Waste identification and elimination in the transportation and assembly process of modular construction

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Abstract

Modular construction, i.e. industrialized construction, is gaining ground compared to traditional construction. By transferring tasks from a construction site environment to a manufacturing environment, a higher productivity rate can be achieved while lowering the project costs. Although, activities that do not add value to the final product, i.e. Non-Value Adding (NVA) activities or waste, can result in an increase in costs and schedule duration. Company X is a construction company that applied industrialized construction to their housing projects. A pilot project performed by Company X showed that xx% of onsite construction activities can be labelled as NVA. Therefore, the objective of this research is to suggest measures that reduce waste in the transport and assembly process of modular construction. The current transportation and assembly process has been mapped first. Data regarding the transportation and assembly process was gathered by observations at the loading process and analysing camera images regarding the unloading and assembly of a modular housing project of Company X.

Modular construction, Industrialized construction, Lean modular construction; Waste; Lean assembly onsite; Lean transportation

1. Introduction

By shifting many aspects of building activity away from traditional onsite projects to offsite manufacturing-style production, modular construction enables productivity improvements (Bertram et al., 2019). Modular construction, also known as industrialized construction, differs from the traditional way of construction by building complete elements and modules in a factory which are then installed on the construction site. Modular construction is characterized by three different principles: *prefabrication*, *standardization*, and *dimensional coordination* (Yu et al., 2013). *Prefabrication* allows construction to move from a craft base to a manufacturing base. According to the report of McKinsey (2019), 80% of the construction activities can be moved from the construction site to a manufacturing environment. Since activities that take place in a production hall are not affected by weather conditions and are *standardized*, so actions are repeated, modular construction allows for a much higher productivity rate. The last principle is *dimensional coordination*, which is explained by the figure in Appendix A. This figure shows that modular construction can differ in terms of complexity (structural to fully functional with complex fixtures), and in terms of scale (from individual units to complete structures).

The modular construction process related to housing projects is visualized in Figure 1. Mainly due to the unavailability and relative costs of skilled construction labour and the growing demand of affordable housing, modular construction is gaining traction compared to traditional construction (Bertram et al., 2019). In 2018, the global modular construction market size was valued at 112.3 billion USD, from which it is expected to register a compound annual growth rate (CAGR) of 6.5% over the forecast period up to 2025 (Grand View Research, 2019). Regarding residential application, it is expected to advance at a CAGR of 7.2% up to 2025.

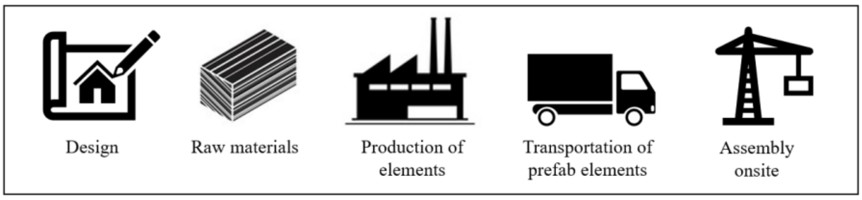

Figure 1: Schematic visualization of the modular construction process

The main advantage of modular construction compared to traditional construction is the possible reduction in construction times and costs. Recent modular construction projects have already established an acceleration of project timelines by 20 to 50 percent (see Appendix B) while potential construction cost savings of 20% apply, in the right environment and trade-offs (Bertram et al., 2019). On the other hand, there is the risk of a cost increase of 10% if labour savings are outweighed by logistics or material costs, as shown in Appendix C. According to Lange & Schilling (2015), the function of construction logistics is to coordinate the core areas material, employees and information in such a way that the correct material is available on a proper price, at the correct place, at the right time, in the exact quality and quantity, for the correct client (7 R's). Therefore, coordination and delivery of modules to the site is critical, since the builders must ensure that the productivity gains outweigh the costs (McKinsey & Company, 2019).

Regarding the installation process onsite, Company X investigated during a pilot project how much time can be labelled as Non-Value Adding (NVA). NVA, or waste, construction activities are processes that do not add value to the completion of the building and therefore should be minimized or eliminated. These wasted times can lead to nullifying the benefits of modular construction and even increase the total construction times and costs. Furthermore, Innella et al. (2019) state that very limited studies have been carried out in the direction of the transportation and installation onsite processes, despite the fact that the transportation phase significantly contributes to the production of waste since structural damages are often detected during the transportation process which results in additional costs (Gustafsson et al., 2012; Innella et al., 2018). Lean strategies for the transportation and assembly processes need to be further explored to achieve the full potential in terms of productivity (Innella et al., 2019). Thus, there is a significant need to pay attention to the transportation and assembly process regarding modular construction. Therefore, the goal of this research is, on the one hand, to identify the causes of waste within the transportation and assembly process, and on the other hand to suggest measures that reduce Non-Value times for Company X for the transportation and assembly process onsite for modular construction.

This paper contributes to the body of knowledge by discussing the causes of the identified wastes in the transportation and assembly phase and by suggesting measures that can minimize or eliminate waste regarding modular construction. This paper is structured as follows. First, the theoretical background of this research is provided in section 2. Here it is discussed which theories and tools are applied to identify and eliminate waste. Section 3 contains an explanation of which methods have been used to (1) map the current process including the amount of waste, (2) identify causes of waste, and (3) propose solutions for waste. The results of this research can be found in section 4, which is followed by the discussion and the conclusion section of the paper.

2. Theoretical background

By moving activities from the construction site to the factory, the comparison between the modular construction industry and the manufacturing industry becomes relevant. Prefabrication allows construction to move from a craft base to a manufacturing base (Innella et al., 2019). However, four substantial differences exist between the construction and manufacturing industry. First, unlike production in areas such as automotive, construction is not a fixed-base industry since the dwellings must still be assembled on a particular site (Innella et al., 2019). Secondly, construction is a one-of-a kind production, which means that, although modular construction is characterized by a higher degree of standardization compared to traditional construction, they may still have access to a high level of customization (Innella et al., 2019). The third difference with the manufacturing industry is that construction is characterised by temporary organization since the realization of different projects in construction is based on working with organizations which are strictly related to the execution and finalization of the project (Innella et al., 2019). Finally, complexity is a characteristic of construction since it is subjected to uncertainties and unforeseen events in comparison with manufacturing, which makes it more difficult to control and manage (Innella et al., 2019).

