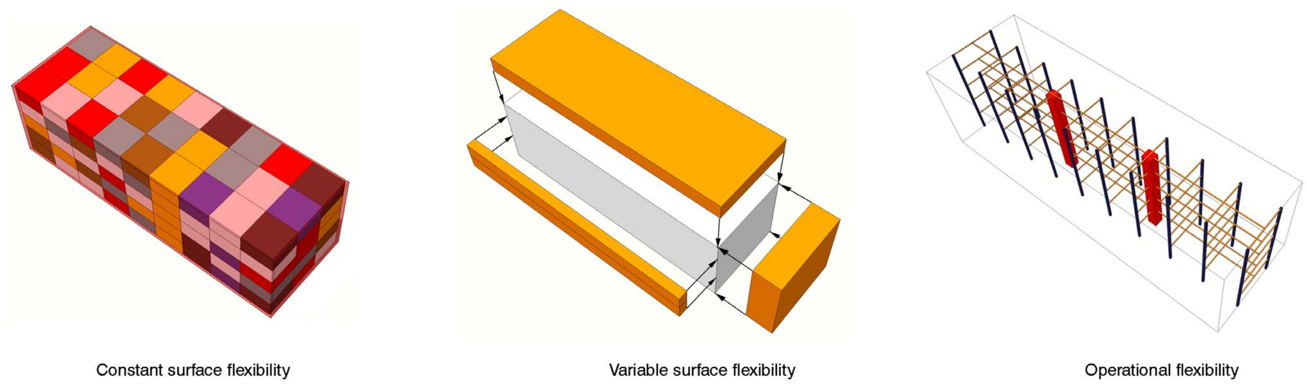


Figure 2.2 types of flexibility (Source: Author, 2016)

In addition to three types there are **four levels of flexibility** in hospital design (Capolongo et al, 2012). The **first level** is individual room, which can be adaptable to the user's needs. The **second one** is functional unit, which can be combined from the set of individual rooms and be able to accomodate any hospital department. **Third one** is a building level, in which different hospital departments can be accomodated in one building; they can be changed based on current demand or even converted into another function, such as offices or housing. Finally, the **fourth level** is a hospital complex level, which is combined from identical buildings and accomodates the entire hospital. Due to rapid changes in healthcare technologies the function of total complex can be changed from hospital to housing or office functions in case of proper applicability of flexibility concepts on the previous levels. Figure 2.3 represents four levels of hospital flexibility.

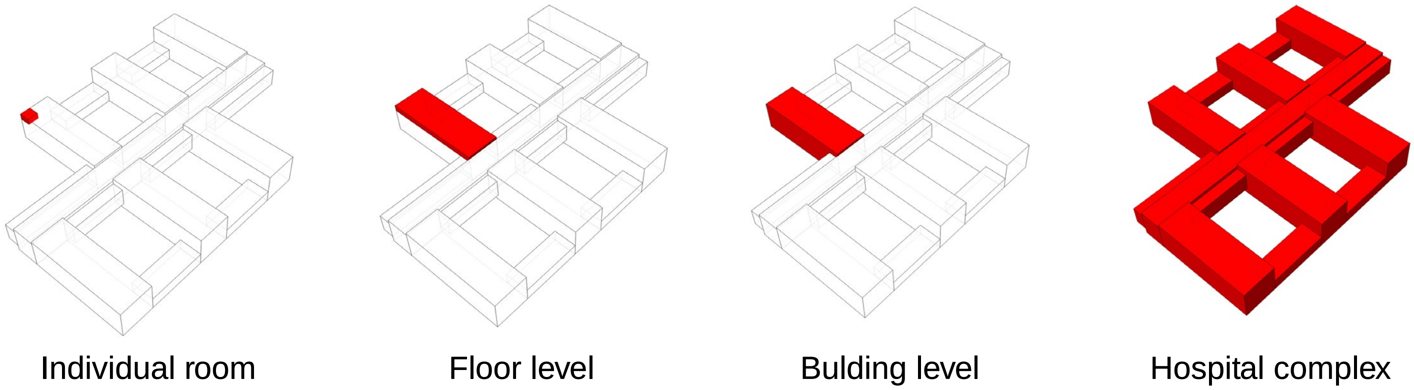


Figure 2.3 levels of flexibility (Source: Author, 2016)

Types and levels, demonstrated in previous paragraph, have a direct link with primary, secondary and tertiary systems of the building in general, and hospital building in particular (see figure 2.4). Stephen Kendall, one of the key researchers and promoters of this vision of the built environment, invented this diagram in order to show the organization of the main systems of hospital building and the limits (or, maximum life spans) for each of them.

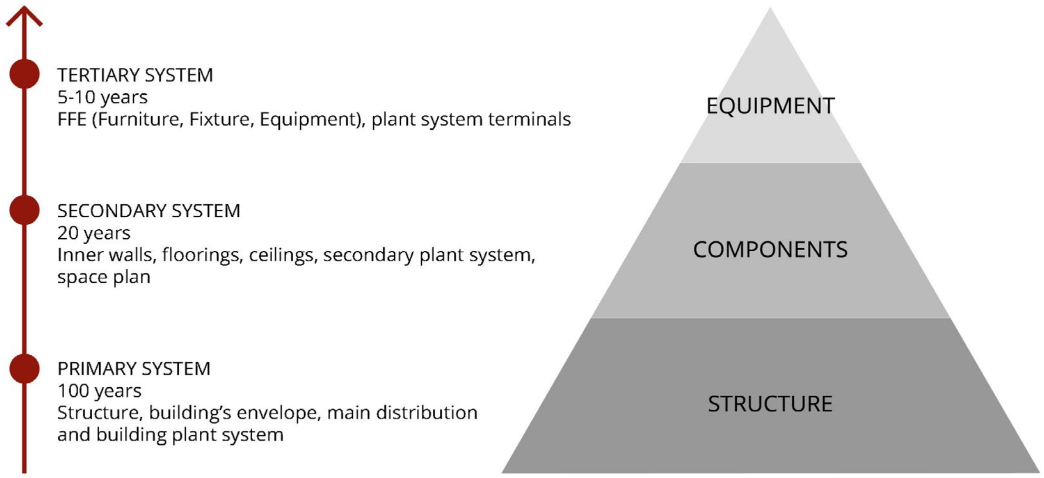


Figure 2.4. Three systems of hospital flexibility (source: Kendall, S., 2005)

Primary structure is the main skeleton and structural frame of the hospital with lifespan of 50 - 60 years (source: Cor Wagenaar, 2006). Primary structure of the hospital mainly consists of structural skeleton with the usual span of 7.2 to 7.2 meters. There is an ongoing debate regarding the effectiveness of increasing the span of primary structure. The promoters of wider spans argue that this increases the flexibility within the floor and allows to adapt the building to the future needs more easily. The opponents of wide spans say that despite the fact that wider spans can facilitate the planning of one or another department within the floor, it brings much more technical and structural difficulties in reality.

Structures with wider spans are more difficult for technical installations because any whole decreases the stability of the structure. Since the fact that hospital contains a lot of vertical communications and installations, which demand a lot of technical wholes and shafts, the increasing of the span in structural grid makes the installation of these communications difficult. That is why for the reasons of structural stability as well as for easier technical installations, the optimal span of structural grid in hospital usually equal to 7.2 x 7.2 meters. On the other hand, in recent years the structural grid of modern hospitals is slightly increasing 7.2 m span based on higher complexity of technical installations. In any case, the choice of one or another span for hospital structural grid is based on individual characteristic features of the project.

Secondary structure mainly includes installations and technical systems of the hospital, such as steam, ventilation, cooling, water, electrical lines, heating systems, ICT communications, etc. The lifespan of secondary structure is 15-20 years. Measures for increasing flexibility of secondary structure include:

- Larger story heights in order to increase the amount of technical communications above the ceiling or under the floor

- All installations are located above the main corridors in order not to disturb different departments while maintenance process and to simplify it.

- No bypassing of room units to reach other departments

Tertiary structure mainly includes finishings of interiors, lighting, furniture and other equipment. The use of prefabricated and standardized elements for finishing interior design can significantly increase flexibility and process of maintenance. Movable walls with fast fixing systems can significantly increase constant flexibility of the hospital by subdivision or unification of the space depends on current needs. Grouping of hospital departments by classes, such as ward cluster, emergency department, surgery block, etc gives possibility to change equipment and installations in particular department locally without disturbing other departments. The spatial needs of one or another cluster can be considered in advance and different supply can be provided in the design phase based on its special needs. Tertiary structure also includes micro-extensions, when territory of existing hospital can be adapted or modified within its current boundaries.
Figure 1.5 summarizes all aspects of hospital flexibility by subdividing them into 4 levels, from entire hospital complex to individual room.

Modular construction as possible answer to demand for flexibility in hospitals.

As it was shown in previous part, hospital building has clear functional division of its components, such as primary, secondary and tertiary structure. Together with types and levels of hospital flexibility, also described above, hospital building is considered as highly technological object with high demand level for flexibility. Modular construction technologies, in this sense, can be one of the key strategies to deliver flexible solutions in hospitals, especially when it deals with relatively small extensions, such as add of one or two floors, or when temporary structure is needed, while permanent new hospital building will be completed next to it (source: Capolongo et al, 2012). That is why my Milan master thesis is done in a modular way and demonstrates design strategies for hospital flexibility applied to renovation of existing general hospital. This research deals with different types and levels of flexibility and combine maximum scenarios and strategies for flexible extension of the hospital complex (Moiseenko, I., 2016). Since ti was an architectural project, this work deals with spatial aspects of flexible hospital design and not with production, logistic and feasibility aspects of modular construction. McGraw&Hill annual report dedicated to prefabrication and modularization mentions healthcare construction sector as the leading one in applying of modular and prefab solutions (source: McGraw&Hill, 2011). Figure 1.6 represents the current use of modular solutions in different typologies, and the highest level of their implementation is in healthcare sector.

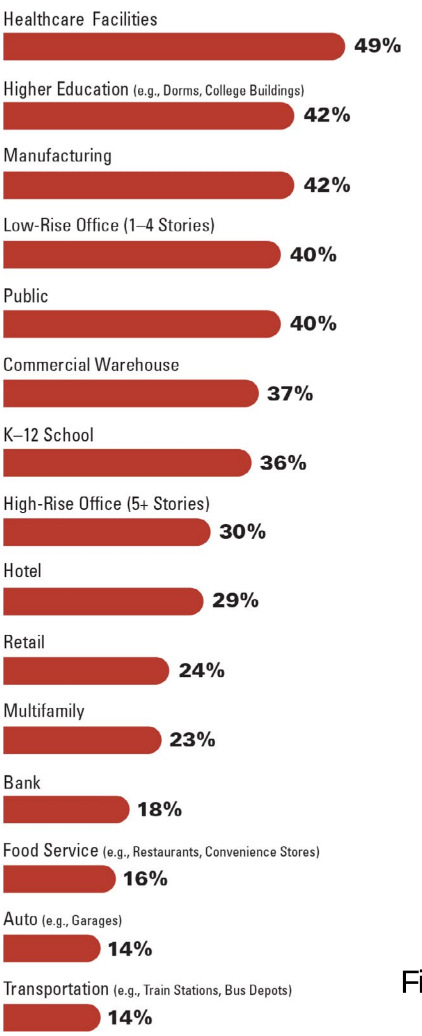
Levels of flexibility	Types of flexibility	Typological-spatial strategies
Hospital complex	Constant surface flexibility	Flexibility of access systems
		Functional flexibility of the system
		Reuse of hospital complex
		Redundancy of space for plant
	Variable surface flexibility	Existence of unused building land
		Strategies for increasing volume of buildings
	Operational flexibility	Modular, replaceable and maintainable plant
		Presence of networked informational systems
		Use of automation and control systems
		Use of flexible contractual/financial arangements
		Outsourcing of support facilities

Levels of flexibility	Types of flexibility	Typological-spatial strategies
Building	Constant surface flexibility	Existence of shell space for expansion
		Structural flexibility
		Oversizing of load-bearing structure
		Modifiability of the envelope
		Presence of spaces for building plant infrastr.
	Variable surface flexibility	Oversizing of load-bearing structure
		Possibility of modular expansion
		Tiered building
	Operational flexibility	Modular, replaceable, maintainable plant
		Efficient programmed maintenance
		Life cycle cost

Levels of flexibility	Types of flexibility	Typological-spatial strategies
Functional unit	Constant surface flexibility	Use of internal dry partition walls
		Use of moveable internal walls
		Use of moveable internal partitions
		Presence of spaces for service building infrast.
	Variable surface flexibility	Possibility of extending entire unit upwards/sideways
		Presence of verandas / setbacks
	Operational flexibility	Plant with flexibility of use

Levels of flexibility	Types of flexibility	Typological-spatial strategies
Individual room	Constant surface flexibility	Functional flexibility of the room
	Variable surface flexibility	Possibility of extensions upward / sideways
	Flexibility of use	Providing multifunctional rooms
		Plant for multifunctionality
		Information systems services for multifunc-ty
	Adaptivity of the user	Use of moveable furniture and vertical screening
		Customisable humanisation of the room

Figure 2.5. Flexibility matrix of healthcare facility (source: Capolongo et al, 2012)



Modular construction technologies is a growing construction sector in modern built environment (source: McGraw&Hill,2011). A lot of reports, books, articles and specialists clearly states that modular construction technologies are grow today in many building typologies. Highly technologically driven nature of the hospitals, together with their great demand for flexibility, or, simply speaking, for change of the layout during operational phase, as well as a lot of technical installations, whcih need to be maintained and changed properly - all these factors make hospital one of the most modular-oriented building typology.

Since the use of modular construction technologies in hospital development is a growing tendency, the question of its economic feasibility rises. Are modular solutions in hospital development really feasible? Which types of prefabrication and modularization in hospital development are mostly suitable from economical point of view? What are the other benefits and costs of modular hospital construction beside financial part? How it affects different phases of building life cycle (e.g., use and refurbishment phases)? All these questions were triggers to formulate my research questions described in the next part.

Figure 2.6. Building sectors using modularization (source: McGraw&Hill,2011

2.3. Final (intended) product of the research.

The goal of this research is to figure out economic benefits of the modular construction in hospital development and possible savings during entire life cycle of the building based on it. That is why financial assessment of modular hospital construction system will be delivered. Since feasibility study is a broad topic, this research will be focused on the cost drivers of hospital modular construction. Which drivers increase financial effectiveness of modular construction and which reduce it, how different factors of modular construction process affect design phase and related phases of life cycle of modular hospital building when needed, what is the economical nature of modular building - these questions will be answered and translated into calculation and financial model, which will show the most important costs and benefits of modular construction process of the hospital in design phase.

The final (intended) product of the research is to figure out the possible savings in cost and time in modular construction comparing to traditional construction.

	Operations Research		Empirical research	
Type	Operation-related	X	Knowledge-related	X
Aim	Creating an artefact Changing situations	X	Producing knowledge Changing situations	X
Relevance	Operational	X	Theoretical	X
Subject	Future	X	Past	X
Goal	Improvement	X	Understanding	X
Methodology	Prescriptive	X	Descriptive	X
Science	Formal sciences	X	Empirical sciences	X

Figure 2.7. Factors of hybrid nature of my research (source: Author, 2016)

2.4. Research design. Representation of the steps of the research.

Rsearch design, according to Bryman (2012) is a framework for collection and analysis of data. This research will consist of two parts. The first part is deep and extensive literature study of current modular construction process in all of its aspects, in order to understand its nature. The second part of the research is empirical one, when all findings, facts, numbers, processes and data will be used in order to design calculation and financial assessment model of the cost drivers in modular hospital construction. Figure 2.10 demonstrates detailed steps and phasing of the entire research.

Since modular construction process has the most complicated issues in design phase, when all benefits of the later phases need to be implemented and pre-planed, the main focus of my research is on design phase of the building life cycle. At the same time, as it was already stated above, other phases of modular building life cycle will be touched and studied during literature review phase as needed, in order to understand possible effects and savings during different phases of modular life span. It might be that higher costs in production phase will be compensated or mitigated by longer lifespan of the building, or, for instance, by possibility to reassemble modules several times in different locations, and, by doing this, to increase their payback, as it will be demonstrated in chapter 2. Figure 2.8 shows simplified conceptual model of the research.

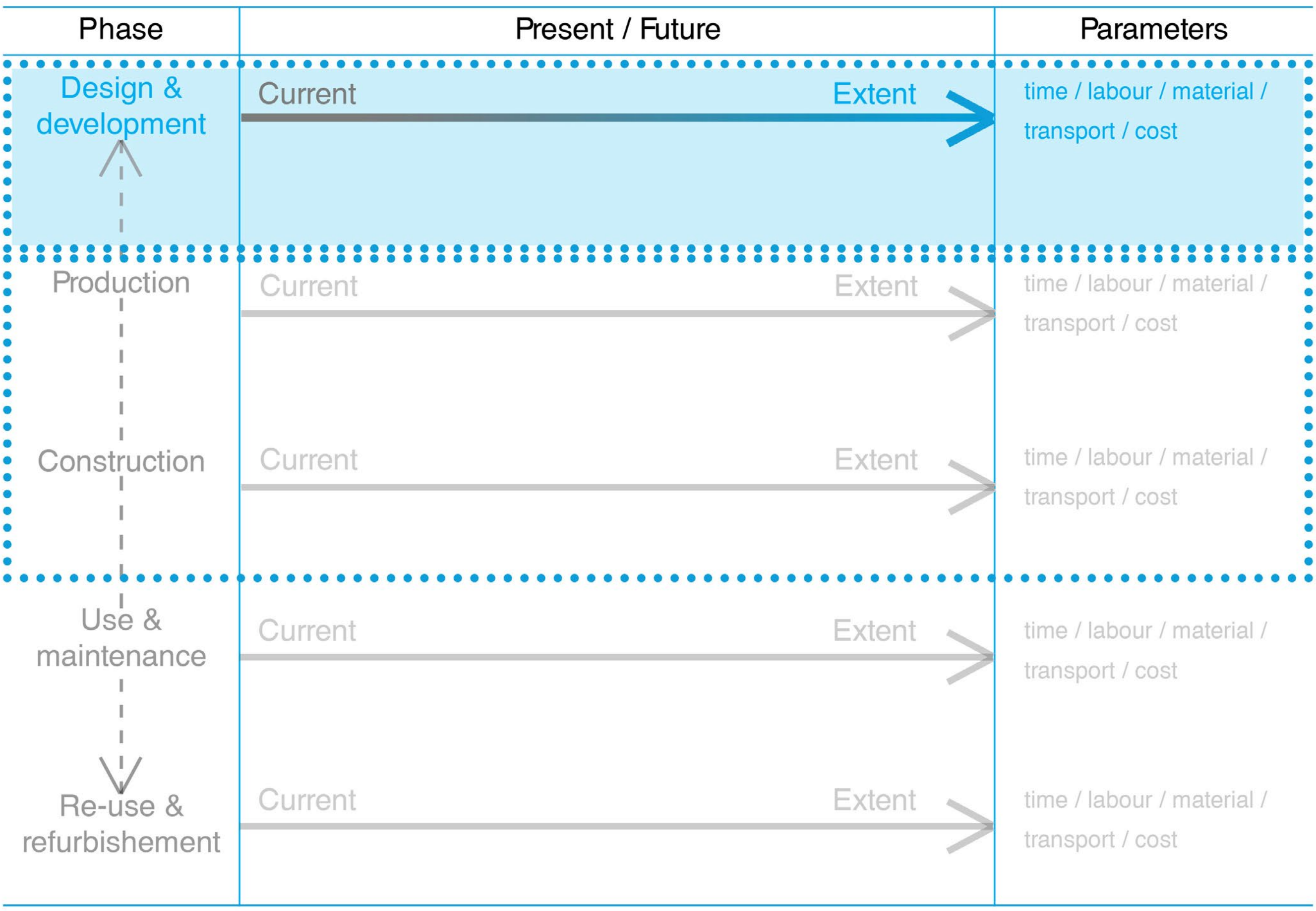


Figure 2.8. Conceptual model of the research (source: Author, 2016).

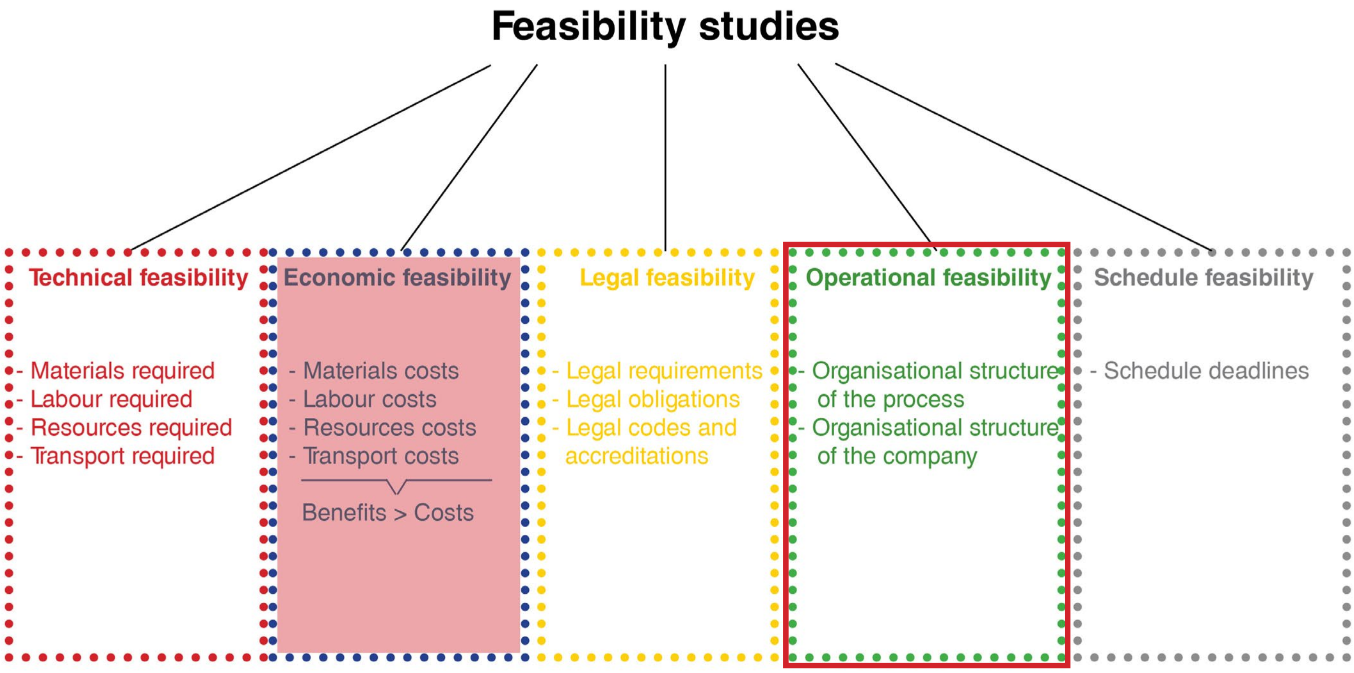


Figure 2.9. Types of feasibility studies (source: Velamati, S., 2012, adopted by author, 2016).

Feasibility analysis is a broad topic which includes different topics and covers different fields. Feasibility analysis is sensitive and highly depends on research field and particular topic. At the same time, there are general deffinitions of feasibility studies, which is going to be explained in this section. Cambridge dictionary defines economic feasibility as:

The degree to which the economic advantages of something to be made, done, or achieved are greater than the economic costs (Cambridge dictionary, 2017).

In other words, feasibility analysis is weighting of costs and benefits of particular project before its execution in order to evaluate possible future effects. Kerzner (2006) explains feasibility study as

Considering technical aspects of conceptual alternatives and providing a firmer basis on which to decide whether to undertake the project.

Five fields of feasibility presented in figure 2.9 will be explained in this paragraph.

Technical feasibility. Technical feasibility deals with resources required to execute the project under one or another scenario. The main resources in construction industry are building materials, resources such as electricity, water, labor resources, and others. This is what required in terms of supply to execute the project according to one or another scenario.

Economic feasibility. Economic feasibility concept was explained in previous paragraph. It is the degree to which the economic advantages of something to be made, done, or achieved are greater than the economic costs (Cambridge dictionary, 2017). Costs and benefits of all resources required for the project (and identified in technical feasibility section) are evaluated here. The outcome of this part of feasibility study, then, is to understand economic benefits of the potential project.

Legal feasibility. Legal feasibility investigates all formal and legal aspects of the potential project. Whether the execution of the project and all related things are in line with local codes, laws and regulations, this is the matter of legal feasibility study. The law consequences of different scenarios for the projects and their evaluation is also task of legal feasibility study.

Operational feasibility. Operational feasibility mainly evaluates structure of company organization and suitability of this structure for execution of particular project. Horizontal or vertical structure of the company, flow of information and human resources, implementation of different technologies important for particular project - all these things are investigated by operational feasibility study. In other words, the suitability of particular company for execution of particular project is a matter for operational study research. In modular construction the organization process of modular factory is crucial thing. Factory layout affects its capacity, number of workers, automatization level and related investments and other parameters (see chapter 5 for more details). Earlier involvement of stakeholders in design phase is another very important aspect of modular construction (see chapter 4 for details). That is why operational feasibility study needs to identify the most suitable company which can execute the particular project, and / or investigate potential ways to change the structure and organization of particular company to adapt it for making a project.

Schedule feasibility. Schedule feasibility deals with time schedule and time resources required and available for particular project. Does the company have enough time to do this project? Does the time evaluated for this project is really sufficient to do it properly? These questions are investigated under schedule feasibility part. It is important to distinguish and to understand the difference between operational and schedule feasibility. While operational feasibility investigates whole management structure of the company and adapts it for particular project, schedule feasibility evaluates just time aspects of the project. If time required for project execution does not correlated with company's schedule, this is a matter of schedule feasibility analysis. Both operational and schedule feasibility need to be assessed together, since structure of the company affects its time resources and vice versa.

One way or another.

It is important to mention that initial strategy of this research was to choose one real case study of modular hospital project and to analyze its financial and economic costs and benefits, or, simply speaking, to make a financial assessment of this project. During the preparation of P1 and P2 reports and collection of data it became clear that to gather financial information from real cases is quite difficult, since no one firm is willing to reveal the actual financial data of their construction projects. Part 2.5 represents questionnaires and interviews conducted to different stakeholders involved in construction process and in hospital development in particular (architects, manufacturers, theoreticians) but none of them agreed to reveal any real case study for deep and sufficient research.

For these reasons the strategy of the research was changed. The final strategy consists of two main phases. First phase is to deeply analyze current processes, costs and benefits of modular construction not only in hospital sector, but also in others (based on availability of data). Second phase is to apply all findings from literature review in order to design financial and assessment model of the cost drivers of modular hospital construction in three main phases - design, construction and maintenance. Since my Milan case was designed in a modular way, the standard module from this project will be deeply analyzed in order to test its financial feasibility comparing to conventional construction. Because of Milan design project was done with the notion of production and construction processes in modular construction, it is relevant to test my financial model by taking part of Milan design. At the same time, possible changes (or, recommendations) in design can take place based on financial and economic reasons and findings. Cases and information from interviews with different stakeholders will be used as well during development of cost drivers' financial model. Overall, an indicative model, which demonstrates economical side-effects of different level of prefabrication in modular design will be delivered. This model will include different indicators which affect the feasibility of modular solutions on different levels of prefabrication. Different components of modular hospital system will be considered.

Timeline of the project development. From P1 to P5.

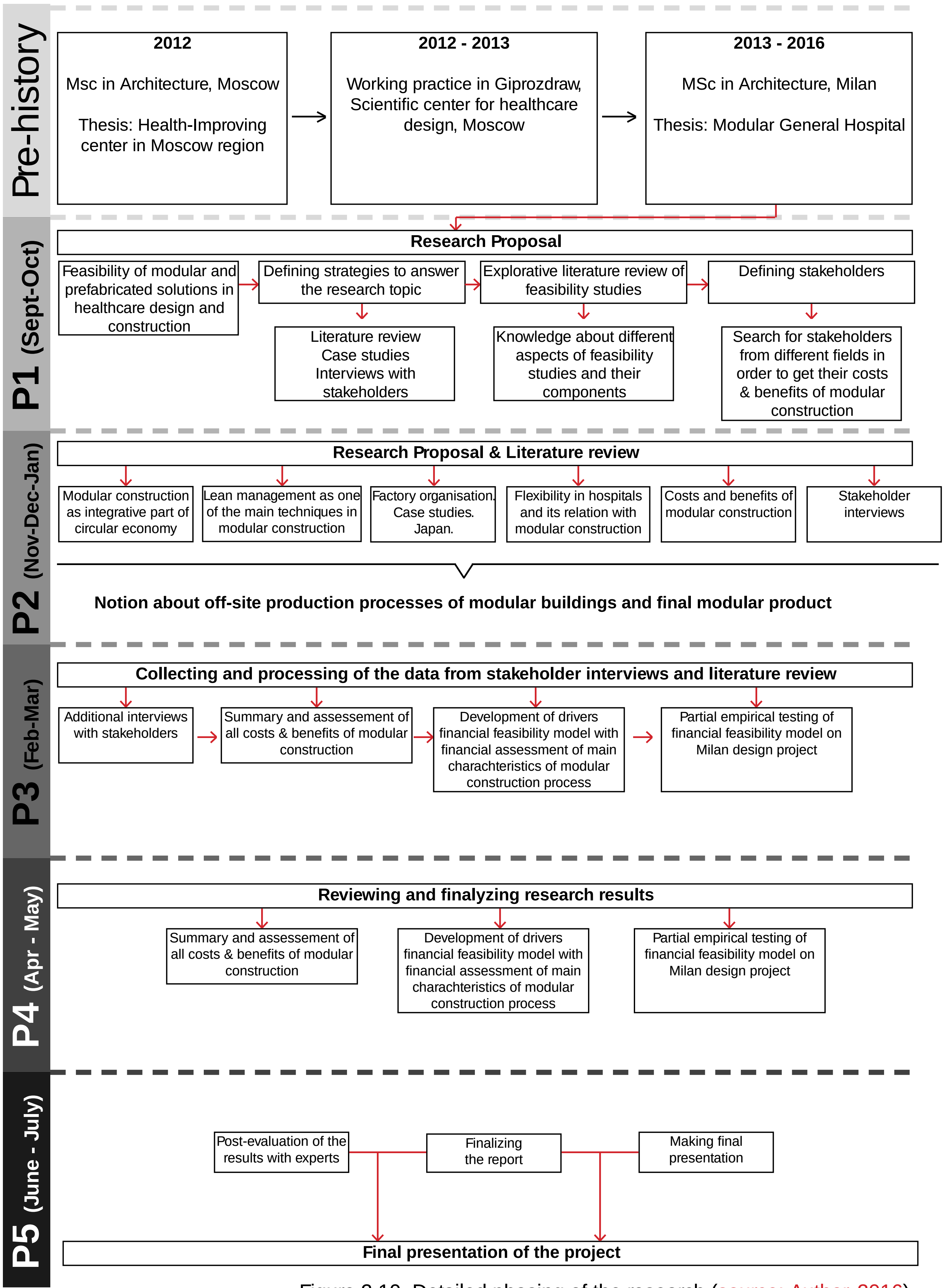


Figure 2.10. Detailed phasing of the research (source: Author, 2016)

Chapter 3.

RESULTS OF LITERATURE SURVEY.

The literature survey phase was represented in all details in P2 report. This chapter will briefly summarize the results of literature survey and explain theoretical findings which became a basis for empirical part of the research.

3.1. Lean management and circular economy are main components of modular production.

The concept and philosophy of lean management is one of the most important ones in modular construction. Two main important points are placed here. First one is mass production philosophy which allows to produce factory-based manufactured product with all benefits accompanied by production flow and conveyor assembly technologies. These benefits are quality control along the entire building life cycle, independence from weather conditions, fixed and predictable production time, interchange of the components of the module between different design products, economy of scale principles. Second one is highly customizable layout of the produced modules which can be changed based on pre-designed layout and finishing schemes of the module. Together, these two concepts provide highly flexible, customized and at the same time mass product based on the scalable economy.

Second benefit which comes out from lean management concept is maintenance of the modular building during entire life cycle. Modular manufacturer provides a warranty for his final product and takes all maintenance costs along the warranty period. Since modular producer usually has all required certificates for his modular components, he can maintain the building on the scheduled basis with the special crew who knows all aspects of the particular object. Figure 3.1 represents warranty system provided by Secisui Heim Japanese modular producer.

Figure3.1. Warranty system of Secisui Heim (source: wwwsecisuiheim.com)

Third outcome of lean management concept incorporated into modular production process is recycling of materials and components (source: Bock, T., Linner, T., Robotic Industrialization, 2015). Factory-based and oriented manufacturing process allows to re-use and re-cycle up to 95 % of materials and components used in modular construction. This fact comes from fixed and controlled production flow, detailed design phase of the project and knowing of all the elements required for the assembly of the module. Re-use and re-cycle of the majority of materials used in modular production allows to implement new types of modules in production without inventing any new details and parts since the same components can be used in new versions. Moreover, recycled materials can be sold to external parties and make a profit for a modular company (Mark van de Ven interview, appendix 15). Probably the most important factor related with lean management in modular construction is great reduction of the waste produced by construction industry. According to Arup, 40 % of global waste is produced by construction industry.(Arup, Circular economy in the built environment report, 2016).Modular construction almost eliminates this problem based on re-cycling process implemented in modular production. Factory-based construction environment controls and counts all materials which are in and out in production process. This makes modular production clean and really sustainable construction method. Figure 3.2 below shows this concept realized in Secisui Heim factories in Japan.

Figure 3.2. Sekisui Heim Reuse System House (source: http://www.sekisuichemical.com, 2016)

Fourth aspect of lean management related with reduction of waste and saving resources is extension of module’s life-cycle by factory inspection and refurbishment process. Figure 3.2 above describes refurbishment process in Secisui Heim. After being used modules are sent back to the factory for detailed inspection and possible refurbishment which takes place based on pre-designed layouts with Interchangeable elements. Factory-based quality inspection makes further use reliable and safely. By applying this practice modules can be in stock for 30 years and even more (Mark van de Ven interview, appendix 15). Refurbishment process done in this way, again, reduces the amount of waste and makes re-development and installations of the modules on site quick, clean and safely process.

3.2. Factory production chain in modular construction. Japan case study.

Japan modular housing industry was selected as a case study for the literature survey based on high level of development of this technology in the country. Conveyor-based manufacture process, TAKT time and production flow, Just-In-Time concept and many other modern principles of factory produced buildings were invented and used in Japan (Bock, T., Linner, T., Robotic Industrialization, 2015). The large number of Japanese modular factories were studied during literature survey. The character and nature of different production layouts were identified. The two main of them are static and linear ones. The first one is organized around the module, when different components are added to the frame by crew while module is in place. Second one is based on conveyor layout, when module is moved long the conveyor strip and different components are settled to it. Static factory layout is mainly used in a small scale factories while linear one is usual for large scale factories. Figure 3.3 below shows typical linear organization of modular factory.

Combination of mass industry and economy of scale with individual and customized product

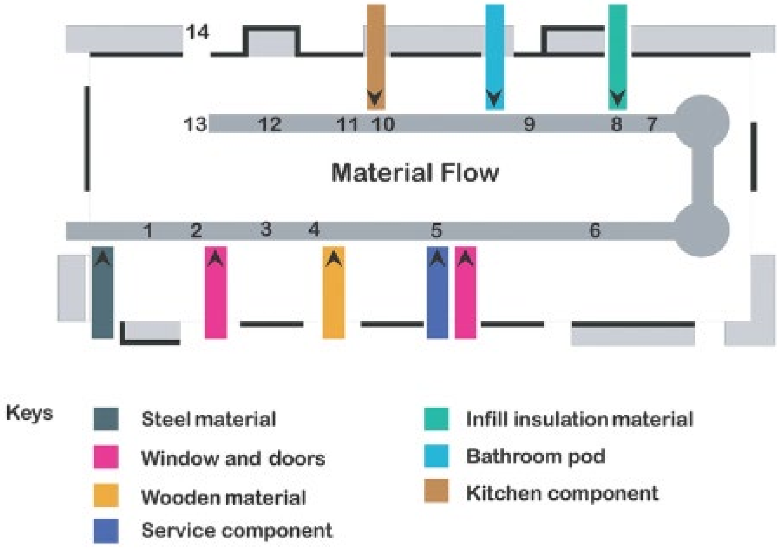


Figure 3.3. Linear (conveyor) organisation of modular factory (source: http://www.sekisuichemical.

is gained by organization of factory layout. The same conveyor production line can make different products. Mark van den Ven states that each production automated line of De Meeuw can produce up to 3 different modules at the same time (Mark van de Ven interview, appendix 15).

Integration of modern technologies and installations into modular houses and other modular typologies is current trend in Japan modular manufacturing. Toyota Home, Sekisui Heim and other modular producers actively integrate electronic and wireless technologies in their modules in order to make it interactive. Hospital, in this way, is really good candidate for modular construction, based on high level of installations, systems and devices. Patient assistance technologies, remote control of in-patient ward environment, health-checking systems and others - all of them can be integrated into module while designed and produced. This aspect makes factory-based hospital units are extremely suitable.

An important success factor of Japan modular building industry is inclusiveness of great number of industries and suppliers into supply and production process. Figure 3.4 represents circle of companies and industries involved in modular production. Such large cooperation allows to make state of the art products and always attract innovations from different fields. Economy of scale is definitely grows from this cooperation and allows to interchange the elements and technologies between them.

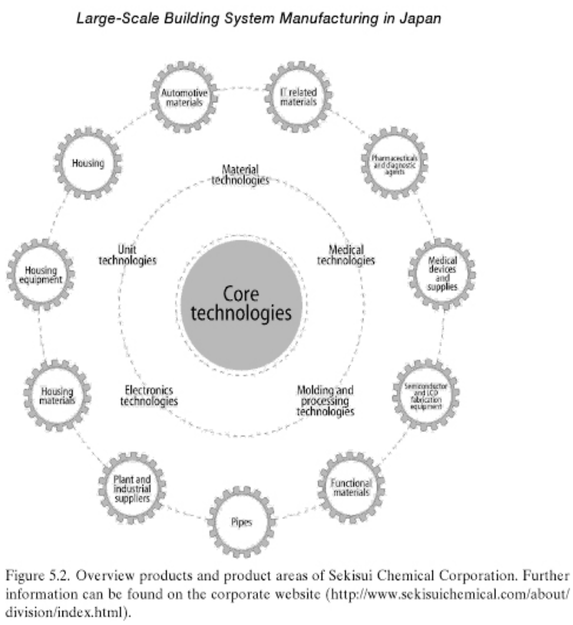


Figure 3.4. Cooperation between prefab housing industry and other industries in Japan (source: Bock, T., Linner, T., Robotic Industrialization, 2015)

3.3. What does it cost to produce modular building and what are the savings comparing to conventional construction?

The aim of the empirical part of this research which will be explained starting from next chapter is to compare design, construction and use costs of modular and conventional hospital building. Here, in literature survey summary part, the main cost distributions of different aspects of modular construction are summarized and explained.

Figure 3.5 below demonstrates breakdown of costs in modular and site-intensive construction process. The main difference here is in site-related activities and in site personnel costs, in particular. While site personnel costs are 40% from entire construction costs in conventional process, in modular one they are only 15% plus another 15% for factory personnel costs, which is still 10% lower than conventional building techniques.

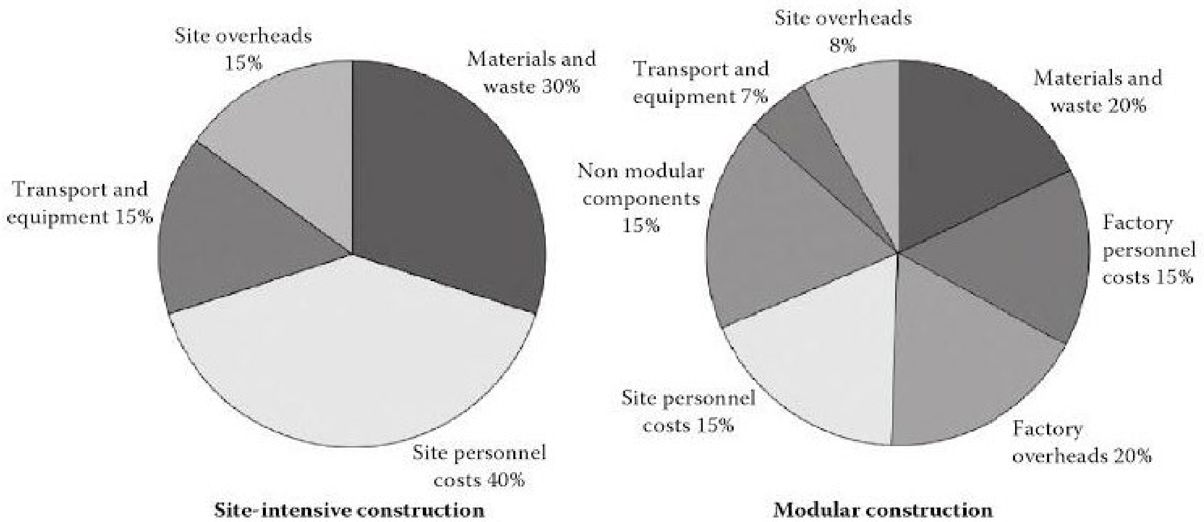


Figure 18.1 Comparison of breakdown of costs of site-intensive and modular construction of a multistorey residential building. (From National Audit Office, *Using Modern Methods of Construction to Build More Homes Quickly and Efficiently*, 2005.)

Figure 3.5. Comparison of breakdown of costs in on-site and modular construction.
(source: Lawson, M et al, Design in modular construction, 2014)

The summary of savings in modular construction comparing to traditional building techniques are explained in figure 3.6 below. The total savings are varied between 11 and 19 % (Lawson, M., Ogden, R, Goodier, C., 2015). The potential risks in different phases of development process in different building methods are shown in figure x. The main risks in modular variant take place in early phases, which is result of higher coordination and interaction demand for all parties involved. In later construction phases, however, the risks are mitigated based on coordination of the processes done earlier. In traditional construction the picture is reversed. Final design decisions can be made even at the beginning of construction phase, while the majority of risks come during execution period.

Benefit of modular construction	*Cost savings relative to site-intensive construction*
Site preliminaries	5–8%
Client's consultant fees	3–4%
Snagging reduction	1–2%
Financial savings due to speed of construction	2–5%
Total savings as proportion of the total building cost	11–19%

Figure 3.7. SUmmary of financial savings of modular construction
Source: Lawson, M et al, Design in modular construction, p. 242 (2014)

Table 18.3 Summary of perceived risks for various forms of construction

Process stage	*Risk description*	*Brick and block*	*Open panel*	*Hybrid*	*Modular*
Planning	Unpredictable planning decisions			○	○
Preconstruction	Late appointment of supplier		○	●	●
Preconstruction	Lack of standardisation possible in the manufactured components		○	●	●
Detail design	Design changes after placement of order		○	●	●
Construction	Foundation inaccuracy affects installation		○	●	●
Construction	On-site components may be incompatible with manufactured components			○	●
Construction	Quality and accuracy problems	○			
Construction	Price fluctuations during construction	●			
Construction	Delays due to bad weather	●	○		
Construction	Lack of trade skills on site	●	○		
Construction	Service installation faults	●	○		
Construction	Health and safety hazards	●	○		
Occupation	Completed construction not to specification	●	○		
Occupation	Defects at handover or in liability period	●	○		

Source: National Audit Office, *Using Modern Methods of Construction to Build More Homes Quickly and Efficiently*, 2005.

Note: ● = high risk, ○ = medium risk.

Figure 3.8. Comparison of risks in different types of construction (source: Lawson, M et al, Design in modular construction, 2014)

Chapter 4.

DESIGN PHASE.

Introduction. Design it!

Modular construction is not a panacea for every construction project. This technique has its own limitations and advantages which need to be considered in each particular case. This chapter will explore limitations in modular design, advantages of modules in design phase of building development process and differences in design between modular and on-site construction.

Design process of modular building requires deep involvement of all related parties and stakeholders since the beginning of the schematic design stage (Lawson, M., Ogden, R, Goodier, C., 2015). This is not just formal statement, but crucial necessity, because the robustness and benefits of later stages in modular development can be gone without this coordination.

4.1. Off-site or on-site? Guide lines for modular design.

Design phase in modular construction is characterized by detailed planning from a very beginning stage (Davidson et al, 2006). Based on the questions related to connections between independent modules, their maximum dimensions, structural grid related to operational nature of the module, etc, all these technical considerations should be taken into account from the conceptual building design.

Mass repetition of the elements in modular construction and their interoperability does not necessarily mean uniform and monotonous architectural perception of the final building. Modular buildings, historically, have a bad perception from the public based on low material and finishings quality as well as on temporary character of these buildings (Lawson, M., Ogden, R, Goodier, C., 2015). Today modern technologies and materials allow to design and construct modular buildings with high quality which even higher than traditional building technologies.

The main design principles of modular building are listed below.

Decide whether four-sided modules satisfy the spatial and functional requirements, or whether open-sided modules are required to achieve more effective space use.

- Design the building layout to achieve as much repetition as possible in the size and fit-out of the modules. The load-bearing capacity of the modular structure can be varied while maintaining the same external geometry.

- Choose the module size to be compatible with transport, local access, and installation con straints. For transportation, the maximum mod ule width is typically 4.2 m, but the module length can be up to 16 m

- Decide how the building may be stabilized by using the group of modules alone, or in combination with additional bracing, or for high-rise buildings, by a concrete or braced steel core.

- Pre-fit the services and equipment within the modules and decide how these services are accessed from the outside of the modules, and how they are distributed through the building.

- Consider the fire safety strategy and effective fire compartmentation provided by a group of modules. Modules with two layers of plasterboard achieve 90 min of fire resistance.

- Consider the cladding system to be used and how it may be connected to the modules. Decide whether the joints between the modules are to be emphasized or hidden as part of the architectural concept. The plan forms that may be considered at the concept design stage of modular buildings fall into well-defined types, which are described as follows.
(Based on Lawson, M., Ogden, R, Goodier, C., 2015)

4.2. Open-side modules vs 4-side closed modules.

The most common type of the module is 4-sided rectangular module (see figure 4.4). 4-sided modules are used in corridor buildings and may be combined with structural core, or can create stand-alone structure (Lawson, M., Ogden, R, Goodier, C., 2015). 4-sided modules are highly sustainable against wind and general loads. 4-sided modules are mostly used in those architectural typologies such as hotels and student accommodation. Hospitals are suitable for 4-sided modules as well, but based on flexibility demand open-side modules are necessary. For example, in-patient wards can be transformed into individual or multi-stay rooms by using internal partition walls (see figure 4.2). In order to stay away from narrow corridors the internal space of hospital building uses open-sided modules to provide flexible layout for support facilities and common in-patient areas (Capolongo et al, 2012).

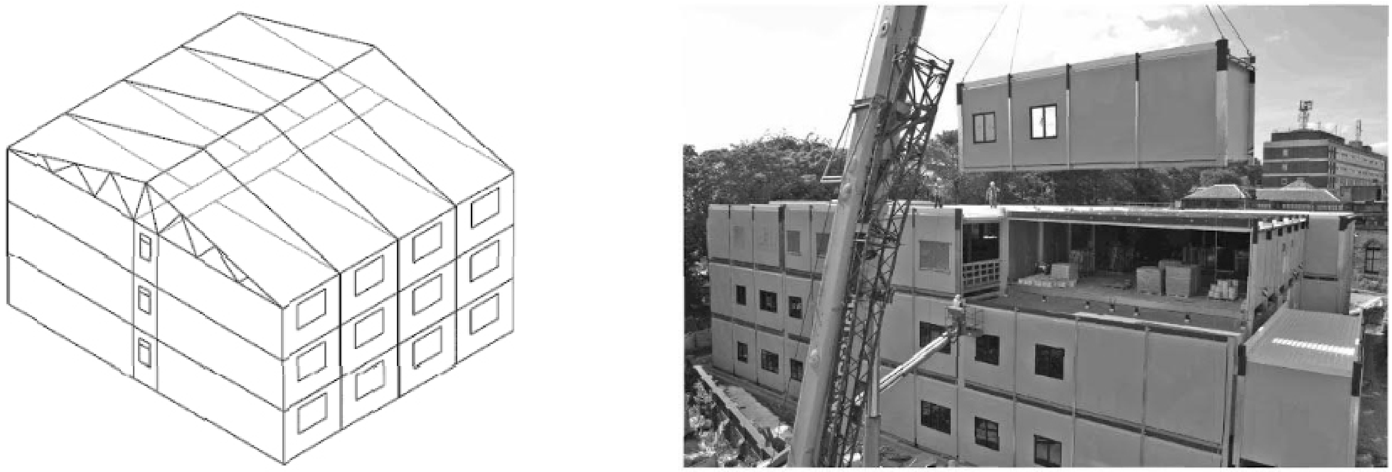
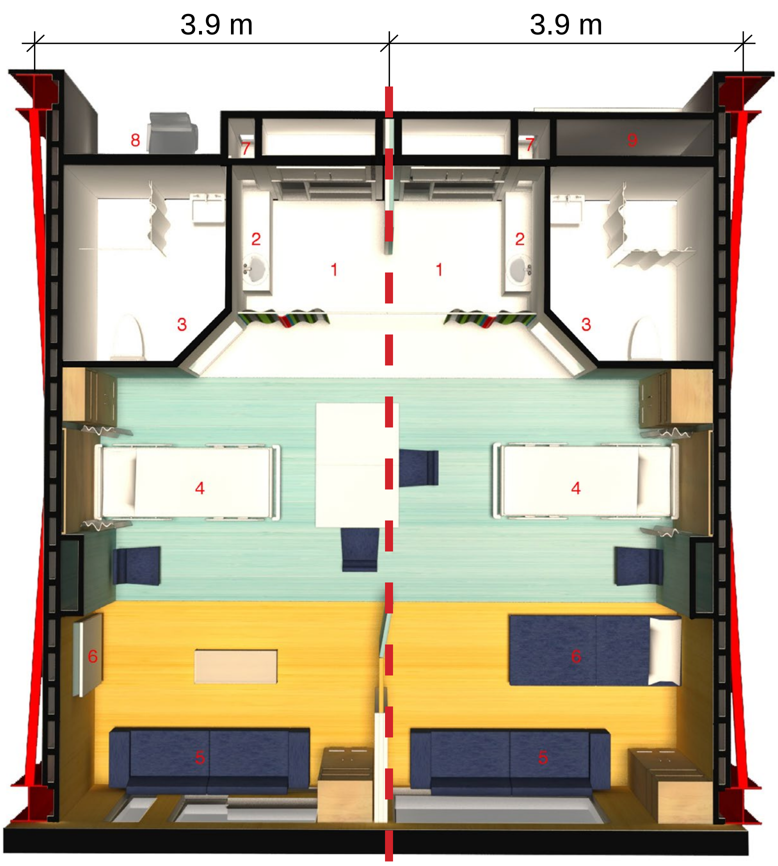


Figure 4.1. 4-sided and open-side modular systems (source: Lawson, M., Ogden, R, Goodier, C.,



Open-sided modules are also suitable for surgery rooms which have most common internal dimensions of 7,8 to 7,8 meters (Capolongo et al, 2012). Intensive care unit also requires wide internal space as well possibility to divide it into two separated zones. Entrance zones and lobbies also require open-sided modules to accommodate all necessarily facilities. Based on flexibility concept, all modules on the floor can be done in open-sided way to provide operational flexible layout for the future, but this decision should be discussed for particular project in collaboration with caregivers, since it could be unnecessarily to do it for particular hospital floor or an entire project.

Figure 4.2. 2 Open-side modules are used in in-patient ward to provide flexible layout (source: Author, 2016)

4-sided modules can have a length up to 16 meters long, while open-sided modules require deeper main horizontal beams and can be up to 12 meters long (Lawson, M., Ogden, R, Goodier, C., 2015). My particular case (Milan) has length of the module 7,8 meters, and consequently, allowed for both open-sided and 4-sided modules.

The main difference between 4-sided and open-sided modules is the maximum load they might pertain, and, consequently, the maximum height and span of the building. Table 4.3 below represents main differences and limits of both open-sided and 4-side modules.

Parameter	**4-sided modules**	**Partially open-sided modules**	**Open-sided modules**
Flexibility (max united space)	3,9 x 16 m	3,9 x 16 m	12 x 12 m
Max length	16 m	16 m	12 m
Depth of main horizon. beams	150 - 200 mm	300 - 450 mm	300 - 450 mm
Depth of combined floor and ceiling	300 - 450 mm	300 - 450 mm	600 - 800 mm
Crossection of main columns	70 - 100 mm	70 - 100 mm	100 - 160 mm
Thikness of longitudial walls	65 - 100 mm	100 mm with additional bracing	100 mm with additional bracing
Max height of the building	2 - 25 floors (combined with concrete or steel core)	6 -10 floors	up to 10 floors
Max height of the module	3,6 m	3,5 m	3,5 m

Table 4.3. 4-sided, partially open-sided and open-sided modules (source: Author, 2017)

Figure 4.4. 4-sided, partially open-sided and open-sided modules (source: Lawson, M., Ogden, R, Goodier, C., 2015

Figure 4.5. Hospital departments which require open-sided modules: Intensive care unit, in-patient ward, public spaces, surgery rooms (source: Author, 2016)

It is important to mention that both 4-sided and open-sided modules described here are load-bearing modules. Non load-bearing modules are used in modular construction as well, but they require additional support structure, or podium, which reduces an effectiveness of modular construction, especially time and site preparation parts. Support structure may also complicate the assembly process. Figure 4.8 shows an example of modular building with support structure.

4.3. Height of modular buildings.

Height of modular buildings depends on type of the module chosen for particular project (see table 4.3 in previous section). Building can be a combination of 4-sided and open-sided modules as well. Table 4.6 below demonstrates minimum number of modules in the entire building to provide structural stability.

Building height (N of storeys)	Min N of modules along front facade	Separate stabilising system required
N = 3	5	No
N = 4	7	No
N = 5	9	No
N = 6	11	Possibly
N = 7	12	Possibly (in stair or elevator core)
N = 8 and higher	12	Yes

Table 4.6. Min number of modules in a building and requirement of stabilising system (source: Lawson, M., Ogden, R, Goodier, C., 2015)

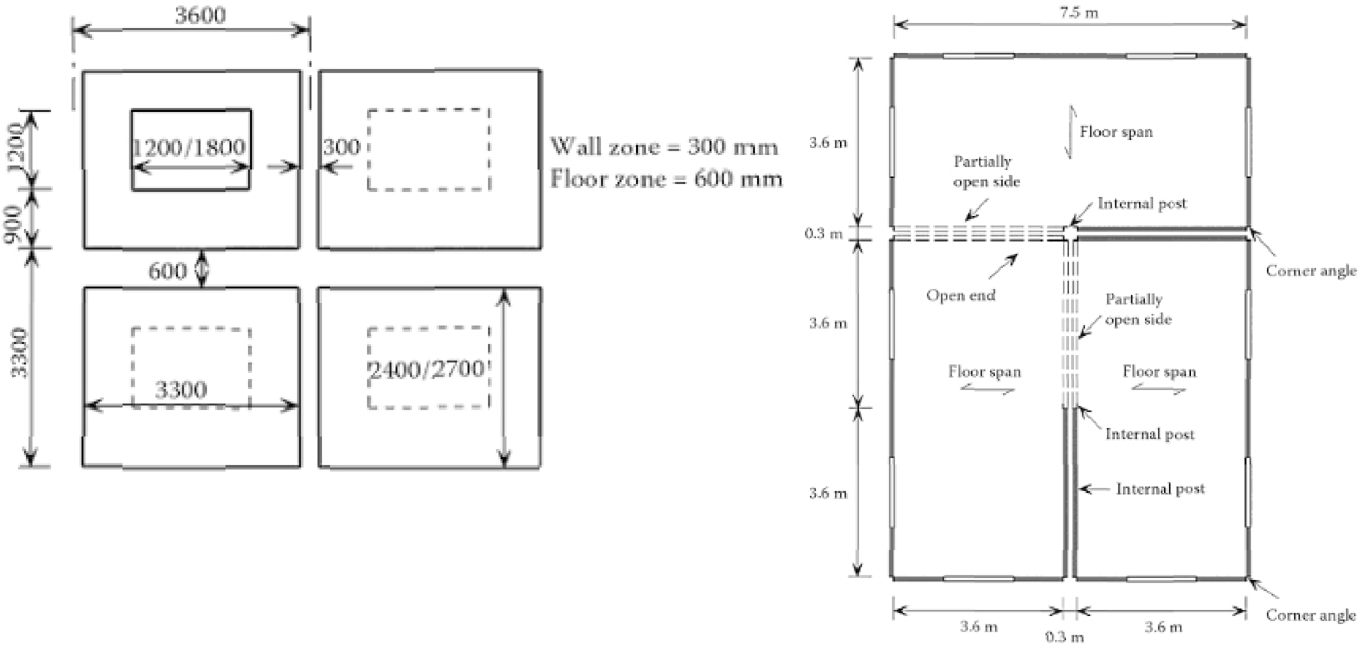


Figure 4.7. Most common dimentions in modular design and partially open-sided modules (source: Lawson, M., Ogden, R, Goodier, C., 2015)

Figure 4.8. Modular construction with support structure and podium structure (source: Lawson, M., Ogden, R, Goodier, C., 2015)

Going back to typology of the modules (4-sided, partially-opened and open-sided), it is important to mention that last two are mostly common in hospital modular construction. Since the number of hospital departments (MRI, surgery rooms, multi-patient wards, intensive care units, radiology departments, etc) require wider spans for equipment installations and operational flexibility, partially open-sided and open-sided modules are most suitable solution in hospital construction.

4.4. Dimentions for planning of modular buildings.

General factors that influence the dimensions of modular building can be summarized as follows:

- Building form, as influenced by its requirements for access, circulation, and communal space
- Planning grid for internal fitments, such as kitchen units
- Transportation requirements, including access and installation (see earlier)
- Alignment with external dimensions of cladding, e.g., brick dimensions
- Efficient utilization of space, which influences the floor and wall widths

(based on Lawson, M., Ogden, R, Goodier, C., 2015)

Detailed design plans of the buildings, and especially hospital buildings, have a uniform grid to facilitate the design process and to unify the layout (Capolongo et al, 2012). In modular construction this grid is even more important, since all dimensions follow this general size system. The most common planning grid dimensions for different building types are:

Offices: 1500 mm

Hospitals / schools: 1200 mm and 600 mm

Housing: 600 mm

(based on Lawson, M., Ogden, R, Goodier, C., 2015)

In modular design, especially in case of high installation density, planning grid can be reduced to 300 mm. This cell for general grid is based on big number of support equipment, such as fittings, connections, pipes for medical gases, etc, which need high level of detail. De Meeuw company, specialized in modular consruction in Netherlands, uses 300 mm x 300 mm general grid while prepare design layout for modular building (De Meeuw interview, 2016, appendix 15). Figure 4.9 represents planning grid of 1200 x 1200 mm in my Milan case study.

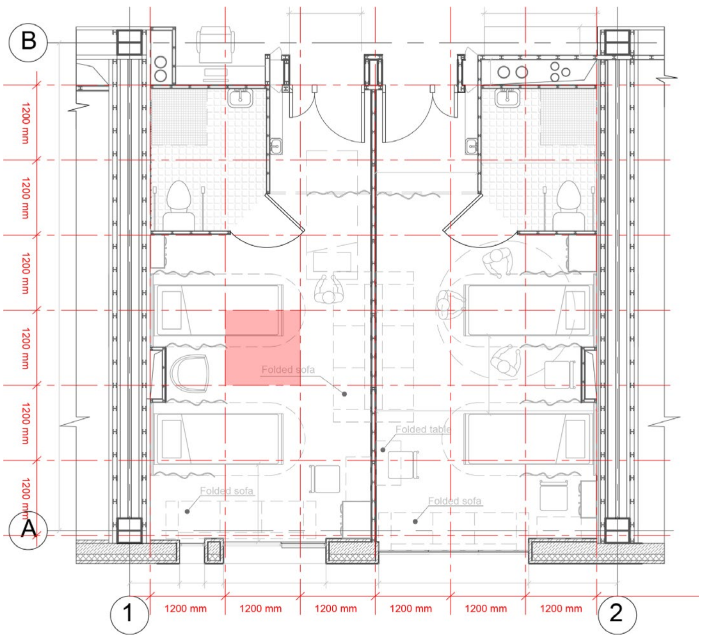


Figure 4.9.
Planning grid of 1200 x 1200 mm in in-patient ward (source: Author, 2016)

4.5. Characteristic features of design of modular building.

Procurement process.

The first and foremost requirement to design documentation when modular construction takes place is collaboration between designers, suppliers and manufacturers (Sean McGovan, 2014). Each module comes to construction site up to 95% of completeness, which means that technical installations (pipes, gases, fittings, lights, electrics, etc.) are already in there. Procurement process, in general, is different for custom-designed products and for ready-made ones. That is why final design layout in modular construction should incorporate all necessary technical equipment and take into account all pre-requisites, which requires deep collaboration between architect, modular manufacturer, medical supplier, caregivers and contractors. Next paragraph describes main types of procurement suitable in modular construction and analyze costs and benefits for each of them.

Design-bid-build.

Design-bid-build is a conventional procurement method when project is designed by an architect and then bid among competing builders. In this method, an architect produces bid documents which are then bid by a qualified general contractor who will select a subcontractor to provide the modular components. The owner can bid the site and modular components separately. If this route is chosen, construction management services are recommended, and extra care must be taken in definition of the separate scopes (Garrison, J., Tweedie, A., 2008). Figure x represents this conventional method.

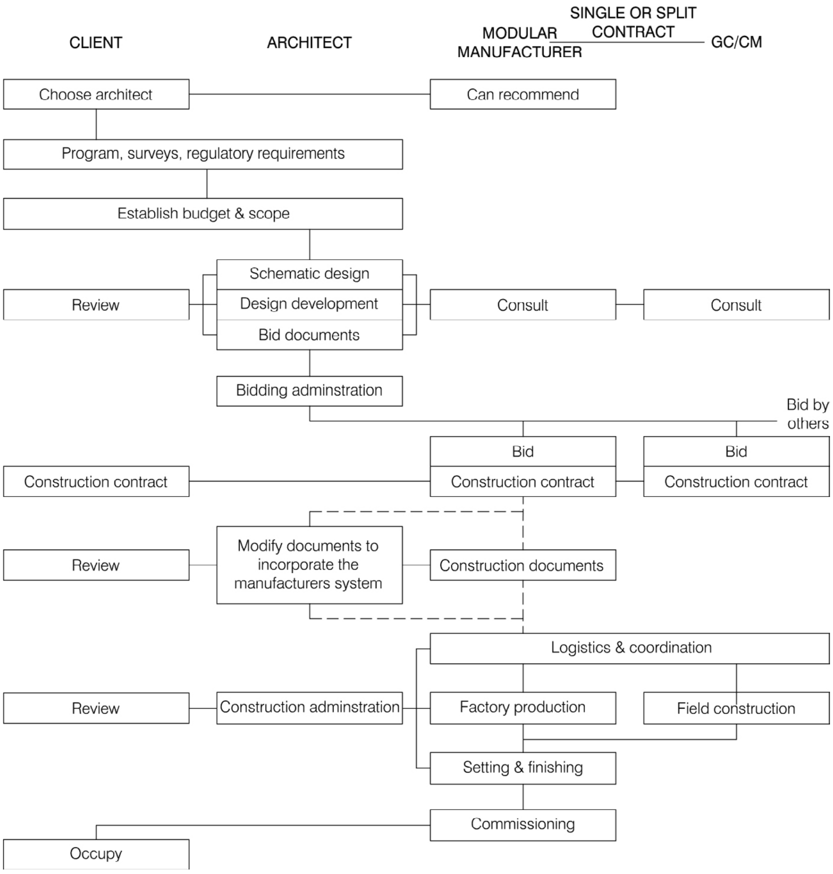


Figure 4.10. Dsign-bid-build procurement scheme (source: Garrison, J., Tweedie, A., 2008)

Design-bid-build method is used in many traditional construction projects, but it is not suitable for modular construction. This method does not take into account all advantages of collaboration, complex and in-parallel off-site production and on-site preparation activities, which are one of the main benefits of modular construction lead to time savings.

Based on complex nature of design documentation in modular construction, one of three following bid schemes are used:

Design using a manufacturer's standard system:

Limits the competitive options for bidding
Expedites the design process

Design using a performance-based or prototypical system:

Less architectural control of final product
Additional design work will be required after the manufacturer is selected
Less certainty of cost early in the design process

Design and engineer a custom modular system:

Severely limits the number of manufacturers interested in bidding
Additional burden on the design process
Maximum design flexibility
Increased cost

Integrated Project Delivery (IPD)

With this type of procurement client and architect hired by him select a modular manufacturer or general contractor who joins to modular manufacturer at the beginning of design process. After selection of modular manufacturer two approaches can take place:

The modular manufacturer can provide general contracting directly or through a general contractor hired by the modular manufacturer This provides single-point procurement.

A general contractor can be selected through design bid-build procurement. The modular manufacturer or manufacturers are specified as a precondition of the contract. Specifying the modular manufacturer is similar to specifying a group of qualified manufacturers for any other typical building product (Garrison, J., Tweedie, A., 2008).

Integrated Project Delivery allows maximum collaboration between architect, client and modular manufacturer. All manufacturer capabilities can be incorporated into design. Figure x demonstrates procurement scheme for IPD type. IPD procurement procedure allows to bring all contractors and sub-contractors (if necessary) to the decision table during design phase as early as possible. This move allows, in its own turn, to solve all questions in early design phase, which results in time savings during production and construction phase.

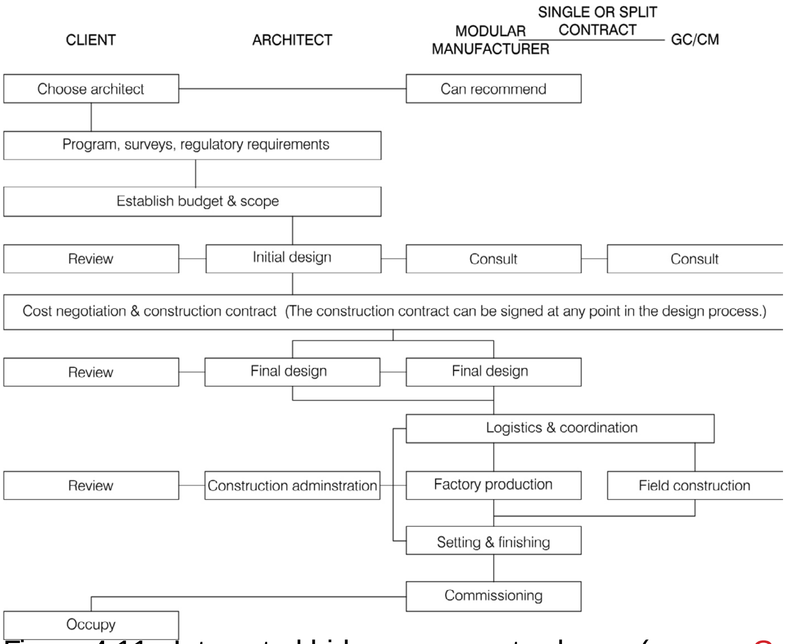


Figure 4.11. Integrated bid procurement scheme (source: Garrison, J., Tweedie, A., 2008)

Design-build.

In design-build client enters to single contract with modular manufacturer to provide partial of full design servicess in addition to construction services. Design-builid procurement has two types:

Traditional design-build

Modular manufacturer provides in-house deisgn services or retains an architect's services.

Design-build with bridging documents

Architect makes initial design documentation, which is sent, then, to modular manufacturer, who finalizes design and construction documents. Figure 4.12 represents both types of design-build procurement.

Strategic partnering.

This procurement method is used when the number of construction projects is going to be done, and when the nature of these projects are highly repetitive. In this case client employs modular manufacturer for multiple projects. Figure x demonstrates this scheme.

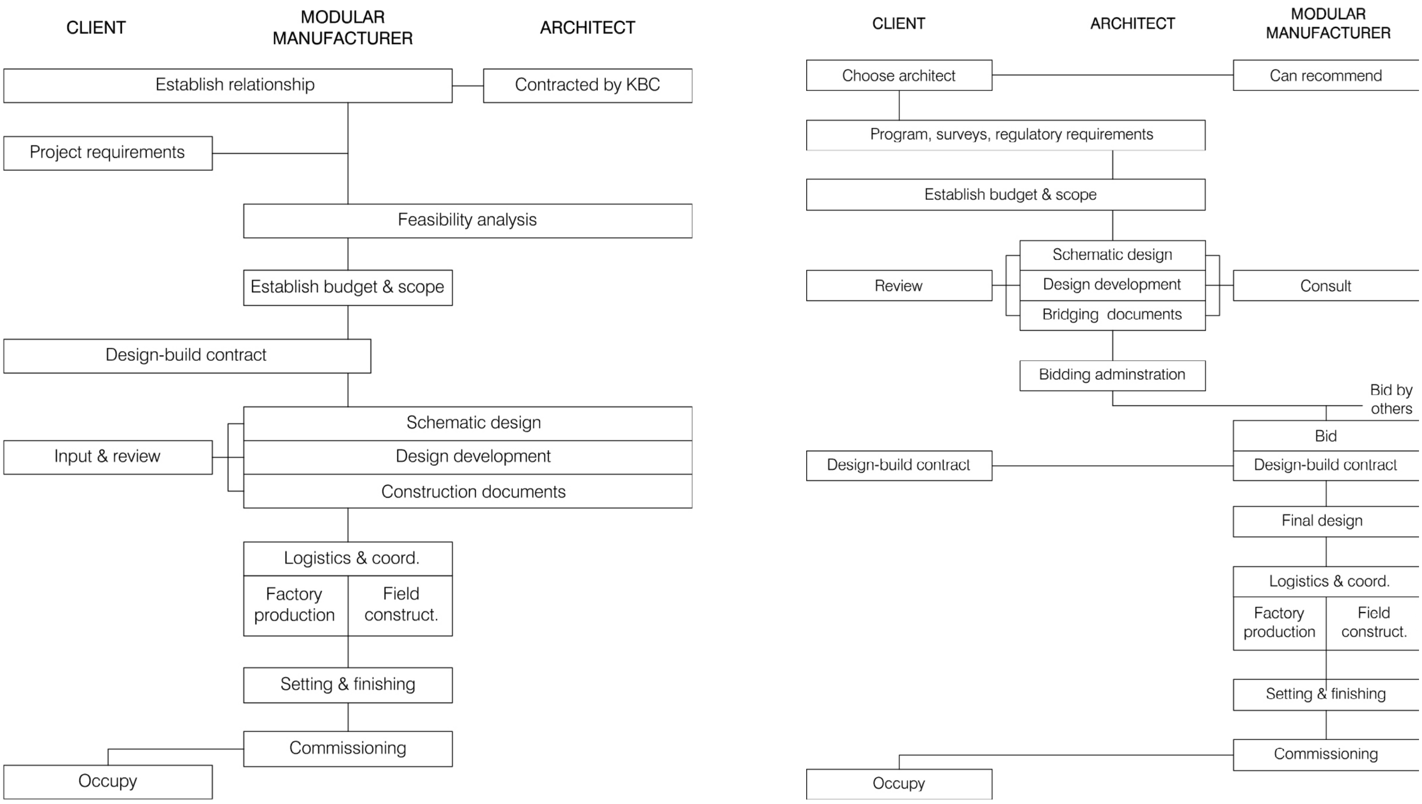


Figure 4.12. Design-build procurement scheme (source: Garrison, J., Tweedie, A., 2008)

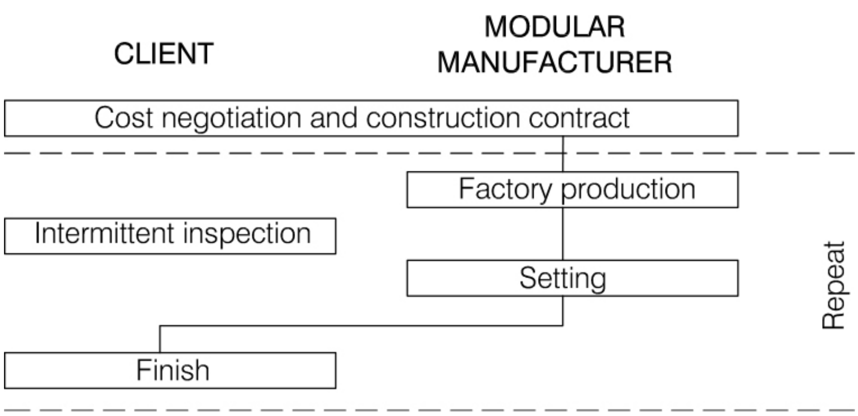


Figure 4.13. Strategic partnering procurement scheme (source: Garrison, J., Tweedie, A., 2008)

Integrative design.

Based on review of procurement construction methods it is possible to state that IPD (Integrative Project Delivery) is the proper choice in design phase of modular construction based on early decision making and integration of all players during design phase. Figure 4.14 shows three main types of procurement in construction projects.

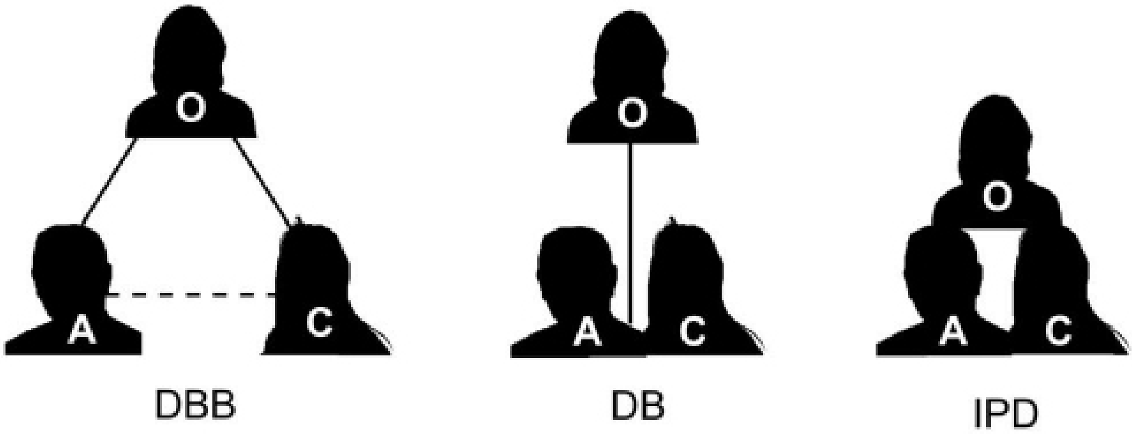


Figure 4.14. Design Bid Build, Design Build and IPD procurement (source: Prefab Architecture, Timberlake, J., 2010)

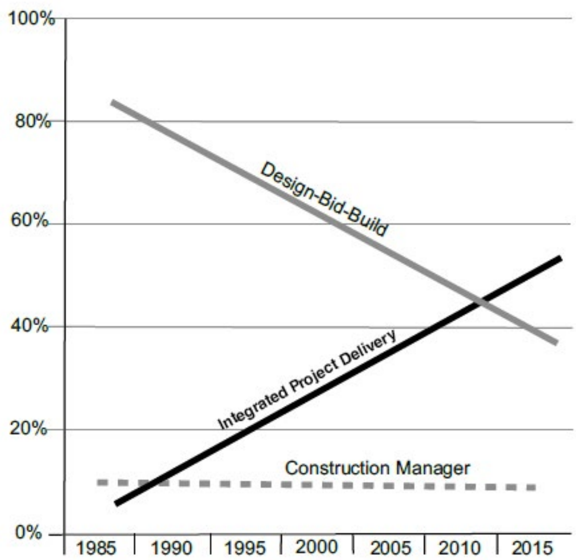


Figure 4.15. Design Bid Build vs Integrated Project Delivery over time (source: Prefab Architecture, Timberlake, J., 2010)

IPD was established in 2007, when American Institute of Architects (AIA) published two IPD families: Transitional AIA A295, built on construction management at risk model, and single purpose entity (SPE). IPD realizes a concept of "relational contracting", when parties create an organization and agree to share risks and with collective and collaborative decision making (source:Timberlake, J., 2010). One of the main benefits of such a team playing is that each party is interested in final result, because if one earns a profit, others earn it as well.

The main philosophical difference between AIA and SPE is that in first one architect is simply a formal regulator, and his role is quite diminished. In SPE architect is more client's consultant and has more power in decision making process. IPD contracts also allow to share an information between architect and other parties (manufacturers, sub-contractors, etc), which is a problem in traditional contracts.

MacLeamy curve, presented on the next page, illustrates the concept of making decisions earlier in design phase in IPD procurement procedure. The risks to make changes in this phase are minimized, while positive outcomes for final product are maximized.