According to Mostafa et al. (2016), relevant improvement may be achieved in the construction industry through the proper implementation of manufacturing initiatives such as lean principles. The Lean approach has been applied in many industries, including the health care and the construction industry. According to Innella (2019), lean transportation and onsite assembly management are essential for productivity enhancement in the construction industry. Lean management originates from the manufacturing industry where it was first pioneered by the Toyota Production System (TPS) (Ohno, 1988). The main goals of TPS, which form the foundation of the lean manufacturing theory, are to perform zero-defect production and to minimize waste within the production process. A production process can be seen as a transformation process from an input (raw material) to an output (end product). Production can also be seen as a flow that consist of different operations, for example: processing, inspecting, waiting, and moving, from which only processing is considered a profitable operation (Innella et al., 2019), which is called Value-Adding (VA).

VA operations consist of conversion activities that contribute to fully satisfy the needs of the customer and respond to their requirements. Thus, according to the flow perspective, only processing operations add value to the product, by converting raw material into an end product with specified features (Innella et al., 2019). On the contrary, inspecting, waiting and moving are NVA operations, because they need time, money, human resources, and space, but do not contribute to the creation of additional value (Innella et al., 2019). Whether something can be seen as an NVA operation depends on the perspective from which it is viewed. For example, if materials are moved from the factory to the construction site, it is seen as a VA operation, since the goal is to deliver these materials to the construction site. If the materials are moved on the construction site itself without adding value to the final product (the dwelling), it is seen as NVA. There are seven types of NVA operations (waste), namely unnecessary transportation movement, inventory, motion, waiting, over-processing, overproduction, and defects (Ohno, 1988). In Table 1, these waste types are explained in the context of modular construction. These wastes all lead to a delay in the process and will eventually increase production costs as a final consequence (Innella et al., 2019).

Table 1: Waste type descriptions

Waste type	Description
Unnecessary transportation movements	Transportation waste involves the unnecessary movement of materials or equipment (Dinis-Carvalho, Moreira, et al., 2015). Moving façade elements on the construction site for instance without transporting it to the assembly number for installation, is considered as waste. It can also refer to the unnecessary transmission of information (Koskela et al., 2013).
Inventory	Inventory waste refers to materials that are waiting to be processed (Dinis-Carvalho, Moreira, et al., 2015). This occurs when overproduction results in excess material on the construction site. Having some inventory is necessary to ensure that the project progresses, but it should be minimized because it ties up budget, requires storage, and often degrade when not used.
Motion	Motion waste is a result of extra steps taken by people to accomplish the activity. This includes movement that is not necessary, like distance between workers, tools, and materials, creates the waste of motion. Motion is a type of waste that is only associated to people (Dinis-Carvalho, Moreira, et al., 2015).
Waiting	The most common scenario that leads to waiting in construction is when workers are ready, but the necessary materials needed for the work to be completed have not been delivered, or the prerequisite prior task has not been completed. Waiting is assigned to people and resources, not to products and parts because when products and parts are 'waiting' it is already labelled as inventory waste (Dinis-Carvalho, Moreira, et al., 2015).
Over-processing	Over-processing waste refers to unnecessary steps taken in the project (Dinis-Carvalho, Moreira, et al., 2015).
Overproduction	Overproduction refers to producing more than required or producing it before it is needed (Dinis-Carvalho, Moreira, et al., 2015). Regarding the modular construction process, overproduction occurs when the productivity rate at the construction site is lower than the productivity rate at the factory from which elements are transported to the construction site, resulting in inventory waste as well.
Defects	Defects are anything that is not done correctly the first time, resulting in rework that wastes time and materials.

Besides VA and NVA activities, there are Necessary Non-Value Adding (NNVA) activities. NNVA operations do not add value to the final product but are needed within the present process to complete the VA tasks. For example, the construction of the scaffoldings is needed to ensure the safety on the construction site and to install façade elements, but they do not directly add value to the final product (the dwelling).

Processes, consisting of VA, NVA, and NNVA activities, can be improved according to the Transformation, Flow, and Value Generation (TFV) theory. This theory implies that there are three different points of view related to construction production, namely: *transformation*, which main focus is on the optimization of each process (VA operations), *flow*, which mainly focusses on the minimization of NVA activities, and *value generation*, which main focus is on the increase of the value of the end product through customers needs' satisfaction (Innella et al., 2019). The point of view this research applies is the conceptualization of a product as a flow, since the goal of this research is to reduce waste within the transportation and onsite assembly process. Regarding the identification and elimination of waste, several techniques have been adopted in the production industry, including construction. One frequently used technique to identify and eventually minimize waste is Value Stream Mapping (VSM). Another technique, which is developed to overcome some shortcomings of VSM is the Waste Identification Diagram (WID). Therefore, these two visualization techniques are explained and compared in the upcoming paragraphs.

2.1. Value Stream Mapping

Value Stream Mapping (VSM) is the most common used tool to represent and analyse the value stream of product families (Dinis-Carvalho, Ferrete, et al., 2015). By making use of arrows, symbols, and metrics as a guide, VSM is able to represent the flows of materials and information (Ismail et al., 2019). One of the main advantages of VSM is its visual nature which allows for a quick assessment of the state of the production process (Dinis-Carvalho et al., 2019). An example of a VSM is shown in Figure 2. In this figure it can be seen that the layout of a VSM consists of three main areas, which are explained below:

1. Flow of information: Here, all information that is (electronically) send between the customer and supplier is visualized.
2. Flow of materials: The flow of materials shows what processes (activities) take place with respect to a product family, so for instance a dwelling. These activities are indicated with process blocks and include relevant information for the analysis of the process. In this example, this relevant information is the cycle time (C/T), the changeover time (C/O), uptime, the number of shifts, and the availability. The thick arrows between the processes are used to indicate the transport of materials from one process to the next process. The triangles are used to indicate an inventory level per process block.
3. Lead time ladder: The lead time ladder indicates how much time is spend on a VA activity (300 seconds in the case of process A) and on a NVA activity (4 days waiting time between process A and B for instance).

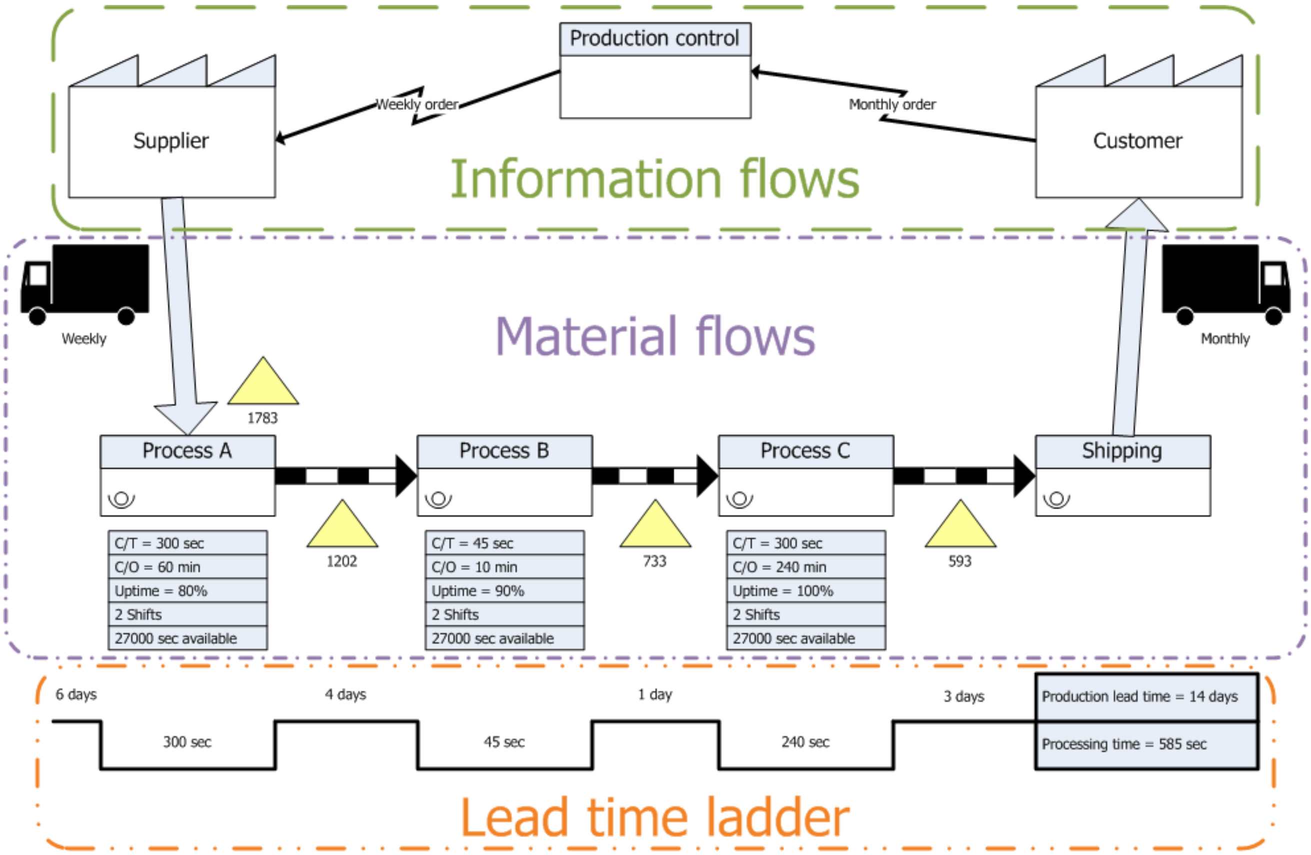

Figure 2: VSM example (Tallyfy, n.d.)

VSM is applied in several areas, such as the automotive industry, electronics, and environment. According to a literature review conducted by el Kihel et al. (2019), the VSM method is more applied to the automotive industry, particularly to the supply and production process. VSM has also been applied to modular construction by Heravi and Firoozi (2017), who used VSM as a lean technique combined with Discrete Event Simulation in the production phase of prefabricated steel frames, which resulted in 34% lead time reduction of production and 16% cost reduction.

Despite the fact that VSM is the most used tool to identify waste, the methodology has some drawbacks, as highlighted by several authors. First, not all types of waste can be identified and quantified by the VSM tool. VSM is not able to represent the wastes related to people, which include motion, transport, waiting, and over-processing (Dinis-Carvalho, Ferrete, et al., 2015). Unnecessary transportation movement waste is not graphically indicated and not quantified or measured in terms of impact (Dinis-Carvalho, Ferrete, et al., 2015). Waiting, motion, and over-processing wastes are difficult to observe since they remain virtually 'hidden' on the VSM (Dinis-Carvalho, Ferrete, et al., 2015). Secondly, VSM lacks in the presence of economic indicators, layout representation, and the bill-of-materials (Dinis-Carvalho et al., 2019). Several authors have acknowledged these VSM limitations and developed alternatives or adaptations to the traditional VSM tool. One of the alternatives was linking simulation to VSM which has been proven effective to overcome the static nature of VSM and allows to test alternative improvement proposals (Parthanadee & Buddhakulsomsiri, 2014). Yu et al. (2009) explicated the major limitations of traditional VSM and proposed a practical approach for utilizing VSM in a traditional construction setting. It is argued that although traditional construction is not the ideal application field for VSM, the modular construction industry is more suitable for such a type of practice due to more repetitive processes and higher monitoring ease (Innella et al., 2019). Villarreal (2012) presented the Transportation Value Stream Map (TVSM), which is an adaption of the traditional VSM to support efficiency improvement programmes in the transport operations environment. An alternative which is mostly focused on the identification of all waste types, is the Waste Identification Diagram, which is explained in the next paragraph.