The project flow from predesign to closeout in an integrated delivery is different from the traditional method in that it does not use the conventions of SD, DD, and CD which tend to create work flow barriers. These phases of a traditional design process do not encourage collaboration. IPD suggests the identification of project goals early, so that decisions regarding production methods are considered from the beginning. The "what," "who," and "how" are integral to the design process and involve not only owner and architect, but also contractor and key subcontractors such as prefabricators who will have a major stake in the project delivery. In an integrated delivery, documents are simply an extension of early decisions regarding the "how"—shortening the overall time of design delivery. In a prefabrication project, they may take the form of bridging documents, allowing the fabricator to develop elements of the package for construction. Early participation of regulatory agencies, subcontractors, and fabricators allows shortening of the agency review and buyout phases. Because the project is coordinated to a high degree before the construction phase begins, offsite fabrication and onsite assembly are more effi cient and provide a shorter construction period (Prefab Architecture, Timberlake, J., 2010).

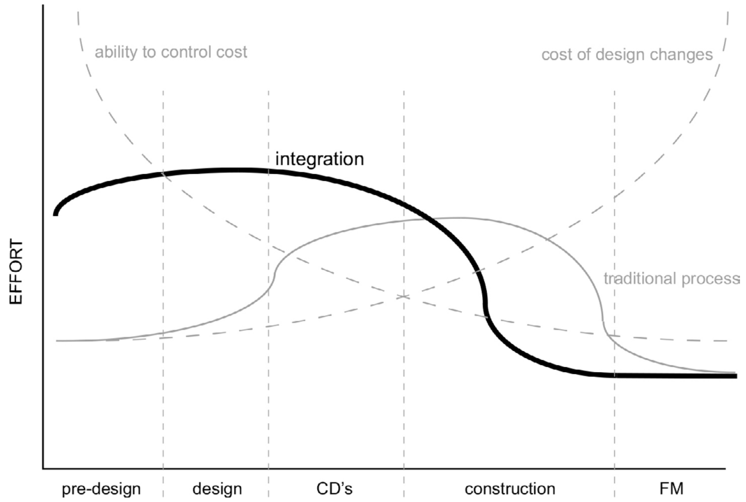
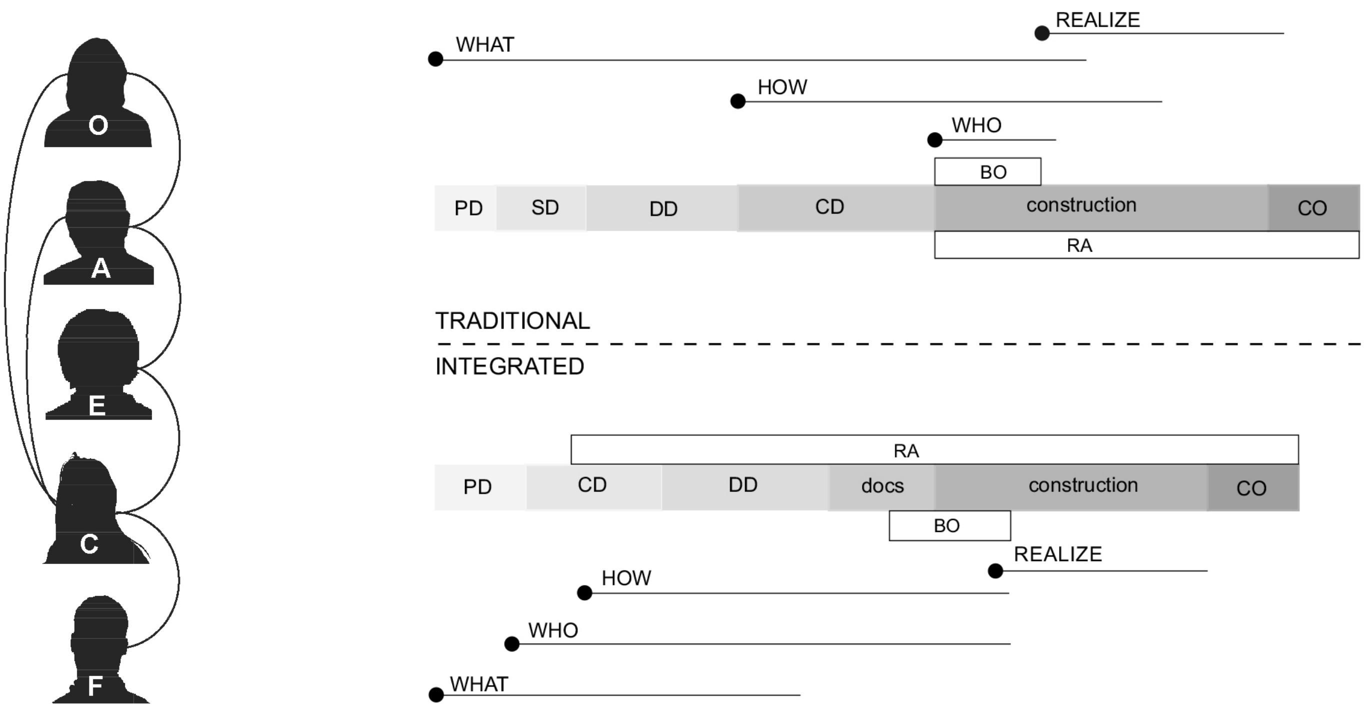


Figure 4.16 MacLeamy curve (source: Prefab Architecture, Timberlake, J., 2010)



What and How in traditional and IPD contracts (source: Prefab Architecture, Timberlake, J., 2010)

Traditional procurement has vertical and hierarchical information flow, which limit process flexibility. IPD contracts have horizontal organization, allowing information exchange across stakeholders.

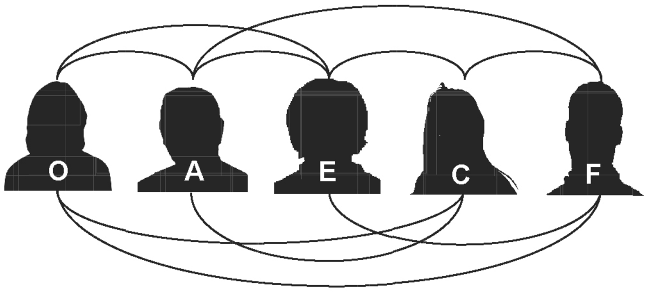


Figure 4.17 Information flow in traditional and IPD contracts (source: Prefab Architecture, Timberlake, J., 2010)

4.6. Duration of the design phase of modular construction.

Duration of design phase in modular construction highly depends on standardization of particular project. Standardized projects proposed by modular manufacturer and based on standard dimensional grid (i.e., 300 x 300 mm) can take much less time, while customized design can take much more time than average design process in on-site construction.

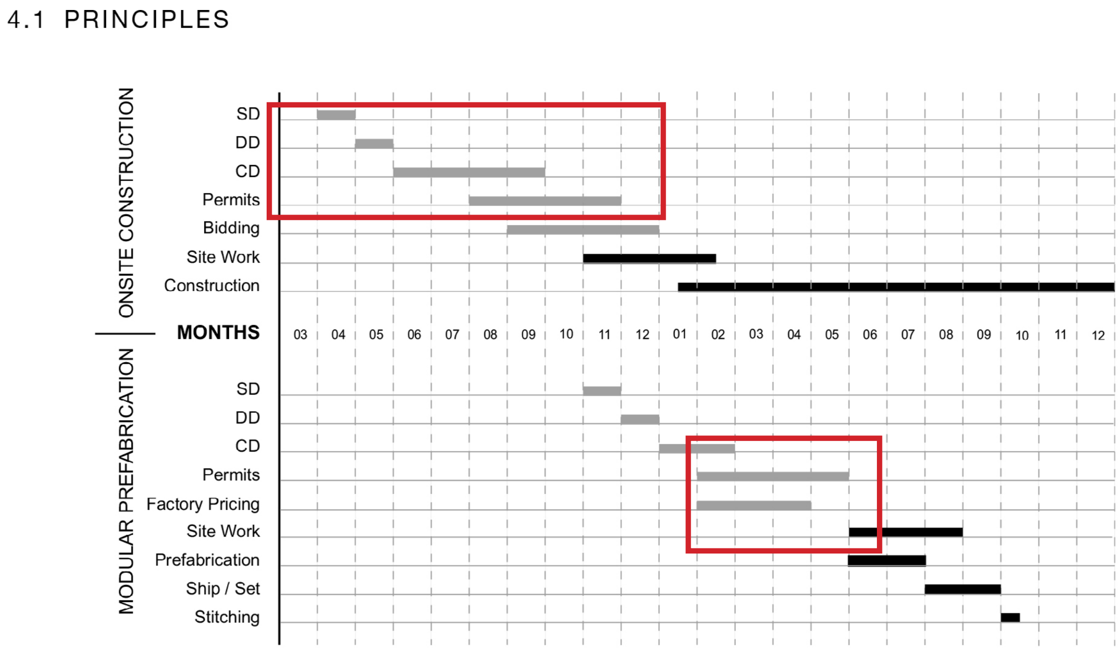


Figure x. Comparison of the duration for 2 projects, from schematic design to completion. (source: Prefab Architecture, Timberlake, J., 2010)

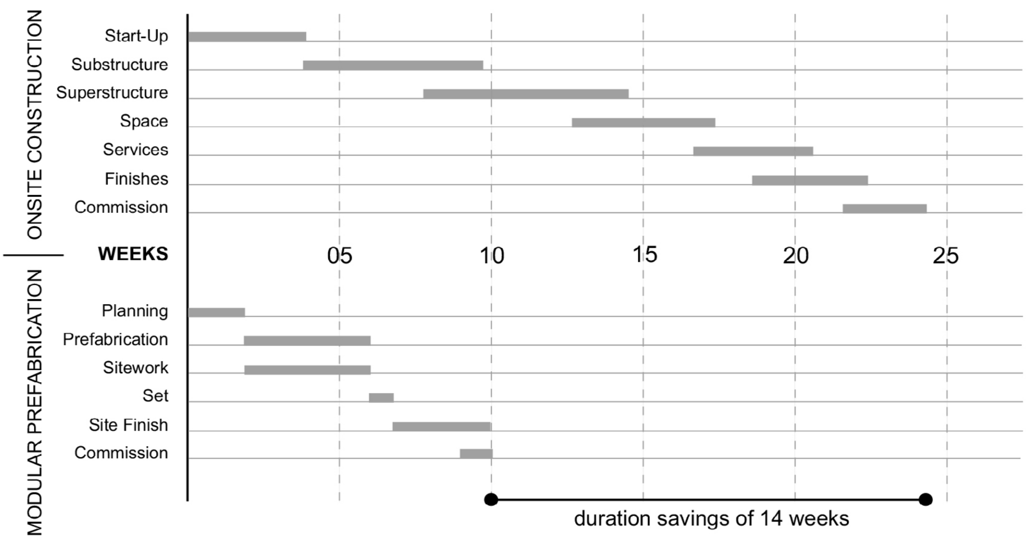


Figure 4.18. Time savings in modular and traditional construction based on in-parallel design and construction process (source: Prefab Architecture, Timberlake, J., 2010)

Figure 4.18 demonstrates comparison of overall construction schedule for modular and traditional construction of two comparable projects. In on-site version design takes 6 months, while in modular one only 4 months. It is important to notice that first two design phases, schematic design and design development, are equal in both schemes, while construction design takes only 50% time from on-site variant in modular schedule. This time saving is based on pre-designed, standardized solutions which can be used in design phase. In this case, conceptual design takes the same time as in on-site construction, but then the detailed construction drawings are based on pre-designed structural grid and other standard parts, which reduce final design stage.

De Meeuw company, for example, proposes the standardized design schemes to the clients, which is based on 300 mm structural grid, and simplifies design of different engineering systems (De Meeuw interview, 2016, appendix 15).

It is also important that major time savings in modular construction are done in production and construction phase, when on-site works (such as foundations, site preparation, etc.) are going in-parallel with off-site fabrication of modules, which gives up to 60% time savings in overall process (Timberlake, J, 2010). Modular building institute report also mentions that the sufficient time savings take place in construction phase (Smith, R.E. et al, 2015). In design phase, even in case of highly standardized scheme, there are many nuances related with left and right-hang modules and other individual characteristics of local placement and assembly.

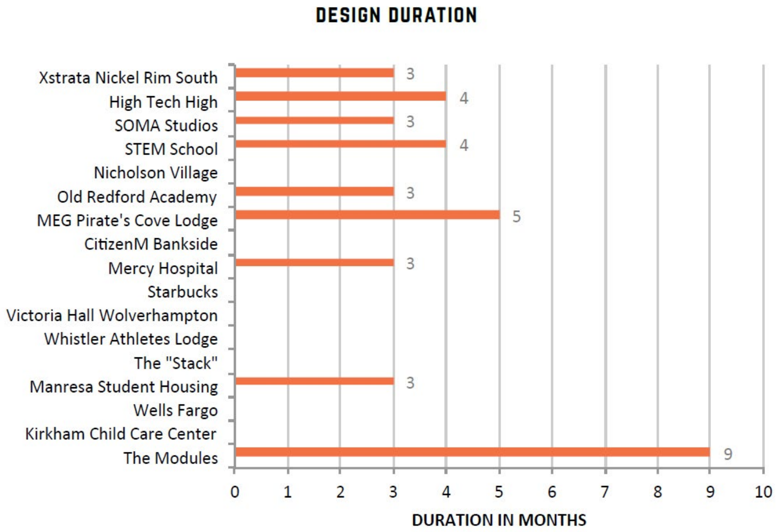


Figure 4.19. Duration of design phase of 10 different modular projects (source: Smith, R.E. et al, 2015)

It is difficult to get "an average" per cent of time savings in modular design phase, since every project has its own specialities. Client can be satisfied with fully pre-designed existing solutions which already designed by manufacturer company. In this case, design phase can be even eliminated from the process. In case of customized design, design phase can take the same, or even longer time than traditional design stage. It is possible to state that the main time savings in design phase of modular construction come from final detailed design period, when standard solutions (i.e. structural grid, MEP systems, etc.) can be used regardless of the level of customization of conceptual design. Next part of the chapter will explain these possible savings.

4.7. BIM as a solution for complicated design in modular buildings.

The complex, integrated nature and decision making environment in design of modular buildings were presented in previous paragraphs. An integration and collaboration between architect, client, contractor and modular manufacturer is obligatory for successful delivery of detailed design. The most state of the art instrument to solve complex nature of design in modular construction is BIM, building information modeling. The abilities of BIM to provide collaborative and streaming environment throughout design team is describbed in this part of the chapter.

Precision matters.

Design in modular building requires high accuracy and development of many MEP systems at the same time. For these reasons to design 3d informational model of modular building is quite important, and allows to ingrate all systems in a correct way. Figure 4.20 represents typical conflict in structural and MEP geometry during design in Revit Architecture software, when HVAC services cross structural elements. Unified BIM environment allows to integrate all pieces of information from parties (architect, contractor, modular manufacturer) into one 3d model

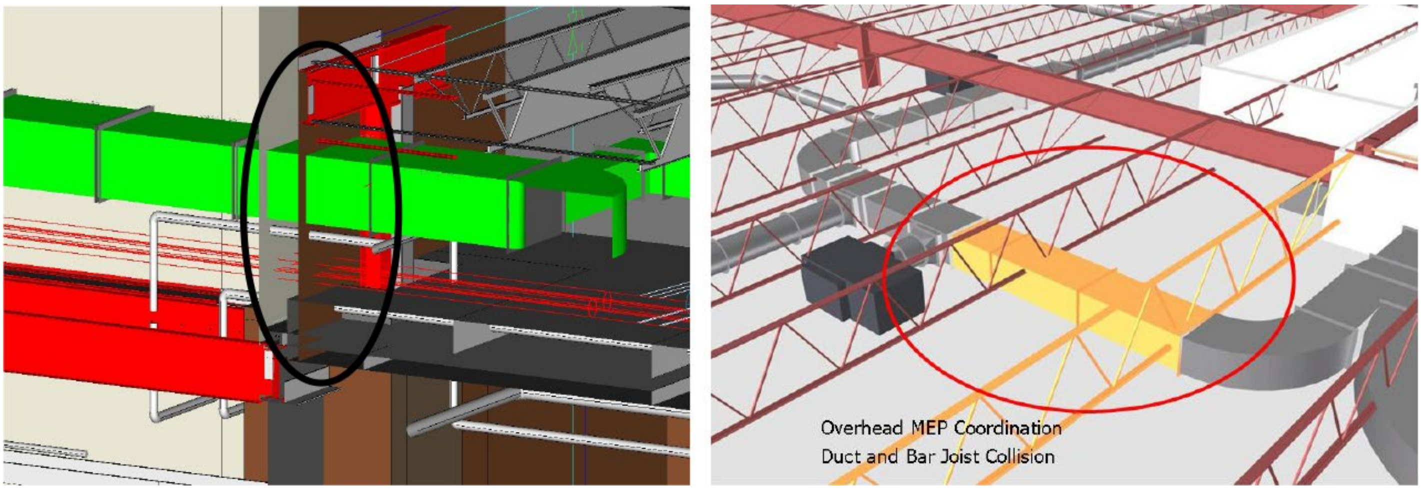


Figure 4.20. Ductwork conflicts in BIM 3d model (source: Lu, N., Korman, T., 2010)

Collective work matters.

Based on horizontal and integrative information flows in design phase of modular building (see section 1.4 of this chapter) it is extremely important for all parties to have an access to BIM molde on the regular basis. Function of collective work in Revit Architecture software allows for different design specialists (architects, engineers, manufactures) to work in the same 3d model in real time from different places, and to put their own part in entire design. All conflicts between different elements (see picture above) are visible in early design stage and can be dismantled (source: Nadtochy, A., 2016). Collective work function allows to combine in-house resources and external consultants. It means that depends on the project requirements particular design team can be combined solely by architects, modular manufacturers or general contractor, or, in case of project complexity, different specialists can work in the same virtual BIM model from different offices. Last variant is deffinitely a case of modular design, when different systems should be designed and tested all together.

Cost of design mistakes.

As it was explained in section 1.5 (procurement process) earlier design involvement of all related stakeholders and their contribution to overall design model lead to highlighting mistakes and discrepancy between different parts and systems. Anton Nadtochy, head of Atrium architectural studio (Moscow), one of the leading design bureaus using BIM technologies in Russia, states that BIM does not reduce the overall time for design a building, but allows to identify mistakes as early as possible based on 3d geometry of all objects installed in common BIM model (Nadtochy, A., 2016).It is important to stress the point that modern BIM technologies cannot simulate compatibility of different engineering systems designed in the building, but can only figure out geometrical discrepancy and mismatching of different building components, such as ductworks illustrated on previous page.

In-house design vs external specialists.

BIM design process allows to combine in-house resources of the company with external consulting. Since all changes can be added to 3d model in real time and in remote (on-line) access, the decision whether or not external consultants are required can be done in any time of design process. BIM model can be demonstrated to external specialists to solve particular questions while the ma jority of design can be done by architect or modular manufacturer. Once again, BIM way of design allows to add new information from different sources and specialists in real time and in earlier design phases.

Automation matters.

Although BIM as a technology is not a magic, and cannot reduce design time dramatically, it can eliminate some routeneous activities in later design stages (source: Nadtochy, A., 2016). For example, all specifications can be created automatically based on the properties of components of 3d BIM architectural model. These specifications are issued according to local requirements and codes, and can be reassembled automatically, if another layout is needed. This automatization in detailed design phase allows redirect resources of design team to initial and schematic design, when architectural quality of the building is just emerged and it is important to test different variants to find the best solution for spatial and architectural quality.

Figure 4.21. Structural, architectural and MEP BIM models of the building (source: Lu, N., Korman, T., 2010)

BIM design technology can redistribute time for different activities within design process. In traditional design phase 55% of the time is spent on final construction documentation and only 15% on initial conceptual planning. BIM software allows to increase the first conceptual planning up to 25%, and to reduce time for issuing construction drawings till 40%, based on automatization nature of making design specifications. Figure 4.24 and 4.25 illustrate this trend. Tis fact leads to higher involvement of architect in initial design phase and helps to dedicate additional time and resources to spatial planning which is quite important in final product.

Another aspect of BIM is relatively newness of this technology in construction sector. First of all, libraries of design elements, or families, as they called in Revit, are not spread in the market, which requires to design and develop these elements (i.e., doors, windows, furniture, etc) from zero level, which takes a lot of time and additional work from architects. Another aspect is qualified designers able to work in BIM and the price for legal software. Anton Nadtochy says that it took from 2 to 4 years for his studio to change the entire design platform from CAD to BIM (Nadtochy, A., 2016). Since it is integrative technology, it is not only architects who need to study it, but also structural engineers, technologists, etc.

BIM technology also requires new job position in design office, called BIM manager, who is responsible for coordination of all design aspects in BIM model during design phase. This results in higher design fees.

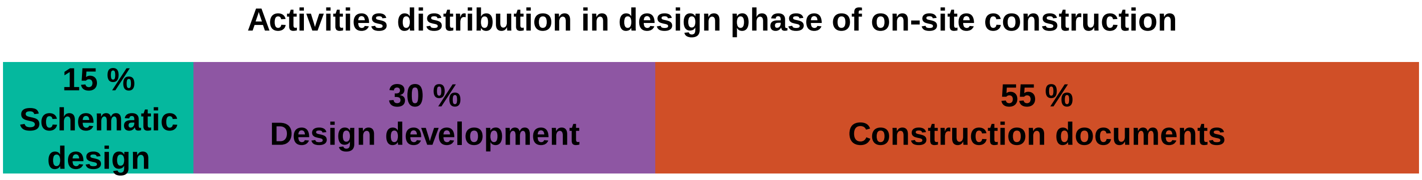


Figure 4.22. Distribution of design stages in design phase in traditional construction (source: Prefab Architecture, Timberlake, J., 2010)

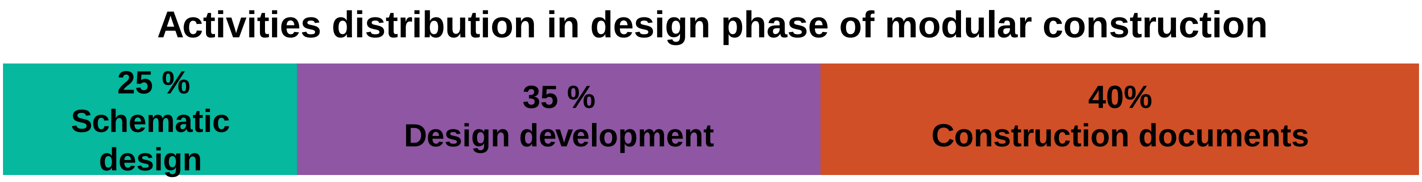


Figure 4.23. Distribution of design stages in design phase in modular construction (source: Prefab Architecture, Timberlake, J., 2010)

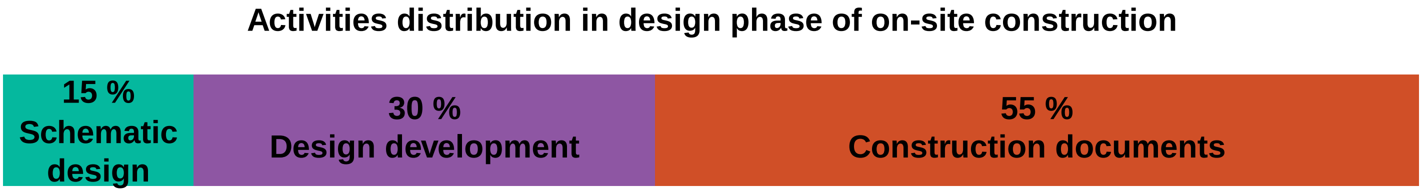


Figure 4.24. Distribution of design stages in design phase in traditional construction (source: Prefab Architecture, Timberlake, J., 2010)

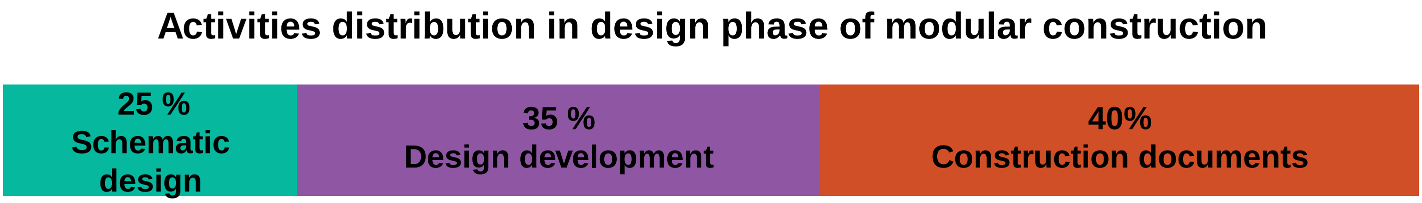


Figure 4.25. Distribution of design stages in design phase in modular construction (source: Prefab Architecture, Timberlake, J., 2010)

Sub-conclusion for section 4.7

It is hardly to say that BIM method of design can significantly reduce overall time of design phase. While higher automatization of BIM technologies (i.e., Revit Architecture) allows to spend less time for final design documentation, the amount of work needs to be done is still comparable to traditional design phase. Placement of all HVAC, MEP and other systems requires collective decision making and checking of geometrical compatibility. Precence of standard BIM libraries for different elements (or, families) can reduce the overall design time, but it is not a significant reduction.

Conclusion of chapter 4.

The conclusion of design phase of modular construction can be made that possible savings in design phase of modular construction can be done based on BIM technologies, which safe time in detailed design phase up to 15%, compared to conventional design. Table below resumes this statement. Cost savings in modular construction can be 3 to 4 per cent , comparing to conventional design process, since the majority of design tasks are done by modular manufacturer, and not by architect, while the last one is still involved as a coordinator of the process (see part “Procurement process” of this chapter) (Lawson, M., Ogden, R, Goodier, C., 2015).

Parameter	**Modular construction**	**Conventional construction**	**Savings, %**
Time savings	**85 - 20 % from conventional design**	**100 %**	**15 - 80 %**
Cost savings	**3 - 4 % from entire construction budget**	**6 - 8 % from entire construction budget**	**50 %**

Chapter 5.

CONSTRUCTION PHASE.

Introduction.

This chapter will explain the main aspects fo production and construction process in modular manufacture. The first paragraph describes factory organization and construction process of the module as well as investments necessary to set up modular factory. Second part explains savings based on lean management concept, the main benefit of modular production process. Third part deals with materials and components required for production of one module with useful area of 28,6 sq m. Next paragraph represents the amount of workers and related labor operations, which should be done to produce one module in a factory. Last two parts, transportation and on-site works, explain on-site assembly of the modules into united building.

Each part of the chapter focuses on different aspects of modular construction process, while its results are compared to conventional site construction based on literature and interview sources. The goal of the chapter, as well as the entire report, in general, to compare costs and amount of time necessary for construction of equal number of square meters in modular and conventional construction. Based on the nature of modularity, one single module with useful floor area of 28,6 m2 is taken for the analysis (see figure 5.1). Depends on the availability of information, comparing process will use the same number of square meters for conventional construction, or, the cost of 1 sq m of modular construction will be presented.

The results and conclusions for different steps in construction process will be summarized in chapter summary and related to time savings (or, overruns) and costs savings (or, overruns) comparing conventional construction process.

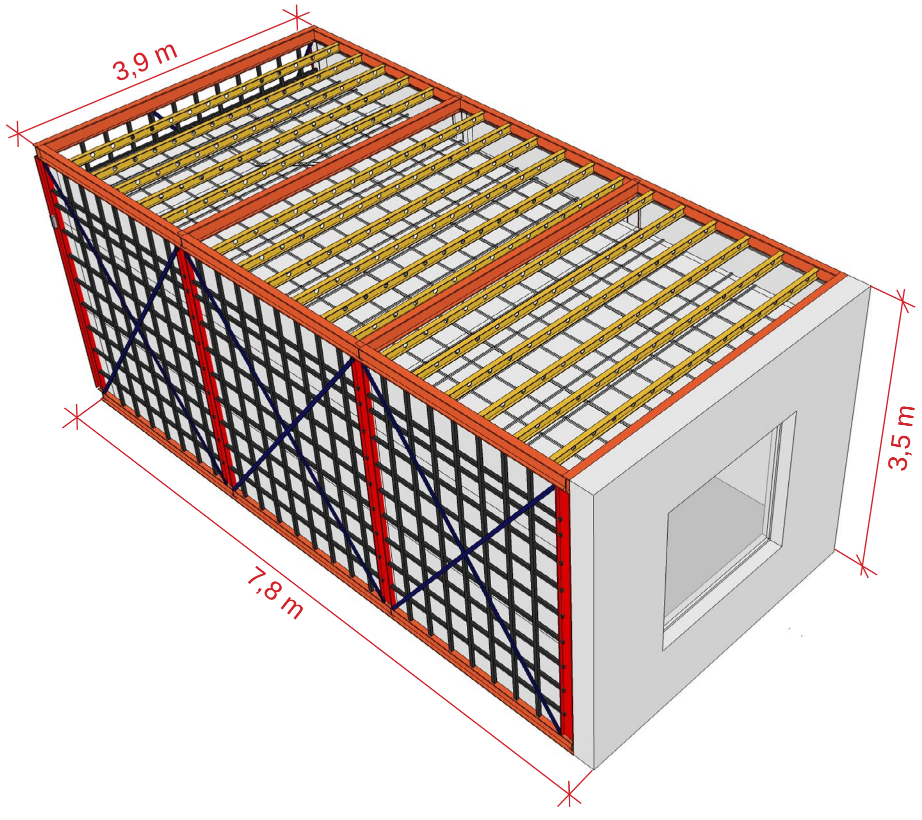


Figure 5.1. Overview of the analyzed module
(Author, 2017)

5.1. Factory organization, investments and production process.

Production of the modules in modular construction takes place in factory environment. At the end of the production process completeness of the module ranges from 70 to 95 per cent (Bock, T., Linner, T., Robotic Industrialization, 2015). The process of module production is similar to car conveyor assembly. Figure 5.2 represents typical layout of modular construction factory, which organization will be described in details later in this section.

Typical construction process of module in the factory is shown in figure 5.3 on next page. Different components of the module come to the factory from different suppliers. Supply chain management of modular factory can include different number of suppliers, depends on production scale (Mark van de Ven interview, 2016, appendix 15). It can be one general contractor who is in charge of all supplies to the factory, or, alternatively, a number of independent contractors who deliver different components, raw materials, etc to the factory. One or another method is different for particular factory and particular project.

Assembly process in modular factory can be organized in two different ways:

Static, when modulers stand in the same place during entire assembly process, and assembly team mounts different components around the module (see figure 5.4).

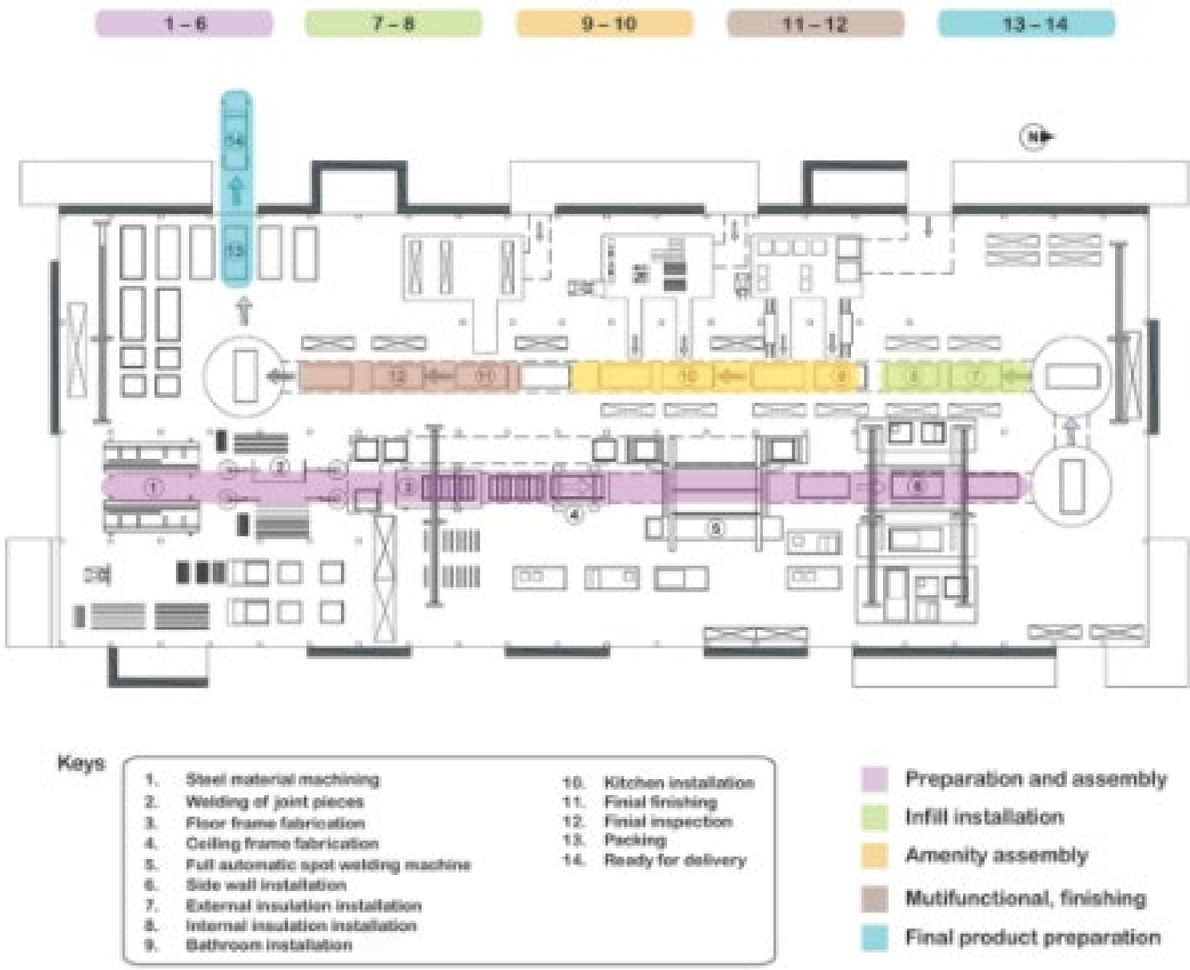


Figure 5.2. Typical modular factory layout (Bock, T., Linner, T., Robotic Industrialization, 2015)

Figure 5.3. Process of modular construction in the factory (Bock, T., Linner, T., Robotic Industrialization, 2015)

Linear, when module stands on the conveyor, or assembly line, and moves from one assembly station to another. Workers of each station mount different components to the module, and send it to the next station (see figure 5.5). An important fact about factory production method is that even most automated and productive factory produces **65% of peak capacity** over the year (Bock, T., Linner, T., Robotic Industrialization, 2015).

Figure 5.4. Static (left) and linear (right) production process. (Bock, T., Linner, T., Robotic Industrialization, 2015)

Figure 5.5. Linear production in Sekisui Heim factory (Bock, T., Linner, T., Robotic Industrialization, 2015)

Level of factory automatization.

Level of factory automatization affects production flexibility and production volume (Bock, T., Linner, T., Robotic Industrialization, 2015). Highly automated production lines increase productivity in factory operations, but the level of automatization also affects level of flexibility, since the more customized automation line is, the more limitations in range of modules which can be produced. Furthermore, higher level of automatization has to be recouped over a large production output. Figure 5.6 represents correlation between factory automatization and flexibility of production range.

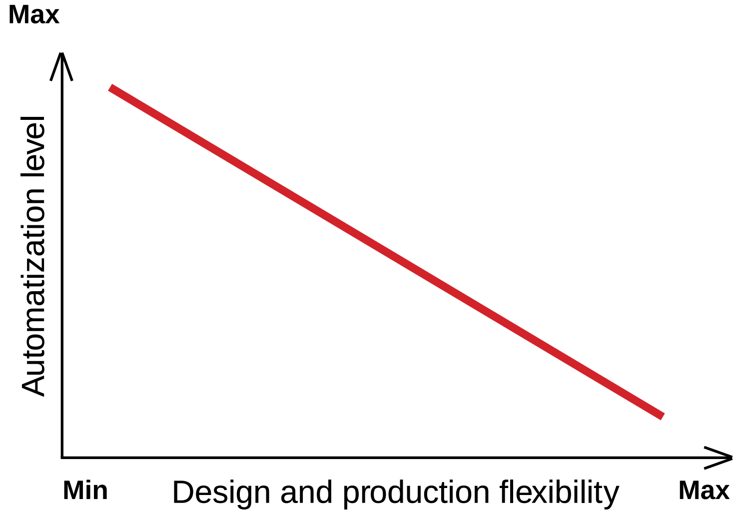


Figure 5.6. Factory automatization level versus production flexibility (Bock, T., Linner, T., Robotic Industrialization, 2015)

When choosing the optimal production method, the balance between productivity and required investment against design flexibility has to be achieved. The right way to find this balance is to identify particular market of modular manufacturer. Differentiated and more flexible modular assembly lines tend to follow static way of production. Factories, targeting markets with highly repetitive nature of the buildings, such as student residences and hotels, can use linear production with fully automated assembly line. Another criteria for choosing between static and linear layout is availability of land on the plot, since static production requires access space from 4 to 5 times of module size. Summary below demonstrates these guide lines when choosing the right layout for modular factory.

Linear, Highly automated assembly line	**Static, Low automated assembly line**
Fever design flexibility options	Greater design flexibility options
Higher amortization and maintenance costs	Lower amortization and maintenance costs
Lower availability of the space in factory floor based on organisation of production	Higher availability of the space in factory floor based on organisation of production
Higher production output of the factory	Lower production output of the factory
Production time: 4-line factory: 3 modules/ liner/day = 12 modules/day 3000 modules / year	Production time: 3-7 days / 1module 4 - 6 modules / day and 800-1200 modules / year

The rate of factory production (how much modules are done and in which period of time) is depend on factory layout. It can be that concrete part of the module needs to become dry in order to go to the next step, and it takes time. In average, the production of each module takes 2 days (Mark van de Ven interview, Appendix 15).

Third type of factory organization layout is **semi-automated production line**. This method is similar to linear production process, but characterized by higher sequential number of operations and dedicated stages. Typically, each component of the module (such as wall, ceiling, floor panels, etc.) has its own production line, and all components are assembled into one structure in final stages of the process. Figure 5.7 demonstrates standard semi-automated modular production line. Semi-automated lines are characterized by sequence of highly automated operations at the beginning of production process, when machines weld, assemble and cut panels, and number of manual operations in later production stages. These lines are highly productive, and can make one module every

20 minutes, or up to 30 modules per day. Consequently, full production capacity of such line is around 6000 modules per year. Taking into account actual demand of modular factory, which is equal to 65% from maximum production volume, it is possible to estimate real production range of semi-automated factory equal to 4000 modules per year.

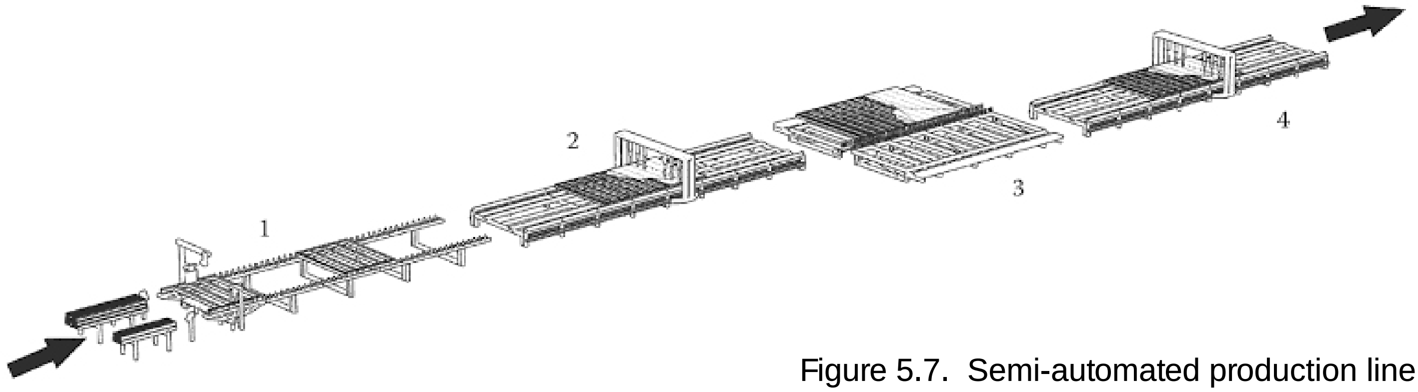


Figure 5.7. Semi-automated production line
(Bock, T., Linner, T., Robotic Industrialization, 2015)

TAKT cycles and production flow.

TAKT cycles and production flow came to modular construction from Japanese automobile industry (Bock, T., Linner, T., Robotic Industrialization, 2015). Conveyor type of assembly in modular construction and in automobile industry is quite similar, and were firstly used in Toyota company in Japan in 1960's. Assembly process is built on sequence of operations and stream of components from beginning till the last stages of construction of car, or building module. Appendix 3 represents typical value stream map (VSM) of modular factory, or, in other words, sequence of assembly operations. The body of the production process is combination of different activities by TAKTs, or time sycles. Each TAKT time, or cycle, when one or another operation is completed, should be equal to each other. This is also called flow of production, when continuity of operations and time necessary for them is established. Mark van de Ven, manager of Demeeuw modular factory, mentions TAKT and flow of production as key principle of modular off-site construction in general and their factory in particular (Appendix 6). TAKT time is used to synchronize different activities along the process. For example, build up of module skeleton and manufacturing the roof slab is done on the same TAKT cycle in parallel production lines. This gives an opportunity to for two of these operations to result in mounting the roof to main skeleton in certain point in time, which allows to correspond this step with later activities. Appendix 5 shows schematic factory layout of Sekisui Heim modular factory, when main assembly line accompanied by several sub-lines. The number of workstations in production line directly affects the production capacity. Figure 5.8 demonstrates this correlation, while figure 5.9 shows relationship between factory scale and production capacity.

Mark van den Ven, De Meeuw manager, states that they have 24 stations which can make 24 units per day, which results in 1:1 ratio.

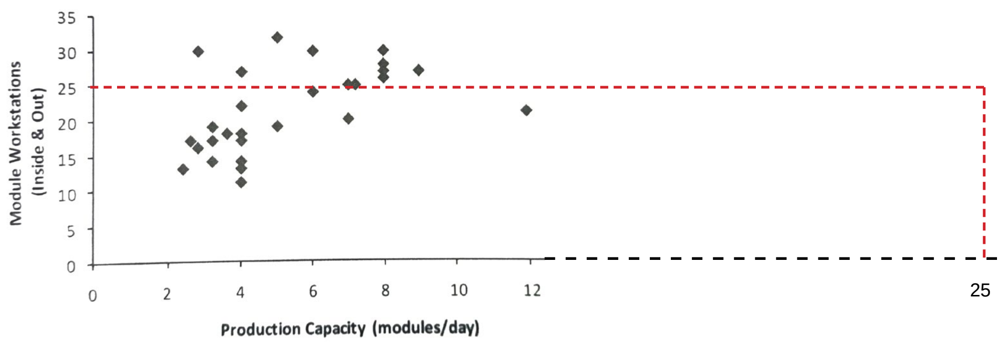


Figure 5.8. Correlation between number of work stations and production capacity
(source: Factory design for modular homebuilding, Mullens, M.A., 2011)

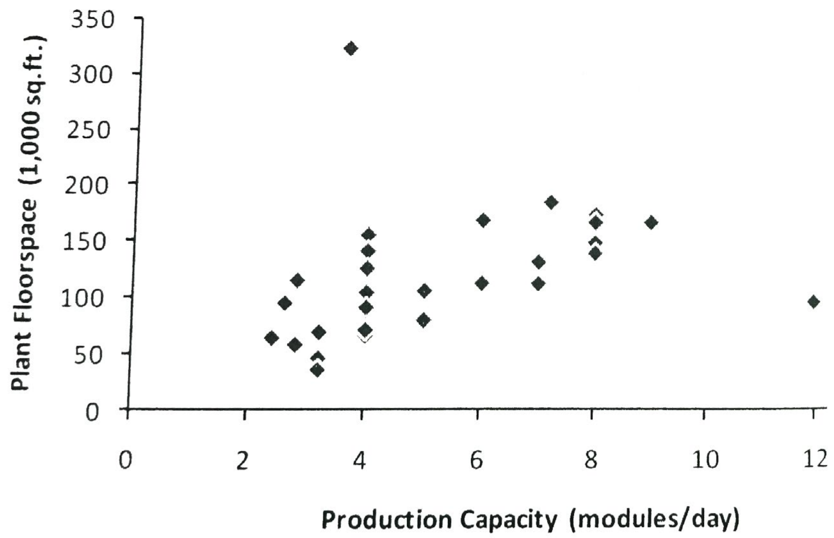


Figure 5.9. Correlation between factory size and production capacity (source: Factory design for modular homebuilding, Mullens, M.A., 2011)

Most typical layouts of modular factory.

Layout of modular factory depends on the scale of production and directly affects initial investments and design time of the facility. This part will describe the most common layouts and analyze their benefits.

Sidesaddle line layouts.

Sidesaddle layout is most common one and used in all production volumes (Factory design for modular homebuilding, Mullens, M.A., 2011). This layout is quite compact and has the shortest line length, which results in compact factory footprint. The production line is straightforward, which eliminates time consuming turns. This layout is easy to expand by extending the line towards expansion direction. Straight sidesaddle line allows efficient material flow from main storage areas to staging locations alongside the line. Another advantage is that all activities are done on floor level, simplifying factory design and production flow.

Main weakness of sidesaddle layout is poor access to most of the parts of the modules, except end walls. Movement of workers and materials is long and congested. Main assembly activities are happen in long narrow gaps between modules which complicate workers' job. Another disadvantage is that there is not enough space for staging materials along the production flow. In this case materials are stored at the end of jigs or outside of workstation, which makes the material flow inefficient. This results in delays and cycle time variation, which leads to increasing of the time and resources for production of each module. Typical sidesaddle layout is shown in Appendix 7.

Shotgun line layouts.

Shotgun layout is used for lower volume modular production. This layout is based on 2 straight, parallel lines. Each line has 50% of the module-build workstations. Cycle time for module movement on each line is twice that of the TAKT time, yielding required overall production rate. Because of the module is built in one-half the number of workstations, twice as much work and twice as many activities are needed at each workstation (Factory design for modular homebuilding, Mullens, M.A., 2011). This is done by longer dwell time, which is twice TAKT time. Each pair of workstations is served by two teams, who swap workstations at the end of each TAKT cycle. To sum up, pairs of modules move together every second TAKT cycle.

An advantage of shotgun layout is reduced by half module movement. Access to sidewalls is also easier. There are no turn movements, which reduces overall time of production.

Disadvantage of shotgun layout is long, narrow building shape which is difficult to position on the plot and expensive to build. Access to the interior of the module is poor. Staging between the lines is limited and difficult to resupply. Main supply materials are duplicated along both lines.

Build-in-place.

Build-in-place layout means that modules stand in fixed workstation and crew moves around them. All materials are flow around the module. Non-moving system saves a lot of resources and eliminates additional movements of the crew.

Disadvantages on this layout are that all materials should be delivered to each workstation. Staging of the materials at the workstation is also limited.

Factory investments.

Typical modern automated modular factories for production of modular units can require set-up investments **from 5 to 10 millions of Euros** (Bock, T., Linner, T., Robotic Industrialization, 2015). Ammortization period is from 5 to 10 years. Annual maintenance investments are equal to 1 mln Euros. Annual investments also depend on the number of projects done by particular factory in particular year. In the project of 100 units design fee may be around 10% of the ex-works of the module for modular manufacturer.

Factory building and start up.

Modular factory can occupy an existing building, or can be located in a new built one. Existing facility can save time and initial investments, but can be not completely suitable for chosen production layout.

Existing facility	**New building**
Construction time: 6-12 months	**Construction time: 12-24 months**
Initial investments: 5-7 mln Euro	**Initial investments: 7-10 mln Euro**

Design-build approach is the most efficient procurement process for modular producer, when single contract is awarded for both design and construction (Factory design for modular homebuilding, Mullens, M.A., 2011). Only one set of documents need to be prepared. Multiple tasks, such as finalizing design, getting permits and begining of construction can be done at the same time. It also allows to install equipment as soon as facility will be occupied.

Sub-conclusion 5.1.

It is possible to say that modular construction requires high level of initial investments of time and money. Even small factory, with static way of production and low level of automatization costs 5 mln Euro and takes half a year to set it up. Table 5.10 below summarizes these conclusions.

	Modular construction	Conventional construction
Costs	Factory set-up investments: 5 - 10 mln Euros	None
	Factory annual investments: 1 mln Euros	None
Time	Time for factory construction and start-up: 6 - 24 months	None

Figure 5.10. Summary of factory investments in modular construction (source : Author, 2017)

5.2. Lean management

Lean management is a second most important benefit of modular construction after the speed of installation of the modules on site. The nature of modular production (see section 2.1) results in up to 70 % recycle of the materials used in modular construction (Mark van de Ven, 2016, Appendix 15). Many companies which use lean management strategies in their practice report 85-95 % of recycling of the materials they use, but this should be considered with a grain of salt. Mark van de Ven, De Meeuw manager says that his company is at 70 % level of recycling at this moment, and they are growing. It means that these materials could not only be recycled in sustainable way, which is environmently friendly, but they can also be sold or used in the next project, which is simply financial benefit. Mark van de Ven states that De Meeuw sells some materials extracted from their modules after the end of the renting contract, and makes a profit based on it (Mark van de Ven, 2016). This part of the chapter will analyze benefits of waste management and pollution reduction in modular construction in comparing to traditional systems.

Traditionally, construction industry has been a major generation of waste (Resources, Conservation and Recycling, 68, 2012). Raw materials used for construction industry consume up to 40 % of stones, sand and gravel, 25 % of timber and 16 % of all water around the globe.

Category	Project sites	Floor space (m^2)	Total construction waste (tons)	Waste generation rate (tons/m^2 floor space)		Waste generation rate (tons/100 m^2 floor space)	
					Average		Average
I: Conventional Construction	Site 1	101297.30	5357.5	0.053	0.048	5.29	4.8
	Site 2	27499.72	1171.7	0.043		4.26	
II: Mixed System	Site 3	111536.00	3792.2	0.033	0.030	3.40	3.02
	Site 4	133308.00	4200.0	0.032		3.15	
	Site 5	178181.81	4454.5	0.025		2.50	
III: Industrialised Building System (IBS)	Site 6	116666.05	1730.0	0.014	0.016	1.48	1.55
	Site 7	37594.81	600.0	0.016		1.60	
	Site 8	71421.85	1130.0	0.016		1.58	

Figure 5.11. Construction waste generation rates (Resources, Conservation and Recycling, 68, 2012)

Conventional construction tends to find ways to reduce these harm effects and to come up with sustainable and recycable process. Kumar S. L. at al analyze 3 main construction systems: conventional, mixed and Industrialized Building System (IBS) (Kumar S. L. at al, 2012), which were used in 8 different construction sites. IBS system, which is closer to modular construction, generates 3 times less amount of waste per 100 m2 floor space than traditional construction process. Figure 5.11 gives the comparison of waste produced by conventional construction methods and modular technologies. This table clearly shows that amount of waste in conventional construction is 4,8 tons per 100 square meters of floor space, while in modular, off-site fabrication it is only 1,55 tons. Figure 5.12 represents segregation of waste on site and the percentage of waste recycle. Modular construction shows the best indicators again, with 94 % versus only 30 % in traditional one. Even if the maximum percentage of recycling in modular construction is taken at 70 % level, as Mark van den Ven states, this level is still twice higher than in traditional building industry.

Category	Project	Segregation of construction waste						Construction waste usage efficiency (%)
		Reused at site		Recycled		Disposed at landfills		
		(%)	Average	(%)	Average	(%)	Average	
I: Conventional Construction	Site 1	28.4	25.4	5.3	4.2	63.3	70.4	29.6
	Site 2	22.5		3.0		74.5		
II: Mixed System	Site 3	28.0	32.0	37.0	33.3	35.0	34.7	65.3
	Site 4	38.0		22.0		40.0		
	Site 5	30.0		41.0		29.0		
III: Industrialised Building System (IBS)	Site 6	89.2	87.9	5.0	6.2	5.8	5.9	94.1
	Site 7	92.0		3.5		4.5		
	Site 8	82.5		10.0		7.5		

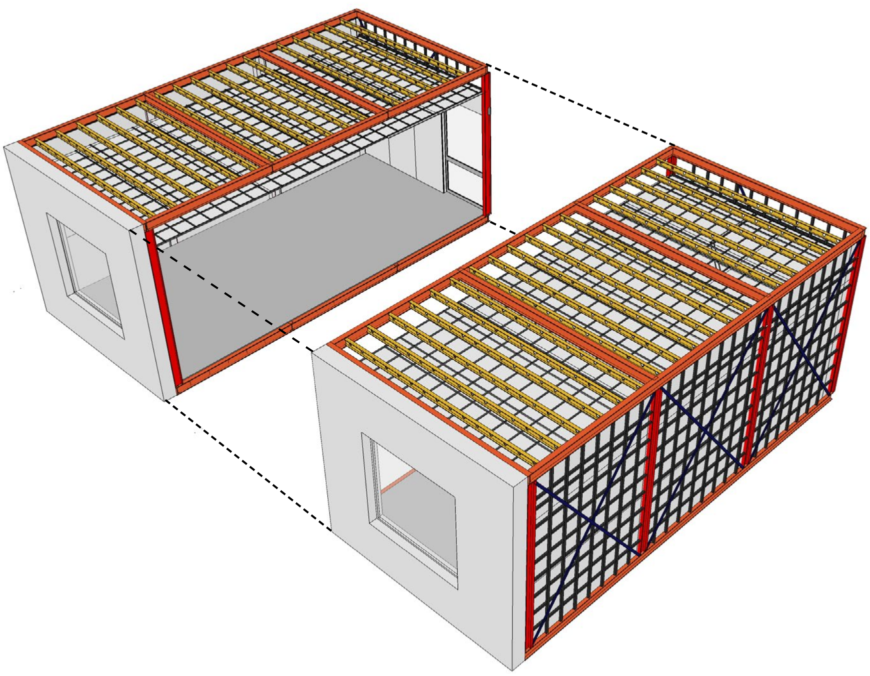
Figure 5.12. Segregation of construction waste and construction waste usage efficiency (Resources, Conservation and Recycling, 68, 2012)

Sub-conclusion 5.2

Parameter	Modular construction	Conventional construction
Amount of waste generated per 100 m2 of construction	**1,5 tons**	**4,5 tons**
Construction waste recycling efficiency	**70 - 85 %**	**30 %**

5.3. Materials and components.

As it was stated in the introduction of the chapter, standard module of 28,6 m useful area will be analyzed and compared with conventional construction. Set of components and materials, their weights, range of prices and manufacturers are represented in Appendix 8 and 9. The limitation of this part is that different hospital departments have different sets of installations and equipment, and some areas require much more of them than others. Surgery rooms, for instance, have one of the highest levels of installations and their layout can be different. Open sided modules are used for operation rooms. Figure 5.13 presents 2 open sided modules which are combined to build surgery room. This solution allows to provide sufficient and flexible layout for this hospital department.



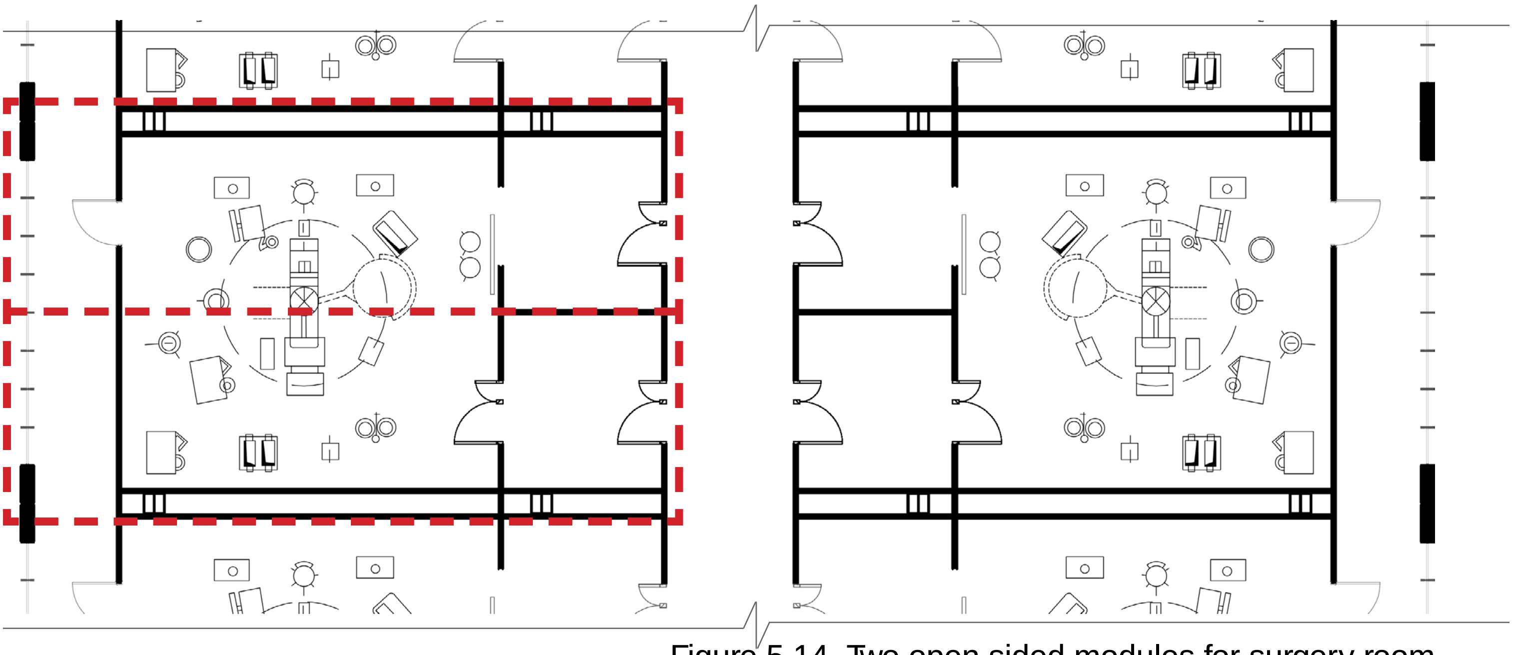


Figure 5.14. Two open sided modules for surgery room (Author, 2017)

Metal frame modules were chosen for this analysis based on their light weight and easier transportation process. Summary of the research chapter describes in details this particular choice for structural material and modular type.

Building and installations.

Hospital complex has very high level of medical equipment. Cor Wagenaar, one of the leading Dutch healthcare experts, compares hospital with a factory, based on strict requirements for daily functioning, 24 / 7 functioning of MEP systems and many other regulations. It is difficult to come up with exact percentage of installations and equipment costs within entire hospital construction budget, since it depends on hospital type, number of beds, etc. At the same time, some examples of such costs are given in this part, and some conclusions are made based on it.

An analysis of construction budget of the hospital designed by Wiegerinck architectural bureau shows that total cost of installations and technical systems is equal to 31% from entire budget (Appendix 9). This summ includes liquid and gas installations, climate plants, energy and lighting systems as well as communication, security and transport systems. Frank Michielen, manager from AT Osborne B.V., a company specialized in construction management of hospitals, gives close numbers. He states that installation costs in total hospital construction budget are between 30 and 45 per cents (Frank Michielen, 2017, Appendix 18). It is important to mention that cost of medical equipment such as patient beds, MRI, surgery tables, etc are not included in balance sheet of Wiegerinck architects. Frank Michielen adds another 35 % from the overall construction budget for medical equipment, based on specificity and high-tech nature of such products. A closer look to my own calculations come to the same ratio. All installations and technical systems make 31 - 46 % from the total price of the module. Medical equipment costs in my case take only 18 - 23 % from entire construction costs, but this is based on the type of analyzed module - individual patient ward, whih has much less medical equipment, comparing to operating theatres and MRI rooms, for instance. In these departments cost of the medical equipment is around 40 % from entire budget. Appendix 9 reveals these cost details.

The moment of the mounting of the installation systems and equipment highly depends on the equipment supplier and readiness of the installations. Based on literature review it is possible to say that in-factory installations increase overal quality of the product based on highly controlled environment, independency of weather conditions and possibility to test all systems. In reality, however, this does not happen all the time. Mark van den Ven, manager of De Meeuw modular construction company, states that equipment suppliers are not ready at the moment when module is done in factory. (Mark van de Ven, 2016, appendix 15). That is why installations and equipment are mounted on construction site in majority of the cases. Mark mentions that once they assembled an entire operation theatre module in their factory with all equipment and installations ahead in order to test fully functionality of the module. After this check part of the equipment was demounted, sent to construction site together with modular frame and mounted once again on construction site (Mark van de Ven, 2016, Appendix 15). It is possible to say that high-tech modules, such as operating theatres, can be equipped by medical devices in the factory in order to test their functionality.

Additional important thing about modular materials and components is that non-modular parts (fittings, connections, etc) are equal to additional 15% of the cost of modular materials themselves (Lawson, M., Ogden, R, Goodier, C., 2015). This cost is added in appendix 10.

Sub-conclusion 5.3.

Comparison of construction materials and elements for modular and conventional construction shows that the percentage of their cost in total budget is equal to each other. This is logical because for both processes the set of similar components and elements required. Table below summarises cost percentages for both types of construction.

Parameter	Modular construction	Conventional construction
Installation costs	**33 - 42 %**	**34 %**
Costs of construction elements	**33 - 37 %**	**38 %**
Costs of medical equipment	**23 - 40 %**	**23 - 40 %**

5.4. Workers and labor productivity.

Next area of construction phase which is going to be examined in both modular an onsite construction is the cost of labor and speed of construction process. While the cost of elements for modular and conventional construction is equal, as it was shown in previous part, speed of construction is significant benefit in modular variant. Wages in manufacturing sector in Netherlands, however, are not lower than in conventional on-site construction. Monthly salary for workers in De Meeuw factory is 2.400 Euros, which results in 15 Euro/hour. Conventional construction pays 14,5 Euro/hour (statline.cbs.nl). Appendix 11 demonstrates set of operations required for assembly of average module in the factory, time required for it and number of workers.

Time for production of one module varies from 4,8 to 14,5 days depends on the factory layout, total number of modules produced per year, level of automatization, number of workers, etc. It is clear that the economy of scale plays a crucial role in modular construction. Higher production volume reduces overall labor hours for one module as well as total cost of the product. Figure 5.15 represents this correlation. From the table in Appendix 11 it is clear that the average time required for module production is 181 hour, or 7,5 days. Depends on the scale of the factory it is possible to produce from 2 to 10 modules per day. Average factory makes from 4 to 6 modules in a day and 800 - 1000 modules per year. Correlation between factory space and production volume is written below.

Factory space 5.000 m2: 2 - 4 modules / day

Factory space 14.000 m2: 10 modules / day

Based on these facts it is possible to state that average modular factory is able to produce 6 modules

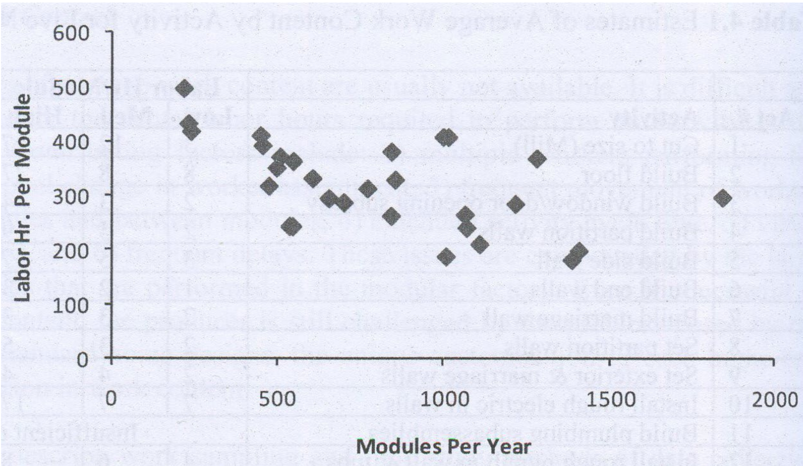


Figure 5.15. Correspondence between labor hours / module and production volumer / year (Factory design for modular homebuilding, Mullens, M.A., 2011)

When the labor hours required for assembly of one module is known, it is possible to calculate an average price of the labor to produce one module. The number of workers for each operation is difficult to define since this data fluctuates from factory to factory. Even Mullens M.A. in his book "Factory design for modular homebuilding" does not give exact figures for this question. The assumption here is that most of the operations are done by single worker, since level of automation allows to do all heavy load operations by machines. Hourly wages in modular construction sector are taken from statline.cbs.nl and represented below. An average hourly wage in manufacturing sector in The Netherlands is 15.7 Euro.

	Gender		
	Male	Female	Pay gap
Managers	25.0	22.3	11%
Professionals	19.0	17.3	9%
Technicians and associate professionals	16.7	16.2	3%
Clerical support workers	14.6	13.8	5%
Service and sales workers	16.0	13.3	17%
Craft and related trades workers	13.7	12.8	7%
Plant and machine operators, and assemblers	13.4	11.1	17%
Elementary occupations	11.6	10.4	10%

Note: Reported only for occupational groups with at least 100 observations

Figure 5.16. Hourly wages in manufacturing sector in The Netherlands(Wage Indicator foundation, 2015)

Hourly wage for non-western imigrants: 16,7 Euro / hour

Hourly wage for western immigrants: 19,6 Euro / hour

Hourly wage for Dutch workers: 21,4 Euro / hour

(Source: www.statline.cbs.nl)

With minimum number of labor hours required for production of 1 module labor cost per one module will be equal to 1.837 Euro. For medium number of labour hours, which is equal to 180 ones, labor cost for module will be 2.826 Euro, while for high number of labour hours this price will be 5.746 Euro.

Low amount of labor hours / module: 1.837 Euro / module

Medium amount of labor hours / module: 2.826 Euro / module

High amount of labor hours / module: 5.746 Euro / module

Conventional construction.

Conventional construction is able to produce less amount of square meters per day on site, while wages in traditional building process is a bit lower than in manufacturing. Frank Michielen, manager of AT Osborne B.V. gives 80 square meters per day as high building capacity of traditional construction industry (Frank Michielen, 2017, Appendix 18). This is twice less than an average modular factory can build per day (see previous paragraph). With an increasing of production capacity modular plant can produce up to 10-12 modules per day, which is equal to 350 square meters per day, which is in 4,3 times more than in conventional construction. Direct Cost of labor in conventional and in modular construction, however, is almost the same, and equal to 14.4 Euro and 15,7 Euro / hour, consequently. (Wage indicator foundation, 2015). Figure 5.17 shows hourly wages in Dutch construction sector depends on the occupied position.

	Gender		
	Male	Female	Pay gap
Managers	23.4	20.3	13%
Professionals	17.3	16.4	5%
Technicians and associate professionals	15.8	15.4	3%
Clerical support workers	13.9	13.3	4%
Service and sales workers	14.6	14.7	-1%
Craft and related trades workers	13.0	11.5	12%
Plant and machine operators, and assemblers	13.7		
Elementary occupations	11.2	10.8	4%

Figure 5.17. Hourly wages in construction sector in The Netherlands (Wage Indicator foundation, 2015)

Sub-conclusion 5.4.

Speed of production is the main benefit of modular construction. Average modular plant produces 170 square meters a day, while on-site construction can give only 80 square meters. Labor cost, however, is almost equal. Table 5.18 summarizes labor time and cost indicators for both types of construction.

Parameter	Modular construction	Conventional construction
Amount of sq m built per day	**170 m2**	**80 m2**
Hourly wage	**15,7 Euro / hour**	**14,4 Euro / hour**

Figure 5.18. Comparison of labor cost and productivity in modular and conventional construction (Author, 2017)

5.5. Transportation.

Transportation takes very important part in the cost map of modular construction. One of the main benefits of modular approach is completeness of the module in factory up to 95 %, but this requires additional transportation costs. Methodologically transportation costs consist of fixed and variable operating costs (Sdoukopoulos, E., Estimating truck operating costs for domestic trips). Fixed operating costs are cost (or, rent) of the truck, cost of license ownership, cost of VAT tax, etc. Variable operating costs are gasoline price, wage of the driver, maintenance cost, etc. Appendix 12 reveals all the details of transportation costs. It is important to mention that there are two finding schemes, basically. Modular manufacturer can buy his own trucks, or he can lease them depending on the amount of transportation needs in particular period.

Last variant is much more beneficial, because the lease cost of the truck is around 1.000 Euro, while the cost of ownership for a new one is from 30 to 50 thousands Euros. Distance and nature of the route from factory to construction site is an important factor in calculating of transportation costs. For this part the distance of 200 kilometers from factory to site is presumed. Effective operation radius of the module is around 500 kilometers (Lawson, M., Ogden, R., Design in modular construction).

Dimensions of the module also affect the price of transportation significantly. Maximum width of the cargo allowed for road transportation without special measures is 2.5 meters with maximum length of 12 meters (International transport, 2016). Cargos with higher dimensions require special measures, from articulated vehicle to special police escort. Mark Lawson and Rey Ogden in their book Design in modular construction differentiate them depends on the cargo's width, since this is the most critical parameter (Lawson, M., Ogden, R., Design in modular construction).

Type of vehicle	*Width of load*	*Vehicle mate required*	*Police notice required*	*Other notice*
Construction and use (C&U)	≤2.9m			
Special type	≤3.5m		✓	
Both C&U and special type	≤4.3m	✓	✓	
Indivisible load on C&U vehicle	≤5m	✓	✓	Form VR1

Figure 5.19 Transportation restrictions for oversized cargo (Lawson, M., Ogden, R., Design in modular construction, 2012)

Dimensions of the module are directly related with flexibility of the entire building. Increasing of width and height of the module allows to design flexible environment with less number of the modules. However, the wider the module is, the more additional measure it takes, such as police guard along the route and low-loader lorrys for transportation. Usually modules have a width limit of 4 meters.

Since the height of the analyzed module is 3,5 meters, low lorry platform is necessary to transport it. Typical height of the platform is 600 mm, which gives total height of 4,1 m, which is almost the maximum allowed. Height restrictions of the road allow to transport cargo of 4,2-4,5 m height maximum, depends on the particular route and presence of the bridges. Figures 5.20 shows the process of module transportation within a city. Insurance of the module during transportation is also specific cost in modular construction. Insurance companies ask for 0,1 - 0,3 % from cost of the cargo plus another 0,5 % as a franchise. Overall, the data represented in Appendix 12 is correlated with the real price of transportation of module with such dimensions. Several companies were asked to give their proposal for transportation cost, and their numbers are close to my own calculations.

Sub-conclusion 5.5.

Average transportation cost of the module is equal to 2.211 Euro, while the low cost is 1.835 Euro and high cost is 2.534 Euro. While the transportation cost in modular construction can be defined relatively easy based on the nature of modularity of the project, transportation cost in conventional construction is very difficult to estimate, because it highly fluctuates from project to project and its particular conditions.

Low transportation cost of module: 1.835 Euro

Average transportation cost of module: 2.211 Euro

High transportation cost of module: 2.534 Euro

Figure 5.20. Low loader platforms. (toptrucks.nl, 2017)

Figure 5.21. Transportation of the module. (Cadolto.com)

5.6. On-site works.

Completeness of the module in the factory varies from 75 % to 95 % as it was explained in section 2.1.It means that the majority of site activities is related with foundation construction and installation of the modules brought from the factory (Lawson, M., Ogden, R., Design in modular construction, 2011). This section will describe typical installation process of the modules on construction site and procedures which are necessary to complete modular building.

Foundation interfaces.

Variety of foundation systems can be used in modular construction. Modules with load-bearing side walls use strip footings and ground beams as the most common foundations (see figure 5.22). For open-sided modules with corner posts pad footings and pipe caps are generally used. For heavier modules made from concrete elements piled foundations are more common. Different foundation types of the modules are shown in figure 5.24. Modular construction has a gap between ground and modular floor, and this gap should be minimum 150 mm according to construction codes in order to have ventilation space.

Tolerances in geometrical stability of the module.

Installation of the module is highly sensitive to geometrical errors in modular structure which can take place in factory manufacturing process or during transportation process. Figure 5.22 represents maximum allowed errors in modular production.

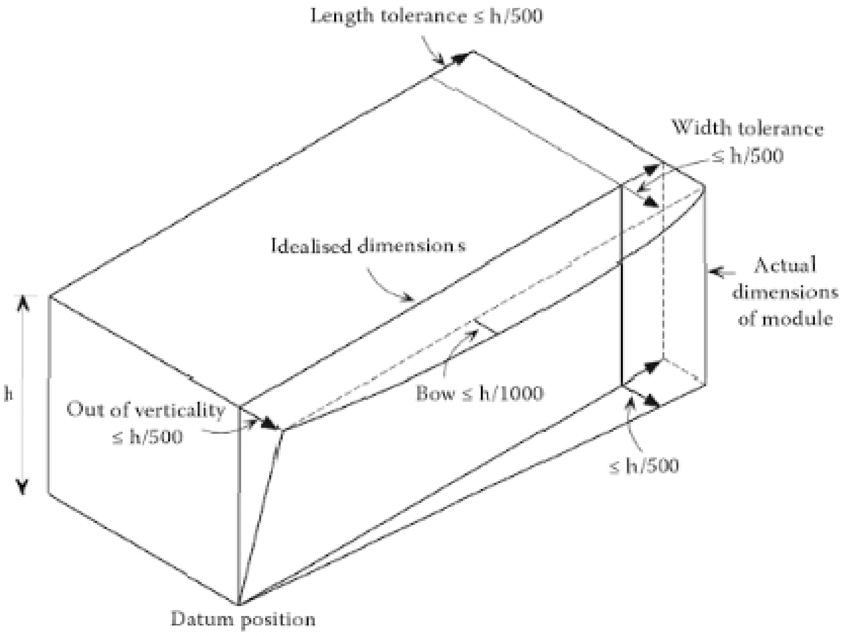


Figure 5.22. Maximum allowed errors in modular manufacturing
(Lawson, M., Ogden, R., Design in modular construction)

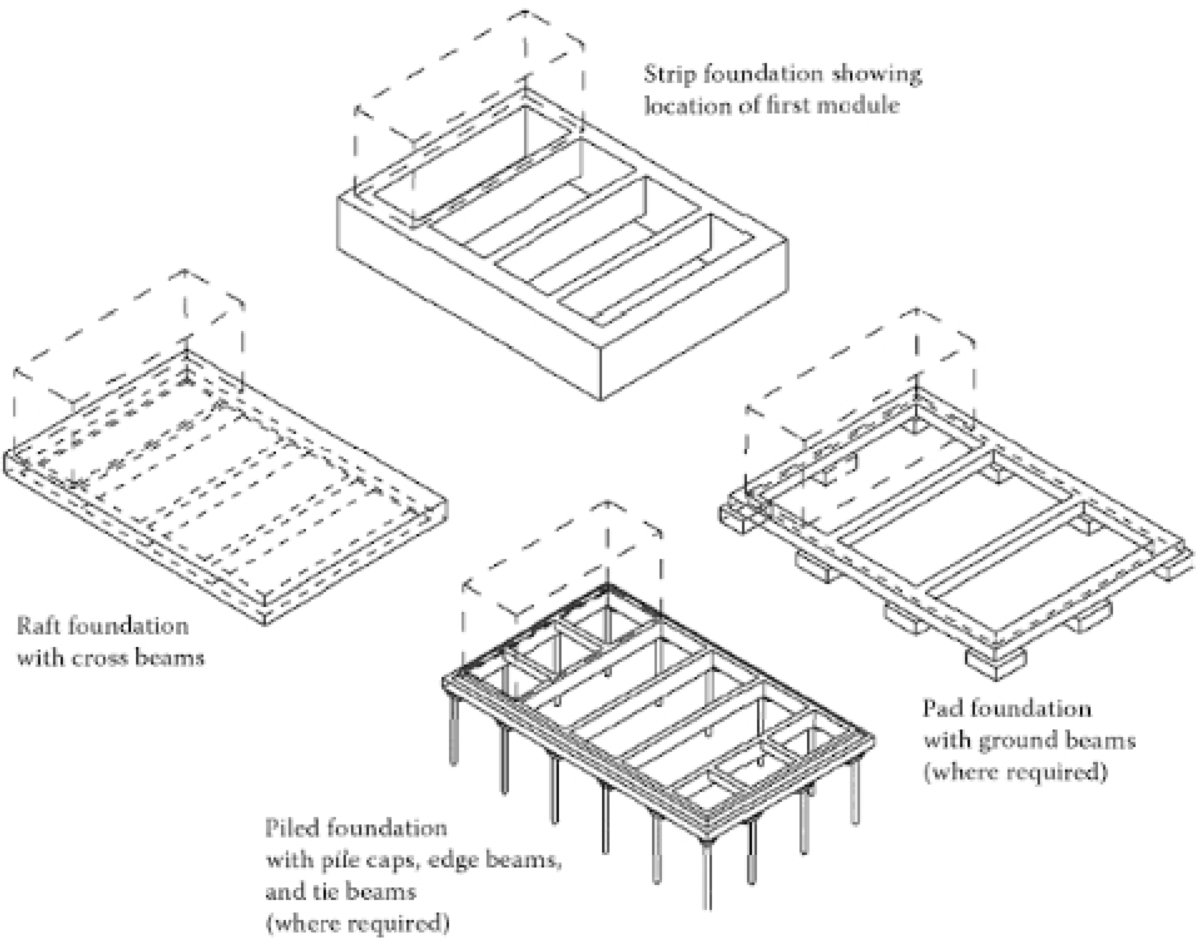


Figure 5.23. Foundation systems of modular buildings
(Lawson, M., Ogden, R., Design in modular construction)

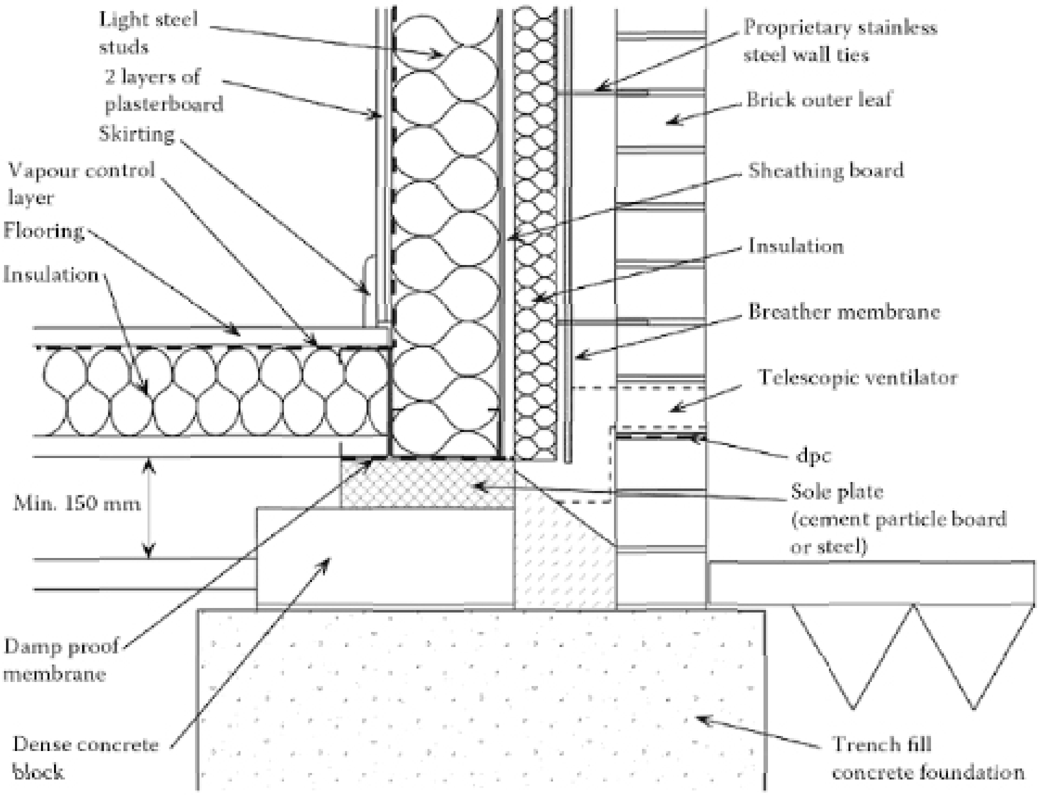


Figure 5.24. Trench fill foundation(Lawson, M., Ogden, R., Design in modular construction)

Craneage and installation.