2.2. *Waste Identification Diagram*

The Waste Identification Diagram (WID) is specifically developed by the Production and Systems Department of the University of Minho to overcome some of the VSM limitations (Dinis-Carvalho, Moreira, et al., 2015). The WID uses physical dimensions of its symbols to transmit information about the production process, for example work in process (WIP), transportation effort (arrow), setup time and idle time (Dinis-Carvalho, Ferrete, et al., 2015). The WID is essentially composed by blocks, arrows, and a pie chart. These main icons, which are visualized in Figure 3, are explained as follows:

- Blocks: The blocks represent stations which can be workbenches, machines, equipment or even sectors (Dinis-Carvalho et al., 2019). The three dimensions of the block give visual information about how lean the station is. Blocks with large volumes mean problems and waste. In other words, the larger the volumes the less lean is the station (Dinis-Carvalho, Moreira, et al., 2015). The dimensions of the block visually represent:
    - Station Time (S_T): The station time is the sum of all operation times of the operations performed in Station X on one product (Dinis-Carvalho, Moreira, et al., 2015).
    - Takt Time (T_T): The takt time is given by dividing the operation time per day by the customer demand per day (Dinis-Carvalho, Moreira, et al., 2015).
    - Work In Process (WIP): The width of the block represents the amount of work in process (WIP) waiting to be processed in the referred station (Dinis-Carvalho, Moreira, et al., 2015).
    - Changeover Time (C/O): The depth of the block represents the changeover time (C/O) for the station. In many cases, large change-over times influence the amount of WIP waiting to be processed on that station.
- Arrows: The arrows represent the transport effort required for moving the parts from one station to another (Dinis-Carvalho et al., 2019). The transportation effort is expressed as the quantity multiplied by the distance (Dinis-Carvalho, Moreira, et al., 2015).
- Workforce occupation circular graph: The pie chart depicts the workforce activities (Dinis-Carvalho et al., 2019). Here, all identified waste related to people is summarized.

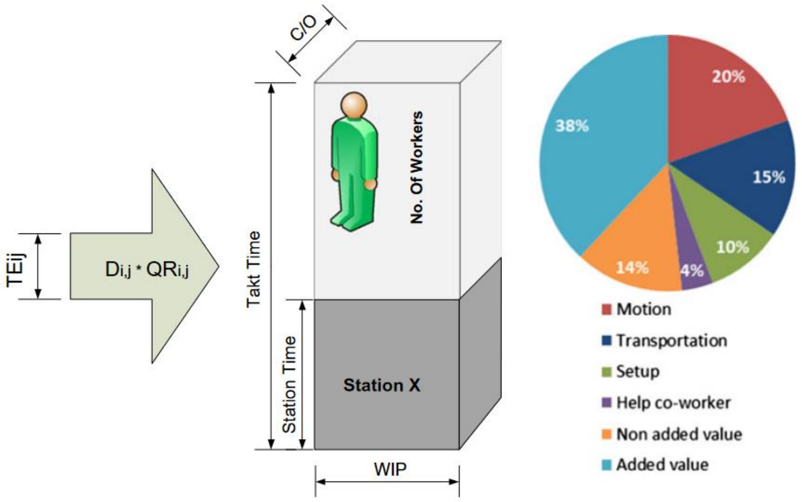

Figure 3: WID main icons: Transportation effort, process block, and pie chart (Dinis-Carvalho, Moreira, et al., 2015)

With these main icons, the WID forms a network of (three-dimensional) blocks and arrows representing production units which is able to represent wastes that are related to materials (inventory, overproduction, transport, and defects) and related to people (motion, transport, waiting, and over-processing) (Dinis-Carvalho, Ferrete, et al., 2015). An example of the WID is shown in Figure 4. In addition to the main icons (Figure 3), the overall performance is added to provide insight into relevant performance indicators related to the process. With the main icons of WID it is easier to identify, understand and interpret bottlenecks within the process compared to VSM (Dinis-Carvalho et al., 2019). Especially in terms of representational power and wastes identification, WID is presented as an advantageous alternative to VSM (Dinis-Carvalho, Moreira, et al., 2015). Nevertheless, compared to VSM, WID is limited by not being able to represent the information flow involving suppliers, purchasing, transportation, and production planning (Dinis-Carvalho et al., 2019).

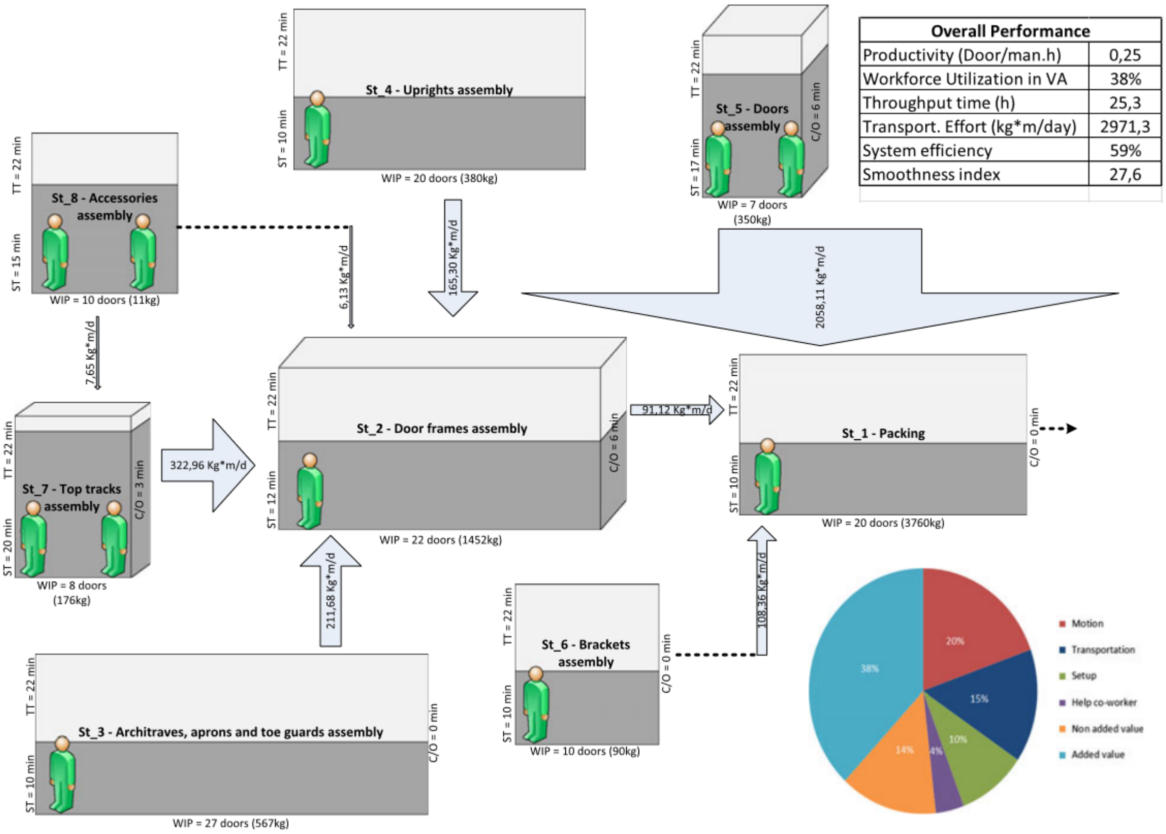

Figure 4: Example of a Waste Identification Diagram for a lift's doors production unit (Dinis-Carvalho, Moreira, et al., 2015)

2.3. Value Stream Mapping and Waste Identification Diagram

A previous research, conducted by Dinis-Carvalho et al. (2015), proposed to improve the effectiveness of VSM with some WID features into the VSM diagrams, as can be seen in Figure 5. The integration of VSM and WID keeps the essence of VSM, which is the representation of the material and information flows across the entire process, while incorporating some valuable WID features, namely the meaningful interpretation of the physical dimensions of WID symbols (Dinis-Carvalho, Ferrete, et al., 2015).

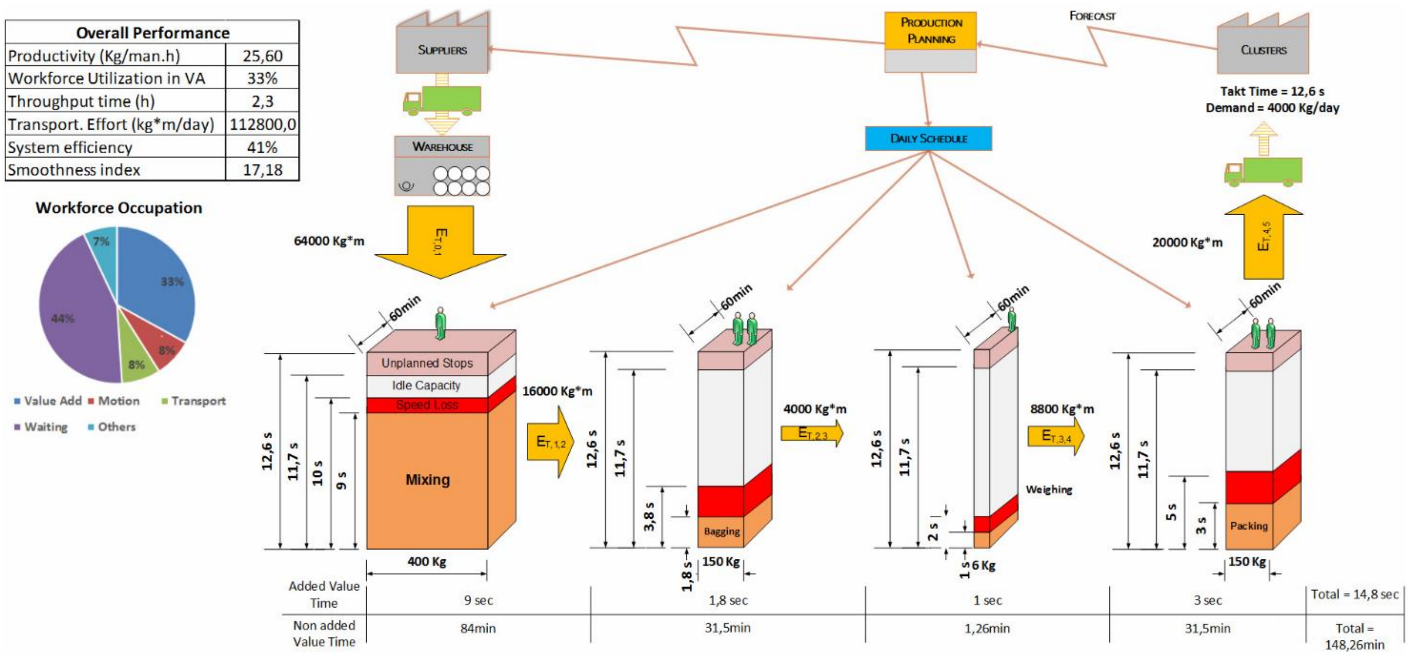

Figure 5: VSM+WID (Dinis-Carvalho, Ferrete, et al., 2015)

In Table 2 it can be seen how the different representation capacities of VSM and WID are combined, as proposed by Dinis-Carvalho et al. (2015). From this table it becomes clear what the advantages are of combining VSM and WID, such as the capacity to represent wastes and information flows within the process.

VSM combined with WID has the potential to map the current transportation and assembly process in of Company X. In the next section (methodology), it is explained how this method is applied in the context of this research.

Table 2: Comparison between VSM, WID, and VSM combined with WID. Source (1) = (Dinis-Carvalho, Ferrete, et al., 2015). Source (2) = (Dinis-Carvalho, Moreira, et al., 2015)

Representation capacity	**VSM**	**WID**	**VSM + WID**
Information flow (1)	Yes	No	Yes
Production flow (1)	Yes	Yes	Yes
Overproduction waste (1)	Yes, but difficult to be interpreted	Yes, but difficult to be interpreted	Yes
Inventory waste (1)	Yes, graphically represented by a triangle. Its level is given by a number	Yes, numerically indicated and graphically represented by the length of the block	Yes
Unnecessary transportation movement (1)	No, it is represented but not evaluated and/or quantified	Yes, it is clearly evaluated by the arrow width	Yes
People related wastes (1)	No	Yes	Yes
Defects related waste (2)	Non-existing	Non-existing	Non-existing
Over-processing (2)	Inspection and testing operations only	Inspection and testing operations as well as other presented in the pie chart	Inspection and testing operations as well as other presented in the pie chart
Motion waste (2)	Non-existing	Presented in the pie chart	Presented in the pie chart
Waiting (2)	Non-existing	Presented in the pie chart	Presented in the pie chart
Dimensional meaning (1)	No	Yes	Yes
Capacity to measure/quantify waste (2)	Only inventory level	Most types of waste are evaluated	Most types of waste are evaluated
Easy to visualize the excess of capacity in each station/process (2)	Only by reading values	Clearly shown visually	Clearly shown visually
Planning and Control information flow (2)	Important information is shown	Non-existing	Important information is shown
Link to suppliers and clients (2)	Material and information link	Non-existing	Yes
Push/Pull symbolic information (2)	Clearly shown	Non-existing	Non-existing

3. Methodology

The aim of this research is to suggest measures that reduce the NVA times in the transportation and assembly process onsite regarding modular construction. The research is divided into three phases, as visualized in Figure 6. First, the current transportation and assembly process, including the amount of waste, is determined. Then the possible causes of the identified waste are determined and lastly solutions are presented to eliminate or minimize the waste in the transportation and assembly process. The methodologies implemented regarding these three phases are explained in the upcoming paragraphs.