Modules are lifted on their final positions on construction site by craneage of the lifting beam or from their corners in order to minimize vibration and to not damage internal finishings. Figure 5.25 demonstrates four most common lifting types of modules on site. First picture is single lifting beam accompanied by cross beams with vertical cables to the corners of the module. Second picture is manufactured frame with protected cage. Third situation is rectangular lifting frame allows to hold the module in intermediate points. Last one is single lifting beam with four inclined cables at the corners of the module. Type of the lifting depends on the structural scheme of the module. Modules with corner posts require cables at the corners (4th situation), while 4 sided modules can be lifted by crossbeam system (1st and 2d situations).

Choice of the crane depends on several factors. First one is particular construction site and operational radius. Second one is weight of the modules and scale of the project. Mobile cranes of 50, 75 and 100 tons capacity are usually used in modular assembly. This type of crane has great mobility on site which allows to move it during the day depends on one or another situation. Moreover, tower cranes, which has greater load capacity, cannot lift heavy loads at their full extension (Lawson, M., Ogden, R., Design in modular construction, 2011). Summary of the factors for choosing the crane for particular modular assembly on site is listed below.

On-site and public safety
Access for the mobile crane
Module dimensions and weights
Max reach of the crane to the module location
Site constrains
Ground-bearing pressures for the crane legs

(Lawson, M., Ogden, R., Design in modular construction, 2011)

Furthermore, additional force of 25% of the crane more than self-weight of the module should be considered for all types of the modules based on dynamic forces while lifting. Weight of steel modules ranges from 7 to 12 tones. However, heavy steel modules can weight from 15 to 25 tones, based on their concrete floor. Preferred method of lifting steel modules is two-dimensional frame. The particular module analyzed here has weight of 11,7 tons. Figure 5.26 shows action of the forces in light steel modules depends on the method of the lifting.

Figure 5.25. Lifting of the modules on construction site
(Lawson, M., Ogden, R., Design in modular construction)

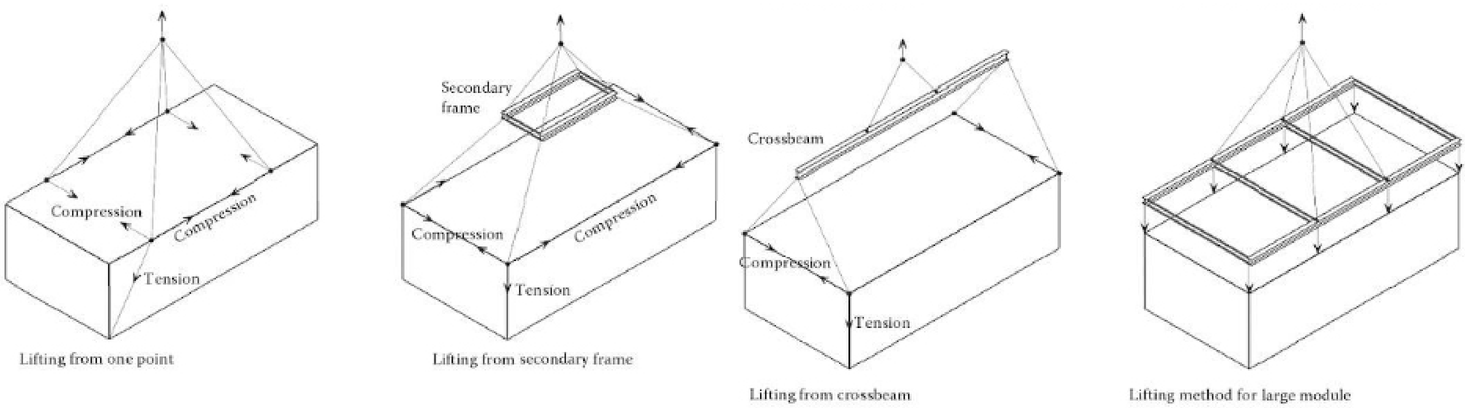


Figure 5.26. Forces in light steel modules depend on lifting method.
(Lawson, M., Ogden, R., Design in modular construction)

Appendix 13 summarizes all my calculations regarding on-site components of modular construction. Comparison with on-site works of traditional construction taken from Wiegerinck architects hospital project gives similar results. This acknowledges my own calculations, based on similarity of the works and operations required for on-site works in both types of construction. These operations include cleaning of the site, excavation, drainage, crane works, construction of foundations themselves.

Beside the aspects of operations required to be done on site and their costs, modular construction gives huge benefit in construction speed. After modules are manufactured and delivered to construction site, from 6 to 10 modules per day can be installed, depends on weather and specificities of construction site. (Lawson, M., Ogden, R., Design in modular construction, 2011). It means that from 180 to 300 square meters can be mounted in a day, if the module of 30 square meters is considered. To the contrast, conventional construction can erect only up to 80 square meters per day (Frank Michielen, 2017).

				0	0,00
(17)	paalfunderingen	m2		0	0,00
				0	0,00
	Hoofdgebouw:			0	0,00
	- paalfunderingen e.d.	1 pst.	2.278.053,00	2.278.053	28,76
	volgens opgave adviseur constructies excl. gebouwdel P			0	0,00
				0	0,00
	Passage:			0	0,00
	- paalfunderingen e.d.	1 pst.	397.613,00	397.613	5,02
	volgens opgave adviseur constructies			0	0,00
				0	0,00
	NSA-gebouw:			0	0,00
	- paalfunderingen	con.		0	0,00
				0	0,00
TOTAAL FUNDERING				**7.616.939**	96,17

B	**BOUWKOSTEN CONSTRUCTION COSTS (incl. BTW)**	**199.859.745**	2.523,48

Figure 5.27. Cost of foundation works and total construction budget of Wiegerinck arhitects hospital project(Wiegerinck architects, 2014)

Speed of installation of the modules on site also matters when the renovation of the hospital is in the focus. Quick mounting process allows not only complete the construction activity in a short time, but also to do it without disruption of the current hospital, since installation process is clean, wasteless and relatively quiet. That is why to build a hospital extension in a modular way is much easier rather than to do it in conventional one. Hospital extensions are relatively small in terms of square meters. De Meeuw company completed 8 healthcare projects, and 6 of them are extensions of current facilities, with total floor area from 600 to 7000 sq meters (De Meeuw, 2017). It allows to complete on-site works within a few weeks and start to use new hospital block in a short time. Time frame is always in the focus when hospital renovation takes place. It is even more important when hospital requires temporary accommodation of one of the departments while new building will be finished. In this case speed of construction is a crucial factor and modular solution is the only feasible way to do it (Mark van de Ven, 2016).

Sub-conclusion 5.6.

Parameter	Modular construction	Conventional construction
Cost of foundation works as % from total budget	**4%**	**4%**
Amount of m2 constructed per day	**180 - 300 m2**	**Up to 80 m2**

Conclusion of chapter 5

It is possible to state that the main savings in construction phase of modular hospital are time ones. While conventional construction can erect up to 80 m2 per day, modular one can result in 300 m2 based on speed of modules' installation on construction site. Another saving in modular variant is waste reduction, based on highly controlled manufacturing process. Modular production elaborates 3 times less waste than traditional on-site construction. Labor costs, however, are almost similar ones in both methods. Initial investments in modular factory are relatively high, and result in minimum 5 mln Euros and 6 months of time for completing the factory. At the same time, the assumption in this chapter is that factory is already built and initial expenses are not included in the total cost. The cost spread between installations and building components in both modular and traditional construction are similar, because there is equal set of elements are required.

Chapter 6.

MAINTENANCE & REFURBISHMENT PHASE.

Introduction.

This chapter dives into use characteristics of modular and traditional buildings. Such aspects as daily maintenance and refurbishment will be considered. The specific features of hospital maintenance will be described. It is important to stress the point that conventional building has different refurbishment procedure rather than modular one. Modular building is designed in advance for re-use, relocation and re-purpose, while traditional building requires higher resources for renovation and cannot be relocated to other site. Relocation of the modules will be also considered in this chapter. Use phase was not in the focus of this research at the beginning (see conceptual diagram). That is why the assumptions, findings and results of this part are limited. It is important, however, to touch maintenance phase of modular construction in order to see possible benefits of this method.

6.1. Daily maintenance

Daily maintenance expenses of the hospital can be considered as equal to construction (initial) investments in a long-term perspective (Frank Michielen, 2017). The period of long-term perspective here can be taken as 50-years one. It means that if the most expected price of construction of one module is equal to 52.800 Euro, the life-cycle expenses will be around 40.000 thousand Euros. The structure of hospital life cycle and the weight of its different components is represented below in figure 6.1. Authors of this article, Shohet M. I., Lavy-Leibovich, S. and Barn-on D. use Building Performance Indicators system in order to evaluate weights of different hospital components during the life span. BPI system is well-known for assessment of physical state and fitness of the building systems. Weighting of each building system represented in the table is accomplished by contribution of particular system to the total cost of erection, maintenance and replacement which all together result in life cycle costs. Each parameter in table 6.1 represents maximum score which can be achieved by the building in a perfect conditions.

Building system	(W_n) BPI
Skeleton	12.4
Interior finishing	34.8
Exterior envelope	5.3
Fire protection	2.2
Water and waste water	7.6
Elevators	4.1
Electrical systems	12.7
Communications	4.6
HVAC	13.7
Medical gases	2.6

Figure 6.1. BPI weights in hospital maintenance (Shohet M. I., Lavy-Leibovich, S. and Barn-on D, 2003)

Total BPI index higher than 80 gives an indication that building is in good conditions. When BPI is between 70 and 80 it means that some systems are at the end of their life cycle and some maintenance needs to be done. BPI rate between 60 and 70 reflects deterioration of the building and indicates that preventive maintenance should be carried out. Finally, if total BPI is lower than 60, it means that building is run-down.

The same article gives the exact percentages in assessment of hospital maintenance costs based on evaluation of 700 hospital buildings with different specializations, such as emergency, acute care, hospitalization, laboratories, clinics, offices. These buildings had also different area and age. All measures were taken for annual maintenance period. The distribution of the weights in hospital maintenance is:

Interior finishing: 32 %

HVAC: 29 %

Electricity: 13 %

Exterior envelope: 13 %

Water and plumbing: 10 %

Low-voltage systems: 3 %

Frank Michielen, manager of AT Osborne BV states that energy costs are the most part of hospital annual maintenance, and can result in up to 40% from hospital replacement costs (Michielen, M., 2017). Numbers above are correlated with this statement. Figure 6.1 on previous page confirms this statement as well and gives 41,2 BPI points for total energy systesms, such as HVAC, medical gases, communications, electrical systems and water (Shohet M. I., Lavy-Leibovich, S. and Barn-on D., 2003). Figure 6.2 below shows absolute summary numbers of the evaluation of 700 hospitals done by Shohet M. I., Lavy-Leibovich, S. and Barn-on D.. Annual maintenance budget is 2,2 % from entire hospital replacement cost. This corresponds with Frank Michielen's assessment of annual maintenance hospital costs equal to 2% (see appendi 18). Frank mentions that based on his experience hospital maintenance costs can be hardly reduced by higher initial measures and investments to the maintenance. Cleaning and maintennce companies, he says, calculate maintenance rates based on average assessments and do not care about additional measures which can be designed and built from the beginning. Frank adds that in one of the hospital projects he was involved maintenance company asked for 2 % annual reward from entire construction hospital cost disregarding on the additional measures AT Osborne BV did in order to provide higher and easier maintenance and to reduce annual maintenance costs (Frank Michielen interview, appendix 18).

Parameter	Mean
Average built-up area (sq m)	79 728
Average number of hospital patients' beds	658.1
Average occupancy (number of beds per 1000 sq m built-up area)	8.25
Average age of hospital buildings	38
Annual materials budget ($US)	347 236 (11.7%)
Annual personnel budget ($US)	1 533 088 (51.6%)
Annual budget for external contractors ($US)	1 088 941 (36.7%)
Total annual maintenance budget ($US)	2 969 265
Mean annual maintenance budget per built-up sq m ($US)	37.20
Annual maintenance budget per bed ($US)	4510
Reinstatement value per built-up sq m ($US)	1678
Average annual maintenance budget (% of reinstatement value)	2.22

Figure 6.2. Summary of sample characteristics of Israelian hospitals (Shohet M. I., Lavy-Leibovich, S. and Barn-on D, 2003)

It is hardly possible to say that the structure of annual maintenanse of modular and traditional hospital is different in many ways. All components of daily and annual maintenance mentioned above are typical for average hospital building. The warranty period in traditional construction, however, is highly depend on the particular building element or system as well as on particular contractor. Practical guide to Dutch building contracts regulates the procedures of appeal, responsibilities of the parties, etc, but does not give the exact periods of the warranty for building component or building in general (Chao Duvis et al, Practical guide to Dutch building contracts, 2008). Modular manufacturers, instead, provide warranty for entire building for 10 years, in general. It means, that any system, component or detail is under the warranty for this time period (Mark van de Ven interview, 2017, appendix 15). Since the module itself is factory-based product, its check-up, maintenance and repair are also factory-based activities. It results in precise time periods for checking of different components of the module (for instance, stability of metal frame). Computer software installed in modular factory warns in time such checking is required, and special crew goes to particular completed object for planned maintenance or repair. Such automatized system provides higher confidence for the client and reduces the number of claims and mismatches in maintenance of modular building. Similar to any factory produced product, such a smartphone, or car, modular factory provides authorized service system with qualified specialists who are able to fix the problems within a fixed period of time and really know all components and details of the entire building. Mark van den Ven gives 1,5 % from construction budget for annual maintenance cost in modular building (Mark van de Ven interview, 2017, Appendix 15). This reduction is based on the factors just described above.

Sub-conclusion 6.1.

Parameter	Modular construction	Conventional construction
Maintenance annual cost as % from construction budget	**2 %**	**2 %**
Warranty's period and nature	**10 Years for all componnents**	**Highly depends on contractor and other factors**

6.2. Refurbishment

Refurbishment phase in modular construction is a third important benefit in addition to shorter construction time and lean management techniques. The last one is mentioned in part 2.2. While refurbishment of traditional hospital is always unique procedure which demands new design layout from the ground level, modular hospital provides the number of pre-designed transformations which can be done in a fixed period of time with known results. From the first point of view refurbishment of modular building allows less number of options in comparing to traditional renovation process, when the unique project starts from the ground. However, production process of the modules is highly flexible and allows to implement changes and new layouts. That is why factory-based refurbishment process can be from 25 to 50 % cheaper comparing to traditional renovation process (Schoenborn, J. M., 2012).This discount is based on several factors:

- modular producer knows in advance all refurbishment options and can predict refurbishment costs

- Check-up of the used module has standard procedure according to the code, while renovation of traditional building requires different procedures depend on building's conditions

- High number of module's elements can be re-used and recycled up to 70 %, while recycle in traditional refurbishment is around 30 % only (see 6.1)

- Design layouts of refurbishment in modular buolding are done in advance, and there is no additional architectural fees required

- Conditions of used modules are generally good enough and do not require a lot of maintenance. The only costs are re-build of the layout

- Used modules are 20 % cheaper on the market comparing to new ones

The comparison of hospital refurbishment in traditional and modular construction is given below based on the assumption of 25-50 % cost reduction in modular refurbishment.

Hospital department	Modular construction (m2)	Conventional construction (m2)
Entrance & lobby	780 - 1100 Euro	1177 - 1670 Euro
Administration & offices	650 - 730 Euro	984 - 1337 Euro
Waiting room spaces	621 - 811 Euro	941 - 1230 Euro
Exam & clinic spaces	950 - 1170 Euro	1440 - 1770 Euro
Emergency	1650 - 772 Euro	2510 - 3134 Euro
Patient wards	1380 - 1750 Euro	2090 - 2666 Euro
Surgery	1700 - 2360 Euro	2587 - 3582 Euro
Intensive care unit	1500 - 1800 Euro	2288 - 2786 Euro
Laboratories, pharmacies	1400 - 1750 Euro	2140 - 2640 Euro
Imaging (MRI)	1540 - 2000 Euro	2340 - 3080 Euro
Dining spaces & cafeteries	790 - 1300 Euro	1200 - 1990 Euro

Figure 6.3. Comparison of refurbishment cost for modular and conventional construction (Based on JE Dunn, Schoenborn, J. M., 2012

Mark van de Ven, De Meeuw manager, mentions that the inspection of used modules can be done on their current site, without transferring them back to the factory (Mark van de Ven interview, appendix 15). This can happen in case new customer accepts current modules' layout. In this regard, transportation costs are reduced by half, because each module is sent directly to the new site without going back to the factory. Maintenance crew of modular factory check the state of the art of modules on site and prepre them for transportation. However, this does not happen a lot, Mark states, and usually refurbishment of walls and other finishings takes place. At the same time, as it was previously mentioned, 70 % of module's elements and materials are re-used or re-cycled, which results in sufficient part of the total savings.

Overall, refurbishment of modular building has pre-defined step-by-step plan, which results in significant cost savings, transparent procedure and highly reliable time schedule. These benefits are summarized in paragraph below. The important factor is that used modules are cost 25-30 % cheaper comparing to new ones based on amortization period.

Sub-conclusion 6.2.

Parameter	Modular construction	Conventional construction
Refurbishment costs savings	**25 - 50 % from conventional one**	**Highly depends on the case**
Refurbishment time savings	**Highly depends on the case; Small chnges takes a day**	**Highly depends on the case**

6.3. Relocation of the modules.

Possibility for relocation of the module to a new site is fourth significant benefit of modular construction, and continuous of the refurbishment phase. The nature of real estate property lies within impossibility to relocate it. Once the building is built, it can only be renovated, refurbished or demolished in the same place. Modular building, to the opposite, can be relocated and used for another period of time. This option is very attractive for those developers and parties who rent the land for a period o time. In this case they can relocate their modular building after the end of the land lease.

In general, relocation of the modular building to new site includes steps such as:

Preparation of modules for transportation (take out fittings, connection, etc)

Transportation of the modules to new site

On-site and assembly works of modules on new site

Last two operations were already described in details and calculated in chapter 2. First part, prepartion of the modules for re-location, can be partially extracted from on-site works part, since cranage, (dis) assembly, on-site personnel are represented there. Appendix 14 reveals cost assumption for relocation of considered module to a new site.

Re-location cost of one module varies from 4.870 Euro to 6.768 Euro with the most expected price of 6.000 Euro. The assumption here is that inspection of the module for safety, structural stability, etc takes place on original construction site, without transportation to the factory. Based on Mark van den Ven experience it is possible and happens in many cases (Mark van de Ven interview, Appendix 15). These costs are compensated by quick erection of the modules on the new site and extension of their life cycle.

Sub-conclusion 6.3

Parameter	Modular construction	Conventional construction
Re-location costs of the module	4.800 - 6.700 Euro (10 - 15 % from total module cost)	Not applicable
Re-location time of one module	Depend on the new site	Not applicable

Conclusion of chapter 6.

Use phase of modular building has a lot of in common with maintenance of traditional building, while such aspects as relocation of the building are unique. Daily maintenance of both building types are similar, with the most expenses dedicated to energy consumption. Relatively small repair can be done faster in modular variant, since all components are standardized. However, additional time may be required to change one or another element, based on over- or underheads in the modular factory. That is why an average percentage equal to 2 % for daily maintenance expenses can be applicable to both conventional and modular construction.

Refurbishment of modular building has a number of advantages in time and cost aspects comparing to traditional one. Conventional building is unique, and its renovation or refurbishment process requires new detailed design project, getting permits for re-development and takes significant amount of time. Modular building, to the opposite, is standardized, and this standardization allows to refurbish it quickly. In general, cost savings in modular refurbishment are 25 - 50 % lower comparing to traditional one. This discount includes possible revenues from re-use and re-cycle of materials and elements used in modules which is around 70%, while in conventional construction it only takes 30 %.

Relocation of modular building is unique option. It consists of the same procedures as original assembly process, except production of the module. An estimated cost of re-location of the module considered in this research varies from 4.800 to 6.700 Euro (Author, 2017). This price does not include inspection of the module in the factory, which might be required in some cases. Module checks-up on site and sends to the new one. The life-span of modular building varies significantly. In average, they are used for 10-15 years, while some can be in use for 30 years (Mark van de Ven interview, appendix 15). The benefit of used modules is that their price is lower for 25- 30 % comparing to the new ones. Re-location of modular structure can be an attractive option for those developers and parties who rents the land. Quick and undisruptive installation procedure of the modules on site makes this solution valuable specifically for hospitals, since there is no need to interrupt healthcare process in existing building. Table below summarises costs benefits of use of modular building.

Parameter	Modular construction	Conventional construction
Annual maintenance costs	2 %	2 %
Refurbishment costs	25 - 50 % from conventional one	Highly depends on the case
Relocation costs	4.800 - 6.700 Euro per module	Non applicable

Chapter 7.

CONCLUSION.

This chapter will summarize research findings, provide an answers to research questions and describe further strategies and ways in research and development of modular construction. Summary of all time and cost savings in all described phases will be presented. Post - assessment interviews with the experts regarding validity of research results will be incorporated in final part of the chapter.

7.1. Savings in modular construction.

The aim of this research is to analyze modular construction process in its design, construction and maintenance phases in order to find possible financial and time savings in each of them. Table 7.1 represented below summarizes all findings of this research regarding potential savings in modular construction.

	Parameter	Modular construction	Conventional construction	Savings, %
Design phase	**Costs**	**50 % from conventional design (3 - 4% of total budget)**	**6 - 8 % from total budget**	**50 %**
	Time	**15 - 80 % faster comparing to conventional design ***	**Depend on the case**	**15 - 80 %**
Construction phase	**Costs**	**52.900 Euro / module 1800 Euro / m2 ***	**2500 Euro / m2**	**28 %**
	Time	**180 - 300 m2 / day**	**Up to 80 m2 / day**	**80 %**
Use phase	**Costs**	**2 % / year from construction budget**	**2 % / year from construction budget**	**None**
Refurbishment phase	**Costs**	**25 - 50 % from conventional construction**	**Highly depends on the case**	**25 - 50 %**
	Time	**Highly depends on the case**	**Highly depends on the case**	**Depends on case**

* - including VAT (21 %)

Figure 7.1. Summary of comparison modular and conventional construction (Author, 2017)

Savings in design phase are highly related with technical request of the client. In ideal situation, the layout pre-designed by modular manufacturer in advance is suitable and construction drawings can be immediately sent to production line. In this case, design costs do not exist. However, in most of the cases every new commission is different from each other, and detailed design layout of particular set of the modules is required. Based on fully standardized set of elements which can substitute each other in different projects, total design costs are equal to 3-4 % from total construction budget. In conventional construction, this percentage is around 6-8 % with possibility to reach 12 % in complicated cases. That is why modular design phase is 50 % cheaper comparing to traditional one. The important circumstance here is an existing of pre-designed modular system at the moment of new project starts. Pre-design of modular system together with use of BIM gives around 15% savings in time schedule, comparing to traditional design phase.

Savings in construction phase are mostly come from speed of construction. Once the modules arrive to construction site, from 6 to 10 of them can be assembled in one day, which is equal to 180 - 300 m2, while traditional construction can provide up to 80 square meters per day. Construction costs of one module calculated in this research are equal to 52.800 Euro, or 1846 Euro / m2. Traditional hospital construction cost fluctuates between 2.000 and 2.500 Euro per square meter. This gap is mainly based on differences in medical equipment costs. The module analyzed here is individual inpatient ward. Despite the fact that medical equipment such medical gas system, patient multi-functional bed, HEPA filters and some other are included in the final price, this department cannot be considered as highly equipped medical department. The cost of surgery room, that is why, will be higher based on medical installations. Case study hospital brief of Wiegerinck architects analyzed in this report has the price of 2.500 Euro / m2. It is based on diferent hospital equipment installed in the project and does not limited by in-patient wards only. Construction costs themselves (without installation costs) are between 33 and 37 % of the total module cost, while in traditional construction it takes 38% and higher (Wiegerinck architects, 2017). Total costs savings in construction phase of the analyzed module varies from 8 to 27 %. This gap mainly depends on the amount of installed medical equipment, described above. Transportation costs of the module is the second important factor, which highly depends on the particular route and distance from factory to the site. Savings in construction phase of the module are also come from labor cost, which is cheaper than conventional on-site wages, and highly regulated in terms of time as well. All operations in module production are predicted, controlled and known in advance, which results in a fixed amount of time required for production. Supply chain and TAKT time, described in chapter 2 are main factors here. Conventional on-site construction is highly depend on big number of independent suppliers and suffers from weather conditions, while factory production is uninterrupted. It is important to say that set-up costs of development of modular factory are not included in these numbers, and the assumption here is that modules are ordered from existing plant. The investment costs of average modular factory, however, are described in section 2.1.

Savings in use phase were not identified during the research, since hospital systems require the same amount of supplies regardless of the type of the building. Annual cost of hospital maintenance is 2 % from total construction budget. It is possible to say that maintenance of building elements (facades, fittings, etc) in modular variant can be lower based on fixed number of elements in modular construction and availability of them in factory storage place, while in traditional construction change of particular element can take more time. However, it is hardly possible to say that modular building has significant savings in front of conventional one in use phase.

Savings in refurbishment phase of modular construction are quite significant comparing to conventional one. First of all, modular construction can re-use and re-cycle 70 % of the materials and elements it takes, and this percentage is growing. It means that additional revenues can be gained based on it. Secondly, refurbishment time is less based on pre-designed layout and fixed number of module's elements, which can be, at the same time, used in different modular systems. However, time is highly depend on the number of refurbishment works need to be done. If it is minor changes, it can be completed in a day on assembly line. If it is great changes, than it takes longer. Third benefit of modular construction is possibility to relocate modules to the new site and extend their life cycle, instead of demolish or refurbish a building, as it happens in traditional construction. In case of land lease, the owner of modular building can relocate it and continue to use it in a new place. Based on these factors, complex process of refurbishment in modular construction is from 25 to 50 % cheaper comparing to traditional building renovation.

7.2. Answers to research questions.

7.2.1. To which extent are prefab solutions in healthcare design and construction are more economically feasible than traditional methods?

Time. Modular hospital can be built from the ground. It is a fact confirmed by several experts in this research (see appendixes 15-19). The main benefit of modular construction is time required to complete the building. Modular building can be assembled from 2 to 3 times faster comparing to traditional one (see chapter 5, construction phase). This results in fast start of hospital's use phase, which brings not only earlier revenues, but also allows to provide healthcare in limited time period which is quite important for hospital typology. The conclusion is that if time is the critical factor, modular construction is definitely feasible solution.

Cost. The cost of each construction project is unique based on its circumstances, goals, location and man y other factors. This research compares the main aspects of design, construction and maintenance process for an average module with UFA of 29 square meters and for one square meter in traditional hospital construction. Construction cost of 1 m2 of the module was calculated equal to 1.846 Euro, while construction cost in compared traditional hospital was equal to 2.533 Euro / m2. It results in 27 % of costs savings when modular method is used. It is important to mention, however, that usual marginal cost per square meter in Dutch state hospitals should be less or equal to 2.000 Euro/m2. Since hospital development is primarily governmental activity, this price per square meter can be taken as a constant. In this case, cost savings based on modular construction are equal to 8 - 9 %. Literature research presented in chapter 3 reports savings between 11 and 19 % comparing to conventional construction methods. It is possible to say, then, that these research findings, which gives cost savings in modular variant between 9 and 27 %, are realistic. A very important factor of hospital development cost is medical equipment and installations. Depends on the nature of the hospital, cost of equipment can vary really high. The module considered in this research is an individual in-patient ward. That is why equipment cost for this hospital typology is not the highest among hospital departments. Surgery room or MRI block will have a higher price/m2 based on higher equipment level.

Time, then, is the most important saving factor in modular construction. A lot of hospital extensions, therefore, are ideal situations for modular construction, when construction process should be done in a very limited period of time and without disruption of existing facility.

7.2.2. To what extent is prefab used in current situation in healthcare sector?

Modular construction in healthcare is currently used mainly in extensions of healthcare facilities. This is partially related with regulations which allow to use modular building as temporary structure for several years. Traditional hospital construction mainly uses prefabricated bathroom pods and facade panels. Some recent projects, such as Miami Valley hospital completed in 2012, use internal prefabricated walls with integrated headwall systems for in-patient wards. Another current modular component used in hospital development is MEP installations, pre-assembled in a factory and mounted above the ceiling and in other places on a construction site in a quick way. Modular construction, at the same time, uses fully prefabricated volumetric modules to complete the hospital. Several companies in Netherlands, Germany and Latvia are specialized in modular hospital construction. The choice of construction method, therefore, is depend on the client and particular project circumstances. Modular hospital construction is the most promising and growing sector, right after sub-urban housing, which is growing now. (Mark van de Ven interview, appendix 15).

7.2.3. To what extent is enlarging the amount of prefab elements feasible considering the design and construction process?

This research explored fully prefabricated 3d-dimentional modules as the maximum scenario in order to see the possible benefits of off-site construction. Pre-designed layout of hospital departments and, at the same time, possibility to customize them for particular client gives a wide range of prefabrication options. When time is the critical factor and the hospital (or, hospital extension) needs to be completed in a short period of time, fully prefabrication and 3d-dimentional construction is definitely an option, since construction schedule is reduced by 50 % in a modular way. It is important to stress the point that time savings do not result in lower quality, but, to the opposite, provide higher quality control and material savings based on lean management and careful production flow (see part 2.2). It is possible to say, then, that when short construction time schedule together with efficient and quality-controlled construction environment is a goal, fully modular construction is an option. Cost savings from 9 to 27 % comparing to traditional construction is another benefit. It is important to say, however, that even if modular variant is more expensive than conventional method, start of use phase of the hospital is still much earlier, and revenues from hospital activity start to accumulate earlier.

7.2.4. Which parts of the healthcare facilities are mostly suitable for implementation prefab solutions in a cost-effective way?

As it was stated in the report, fully operated hospital can be built from the ground in a modular way. That is why all hospital departments are suitable for modular construction. However, based on the set of interviews and literature review done in this research it is possible to state that those hospital departments which are highly equipped with electronic and special medical devices are the first candidates for modular construction. Surgery rooms, MRI units, intensive care wards - these departments are recommended to build in a modular way in order to test all systems in advance in a factory and then transport them to construction site (Mark van de Ven interview, appendix 15). The benefit of their construction in a modular way is a short time of completion. Based on the actual hospital demand these units can be assembled in the factory in a short way and installed in the hospital quite quickly without any disruption of current facility, which is very important for continuity of hospital operation flow. These modules are ordered as real manufactured products, with high level of quality control and warranty for all electronic systems they contain. This complex warranty is another benefit of such devices. Easier and integrated maintenance provided by modular manufacturer eliminates daily problems and reduces time for maintenance. The cost of maintenance, however, is not lower than in traditional construction (see part 3.1).

7.4. Post-assesment of the research results by experts.

Last part of conclusion chapter is results of assessment of the research by external experts and figure out do the results make sence. The report presnts 3 main stages in modules life cycle - design, manufacturing and use. Results of each phase were discussed with experts. Their comments are given below.

7.4.1. Mark van de Ven, manager of De Meeuw modular company. Validation interview.

Design phase.

The results of design phase, where the 15% savings in time and 50% savings in cost were identified is approved by the experts (see chapter 4). Cost savings are mainly based on possibility to recycle and reuse 90% of the module's components. Based on the profit gained by company from re-use of such components, as well as on standardized elements which can still be resulted in very different design layouts, design cost is twice cheaper in modular variant rather than in conventional one. Speaking about the time required to design proposal in modular and in traditional way, it takes 1-2 days to prepare a hospital layout, while for external architect (with whom modular companies cooperate sometimes), it takes 2 weeks. This is based on use of standard components which can still result in quite different design layouts (Mark van de Ven interview, 2017, Appendix 15). That is why modular design is mostly about combining separate units into entire building, when the modules themselves are pre-designed in Revit. It is possible to make a special and unique design, but in this case De Meeuw would not take such module back, because its components are not usable in other modules. That is why most of the clients agree on design proposed by De Meeuw, which, again, can be quite specific but is based on their standard elements.

Construction phase.

Some of the construction phase results are not in line with actual practice of De Meeuw. The number of hours required to produce one module presented in the book A guide for home factory building is totally wrong, compared with De Meeuw practice. Author of the book gives a range from 117 to 366 man-hours, while De Meeuw spends between 16 hours for simple module and 60 hours for very complicated and luxury module which needs to be tested against explosion.

Another dis-match is in calculation of labor costs. The hourly wage of workers in factory is correct, and equals to 17-19 Euros / hour, but it is only direct costs. Indirect costs, which are cost of equipment, cost of electricity, maintenance, raw materials, etc give total hourly cost of 40-50 Euros. The most important mis-match is the number of hours required to produce a module. While Mullens M.A. gives a range from 117 to 366 labor-hours, De Meeuw provides an amount of 16-60 hours. 16 hours is a minimum one, while for really complicated module it takes up to 60 hours. It also depends on factory organization and module's structure. For example, if the concrete needs to be dry before going to the next work station, it takes more time than in steel module, which does not require dry period.

Speaking about speed of construction, the rate from 170 - 300 m2 per day, or up to 10 modules is true and can be gained in real practice. De Meeuw can mount even 20-24 modules in a day, which results in 360 m2, when each modules is 18 square meters. Transportation cost of the module is too high, however. It is around 1.000 Euros in The Netherlands. Transportation costs in other can vary significantly.

On-site works are really tricky. It is difficult to calculate their total price, and it is highly depend on foundation, which can be very cheap, 50 Euros/m2.

Use phase.

Annual daily maintenance equal to 2% from construction budget sounds feasible, as well as discount of 25-50 % for refurbishment comparing to traditional one. Refurbishment is really depend on what the client wants, and it is difficult to name the exact time it takes. If it is cosmetic refurbishment, or if only some minor elements need to be changed, it takes a few hours on assembly line to do it. Module is taken to the factory, where crew changes some elements. In general, it would not take longer than a day.

Relocation of the module would cost 4,5 - 6,5 thousands Euros per module, this number itself is correct but it also should be equal to 30% of the module's cost, which results in 18-20 thousands Euros as a total cost of the module, which is much higher, in my calculations.

Total price of the module.

Total price of the module calculated in this research is 52.900 Euro, or 1.800 Euro / m2. It is high price, and De Meuuw hospital unit costs 1.500 Euro / m2, with really luxury finishings and installations. De Meuuw also produces module with price per square meter of 2.250 Euros, but it was special one. The main shift in price is based on finishings and external cladding materials. The more luxury finishings are, the more costly the module is.

7.4.2. Wiegerinck Architects. Dutch architectural bureau specialized in hospital design. Validation inteview.

Despite great number of hospitals designed and built by Wiegerinck architects, they didn't use fully modular solutions in their practice. Problem of hospital flexibility, described in details in chapter 2, is mainly solved by wider grid of the columns in bureaus' projects. Wider span allows to put different hospital departments between columns. At the same time, the practice of changing function of the floor of hospital building is not common, Wiegerinck Architects state. A hot floor, for instance, is too complicated to replace it by another department within the same place. Wiegerinck didn't change original function of the hospital floor they designed to another one, in their practice. It is possible to do it based on design, but it does not happen in practice, usually. When particular hospital needs renovation or requires additional space, it is designed and built next to original complex.