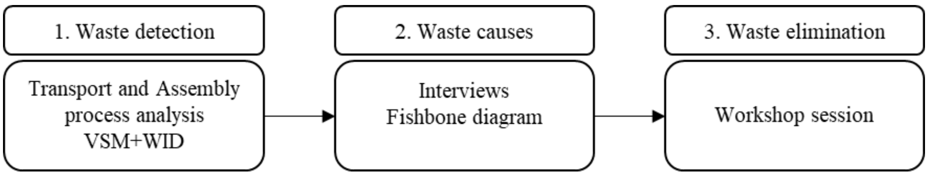

Figure 6: Research methodology; waste management framework

3.1. Step 1: Mapping the current transportation and assembly process

The analysis of the current situation is done based on the principles and visualization methodology of the VSM+WID, as explained in section 2.3. The analysis is based on a case study where the transportation and assembly of 10 modular houses with assembly numbers 14 to 23 is monitored based on camera images. These dwellings are assembled in two blocks, of which the first one with assembly numbers 14-18 is visualized in Appendix D. To map the current transportation and assembly process, a combination between VSM and the WID is applied, since the combination of these methods nullify each other's shortcomings (section 2.3). VSM does not allow to identify and quantify all types of waste and WID does not represent the information flow, which is seen as relevant for mapping the current process and identifying any bottlenecks. Therefore, it is decided to combine the two methods. According to Dinis-Carvalho et al. (2015), an adequate process map should provide important information about the waste within the process, while other relevant aspects should also be included (for instance productivity, efficiency, throughput time). The combination of VSM and WID allows to gather all relevant information to provide insight into where wastes occur.

However, the VSM+WID method proposed by Dinis-Carvalho et al. (2015) is not directly applicable to map the current transportation and assembly process of modular construction, since the method is supposed to be applied to a manufacturing environment. That is mainly because VSM and WID represent production units (Dinis-Carvalho et al., 2019). Production units are work centres that are capable of performing an activity to manufacture a product. Regarding the transportation and assembly process, there are no real production units as in a factory, but the activities involved in the transportation and assembly process can be seen as production units, since at every activity something is added to the final product, the dwelling. On a construction site, houses do not move along a production line. However, construction workers move from one house to another. Hence, the operations performed by a trade crew can be viewed as a continuous flow (Yu et al., 2009). Therefore, the VSM+WID method is applicable to this research and will be applied to identify waste in the current transportation and assembly process regarding the case study. There are some modifications implemented compared to the VSM+WID that is showed in Figure 5 (section 2.3), of which the main changes can be found in Table 3.

Table 3: Mutation table VSM+WID

<table>
<tr><th>Topic</th><th>VSM+WID (as explained in section 2.3 and shown in Figure 5)</th><th>Mutation VSM+WID</th></tr>
<tr><td>Layout</td><td>Visualizes the whole process in one figure (see Figure 5). Shows VA and NVA durations in the lead time layer without visually indicating high values.</td><td>Due to the large number of activities, the layout of the map is divided into the three assembly layers of the dwelling (Appendix E). Regarding the lead time layer, VA, NVA (waiting times between activities), and NNVA is shown. NVA durations are visualized according to a colour scheme (0 = green, 1-15 = yellow, 15-30 = orange, 30 or higher = red).</td></tr>
<tr><td>Process blocks</td><td>Three-dimensional block. The height represents the total station time including disruptions. Transportation and defect waste are not included in the process block. The depth of the blocks represents changeover time (60 minutes in Figure 7) while the width represents the Work In Process (150 kg in Figure 7).

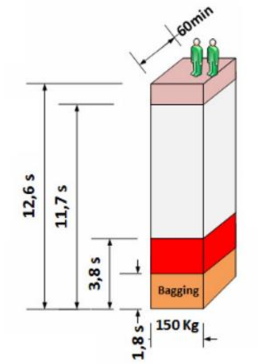

Figure 7: Subsection VSM+WID process block</td><td>In the process blocks it is shown if waste in terms of defects or unnecessary transportation movements occurs. The durations of this waste, together with the VA duration, form the cycle time (height of the process block). The blocks are two-dimensional, so no changeover time included. Work in Process corresponds to the average inventory time of an element linked to the activity in the process block. The wider the process block, the longer it was in stock on average.

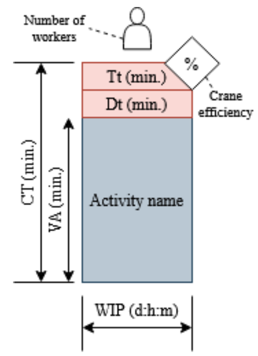

Figure 8: Illustration of modified process block</td></tr>
<tr><td>Unnecessary transportation movements</td><td>Indicated by arrows between the process blocks (activities) and expressed by the number of materials that are transported over a certain distance between stations.

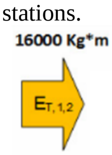

Figure 9: Subsection VSM+WID transportation waste</td><td>If this waste type is linked to an activity, it is indicated in the process block itself (see Figure 8). This is because transport waste does not only occur between consecutive activities. Waste that is not related to a specific activity is included in the overall performance table.</td></tr>
<tr><td>Overall performance table</td><td>Relevant information regarding the overall process, so depending on the context these are included.</td><td>Relevant information regarding this study:

- Throughput time: Since activities can take place at the same time, the throughput time is not the same as the sum of alle activities combined. Therefore, a corrective factor is applied that is calculated by dividing the total sum of all activities in days by the number of assembly days. This corrective factor equals 132%.
- Identified waste types including the VA/NVA/NNVA ratio.
- Crane efficiency: The duration the crane is in use as a percentage of the total time.</td></tr>
</table>

To indicate if an activity adds value to the final product, the following perspective was applied. VA operations are loading, transporting, unloading, installation (of elements) activities. NNVA activities are for example moving supplies (toolboxes) to the construction number or installing the scaffolding. NVA activities are related to a specific waste type. The waste types as described in Table 1 (see section 2) are considered in the VSM+WID. Additionally, two waste types were added specifically for the transportation phase; fill loss and excess load time. Fill loss occurs when the vehicle is not fully loaded and an excess load time occurs when loading/unloading exceeds the standard time allowed for loading the truck (Villarreal, 2012).

To calculate the key concept values, input data was gathered by observations (loading activities) and the analysis of camera images on the construction site (unloading and assembly activities). All input data types that are gathered regarding all activities during the transportation and assembly process have been listed and explained in Appendix F. This data was gathered and analysed in Microsoft Excel, of which a detailed description can also be found in Appendix F. Regarding the transportation process, the loading activities of two assembly numbers and the unloading activities of all assembly numbers were analysed. This analysis was linked to the inventory analysis. The inventory analysis is performed per assembly number and per element type. Regarding the assembly process, the following sequence was applied to come to the sources of waste:

(1) Overall analysis: To provide an overall insight into the current situation, the amount of waste in the whole process over 10 houses is calculated. This is done by calculating the average VA/NVA/NNVA ratio over all assembly numbers. These values are used to set up the VSM+WID to provide an overall insight into the current process.
(2) Analysis per activity: The VSM+WID is based on the average of 10 houses. Since waste can also occur incidentally and are therefore not standard in the process, a waste identification table has also been used. In this table it was checked per activity whether waste occurred including its duration. In this waste identification table, the calculations of the VA, NNVA, and NVA values per assembly number per activity can be found including the maximum, minimum, and average values. The NVA calculations are divided into unnecessary transportation movement waste, defect waste, and waiting waste. Accordingly, the values in the table were coloured to indicate a higher-than-average NVA value.

3.2. Step 2: Analysis of root causes of identified waste in the transportation and assembly process

The root causes of the identified waste were traced by means of interviews with the site manager, transport manager, production manager, engineering, the manager of Houtindustrie (production), and the person responsible for the modules. The VSM+WID (general waste) and the waste identification table (incidental waste included) served as an input for the interview sessions. During these semi-structured interviews, interviewees were asked what, from their perspective, is the reason for the identified waste in the process. The interviews were elaborated by transcribing and coding them based on the identified waste. These identified wastes are referred to by means of '[number]' in the result section. The results from the different interviews were then compared. If the answers of the interviewees matched or were in line with each other, that answer was considered as the cause for the specific waste type. If the answers of the interviewees did not match, the interviewees were asked to clarify the answers.

To validate the identified causes, literature was consulted. The literature search was conducted by keywords in Google Scholar. Searching terms were 'Waste type + causes + (industrialized or modular) construction', 'Identified waste type' + 'identified cause' + (industrialized or modular) construction', 'Root cause + waste type + (industrialized or modular) construction', and Literature review + waste causes + (industrialized or modular) construction'. The snowball method is applied by consulting bibliography in the literature found and focussing on the causes of waste while excluding environmental waste from the results.

According to Lee et al. (1999), the root causes of waste should be identified with the support of an appropriate flow diagram. By means of a fishbone diagram, which is a causal diagram that shows the potential causes of a specific event, the causes were mapped. The fishbone diagram displays the problem, which is waste in the current process, at the head of the fish and lists the causes per cause category at the bones.

3.3. Step 3: Implementing measures

After identifying the root causes of the waste in the transportation and assembly process, the next step was to propose measures to eliminate this waste. The root causes, as analysed at step 2, serve as input for the measure proposal. Based on these causes, lean principles are consulted after which solutions are proposed.

These (lean) principles/solutions have been obtained by analysing the results of the interviews, which sometimes gave a direction for a possible solution to the problem, and by consulting literature. The literature search was again conducted by keywords in Google Scholar. Searching terms were 'Waste type + solutions + (industrialized or modular) construction', 'Lean tools + (industrialized or modular) construction', 'Measures + waste + (industrialized or modular) construction'. The snowball method is applied by consulting bibliography in the literature found and focussing on the solutions of waste while excluding environmental waste from the results.

This led to a list of solutions for the identified waste in the transportation and assembly process. These possible solutions were presented to the interviewees during a joint session. Input from that session has resulted in the recommendations to reduce waste.

4. Results

In this section the results of this research can be found. As mentioned in the methodology section (see section 3), the results are split up in three parts, namely the analysis of the current transportation and assembly process, the root-cause analysis regarding the identified waste, and the possible solutions to minimize waste in the current process.

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A. Complexity and scale of modular construction