Prefabricated elements which are mostly used in hospital design are facade panels, floor slabs, windows and big number of smaller components. 3d modular components and units are not used in bureau practice. Fully modular extension of the hospital is not considered as an optimal solution by the architects of the bureau, based on architectural quality of the module. Following by traditional way of design, architects require and stand for normal facade design and other things applied to conventional architectural process. An extension of the hospital in a modular way is considered as disturbing factor for original design. New modules cannot be in line with original design code of the complex, and bring haos in the hospital complex. That is why modular extension does not favor option from traditional design point of view.

The design fee as % from entire budget in traditional design is 5 - 6 %. This number is in line with findings of this research. Total price per square meter is also correlate with research findings, and equal to 2,5 thousand Euros. This number is an average price of hospital development. Refurbishment price of the hospital building is estimated as 65 % from original construction cost. This number is applied to heavy refurbishment, when all interior structures are demolished.

7.4.3. Hatice Cigdem Demirel, PhD Researcher, TU Delft. Validation interview.

Cigdem is a PhD researcher in TU Delft and member of Arup office in The Netherlands. Despite the fact that she is not an expert in modular construction in particular, she kindly agreed to revise the conclusions of my research and give further recommendations.

The two parameters which were investigated in my research are cost and time. Since economic feasibility of modular hospital construction was the main focus of the research, its monetary aspects were considered by me since the beginning. I specifically was not focused on qualitative parameters, since the entire MBE track, in my point of view, is about quantitaive parameters of management in a built environment. Moreover, Politecnico di Milano master thesis done by me a year ago was entierly dedicated to spatial, architctural, aesthetic and qualitative characteristic features of modular flexible hospital. Cigdem, however, rised the questions of risk allocation along the modular development process and organizational structure of modular construction process. The proposal from her side was to add these two parameters - risk and organizational structure - to initial time and cost factors investigated in the research. Organizational structure of modular company was explained in the research in chapter 4, Design phase, as well as in chapter 5, Construction phase, where factory layouts and their effect on production process were described. Based on the fact that Cigdem was involved in my research process on the very last stage (3 weeks before graduation), the decision do not change the initial structure of the report was made. At the same time, based on the fact that this chapter can be used for additional information and comparing my own results with experts' point of view, this part will explain risks and stakeholder involvement in modular construction.

Risks in modular construction.

Design phase chapter 2 presented a table of risk comparison between different construction systems, from traditional, fully on-site ones to fully modular ones (see figure 7.2 below). It is clear that risk allocation in modular construction is grouped at the beginning of the development process, since early decisions affect the later phases. While in traditional construction risks are mainly related with

Table 18.3 Summary of perceived risks for various forms of construction

Process stage	*Risk description*	*Brick and block*	*Open panel*	*Hybrid*	*Modular*
Planning	Unpredictable planning decisions			○	○
Preconstruction	Late appointment of supplier		○	●	●
Preconstruction	Lack of standardisation possible in the manufactured components		○	●	●
Detail design	Design changes after placement of order		○	●	●
Construction	Foundation inaccuracy affects installation		○	●	●
Construction	On-site components may be incompatible with manufactured components			○	●
Construction	Quality and accuracy problems	○			
Construction	Price fluctuations during construction	●			
Construction	Delays due to bad weather	●	○		
Construction	Lack of trade skills on site	●	○		
Construction	Service installation faults	●	○		
Construction	Health and safety hazards	●	○		
Occupation	Completed construction not to specification	●	○		
Occupation	Defects at handover or in liability period	●	○		

Source: National Audit Office, *Using Modern Methods of Construction to Build More Homes Quickly and Efficiently*, 2005.

Note: ● = high risk, ○ = medium risk.

Figure 7.2. Comparison of risks in different types of construction (source: Lawson, M et al, Design in modular construction, 2014)

execution phase, and based on delays in construction materials supply, weather conditions, etc., risks in modular construction are grouped in ealry design phases, when key decisions, such as dimensions of the module, its structural frame and other parameters are settled.

Louise Matheson in his research “Modular buildings - associated issues and risks” mentions several risks related with modular construction (Matheson, L., 2012).

Value for money is significant risk in his classification. It is mainly based on time required to produce a module itself and time required to prepare the site and to procure all related infrastructure works on site. The type of procurement, in this sense, is quite important. Procurement of on-site works under traditional procedure can result in delay of finishing the whole project. IPD contracts, mentioned in Design phase, chapter 4, have an aim to avoid these delays and start site preparation and procurement earlier based on involvement of on-site specialists and modular manufacturers in early process stages.

Maintenance is the second risk mentioned by Matheson. In a long-term basis, modular building demands higher maintenance investments while the value of the building decreases significantly, Matheson states. In other words, capital value of modular buildings depreciates over time, while capital value of traditional building tends to be more stable (Matheson, L., 2012).

Engagement of other parties is another risk. Manufacturing of all components for modular building takes place in modular factory. Modular manufacturer, then, is the only player who controls quality, supply chain and management of production process. Such type of organization helps to control quality and to reduce delays, but, on the other hand, maintenance is highly dependent on modular manufacturer as well. In this case, all substantial elements and maintenance operations required for modular building are executed by one modular manufacturer. To find another supplier and maintenance operator for modular building, therefore, is quite difficult. This situation can result in increase of maintenance costs based on exclusive position of modular manufacturer.

Organizational structure of modular construction development process.

The layouts of modular factory which is the main stage in modular production were explained in details in Construction phase, chapter 5. The organization of the development process in modular construction, however, was not in focus of this research. That is why some aspects of such organization will be present in this part of the chapter.

Design phase.

Design phase in modular construction is usually executed by modular manufacturer (Lawson, M., Ogden, R., Design in modular construction). That is why, modular manufacturer is a main contractor in modular construction process. Related specialists, such as engineers, designers, etc. are special departments of modular construction company. Depends on the size of the company, some advisors and consultants can be hired outside. However, modular constructors tend to get the main specialists in-house, since in this case they work in line with exact requirements of modular construction company. Clients, in many ways, are more comfortable to communicate with the main contractor, who is responsible for all processes. Modular construction, in this sense, has higher quality control and reliable time frame based on lean management concept (see chapter 3). Based on pre-designed layouts, the design phase itself can be eliminated, or take ust a few days. There is more time is spent to negotiation and consultation with the client regarding final design rather then on design itself.

Construction phase.

Construction process takes place in modular factory, where 90 % of the building is completed. Based on direct collaboration between client and modular manufacturer, and fixed number of operations in the factory, when time, cost and quality are highly controlled, construction phase goes in line with design solutions. Figure 7.3 shows IPD type of contract in modular development process, when

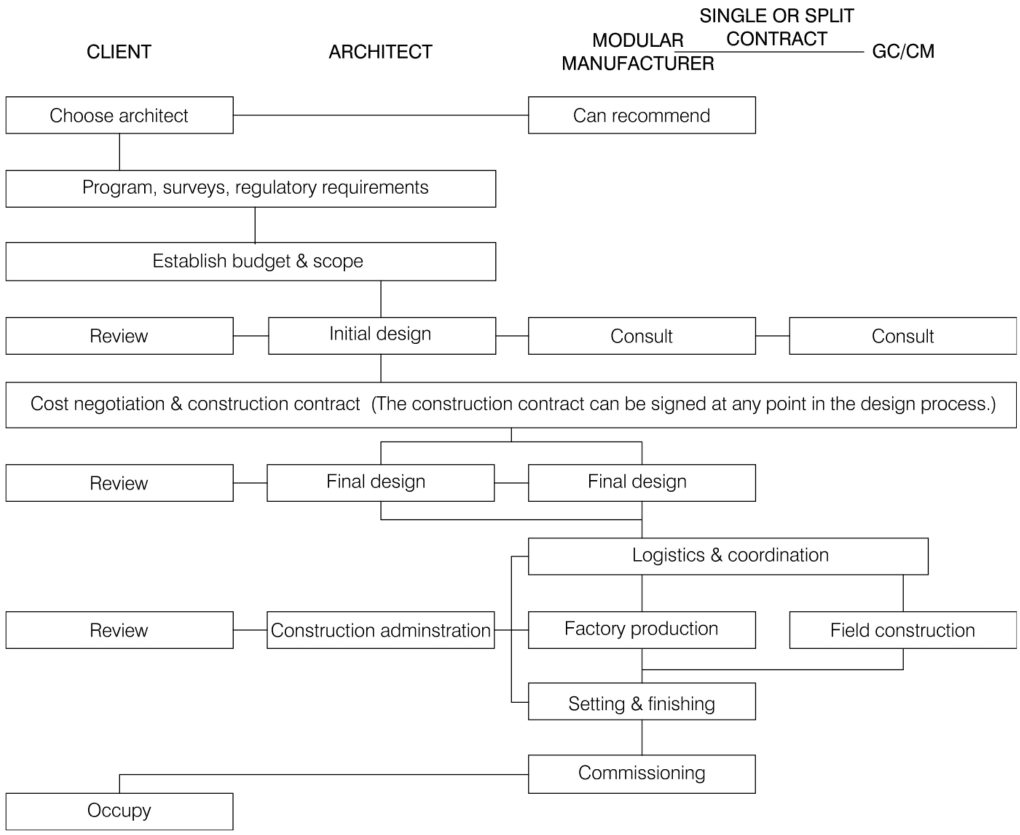


Figure 7.3. IPD contract flowchart
(source: Lawson, M et al, Design in modular construction, 2014)

Modular manufacturer is responsible for final product in all phases, while external consultants, such as external architect, can be hired to advise on some points. It is important to mention that modular building producers do not allow external architects to influence project a lot, since the final product would be changed drastically and completion of the final product would be delayed significantly. It is possible to state, then, that modular construction process is vertically integrated system with fixed number of steps and possibility to attract external consultants in case they are needed.

Use phase.

Based on presence of modular manufacturer as the main actor in modular construction, maintenance of modular building is also his exclusive responsibility. Since design of the module was done by modular manufacturer, he has all additional components for replacement, maintenance and refurbishment of modular building during its life cycle. That is why common warranty period given by modular manufacturer is 10 years or more. Client is directly connected with modular supplier during warranty period and can solve all problems with personal manager of the modular company, instead of spending time for different suppliers.

7.4.4. Literature review.

In order to make additional validation round of research results, another set of literature review was done. This review investigated time and cost savings in modulr construction - two parameters analyzed in the research.

Modular Building Institute.

Modular Building Institute is one of the most prominent resources for modular construction. There is a wide range of publications and papers under the brand MBI. This collection of articles investigates costs and benefits of modular construction and keep the reader with most up-to date innovations in this construction sector. **MBI identifies total time savings in modular construction from 30 to 50 %**. Figure 7.4 shows that most of these savings come from construction phase, when module's manufacturing and site development go in parallel. 50 % savings are quite optimistic, but 30 % is in line with my own findings (Modular Building Institute, 2016).

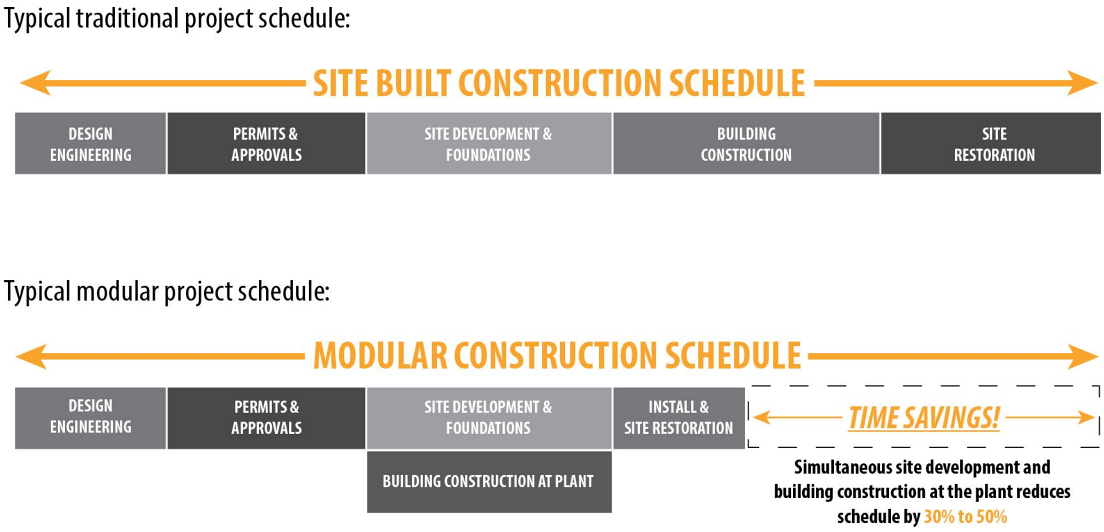


Figure 7.4. Comparison of on-site and modular construction process (Modular Building Institute, 2016)

Cost savings in modular construction identified by MBI are vary from 25 to 40% less than traditional construction costs are (Modular Building Institute, 2016). According to MBI, the majority of these savings come from construction phase, based on strict lean management, highly controlled factory environment and fixed time schedule. MBI does not identify any savings in use and maintenance phase, while concentrates on design and construction phases only.

McGraw & Hill. Modularization in construction industry. Report 2016.

McGraw & Hill is one of the major magazines dedicated to modular construction. Their annual report analyzes great number of indicators in modular construction. Report of 2016 identifies savings in both time and costs. Time savings identified in design phase vary from 5 to 25 % comparing to traditional construction, while construction phase gets up to 4 weeks savings (McGraw & Hill, Modularization in construction industry report, 2016). Cost savings identified by the report for design phase are highly varied, but identified up to 75% comparing to on-site methods. Construction phase gives 25% savings, while there are no savings mentioned in maintenance phase.

7.4.5. Cepezed validation interview.

Cepezed architectural bureau is situated in Delft and specialized in different architectural typologies. They also work with healthcare typologies. Since modularity and prefabrication is the philosophy of Cepezed, their validation of my research results is quite valuable. Joost Heijnis, an architect, kindly agreed to discuss my results of the research.

Design phase

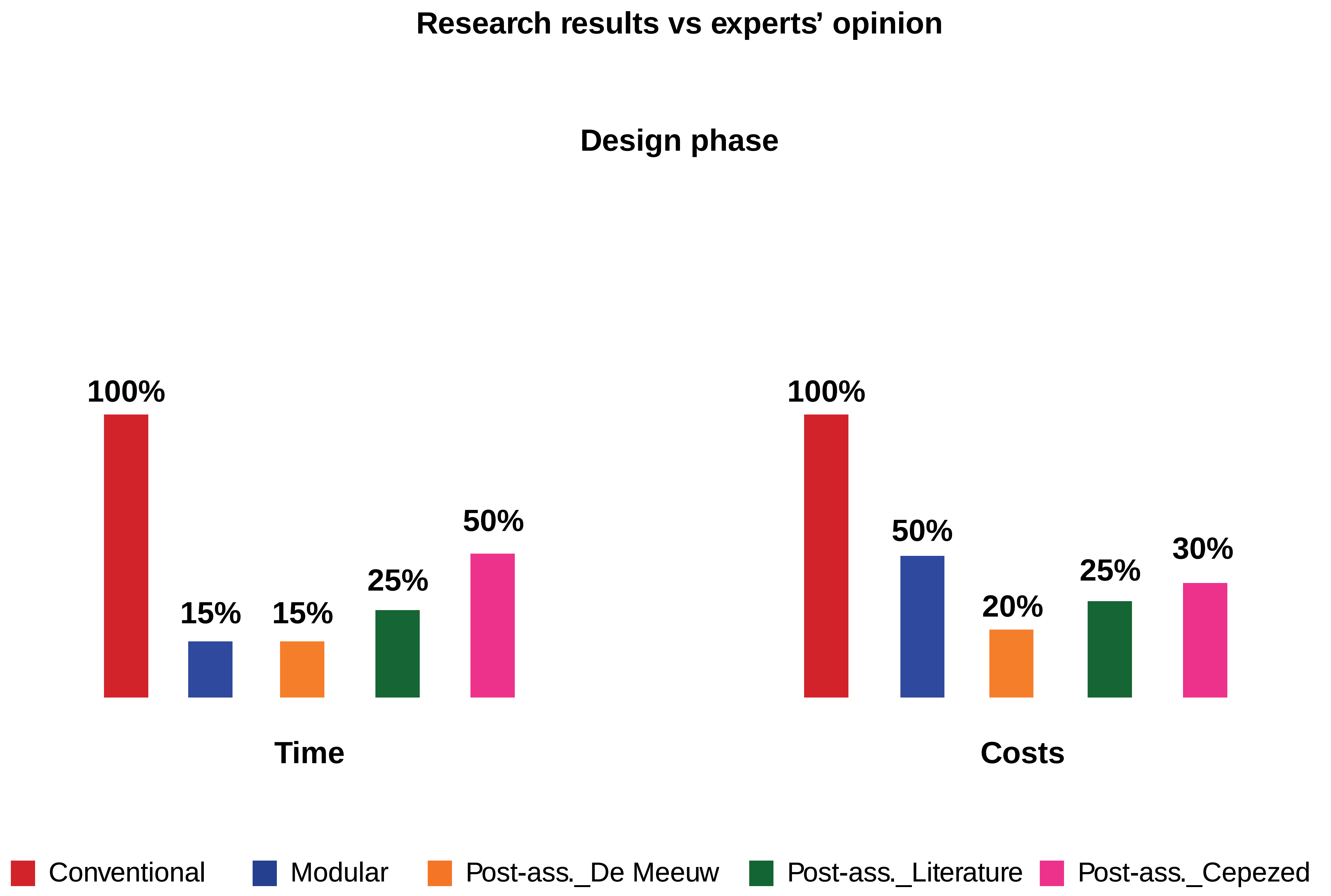
Design phase is highly depend on the client and negotiation process, according to Cepezed. The bureau can design a hospital in one year, but discussion and negotiations with the client and different hospital practitioners extend design phase to 5 years, as it happened with MCA hospital project designed by Cepezed. Time savings in design phase, that is why, can be maximum 50%, comparing to conventional design time. 25% time for design phase, presented by De Meeuw seems unrealistical for Cepezed (Cepezed interview, 2017). Cost of design phase is depend on the total budget of the project. The higher the amount of total building cost, the lower an architect's fee. For example, if total construction budget is 100.000 Euros, the design fee would be 10% from it. If total construction budget is 1.000.000 Euros, the design fee would be 8% from it. If the project is really modular, and is based on standard design layouts, its cost can be 25-30% from traditional design cost.

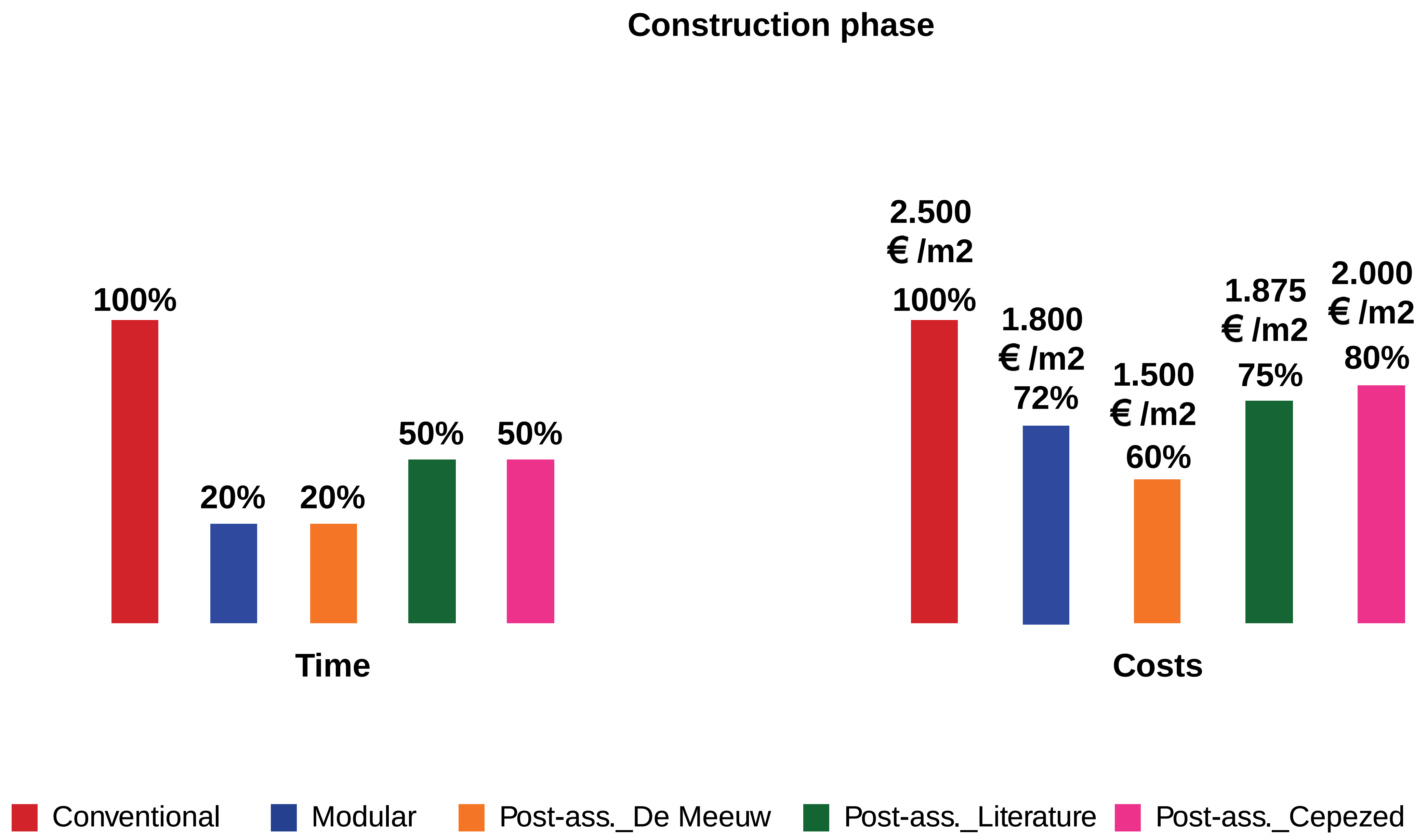
Construction phase

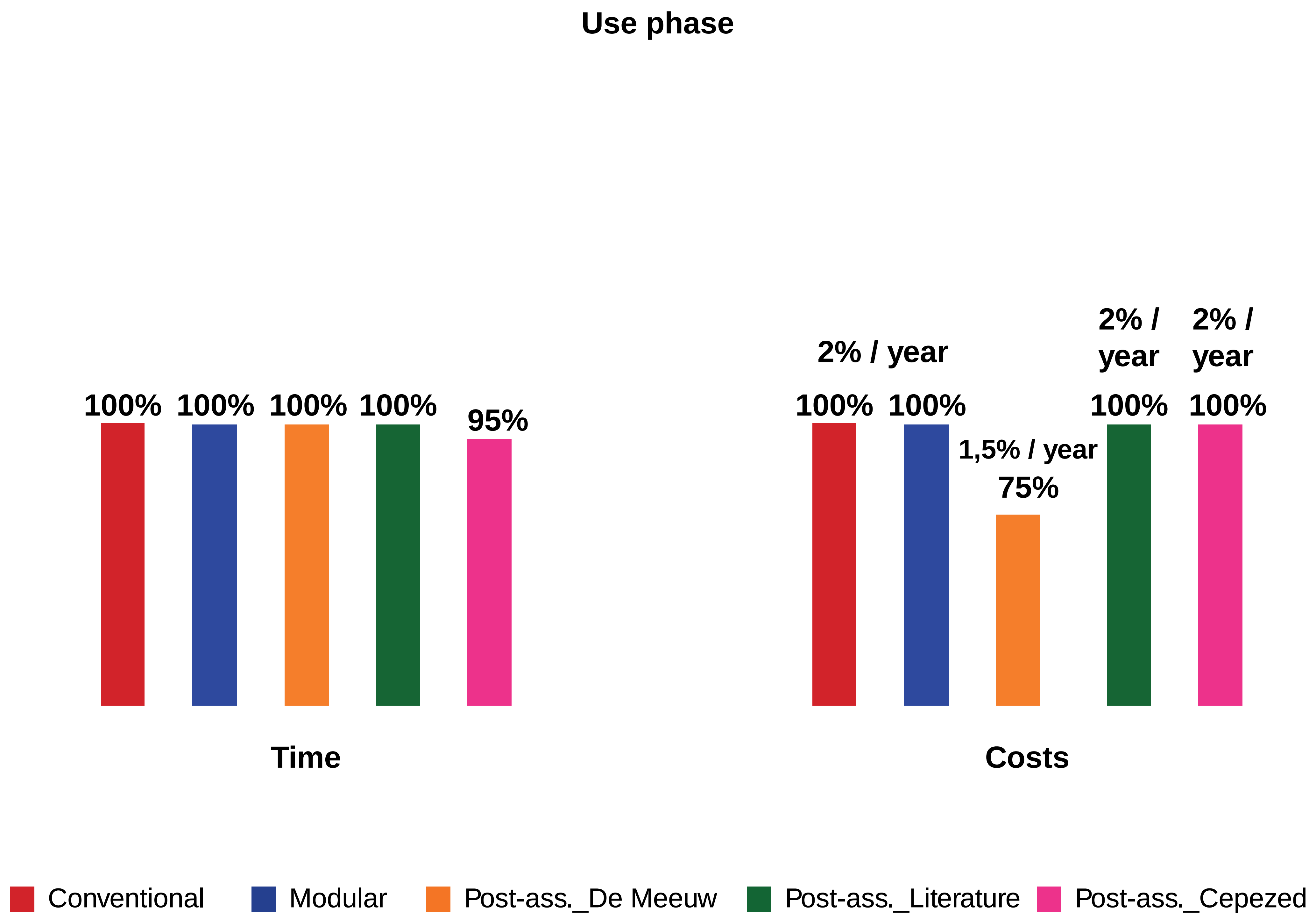
Time reductions in construction phase can be up to 50%, based on the bureau's experience. 20%, presented by De Meeuw, is quite high and doubtfull. It is important to take into account the time required for testing medical equipment, get an approval from the government and installation of medical systems. For example, time required for installation of one MRI unit is one month. It seems ridiculous, but it is true. That is why 50% time savings in modular construction are the maximum. Cost savings based on modularity and prefabrication can deliver 20% savings in cost of construction, or be equal to 80% from traditional hospital construction budget. In real numbers, it results in 2.000 Euro/m2 for hospital construction, against 2.500 Euros in traditional on-site process. Cepezed mostly uses flat packs, or kits of prefab components which are delivered to construction site by trucks and mounted to the building. Cepezed tested 3d (volumetric) modular units against flat packages, and last ones showed higher economic benefits and savings in both time and costs. That is why the bureau does not use 3d modules, usually.

Use phase

Time savings in use phase are not so familiar for Cepezed. Cleaning and related maintenance can be done faster and easier based on use of special materials, such as corian, but the same materials can be used in traditional finishings as well. Some prefab elements make maintenance phase easier. For example, special prefab facade system used in MCA hospital allows to replace MRI units easily and quickly. In traditional hospitals such changes take up to 1 month. MRI is delivered on site, deassembled into pieces, transported to the final place by internal elevators and assembled again there. Based on these facts, time frame for maintenance of modular hospital can be estimated as 95% from traditional maintenance. Cost aspects of hospital maintenance are not in the focus of Cepezed. However, 2% per year from total construction budget sounds reasonable (Cepezed interview, 2017).


Research results vs experts' opinion
Design phase
100%
15%
15%
25%
50%
Time
100%
50%
20%
25%
30%
Costs
Conventional
Modular
Post-ass._De Meeuw
Post-ass._Literature
Post-ass._Cepezed


Construction phase
100%
20%
20%
50%
50%
Time
2.500 € /m2
100%
1.800 € /m2
72%
1.500 € /m2
60%
1.875 € /m2
75%
2.000 € /m2
80%
Costs
Conventional
Modular
Post-ass._De Meeuw
Post-ass._Literature
Post-ass._Cepezed


Use phase
100%
100%
100%
100%
95%
Time
2% / year
100%
100%
1,5% / year
75%
2% / year
100%
2% / year
100%
Costs
Conventional
Modular
Post-ass._De Meeuw
Post-ass._Literature
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Chapter 8.

REFLECTION.

8.1. Modular construction in other building typologies. Does it make difference?

The number of aspects which make modular construction in hospitals feasible and attractive was explained in details in previous chapters. The specific features of use modules in hospital development were also addressed in the report. This part of reflection chapter deals with school buildings as a candidate for modular construction in order to identify some differences in modular development and to understand does the modular construction can be used widely.

School buildings have a large number of wide span spaces, which are requested by design codes and applied to classrooms, lecture and sport halls and some others (Lawson, M., Ogden, R., Design in modular construction). That is why open sided modules are ideal typology for school building. It is possible to say that flexibility demand in school building is higher than in hospital based on classroom dimensions equal to 10 x 10 meters, or 85-100 m2 in square. Hospital building, at the same time, has a great number of independent spaces, which can be unified or re-purposed, but do not require wide spans. The usual modern hospital grid is 7.8 to 7.8 bay, where surgery block can be located. In-patient wards, practitioner offices, laboratories, etc. can be located in the half of the bay with 3,9 meters width. Figure 8.1 illustrates principal plans of school and hospital.

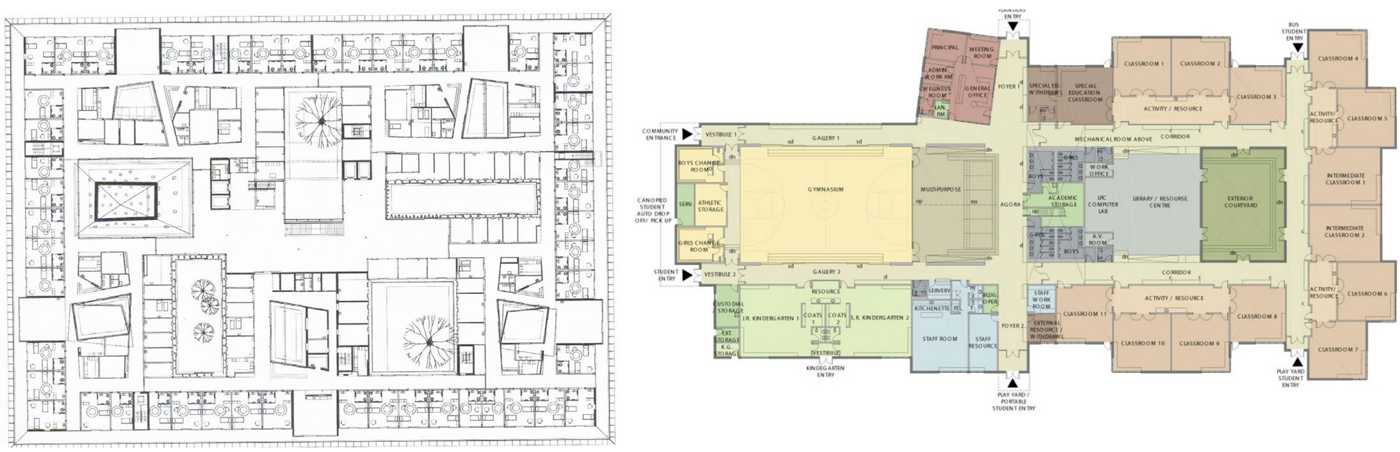


Figure 8.1. Layouts of typical hospital and school building. (source:

Both school and hospital buildings contain the number of identical spaces. In case of school they are classrooms, while in hospital it is in-patient wards, practitioner offices and support facilities. School building, however, contains large number of wide span and unique facilities, such as lecture halls, gyms, common spaces and recreations. The wider spans which are necessary in schools dictate the height limitations which can be up to 3 floors without stabilized core ad up to 6 storeys with it (Lawson, M., Ogden, R., Design in modular construction, 2012). Hospital building, to the opposite, can be built in a modular way up to 7 storeys without additional bracing and stabilization cores. This feature makes hospital more suitable for modular construction method rather than school typology.

Second specific aspect of hospital building is a great number of pre-installed equipment and installations which are required by design codes (Lawson, M., Ogden, R., Design in modular construction, 2012). The majority of these operations, especially electric, bathroom pods, lighting, medical gases, ventilation and other systems can be installed in factory in a strict schedule without any delays, weather disruptions, etc. This fact significantly reduces not only on-site construction phase (see chapter 2), but also allows to start use phase earlier based pre-assembled installations. School does not contain such complicated equipment and MEP services, and, consequently, does not require in factory assembly conditions.

Based on these two facts, wider structural span and lower amount of technical installations, school building has less potential for modular construction. Classroom extensions of existing school facilities, however, which may do not require wide spans are possible. It can be both ground floor extensions as well as addings on top of the existing building.

8.2. Reflection on the research process and final product.

This part of reflection chapter will briefly summarise the main steps of the research project and my personal reflection on it.

Start phase. All quite on the western front.

The goal of this research was to find possible savings in modular hospital construction based on the benefits it provides. The choice of the topic for the research was based on my involvement in hospital design for significant period of time and theoretical potentials modular construction provides specifically in this building typology. The main research question rised in this research was formulated as to which extent are modular hospital construction more feasible comparing to conventional building techniques? The initial idea was to find two real cases from the companies, one for modular hospital project and another one for traditional hospital development. The comparison of these two cases, based on their briefs, set of interviews with involved parties and literature review, was intended to identify the exact savings in time and cost as well as the precise moments in construction schedule where these savings might take place.

Literature reivew phase. Modules in a nutshell.

Literature review phase started from the broad selection of the articles in academic libraries dedicated to modular construction. Soonly it became clear that the actual information such as real numbers, turnovers, volumes of production, construction technologies etc are not mentioned in these materials at all. Articles available in stock research filed mainly contain advertisement-based materials with a few details regarding actual savings and mostly suitable for the first call to particular company. As it was investigated later by me, this situation is based on quite closed nature of modular manufacturers since there is a few number of them in Europe and they do not reveal any information beside advertising booklets. In order to get the deeper knowledge in modular development I bought several books which describe design and construction modular process more precisely and in details. In parallel with academic reading I arranged a set of interviews with the parties involved in modular design and construction, thanks to my mentors Ruben Vrijhoef and Peter de Jong. It has become clear, then, that no one party is willing to share any precise and concrete information, even if you are a good student of TU Delft. They can demonstrate the module after completion in showroom, they can answer to some general questions (see interviews in appendixes), but they never ever ever will dive into manufacturing, construction and especially financial details. This is pitty to constant, but graduation within MBE and TU Delft do not guarantee any entries to the construction world. Although it highly depends on the selected topic, particular market situation and student personality, the actual involvement of the MBE faculty to the real construction sector is overestimated, in my point of view. Based on these reasons I switched my initial research plan from case study research to generic analysis of life cycle process of modular hospital and its aspects with divings into particular details in design, construction and use phases based on their availability. Thanks to my mentors I got a number of experts from architecture, module manufacturing and hospital management fields which answered to the number of questions of modular development (see appendixes 15-19). All their responses and comments are included in the body of the report. However, they were fluctuate to go into details regarding any numbers and real cases.

Final report development phase. Yes, I can.

Final report of this research are based on literature findings and interviews with experts mentioned in a previous paragraph. It touches the main parameters of hospital development and life cycle in three phases - design, construction and use. Every parameter of both construction methods is compared with each other and the conclusions regarding feasibility of modular construction in this particular step of building’s life are made. Finally, the conclusion chapter summarizes all findings and describes the main savings in all phases. It is important to mention that findings in particular phase cannot be simply summarized since they are not equl to each other and represent different categories sometimes. The results of the research are findings of possible savings in modular construction as a percentage comparing to conventional building methods (see conclusion chapter).

8.3. Time and costs savings are done. What about quality?

Two indicators investigated in this research were time and costs savings in modular construction. These two indicators were chosen specifically for this research in order to investigate quantitative savings in modular construction. Quality aspects, such as architectural, planning, spatial and aesthetic ones, were partially investigated during my Milan work, when I completed renovation project for general modular hospital. For these reasons quality aspects were not studied specifically, since it is separated and big topic for further research. Quality assessment has its own number of indicators and other measurements. Specific questionnaires need to be prepared to interview respondents. This topic can be considered for future investigation, based on monetary and time savings identified here.

At the same time, it is possible to conclude, based on current research, that quality increasings take place in modular construction. These issues were partially explained in Construction phase, chapter 5. Main quality improvements are based on two factors. First one is indoor assembly process takes place in modular factory. It means that production process does not depend on weather conditions. Second one is fixed number of operations required to assemble a module. Lean management concept, explained in chapter 6, helps to minimize delays and overheads in supplies. McGraw & Hill annual report mentioned in part 7.4.4 confirms quality improvements in modular construction based on surveys of respondents (McGraw & Hill, Modularization in construction industry report, 2016). 15 % of respondents state high level of improvements, while another 50% report about medium impact on quality improvement. These two factors are basis for higher production conditions, absence of delays and higher quality of the final product.

8.4. Are the in-between scenarios in modular construction?

This research specifically explained 3d modular, or, volumetric construction benefits. This maximum scenario was chosen in order to investigate the limits and potentials of this construction method. Specific questions such as transportation of module to the site, dealing with installation of 3d module to the building, assembly of 3d frame, etc. are raised in this maximum scenario. The purpose of such maximum variant was to check the benefits of this method in front of more traditional ones, where some prefabricated elements are still used. Construction industry, in general, is quite conservative area, and innovations take place here infrequently. Modular construction, that is why, is one of these innovations. Despite relatively long history and a lot of attempts to build modular buildings in the past, modern industry is able to combine economy of scale with customizable layout, as it was shown in this research. The benefit of fully modular construction is complexity of environment and ability to control all processes on a higher level. Current use of prefabricated components in construction, however, does not emerge in qualitatively new features. It is possible to say that use of modular components in traditional construction eliminates some technological problems and reduces time for installation on site, but it is hardly possible to name these things by real changes in construction industry. Wiegerinck Architects, specialized in hospital construction, name 6 main types of prefab elements currently used in healthcare construction (Wiegerinck Architects, 2017). They are prefab facades, window frames, floor slabs, steel structures, bathroom pods and many small fitting parts. While these elements can save some time on construction site, based on their prefabricated character, they are still small part in a general traditional construction on-site process. Figure 8.2. represents all these components.

Are the in-between scenarios?