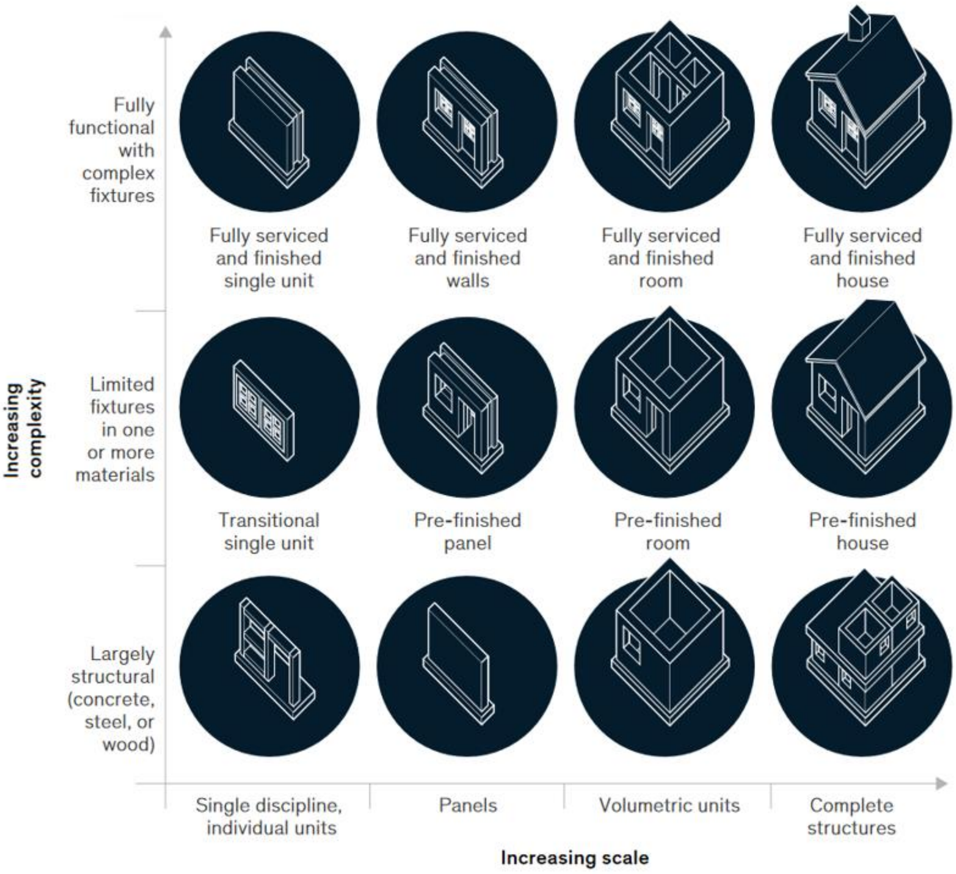

Figure A1: Complexity and scale of modular construction – comparison of approaches (McKinsey and Company, 2019)

B. Project construction duration comparison between traditional and offsite construction

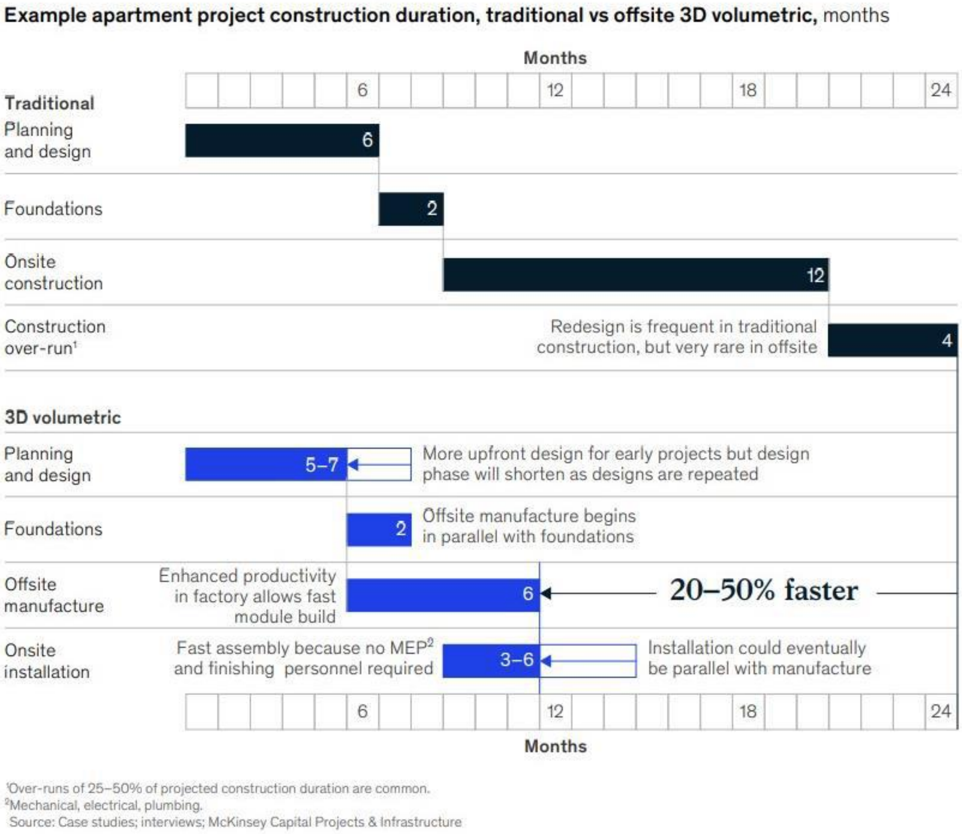

Figure B1: Project construction duration comparison between traditional and offsite construction (McKinsey & Company, 2019)

C. Traditional construction costs compared to potential offsite savings/costs modular construction

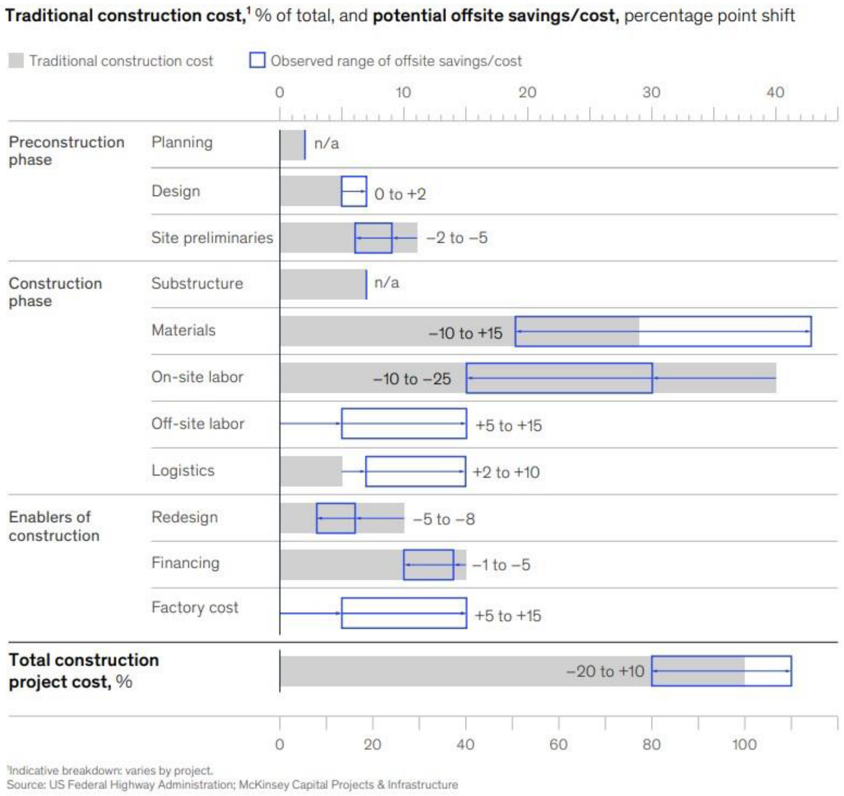

Figure C1: Traditional construction costs compared to potential offsite savings/costs modular construction (McKinsey & Company, 2019)