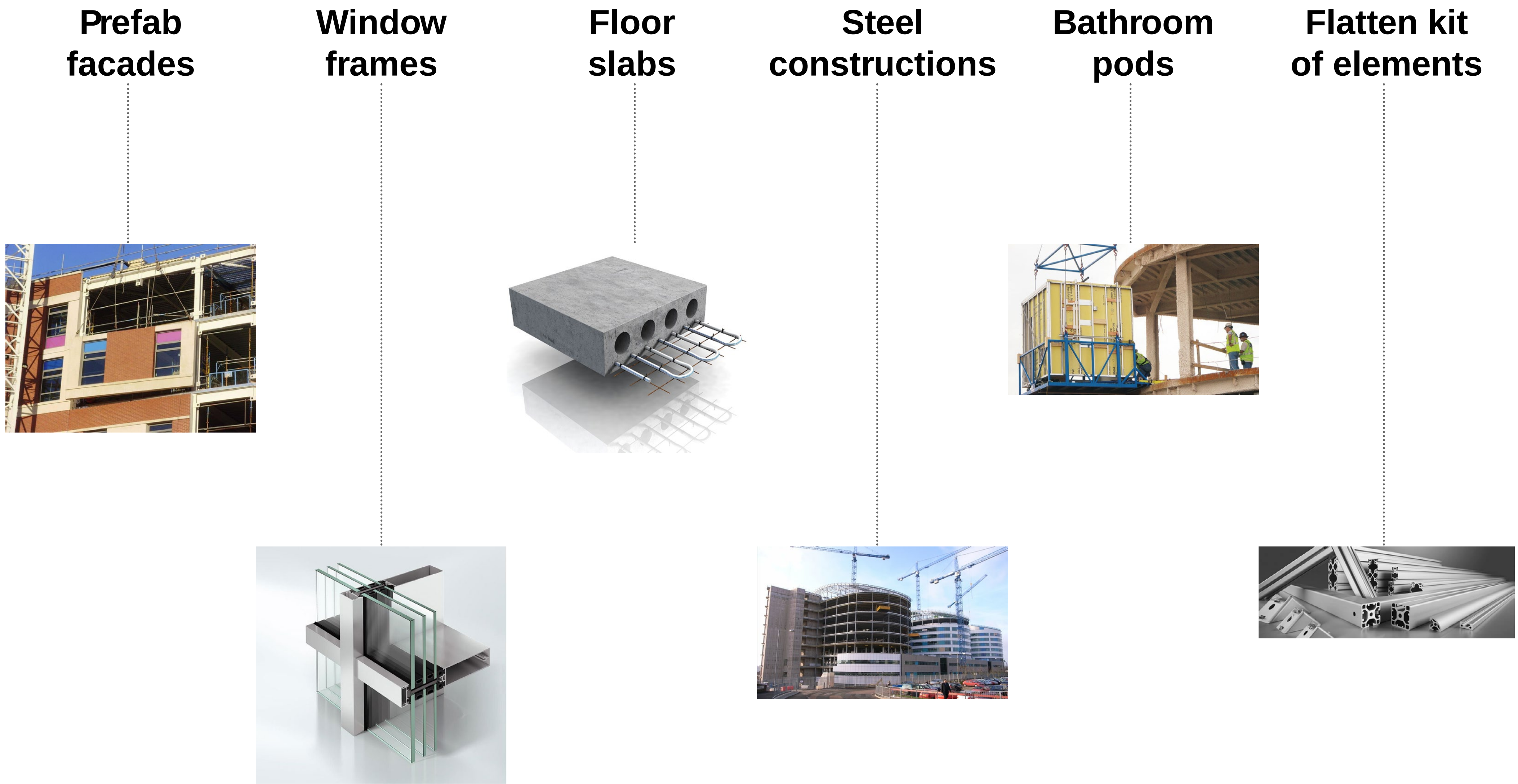


Figure 8.2. Prefab components used in traditional construction today (source: Author, 2017)

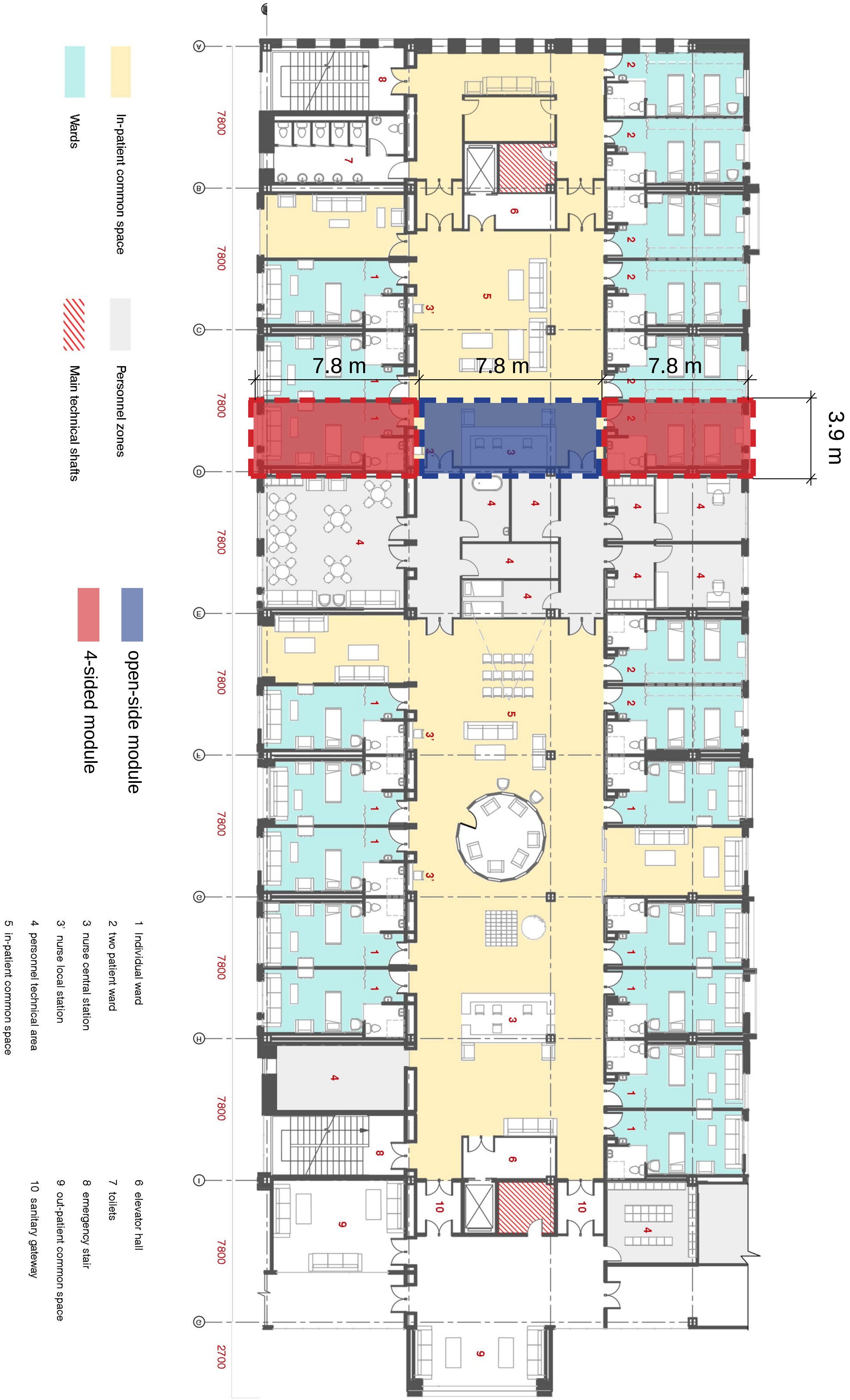
8.5. Recommendations for further research.

The real testing of benefits and limitations of modular construction in comparison with conventional one needs to be provided in a further research. Despite the fact that this report used some real numbers from case studies, interviews and literature sources and provided the comparison of the most important phases, operations and parameters, it does not provide the entire comparison of modular and traditional construction by a fixed similar set of parameters. This is based on unavailability of the full real case study for both modular and conventional construction. Further testing and deeper comparison with measuring of real time required for comparable operations is necessarily.

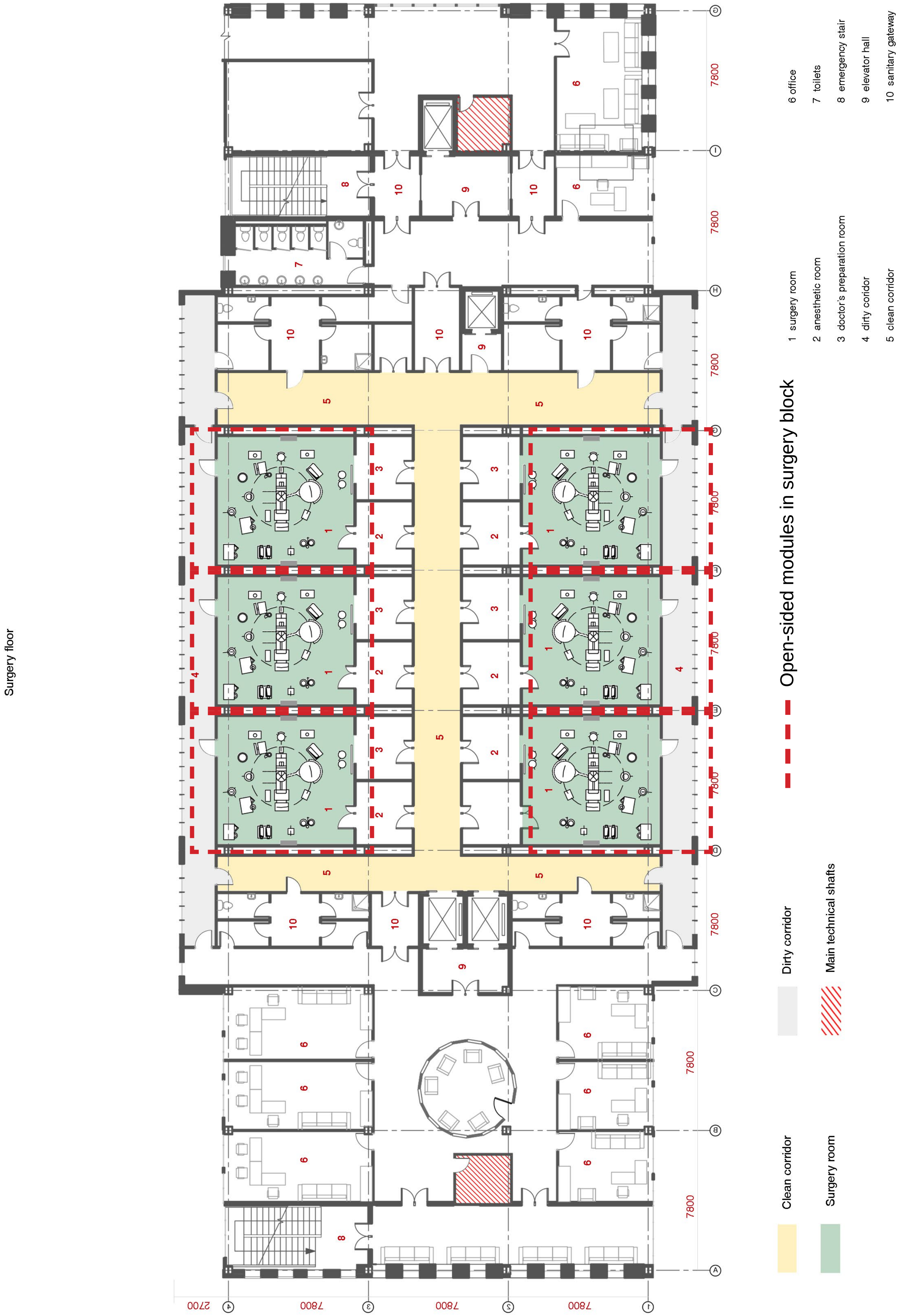
Another important direction of additional research is comparison of life cycle cost of different hospital departments in both conventional and modular construction. This report mainly concentrated on one type of the module and compared its life cycle cost with one square meter of normal construction. Understanding of different aspects of construction of different units (wards, surgery rooms, etc.) will allow to clearly understand economical effectiveness of combination of modular and traditional construction.

Another direction of further research is risk allocations on modular construction, partially mentioned in post-assessment chapter, already. Time savings are mostly based on earlier decisions made at the beginning of the process. However, the risks in this phase are higher based on higher number of decisions needs to be made. That is why risks need to be investigated additionally and their allocation in design, construction and use phases needs to be clarified.

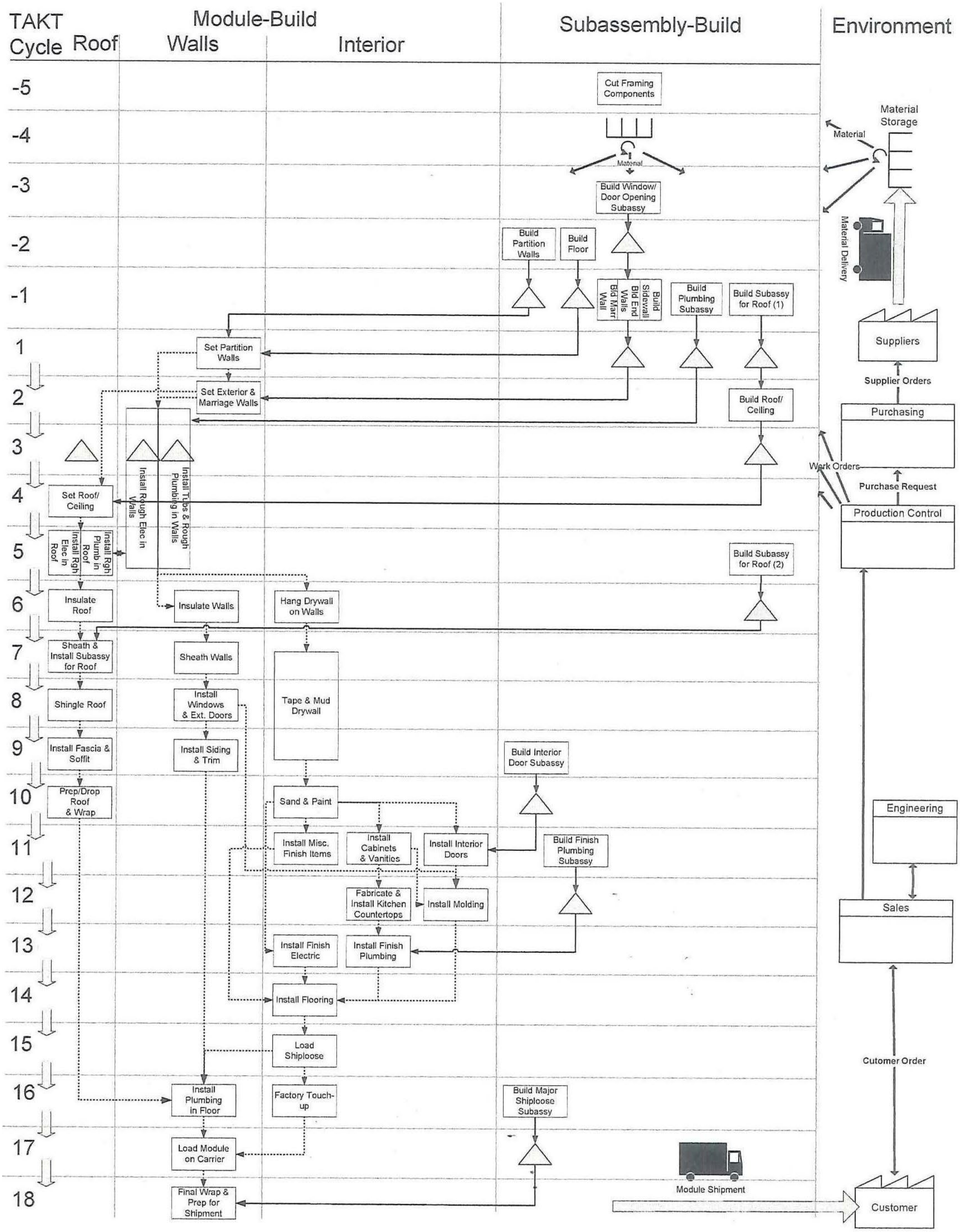
APPENDIXES



Appendix 1. Typical in-patient ward floor of the hospital (source: Author, 2016)



Appendix 2. Surgery floor with open-sided modules for surgery rooms (source: Author, 2016)



Appendix 3. Generic Value Stream Map (VSM) of modular production (Factory design for modular homebuilding, Mullens, M.A., 2011)

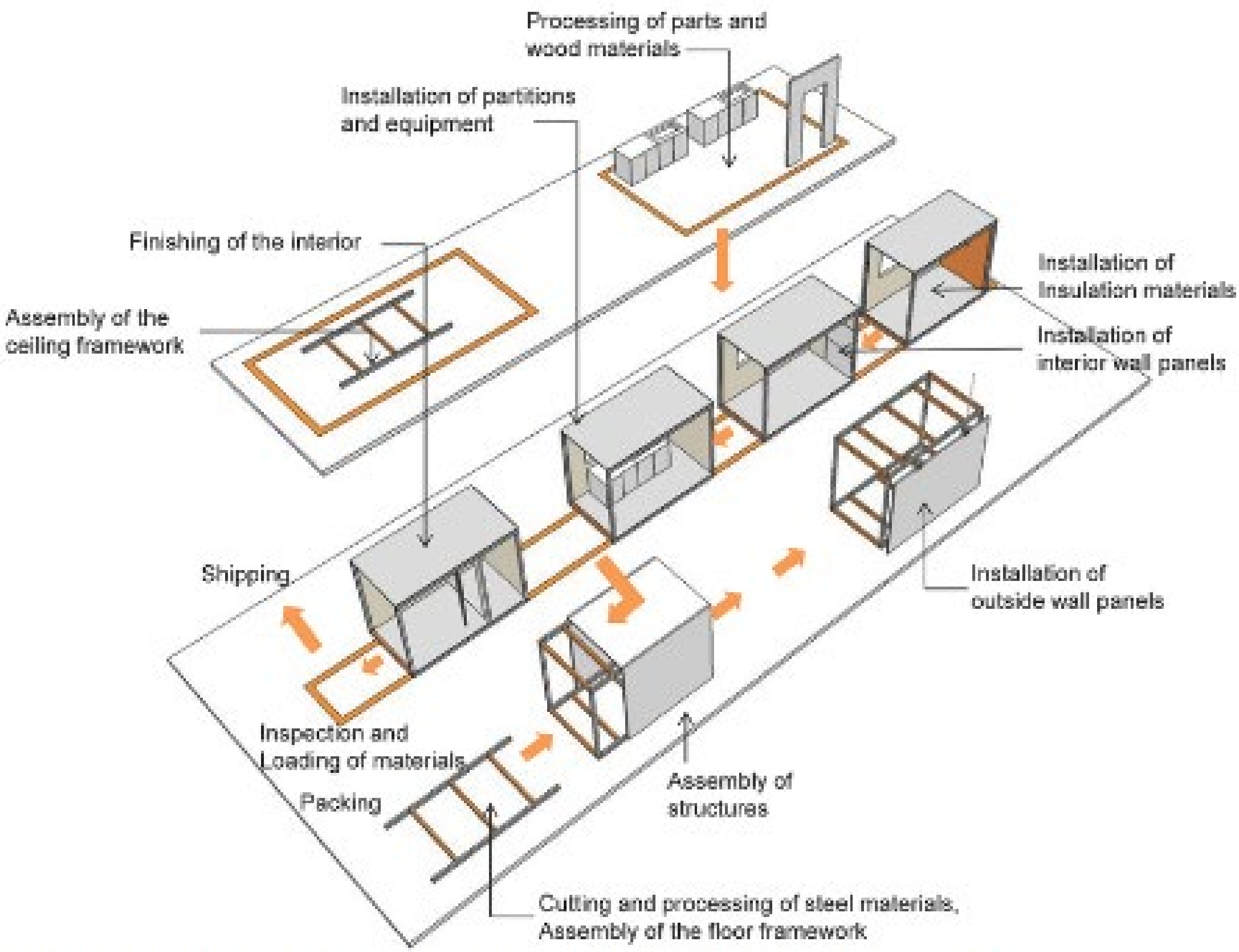
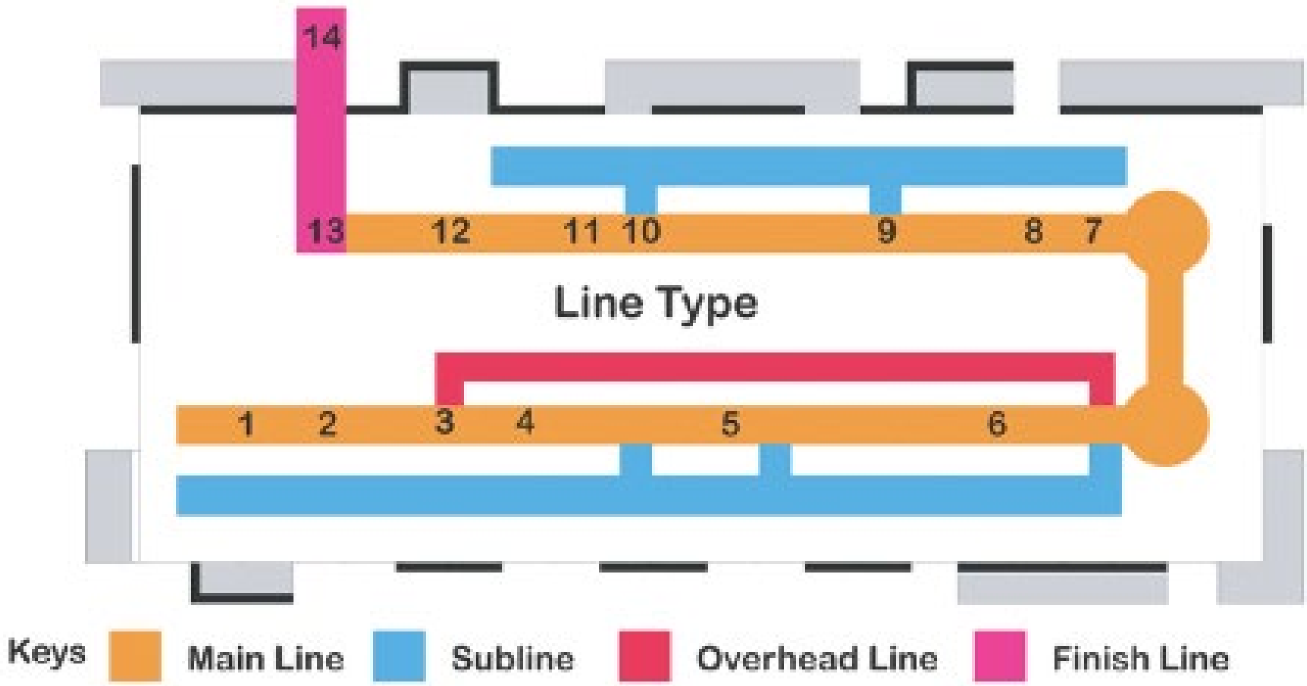
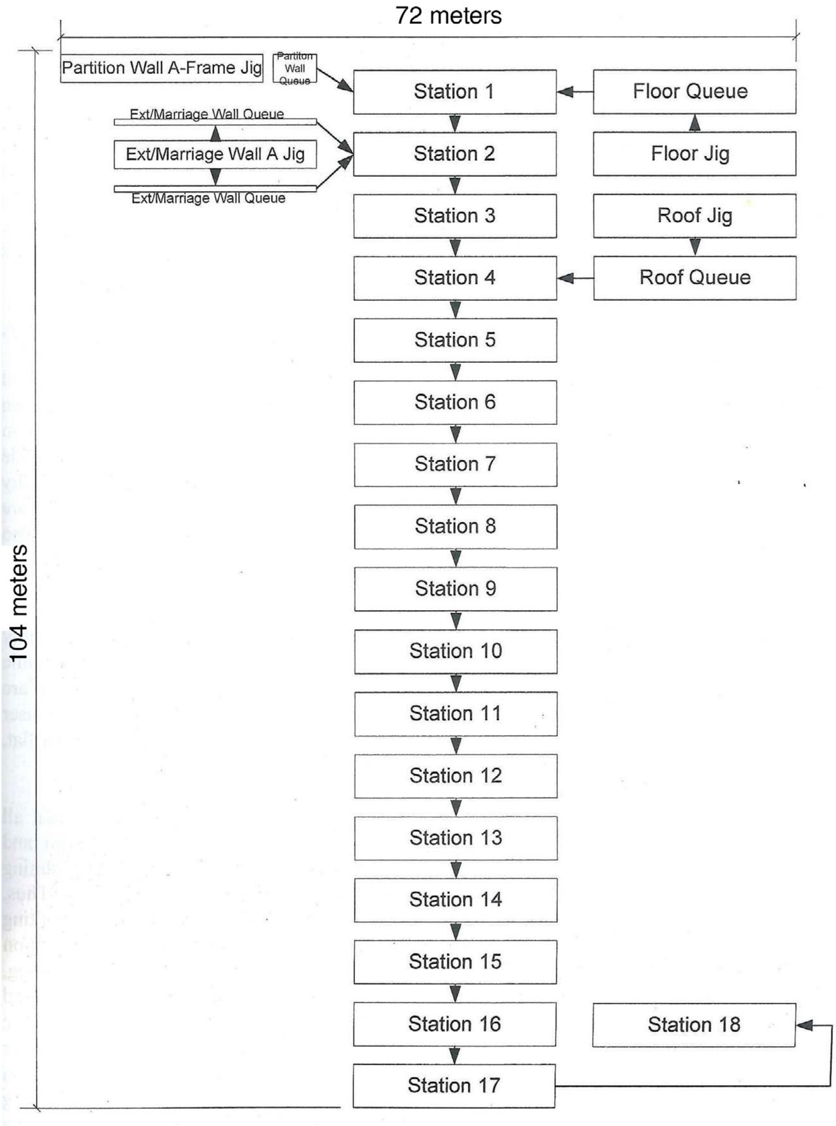


Figure 5.19. General idea of Sekisui Heim's production line principle.

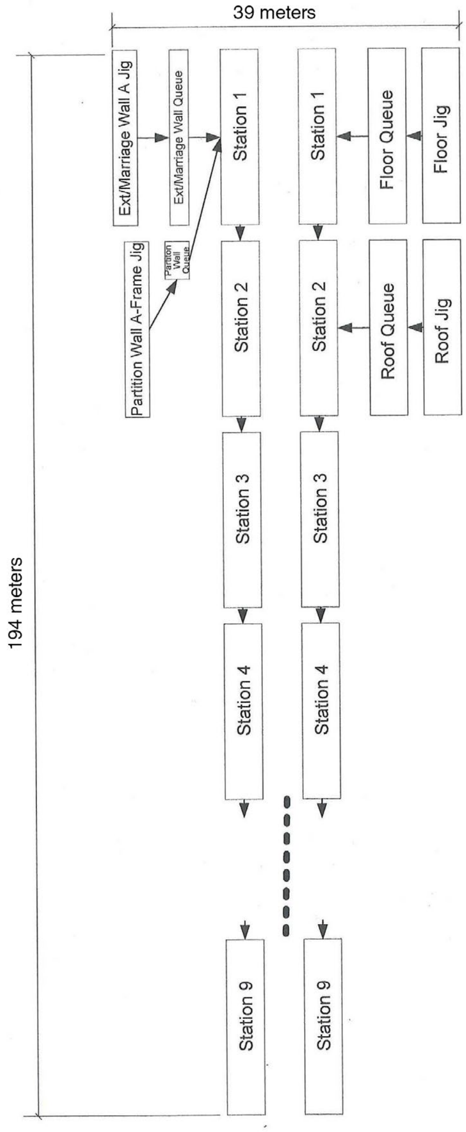
(Drawing on basis of Sekisui Heim)



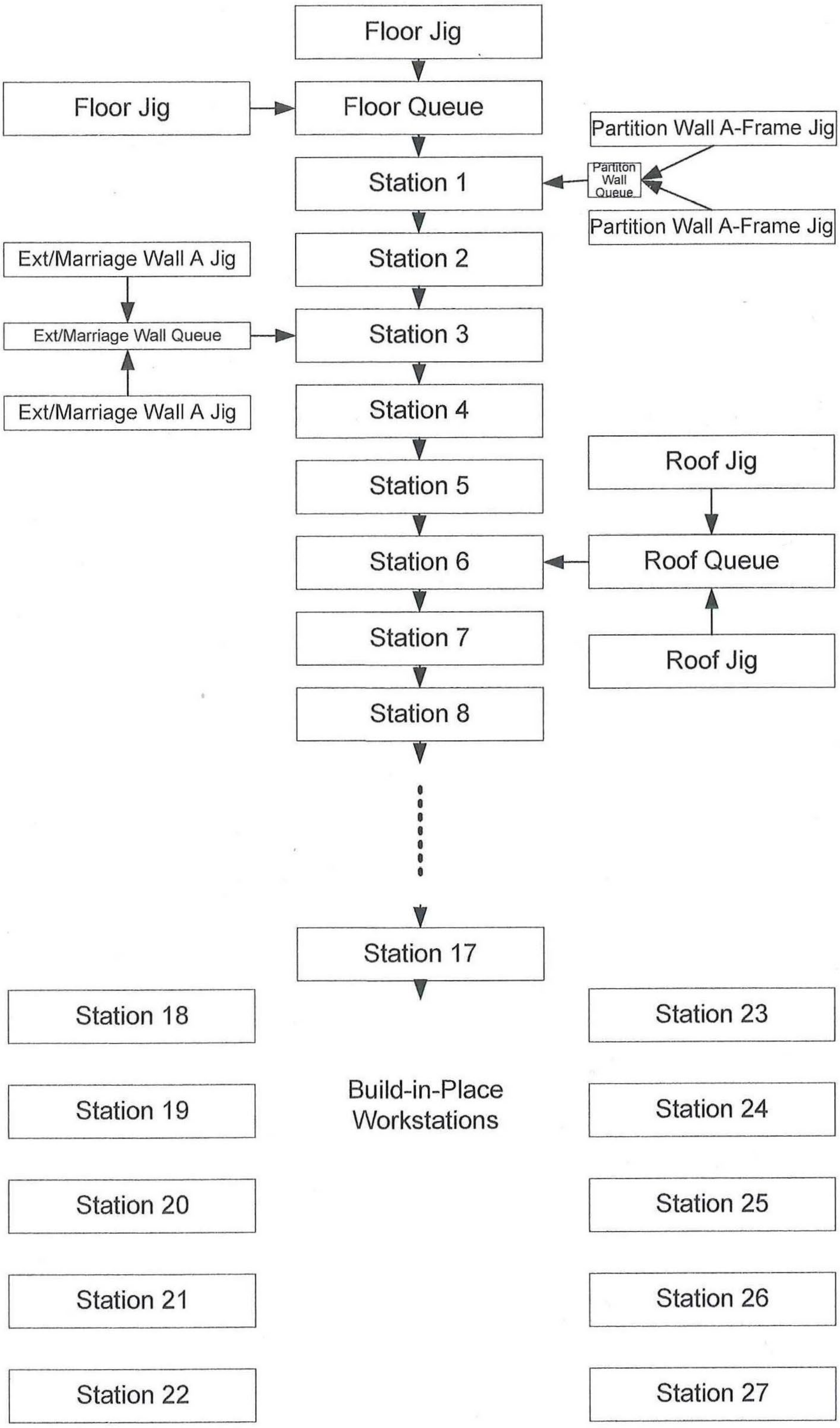
Appendix 4. Production layout of Sekisui Home factory
(source: Bock, T., Linner, T., Robotic Industrialization, 2015)



Appendix 5. Sidesaddle line layout
(Factory design for modular homebuilding, Mullens, M.A., 2011)

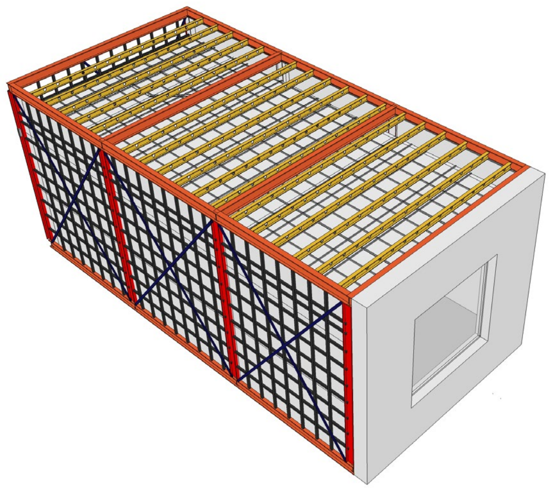


Appendix 6. Shotgun line layout
(Factory design for modular homebuilding, Mullens, M.A., 2011)



Appendix 7. Hybrid sidesaddle and Build-in-place line layout
(Factory design for modular homebuilding, Mullens, M.A., 2011)

Element	Quantity	Weight of 1m length, kg	Price per m length	Total price, Euro	Total weight, kg	Manufacturer	Min price	Manufacturer (so	Most expected price	Manufacturer (sour	Max price	Manufacturer (source)
Main load-bearing skeleton												
Main column I-beams HEA 120 160x114 mm, red (N 12)	8 (length 3 m)	20,3 kg	1,36 Euro / kg	662,6 Euro	487.2 kg	Taken from bouwkosten.nl	10 Euro/m length = 240 Euro	Severstal (Russia)	17,5 Euro/m length (1,36 Euro/kg) = 420 Eur	bouwkosten.nl	27.6 Euro/m length = 662.6 Euro	bouwkosten.nl
Main horizontal I-beams HEA 160, 160x152 mm,orange (N 16	4 (length 7,6 m)	31 kg	1,35 Euro / kg	1.272 Euro	942 kg	Taken from bouwkosten.nl	10 Euro/m length = 304Euro	Severstal (Russia)	27,5 Euro/m length (1,36 Euro/kg) = 836 Eur	bouwkosten.nl	1.35 Euro/kg x 30.4 m x 31 = 1272 Euro	bouwkosten.nl
Main horizontal I-beams HEA 160, 160x152 mm,orange (N 16	8 (length 3,7 m)	31 kg	1,35 Euro / kg	1.238,7 Euro	917.6 kg	Taken from bouwkosten.nl	10 Euro/m length = 296 Euro	Severstal (Russia)	17,5 Euro/m length = 518 Euro	bouwkosten.nl	27.6 Euro/m length = 817 Euro	bouwkosten.nl
Secondary I-beams, HEA 100, 100x96 mm yellow (N 10)	34 (length 3,7 m)	20,8 kg	1,35 Euro / kg	3.532 Euro	2138 kg	Taken from bouwkosten.nl	7,8 Euro/m length = 981 Euro	Severstal (Russia)	14 Euro/m length = 1761 Euro	bouwkosten.nl	1,35 Euro/kg x 2.616 kg = 3.532 Euro	bouwkosten.nl
Diagonal stiffness connections	6 pieces	1,1 kg	1,36 Euro / kg	25,6 Euro	18.84 kg	Taken from bouwkosten.nl	1,2 Euro/m length = 57,6 Euro	Severstal (Russia)	6 Euro/m length = 144 Euro	bouwkosten.nl	15 Euro/m length = 720 Euro	bouwkosten.nl
Tertiary sheathing (quadrant rods 30 x 30 mm)	114 rods	1.39 kg / 1 m length	1,36 Euro / kg	756 Euro	556 kg	Taken from bouwkosten.nl	1,2 Euro/m length = 479 Euro	Severstal (Russia)	114 x 3,5m x 1,39 kg x 1,35 Euro/kg = 756 Eur	bouwkosten.nl	3,8 Euro/m length = 1516 Euro	bouwkosten.nl
Walls												
Gipsum-fiber board (2500x1200x12,5 mm)	56 sheets	31,5 kg / board	45,15 Euro / board	2520 Euro	1764 kg	Knauf, taken from bouwkosten	31,5 Euro/board x 56 = 1764 Euro	Knauf (Russia)	37,3 Euro/board x 56 boards = 2089 Euro	snabmsk.ru	45,15 Euro/board x 56 = 2.528 Euro	bouwkosten.nl
Wall finishing layer (anti-bacterial paint)	65 m2 = 10,8 liters	0,166 liter/m2	24 Euro/1 liter	1800 Euro		Taken from bouwkosten.nl	19,2 Euro/Liter x 10,8 L x 2 =415 Euro	bouwkosten.nl	27,8 Euro/Liter x 10,8 L x 2 layers = 600,5 E	bouwkosten.nl	34,2 Euro/Liter x 10,8 Euro x 2 = 738,7 Euro	bouwkosten.nl
Ward door	1			588 Euro	35 kg		467 Euro/door	spi-polymer.ru	587 Euro/door	bs.stroynet.ru	588 Euro/door	
Insulation layer (6.000x600 mm, thikness 80 mm)	1, 96 m3 per module	52 m2 per module is required	6,95 Euro / m2	360 Euro	77 kg	Rockwool, 6000x600x50 mm, NL	6.95 Euro/m2 x 52 m2 = 361,4 Euro	bouwkosten.nl	8,4 Euro/m2 x 52 m2 = 437 Euro	bouwkosten.nl	10,2 Euro/m2 x 52 m2 = 530 Euro	bouwkosten.nl
Ceiling												
Metal profiles for suspended ceiling	85 profiles	0,1 kg per profile	4 Euro per profile	340 Euro	8.5 kg	ALBES ceilings (Russia)	3 Euro/1 profile x 85 profiles = 255 Euro	bouwkosten.nl	4 Euro/1 profile x 85 profiles = 340 Euro	ALBES ceilings (Russia	5,5 Euro/1 profile x 85 profiles = 468 Euro	ALBES ceilings (Russia)
Ceiling finishing boards	28 m2 (1 tile =600x600 mm)	6 kg/tile	28 Euro/m2	784 Euro	468 kg	Taken from bouwkosten.nl	19,95 Euro/m2 x 27,7 m2 = 552,6 Euro	bouwkosten.nl	28 Euro/m2 x 27,7 m2 = 775,6 Euro	bouwkosten.nl	34,8 Euro/m2 x 27,7 m2 = 964 Euro	bouwkosten.nl
Floor												
Finishing layer	25 m2		3,5 Euro / m2	87,5 Euro	600 kg		17 Euro/m2 x 25 m2 = 425 Euro	teohim.ru	17,7 Euro/m2 x 25 m2 = 442,5 Euro	prompol.ehg.su	33,3 Euro/m2 x 25 m2 = 833 Euro	evropoll.nl
draft layer (insulation layer)	25 m2		17,4 Euro/m2 -> discount 30 % from 70 m	300 Euro		Taken from bouwkosten.nl	17,4 Euro/m2 x 25 m2 = 435 Euro	teohim.ru	26 Euro/m2 x 25 m2 = 650 Euro	bouwkosten.nl	39 Euro/m2 x 25 m2 = 975 Euro	bouwkosten.nl
Bathroom pod												
Metal wall frame railings	10	0,3 kg per 1 rail	4 Euro per profile	40 Euro	3 kg	Knauf (Germany)	2,5 Euro/profile x 10 profiles = 25 Euro	knauf.com	4,35 Euro/profile x 10 profiles = 43,5 Euro	knauf.com	5,8 Euro/profile x 10 profiles = 58 Euro	knauf.com
Gipsum-fiber board (2500x1200x12,5 mm)	5	31,5 kg / board	45,15 Euro / board	225,7 Euro	157.5 kg	Knauf, taken from bouwkosten.nl	31,5 Euro/board x 5 = 157,5 Euro	Knauf (Russia)	37,3 Euro/board x 5 boards = 186,5 Euro	snabmsk.ru	45,15 Euro/board x 5 = 225,7 Euro	bouwkosten.nl
Ceramic finishing tiles walls	17,6 m2	15 kg / m2	17 Euro / m2	300 Euro	264 kg	Taken from bouwkosten.nl	10 Euro/m2 x 17,6 m2 = 176 Euro	shopceramica.ru	17,3 Euro/m2 x 17,6 m2 = 305 Euro	bouwkosten.nl	37 Euro/m2 x 17,6 m2 = 651 Euro	xplit.ru
Ceramic finishing tiles floor	3,5 m2	23,3 kg / pack -> 3 packages	39,8 Euro / m2	139 Euro	70 kg	Taken from bouwkosten.nl	18,5 Euro/m2 x 3,5 m2 = 64,75 Euro	plitka-sdvk.ru	37 Euro/m2 x 3,5 m2 = 130 Euro	santa-keramika.ru	47 Euro/m2 x 3,5 m2 = 164,5 Euro	plitka-sdvk.ru
Watercloset	1			500 Euro	37 kg	Taken from bouwkosten.nl	275 Euro	kranik.ru	450 Euro	kranik.ru	500 Euro	kranik.ru
Shower pod	1 (800x80x500 mm)			250 Euro	48 kg	Taken from bouwkosten.nl	130 Euro	ruspanel.ru	260 Euro	hatria.ru	360 Euro	hatria.ru
Sink	2	6 kg /sink	30 Euro / sink	60 Euro	12 kg	Santek (Russia)	60 Euro	santek.ru	140 Euro	santek.ru	200 Euro	santek.ru
Door	1			110 Euro	14 kg	Rem-Sovet (Russia)	110 Euro	Rem-Sovet (Russia)	160 Euro	Rem-Sovet (Russia)	220 Euro	Rem-Sovet (Russia)
Light	4 (LED lights inside ceiling)		60 Euro / spot	240 Euro	9 kg	Lucide (Belgium)	150 Euro x 2 lights = 300 Euro		240 Euro x 2 lights = 480 Euro		350 Euro x 2 lights = 700 Euro	
Ward medical furniture and equipment												
Patient bed	1			4.700 Euro	125 kg	Linet Eleganza (Italy)	2.800 Euro	phc-online.com	4.700 Euro	Linet Eleganza (Italy)	5.200 Euro	phc-online.com
Caregiver entrance sink	1			330 Euro	11.5 kg	Duravit (Germany)	300 Euro	Duravit (Germany)	330 Euro	Duravit (Germany)	460 Euro	phc-online.com
Headwall system (medical gases, life system control, etc)	1			5.400 Euro	52 kg		4500 Euro		5.400 Euro		6.300 Euro	
Medical gas system	1			660 Euro								
Medical gas pipes	20 m (length)		13.4 Euro/1 m length	268 Euro		Taken from bouwkosten.nl	13,4 Euro/m length x 20 m length = 268 Eur	bouwkosten.nl	15,6 Euro/m length x 20 m = 312 Euro	bouwkosten.nl	19 Euro/m length x 20 m = 380 Euro	bouwkosten.nl
Ventilation pipes												
Main ceiling light	1			85 Euro	4 kg		Included in lights		Included in lights		Included in lights	
Bed light	2			40 Euro	1 kg		40 Euro x 2 lights = 80 Euro		65 Euro x 2 lights = 130 Euro		75 Euro x 2 lights = 150 Euro	
Visitor sofa	2			120 Euro	3 kg		120 Euro x 2 = 240 Euro		300 Euro x 2 = 600 Euro		410 Euro x 2 = 820 Euro	
Table (foldable)	1		60 Euro	60 Euro	25 kg		60 Euro		60 Euro		80 Euro	
Chair	2	5 kg per chair	40 Euro / chair	80 Euro	10 kg		50 Euro x 2 chairs = 100 Euro		90 Euro x 2 chairs = 180 Euro		120 Euro x 2 chairs = 240 Euro	
bed stend	1			120 Euro	7 kg		120 Euro		140 Euro		180 Euro	
Electrical radiator (heating system)	2	18 kg (1) + 9 kg (2)	100 Euro (1) + 360 Euro (2)	460 Euro	27 kg	Varmann (Russia)	219 Euro x 2 = 438 Euro		244 Euro x 2 = 488 Euro		379 Euro x 2 = 758 Euro	
HEPA filter (air cleaning and anti-bacterial environment)	1			542 Euro	15 kg	Tion (Russia)	542 Euro		658 Euro		702 Euro	
Fan-coil (central heating and ventilation system)	2 (this is the rule for hosp)	38 kg per unit	3.400 Euro per unit	6.800 Euro	76 kg	Daikin (Japan)	1.342 Euro x 2 = 2.684 Euro		3.400 Euro/unit x 2 = 6.800 Euro		3.800 Euro x 2 = 7.600 Euro	
Patient control status monitor system	1			1.420 Euro	5.5 kg	Armed (China)	900 Euro		1.420 Euro		1.820 Euro	
Facade external panel	1 (13,3 m2)	42,4 kg / m2	25 Euro / m2	332 Euro	563.92 kg		245 Euro		350 Euro		510 Euro	
Metal frame (skeleton)												
Insulation layer												
Waterproofing membrane												
External finishing layer (metal casseste facade)												
Window	1			500 Euro	300 kg		550 Euro		870 Euro		1500 Euro	
TOTAL				**41.069 Euro**	**11.748 kg**		**20.964 Euro**		**33.501 Euro**		**44.132 Euro**	



Appendix 8. Components of the typical module, thier costs, weights and manufacturers (Author, 2017)

Modular construction. Elements for 1 module.

Element	Quantity	Weight of 1m length, kg	Price per m length	Total price	Total w	Manufacturer	Min price	Manufacturer (s	Most expected price	Manufacturer (sou	Max price	Manufacturer (source
Main load-bearing skeleton												
Main column I-beams HEA 120 160x114 mm, red (N 12)	8 (length 3 m)	20,3 kg	1,36 Euro / kg	662,6 Euro	487.2 kg	Taken from bouwkosten.nl	10 Euro/m length = 240 Euro	Severstal (Russia)	17,5 Euro/m length (1,36 Euro/kg) = 420 Eur	bouwkosten.nl	27.6 Euro/m length = 662.6 Euro	bouwkosten.nl
Main horizontal I-beams HEA 160, 160x152 mm,orange (N 1	4 (length 7,6 m)	31 kg	1,35 Euro / kg	1.272 Euro	942 kg	Taken from bouwkosten.nl	10 Euro/m length = 304Euro	Severstal (Russia)	27,5 Euro/m length (1,36 Euro/kg) = 836 Eur	bouwkosten.nl	1.35 Euro/kg x 30.4 m x 31 = 1272 Euro	bouwkosten.nl
Main horizontal I-beams HEA 160, 160x152 mm,orange (N 1	8 (length 3,7 m)	31 kg	1,35 Euro / kg	1.238,7 Euro	917.6 kg	Taken from bouwkosten.nl	10 Euro/m length = 296 Euro	Severstal (Russia)	17,5 Euro/m length = 518 Euro	bouwkosten.nl	27.6 Euro/m length = 817 Euro	bouwkosten.nl
Secondary I-beams, HEA 100, 100x96 mm yellow (N 10)	34 (length 3,7 m)	20,8 kg	1,35 Euro / kg	3.532 Euro	2138 kg	Taken from bouwkosten.nl	7,8 Euro/m length = 981 Euro	Severstal (Russia)	14 Euro/m length = 1761 Euro	bouwkosten.nl	1,35 Euro/kg x 2.616 kg = 3.532 Euro	bouwkosten.nl
Diagonal stiffness connections	6 pieces	1,1 kg	1,36 Euro / kg	25,6 Euro	18.84 kg	Taken from bouwkosten.nl	1,2 Euro/m length = 57,6 Euro	Severstal (Russia)	6 Euro/m length = 144 Euro	bouwkosten.nl	15 Euro/m length = 720 Euro	bouwkosten.nl
Tertiary sheathing (quadrant rods 30 x 30 mm)	114 rods	1.39 kg / 1 m length	1,36 Euro / kg	756 Euro	556 kg	Taken from bouwkosten.nl	1,2 Euro/m length = 479 Euro	Severstal (Russia)	114 x 3,5m x 1,39 kg x 1,35 Euro/kg = 756 Eur	bouwkosten.nl	3,8 Euro/m length = 1516 Euro	bouwkosten.nl
Walls												
Gipsum-fiber board (2500x1200x12,5 mm)	56 sheets	31,5 kg / board	45,15 Euro / board	2520 Euro	1764 kg	Knauf, taken from bouwkosten	31,5 Euro/board x 56 = 1764 Euro	Knauf (Russia)	37,3 Euro/board x 56 boards = 2089 Euro	snabmsk.ru	45,15 Euro/board x 56 = 2.528 Euro	bouwkosten.nl
Wall finishing layer (anti-bacterial paint)	65 m2 = 10,8 liters	0,166 liter/m2	24 Euro/1 liter	1800 Euro		Taken from bouwkosten.nl	19,2 Euro/Liter x 10,8 L x 2 =415 Euro	bouwkosten.nl	27,8 Euro/Liter x 10,8 L x 2 layers = 600,5 Eu	bouwkosten.nl	34,2 Euro/Liter x 10,8 Euro x 2 = 738,7 Eu	bouwkosten.nl
Ward door	1			588 Euro	35 kg		467 Euro/door	spi-polymer.ru	587 Euro/door	bs.stroynet.ru	588 Euro/door	
Insulation layer (6.000x600 mm, thikness 80 mm)	1, 96 m3 per module	52 m2 per module is required	6,95 Euro / m2	360 Euro	77 kg	Rockwool, 6000x600x50 mm, N	6.95 Euro/m2 x 52 m2 = 361,4 Euro	bouwkosten.nl	8,4 Euro/m2 x 52 m2 = 437 Euro	bouwkosten.nl	10,2 Euro/m2 x 52 m2 = 530 Euro	bouwkosten.nl
Ceiling												
Metal profiles for suspended ceiling	85 profiles	0,1 kg per profile	4 Euro per profile	340 Euro	8.5 kg	ALBES ceilings (Russia)	3 Euro/1 profile x 85 profiles = 255 Eur	bouwkosten.nl	4 Euro/1 profile x 85 profiles = 340 Euro	ALBES ceilings (Russi	5,5 Euro/1 profile x 85 profiles = 468 Euro	ALBES ceilings (Russia)
Ceiling finishing boards	28 m2 (1 tile =600x600 mm	6 kg/tile	28 Euro/m2	784 Euro	468 kg	Taken from bouwkosten.nl	19,95 Euro/m2 x 27,7 m2 = 552,6 Eur	bouwkosten.nl	28 Euro/m2 x 27,7 m2 = 775,6 Euro	bouwkosten.nl	34,8 Euro/m2 x 27,7 m2 = 964 Euro	bouwkosten.nl
Floor												
Finishing layer	25 m2		3,5 Euro / m2	87,5 Euro	600 kg		17 Euro/m2 x 25 m2 = 425 Euro	teohim.ru	17,7 Euro/m2 x 25 m2 = 442,5 Euro	prompol.ehg.su	33,3 Euro/m2 x 25 m2 = 833 Euro	evropoll.nl
draft layer (insulation layer)	25 m2		17,4 Euro/m2 -> discount 30 % from 70 m	300 Euro		Taken from bouwkosten.nl	17,4 Euro/m2 x 25 m2 = 435 Euro	teohim.ru	26 Euro/m2 x 25 m2 = 650 Euro	bouwkosten.nl	39 Euro/m2 x 25 m2 = 975 Euro	bouwkosten.nl
Bathroom pod												
Metal wall frame railings	10	0,3 kg per 1 rail	4 Euro per profile	40 Euro	3 kg	Knauf (Germany)	2,5 Euro/profile x 10 profiles = 25 Euro	knauf.com	4,35 Euro/profile x 10 profiles = 43,5 Euro	knauf.com	5,8 Euro/profile x 10 profiles = 58 Euro	knauf.com
Gipsum-fiber board (2500x1200x12,5 mm)	5	31,5 kg / board	45,15 Euro / board	225,7 Euro	157.5 kg	Knauf, taken from bouwkosten.n	31,5 Euro/board x 5 = 157,5 Euro	Knauf (Russia)	37,3 Euro/board x 5 boards = 186,5 Euro	snabmsk.ru	45,15 Euro/board x 5 = 225,7 Euro	bouwkosten.nl
Ceramic finishing tiles walls	17,6 m2	15 kg / m2	17 Euro / m2	300 Euro	264 kg	Taken from bouwkosten.nl	10 Euro/m2 x 17,6 m2 = 176 Euro	shopceramica.ru	17,3 Euro/m2 x 17,6 m2 = 305 Euro	bouwkosten.nl	37 Euro/m2 x 17,6 m2 = 651 Euro	xplit.ru
Ceramic finishing tiles floor	3,5 m2	23,3 kg / pack -> 3 packages	39,8 Euro / m2	139 Euro	70 kg	Taken from bouwkosten.nl	18,5 Euro/m2 x 3,5 m2 = 64,75 Euro	plitka-sdvk.ru	37 Euro/m2 x 3,5 m2 = 130 Euro	santa-keramika.ru	47 Euro/m2 x 3,5 m2 = 164,5 Euro	plitka-sdvk.ru
Watercloset	1			500 Euro	37 kg	Taken from bouwkosten.nl	275 Euro	kranik.ru	450 Euro	kranik.ru	500 Euro	kranik.ru
Shower pod	1 (800x80x500 mm)			250 Euro	48 kg	Taken from bouwkosten.nl	130 Euro	ruspanel.ru	260 Euro	hatria.ru	360 Euro	hatria.ru
Sink	2	6 kg /sink	30 Euro / sink	60 Euro	12 kg	Santek (Russia)	60 Euro	santek.ru	140 Euro	santek.ru	200 Euro	santek.ru
Door	1			110 Euro	14 kg	Rem-Sovet (Russia)	110 Euro	Rem-Sovet (Russi	160 Euro	Rem-Sovet (Russia)	220 Euro	Rem-Sovet (Russia)
Light	4 (LED lights inside ceiling)		60 Euro / spot	240 Euro	9 kg	Lucide (Belgium)	150 Euro x 2 lights = 300 Euro		240 Euro x 2 lights = 480 Euro		350 Euro x 2 lights = 700 Euro	

Building components: 37 - 43 % from entire construction cost

Installation systems												
Electrical radiator (heating system)	2	18 kg (1) + 9 kg (2)	100 Euro (1) + 360 Euro (2)	460 Euro	27 kg	Varmann (Russia)	219 Euro x 2 = 438 Euro		244 Euro x 2 = 488 Euro		379 Euro x 2 = 758 Euro	
HEPA filter (air cleaning and anti-bacterial environment)	1			542 Euro	15 kg	Tion (Russia)	542 Euro		658 Euro		702 Euro	
Fan-coil (central heating and ventilation system)	2 (this is the rule for hosp)	38 kg per unit	3.400 Euro per unit	6.800 Euro	76 kg	Daikin (Japan)	1.342 Euro x 2 = 2.684 Euro		3.400 Euro/unit x 2 = 6.800 Euro		3.800 Euro x 2 = 7.600 Euro	
Patient control status monitor system	1			1.420 Euro	5.5 kg	Armed (China)	900 Euro		1.420 Euro		1.820 Euro	
Headwall system (medical gases, life system control, etc)	1			5.400 Euro	52 kg		4500 Euro		5.400 Euro		6.300 Euro	
Medical gas system	1			660 Euro								
Medical gas pipes	20 m (length)		13.4 Euro/1 m length	268 Euro		Taken from bouwkosten.nl	13,4 Euro/m length x 20 m length = 26	bouwkosten.nl	15,6 Euro/m length x 20 m = 312 Euro	bouwkosten.nl	19 Euro/m length x 20 m = 380 Euro	bouwkosten.nl
Ventilation pipes												

Installation systems: 40 - 46 % from entire construction cost

Medical equipment												
Patient bed	1			4.700 Euro	125 kg	Linet Eleganza (Italy)	2.800 Euro	phc-online.com	4.700 Euro	Linet Eleganza (Italy)	5.200 Euro	phc-online.com
Caregiver entrance sink	1			330 Euro	11.5 kg	Duravit (Germany)	300 Euro	Duravit (Germany)	330 Euro	Duravit (Germany)	460 Euro	phc-online.com
Main ceiling light	1			85 Euro	4 kg		Included in lights		Included in lights		Included in lights	
Bed light	2			40 Euro	1 kg		40 Euro x 2 lights = 80 Euro		65 Euro x 2 lights = 130 Euro		75 Euro x 2 lights = 150 Euro	
Visitor sofa	2			120 Euro	3 kg		120 Euro x 2 = 240 Euro		300 Euro x 2 = 600 Euro		410 Euro x 2 = 820 Euro	
Table (foldable)	1		60 Euro	60 Euro	25 kg		60 Euro		60 Euro		80 Euro	
Chair	2	5 kg per chair	40 Euro / chair	80 Euro	10 kg		50 Euro x 2 chairs = 100 Euro		90 Euro x 2 chairs = 180 Euro		120 Euro x 2 chairs = 240 Euro	
bed stend	1			120 Euro	7 kg		120 Euro		140 Euro		180 Euro	

Medical equipment: 13 - 23 % from entire construction cost

Conventional construction. Price of construction and installations.

E	TRANSPORTINSTALLATIES TRANSPORT SYSTEMS				
(66)	transport transport	m2		0	0,00
	- transporttechnische voorzieningen transportation technical provisions	incl.		0	0,00
	volgens opgave door de adviseur installaties as specified by the consultant installations			0	0,00
	(opgenomen bij included in amount (61))			0	0,00
	-- incl. buispost voorziening incl. tube station supply	1 pst.	485.500,00	485.500	6,13
				0	0,00
(69)	algemeen general			0	0,00
	- bouwkundige voorzieningen t.b.v. T-installaties structural facilities receivers for T-systems	79.200 m2	2,50	198.000	2,50
				0	0,00
	TOTAAL TRANSPORTINSTALLATIES TOTAL TRANSPORTATION SYSTEMS			**683.500**	8,63
	TOTAAL INSTALLATIES TOTAL SYSTEMS			**60.003.650**	757,62

B	**BOUWKOSTEN CONSTRUCTION COSTS (incl. BTW)**			**199.859.745**	2.523,48

Figure x. Cost of installations and total budget of hospital designed by Wiegerinck architects (Wiegerinck Architectuur stedenbouw, 2014)

	Plafondbekledingen onder gebouw-/dakoverstekken			0	0,00
	- 2 lagen gipsvezelplaten + stucwerk ceiling coverings include building / roof overhangs - 2 layers of gypsum fiber board + plaster	165 m2	175,00	28.875	0,36
	incl. isolatie tegen onderzijde dakvloer – gedeeltelijk incl. insulation underneath roof deck - partially			0	0,00
				0	0,00
	NSA-gebouw NSA building:			0	0,00
	- plafondafwerking -- onderzijde dakvloer in het zicht ceiling finish - lower roof deck in sight	285 m2	10,00	2.850	0,04
	** toeslag voor schoonwerk charge for cleaning work			0	0,00
				0	0,00
	TOTAAL PLAFONDS (binnen en buiten) TOTAL CEILING (inside and outside)			**2.602.695**	32,86
	TOTAAL BOUWKUNDIGE WERKEN TOTAL CONSTRUCTION WORK			**76.925.293**	971,28

blad 10

B	**BOUWKOSTEN CONSTRUCTION COSTS (incl. BTW)**			**199.859.745**	2.523,48

Appendix 10. Construction cost and total budget of hospital designed by Wiegerinck architects (Wiegerinck Architectuur stedenbouw, 2014)

Type of operation	Labor hour per module				
	Low	Medium	High	N of men/operation	Total hrs
Cut to size (Mill)	3	12	17	1	12
Build floor	8	8	27	2	8
Build window / door opening subassy	2	3	4	2	2
Build partition walls	2	5	9	1	5
Build side walls	3	5	7	1	5
Build end walls	1	2	3	1	2
Build marriage wall	2	3	3	1	3
Set partition walls	2	3	5	1	3
Set exterior & marriage walls	2	4	4	1	4
Install rough electric in walls	7	7	17	1	7
Build plumbing subassemblies	no data	no data	no data	1	
Instal rough plumb in wall & tubs	4	6	8	1	6
Build subassemblies for roof	2	4	6	1	4
Build roof / ceiling	6	10	13	2	6
Instal rough plumbing for roof	6	10	13	1	10
Instal rough electric in roof / ceiling	5	5	7	1	5
Insulate roof	3	4	12	1	4
Instal fascia & soffit	5	7	9	1	7
Insulate walls	6	7	9	1	7
Sheath walls	2	4	13	1	4
Install windows & exterior doors	0,28h/m2=1,3 h/window	1,6	2,2	2	1.6
Install siding & trim	no data	no data	no data	1	
Hang drywall on walls	4	7	18	1	7
Tape & mud drywall	1	2	20	1	2
Sand & paint	1	4	20	1	4
Install cabinets & vanities	3	4	8	1	4
Build finish plumbing subassemblies	8	12	22	1	12
Install finish plumbing	4	5	12	1	5
Install finish electric	2	2	4	1	2
Build interior door subassemblies	1	1	2	1	1
Install interior doors	2	3	4	1	3
Install molding	3	4	12	1	4
Install miscellaneous finish items	1	4	6	1	4
Install floring	1	2	7	2	1
Load shiploose	5	8	24	1	8
Factory touch-up	1	2	4	1	2
Install plumbing in floor	3	4	4	1	4
Load module on carrier	4	5	9	Mashine	
Final wrap & prep for shipment	no data	no data	no data	2	
Build major shiploose subassemblies	2	3	4	2	2
Total	117	181	366	**46**	170.6
	4,8 days	**7,5 days**	**14,5 days**		**7 days**

Appendix 11. Set of operations for assembly of the module and time requirements for it (Factory design for modular homebuilding, Mullens, M.A., 2011)

Fixed operating costs	Price 1,minimum, Euro	Price 2, most expected one, Euro	Price 3, maximum, Euro	Source
Cost of vehicle ownership	29,750	39,500	52,500	toprtucks.nl
Cost of vehicle rent, per month	639/21 working days = 30,4 Euro/day	658/21 working day = 31,3 Euro/day	1541/21 working day =73,3 Euro/day	toprtucks.nl
VAT of vehicle ownership = 21 %	6,247	8,085	11025	toprtucks.nl
VAT of vehicle rent = 21 %	134 Euro	138 Euro	323 Euro	
Cost of lorry	18,750	19,750	24,500	toprtucks.nl
Cost of lorry rent, per month	528/21 working day = 25,1 Euro/day	551/21 working day = 26,2 Euro/day	690/21 working day = 33 Euro/day	
VAT of lorry ownership = 21 %	3,937	4,147	5,145	toprtucks.nl
VAT of lorry rent = 21%	111 Euro	115 Euro	145 Euro	toprtucks.nl
Funding scheme (vehicle)	Bank loan	Bank loan	Bank loan	
Cost of license ownership	9,000 Euro for 1st truck	5,000 Euro for every other truck		
Road tax	1,250/year= 3,42 Euro/day	125/month	33/week, 8/day	eurovignettes.eu
Cargo insurance	0.1-0.3 % from cargo cost + 0,5% as franchise = 0,8% from cargo cost			
Vehicle insurance	210 Euro/6 months=1,16 Euro/day	800 Euro/year= 2,2 Euro/day	2000 Euro/year = 5,5/day	
Vehicle parking cost	1,200/Year/365=3,2 Euro/day			
Cost of technical inspection of the vehicle	80 Euro/year/365=0,2 Euro/day	158 Euro/year= 0,43 Euro/day	260 Euro/year= 0,71 Euro/day	
Total fixed costs for selected route (truck ownership) for 1 module	**68.191 Euro**			
Total fixed costs for selected route (truck lease)	**725 Euro**	**814 Euro**	**1000 Euro**	

Variable operating costs	Price 1, Euro	Price 2, Euro	Price 3, Euro	Source
Fuel price	1,34 Euro/1 liter (diesel)	1,69 Euro/liter (95)		statline.cbs.nl
Average fuel consumption for truck/100 km	31,9 liters x 2(round trip) = 63.8 liters	33,2 liters x 2 (round trip) = 112,2 Euro	35 liters	volvo.com
Cost for tires	85 Euro	110 Euro	185 Euro	
Maintenance cost	800 Euro/year/365=2,19 Euro/day	1000 Euro/year = 2,73 Euro/day	3.500 Euro/year/365 = 9,6 Euro/day	
Repair cost	900 Euro/year = 2,46 Euro/day	2.500 Euro/year = 6,85 Euro/day	6.600 Euro/365 = 18 Euro/day	
Tolls (пошлины)				
Driver wage x2, 2d driver is required for modules > 3,5 m width	1718 Euro/month = 78 Euro/day x2 = 156 Euro	2134 Euro/month = 97 Euro/day x2 = 194 Euro	3223 Euro/month = 153 Euro/day x2 = 306 Euro	
Driver insurance	1.350 Euro/year = 3.7 Euro/day	1950 Euro/year = 7.5 Euro/day	2.500 Euro/year = 6.2 Euro/day	
Police guard along the route	1,5 Euro/km = 150 Euro/route	2 Euro/km = 200 Euro/route		
Official permission for transportation of non-dimencional cargo	660 Euro	660 Euro		negabaritof
Taxes				
Ocupation tax	0,17 Euro/ 1 km (Germany)			
Communication costs (telephone, internet)	10 Euro/month	10 Euro/month	10 Euro/month	
Truck wash	55 Euro	64 Euro	69 Euro	
Fines				
Daily costs				
Accomodation costs				
Meals	20 Euro/day	30 Euro/day	40 Euro/day	
Total variable costs for selected route	**1.110 Euro**	**1.397 Euro**	**1.534 Euro**	
Total costs for selected route (truck ownership)	**69.126 Euro**			
Total costs for selected route (truck lease)	**1.835 Euro**	**2.211 Euro**	**2.534 Euro**	

Appendix 12. Variable and fixed operating transportation costs (Author, 2017)

Parameter	Quantity	Time (duration)	Comments	Price 1, Euro	Price 2, Euro	Price 3, Euro	Source
Excavation							
Excavation personnel	3 workers	2 hours		38,3 Euro/hour = 76,6 Euro	45 Euro/hour = 90 Euro	51 Euro/hour = 102 Euro	bouwkosten.nl
Excavator	1 mashine	2 hours		65,75 Euro/hour = 131,5 Euro	68,25 Euro/hour = 136,5 Euro	71,55 Euro/hour = 143,1 Euro	bouwkosten.nl
Weel loader (buldozzer)	1 mashine	2 hours		61,4 Euro/hour = 122,8 Euro	68,85 Euro/hour = 137,7 Euro	79,8 Euro/hour = 159,6 Euro	bouwkosten.nl
Foundation construction							
Piles	8 piles			8,75 Euro/m length; 5 m pile x 8,75 x 8 = 350 Euro	13 Euro/m length; 5 m pile x 12 x 8 = 480 Euro	15 Euro/m length; 5 m pile x 14 x 8 = 560 Euro	bouwkosten.nl
De-watering site		0,32 men-hour/unit					
Site drainage							
Sewer pipe system, concrete	10 m			31 Euro/1 m length = 310Euro	38 Euro/1 m length = 380 Euro	43 Euro/1 m length = 430 Euro	bouwkosten.nl
Sewer pipe, fittings	5/module			5 Euro/fitting = 25 Euro	25 Euro/fitting = 125 Euro	47 Euro/fitting = 235 Euro	bouwkosten.nl
Crane (40-75 tons capacity required)	1 crane	1 hour/module		470 Euro/8 hours = 59 Euro/hour	566 Euro/8 hours = 71 Euro/hour	700 Euro/8 hours = 88 Euro/hour	bouwkosten.nl
On-site personnel workers for module installation	2 persons	1 hour/module		11,8 Euro/hour	13.26 Euro/hour	14.88 Euro/hour	EFBWW (EU)
Personnel for technical installations and connections	2 persons			32 Euro/hour = 64 Euro	46 Euro/hour = 92 Euro	53 Euro/hour = 106 Euro	bouwkosten.nl
Construction manager	1 person			14 Euro/hour	19.8 Euro/hour	23.7 Euro/hour	indeed.nl
Assembly-dismantling staff accommodation (site office)	1 site-office			81 Euro/unit	137 Euro/unit		bouwkosten.nl
Interior finishings	2 hours			37,2 Euro/hour	41.86 Euro/hour	46,9 Euro/hour	bouwkosten.nl
Landscape design and finishes							bouwkosten.nl
Pavement	5 m2			19 Euro/m2 = 95 Euro	22 Euro/m2 = 110 Euro	24 Euro/m2 = 120 Euro	bouwkosten.nl
Processing of soil, sand, gravel	78 m3			8 Euro/m3 = 624 Euro	9 Euro/m3 = 702 Euro	9 Euro/m3 = 702 Euro	bouwkosten.nl
Trees	1						
Module installation	1	0,2 h/module	Price included in crane and personnel				
Waste disposal from construction site (in containers)	1		Container dimentions:	82 Euro	140 Euro	164 Euro	bouwkosten.nl
			2.50 x 1.60 x 1.00 (3m3)				
			3.35 x 1.85 x 1.10 (6 m3)				
			3.60 x 1.90 x 1.60 (10 m3)				
Total				2.084 Euro	2.676 Euro	2.839 Euro	

Appendix 13. On-site works cost calculations (Author, 2017)

Parameter	Quantity	Time (duration)	Comments	Price 1, Euro	Price 2, Euro	Price 3, Euro	Source
On-site works (new site)							
Excavation							
Excavation personnel	3 workers	2 hours		38,3 Euro/hour = 76,6 Euro	45 Euro/hour = 90 Euro	51 Euro/hour = 102 Euro	bouwkosten.nl
Excavator	1 mashine	2 hours		65,75 Euro/hour = 131,5 Euro	68,25 Euro/hour = 136,5 Euro	71,55 Euro/hour = 143,1 Euro	bouwkosten.nl
Weel loader (buldozzer)	1 mashine	2 hours		61,4 Euro/hour = 122,8 Euro	68,85 Euro/hour = 137,7 Euro	79,8 Euro/hour = 159,6 Euro	bouwkosten.nl
Foundation construction							
Piles	8 piles			8,75 Euro/m length; 5 m pile x 8,75 x 8 = 350 Euro	13 Euro/m length; 5 m pile x 12 x 8 = 480 Euro	15 Euro/m length; 5 m pile x 14 x 8 = 560 Euro	bouwkosten.nl
De-watering site		0,32 men-hour/unit					
Site drainage							
Sewer pipe system, concrete	10 m			31 Euro/1 m length = 310Euro	38 Euro/1 m length = 380 Euro	43 Euro/1 m length = 430 Euro	bouwkosten.nl
Sewer pipe, fittings	5/module			5 Euro/fitting = 25 Euro	25 Euro/fitting = 125 Euro	47 Euro/fitting = 235 Euro	bouwkosten.nl
Crane (40-75 tons capacity required)	1 crane	1 hour/module		470 Euro/8 hours = 59 Euro/hour	566 Euro/8 hours = 71 Euro/hour	700 Euro/8 hours = 88 Euro/hour	bouwkosten.nl
On-site personnel workers for module installation	2 persons	1 hour/module		11,8 Euro/hour	13.26 Euro/hour	14.88 Euro/hour	EFBWW (EU)
Personnel for technical installations and connections	2 persons			32 Euro/hour = 64 Euro	46 Euro/hour = 92 Euro	53 Euro/hour = 106 Euro	bouwkosten.nl
Construction manager	1 person			14 Euro/hour	19.8 Euro/hour	23.7 Euro/hour	indeed.nl
Assembly-dismantling staff accommodation (site office)	1 site-office			81 Euro/unit	137 Euro/unit		bouwkosten.nl
Interior finishings	2 hours			37,2 Euro/hour	41.86 Euro/hour	46,9 Euro/hour	bouwkosten.nl
Landscape design and finishes							bouwkosten.nl
Pavement	5 m2			19 Euro/m2 = 95 Euro	22 Euro/m2 = 110 Euro	24 Euro/m2 = 120 Euro	bouwkosten.nl
Processing of soil, sand, gravel	78 m3			8 Euro/m3 = 624 Euro	9 Euro/m3 = 702 Euro	9 Euro/m3 = 702 Euro	bouwkosten.nl
Trees	1						
Module installation	1	0,2 h/module	Price included in crane and personnel				
Waste disposal from construction site (in containers)	1		Container dimentions: 2.50 x 1.60 x 1.00 (3m3) 3.35 x 1.85 x 1.10 (6 m3) 3.60 x 1.90 x 1.60 (10 m3)	82 Euro	140 Euro	164 Euro	bouwkosten.nl
Sub-total				2.084 Euro	2.676 Euro	2.839 Euro	
Fixed operating costs							
				29,750	39,500	52,500	
Cost of vehicle ownership				639/21 working days = 30,4 Euro/day	658/21 working day = 31,3 Euro/day	1541/21 working day =73,3 Euro/day	
Cost of vehicle rent, per month				6,247	8,085	11025	
VAT of vehicle ownership = 21 %				134 Euro	138 Euro	323 Euro	
VAT of vehicle rent = 21 %				18,750	19,750	24,500	
Cost of lorry				528/21 working day = 25,1 Euro/day	551/21 working day = 26,2 Euro/day	690/21 working day = 33 Euro/day	
Cost of lorry rent, per month				3,937	4,147	5,145	
VAT of lorry ownership = 21 %				111 Euro	115 Euro	145 Euro	
VAT of lorry rent = 21%				Bank loan	Bank loan	Bank loan	
Funding scheme (vehicle)				9,000 Euro for 1st truck	5,000 Euro for every other truck		
Cost of license ownership				1,250/year= 3,42 Euro/day	125/month	33/week, 8/day	
Road tax				0.1-0.3 % from cargo cost + 0,5% as franchise = 0,8% from cargo cost			
Cargo insurance				210 Euro/6 months=1,16 Euro/day	800 Euro/year= 2,2 Euro/day	2000 Euro/year = 5,5/day	
Vehicle insurance				1,200/Year/365=3,2 Euro/day			
Vehicle parking cost				80 Euro/year/365=0,2 Euro/day	158 Euro/year= 0,43 Euro/day	260 Euro/year= 0,71 Euro/day	
Cost of technical inspection of the vehicle							
				68.191 Euro			
Total fixed costs for selected route (truck ownership) for 1 module				**725 Euro**	**814 Euro**	**1000 Euro**	
Total fixed costs for selected route (truck lease)							
				Price 1, Euro	Price 2, Euro	Price 3, Euro	
Variable operating costs							
				1,34 Euro/1 liter (diesel)	1,69 Euro/liter (95)		
Fuel price				31,9 liters x 2(round trip) = 63.8 liters	33,2 liters x 2 (round trip) = 112,2 Euro	35 liters	
Average fuel consumption for truck/100 km				85 Euro	110 Euro	185 Euro	
Cost for tires				800 Euro/year/365=2,19 Euro/day	1000 Euro/year = 2,73 Euro/day	3.500 Euro/year/365 = 9,6 Euro/day	
Maintenance cost				900 Euro/year = 2,46 Euro/day	2.500 Euro/year = 6,85 Euro/day	6.600 Euro/365 = 18 Euro/day	
Repair cost							
Tolls (пошлины)				1718 Euro/month = 78 Euro/day x2 = 156 Euro	2134 Euro/month = 97 Euro/day x2 = 194 Euro	3223 Euro/month = 153 Euro/day x2 = 306 Euro	
Driver wage x2, 2d driver is required for modules > 3,5 m width				1.350 Euro/year = 3.7 Euro/day	1950 Euro/year = 7.5 Euro/day	2.500 Euro/year = 6.2 Euro/day	
Driver insurance				1,5 Euro/km = 150 Euro/route	2 Euro/km = 200 Euro/route		
Police guard along the route				660 Euro	660 Euro		
Official permission for transportation of non-dimencional cargo							
Taxes				0,17 Euro/ 1 km (Germany)			
Ocupation tax				10 Euro/month	10 Euro/month	10 Euro/month	
Communication costs (telephone, internet)				55 Euro	64 Euro	69 Euro	
Truck wash							
Fines							
Daily costs							
Accomodation costs				20 Euro/day	30 Euro/day	40 Euro/day	
Meals							
Total variable operating costs				**1.110 Euro**	**1.397 Euro**	**1.534 Euro**	
Sub-total costs for selected route (truck lease)				**1.835 Euro**	**2.211 Euro**	**2.534 Euro**	
Dis-assembly works on the original site							
Crane (40-75 tons capacity required)	1 crane	1 hour/module		470 Euro/8 hours = 59 Euro/hour	566 Euro/8 hours = 71 Euro/hour	700 Euro/8 hours = 88 Euro/hour	bouwkosten.nl
On-site personnel workers for module installation	2 persons	1 hour/module		11,8 Euro/hour	13.26 Euro/hour	14.88 Euro/hour	EFBWW (EU)
Personnel for technical installations and connections	2 persons			32 Euro/hour = 64 Euro	46 Euro/hour = 92 Euro	53 Euro/hour = 106 Euro	bouwkosten.nl
Construction manager	1 person			14 Euro/hour	19.8 Euro/hour	23.7 Euro/hour	indeed.nl
Assembly-dismantling staff accommodation (site office)	1 site-office			81 Euro/unit	137 Euro/unit	162 Euro/unit	bouwkosten.nl
Sub-total costs of di-assembly of the module				**230 Euro**	**333 Euro**	**395 Euro**	
Total re-location costs				**4874 Euro**	**6034 Euro**	**6768 Euro**	

Appendix 14. Cost of module re-location to a new site (source: Author, 2017)

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