# Exploring alternatives to offshore jacket production methods

A case study at Heerema Fabrication Group

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Jacket structures, used for supporting offshore oil & gas platforms, are being produced by fabrication companies using conventional production methods, such as, performing manual welding, using crawler cranes for construction etc. With fewer projects in the market due to the still recovering offshore oil & gas sector, alternative methods for producing jacket must be explored, for fabricators to stay competitive and profitable.

Previously, research has been carried out to check the feasibility of batch production of offshore wind jackets. The proposed design alternatives were evaluated by modelling the process as a batch production line. In this research, an attempt is made to model the present one-off production process and use it as a tool to evaluate the proposed alternatives.

Conventional jacket construction methods have been in use for many years without any significant changes to the construction methods. Heerema Innovation Centre wants to explore different options to improve their current production process. The main objective of this research is to find possible cost effective alternative configurations for offshore jacket production methods and evaluate their effect on production time and production cost.

Chair,

Prof. dr. R.R. Negenborn

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A case study at Heerema Fabrication Group

by

Pritish Bose

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# Summary


Decrease in oil prices have negatively affected the investment towards offshore oil and gas explorations. This has in turn compelled offshore structure fabricators to find cost effective ways of fabricating oil platforms and jackets, to stay competitive in the industry. The jacket is a welded, tower-like, steel structure which supports the oil platform and its equipment. Specific resources are used to perform fitting, welding and handling of parts during its production process. Currently, these tasks are largely performed using conventional resources, such as workers for welding and crawler cranes for handling parts. In this research, to combine these tasks and their respective resources, a morphological table is produced as a structured tool and subsequently used to list alternatives for the resources.

Drawing inspiration from the business strategy of a fabrication company and from other industries, alternatives to the resources used for each task, are explored. Examples include replacing manual welding by a TKY welding robot or using gantry cranes in place of crawler cranes during final construction. The morphological table in this work allows the user to propose multiple alternative configurations. However, to improve its current production method, when exploring these configurations, the effects on production time and production cost are important performance indicators for a fabrication company. Subsequently, the performance of these configurations can be evaluated using a simulation model created in Simio®, a discrete-event modelling package.

To improve the accuracy and applicability of the simulated results, a validated simulation model is required. However, in this research, it is observed that simplifying certain aspects of reality leads to high variation in simulation outputs. Hence, the discrepancies prevent the model from being validated. Possible causes identified are related to the number of shared lifting resources, workspace utilization of the available fabrication area and release dates of orders of parts used in jacket production. Nonetheless, within the limitations of the simulation model, three alternative configurations are evaluated:

1. Configuration 1: Jacket production using TKY welding robot
2. Configuration 2: Jacket production using gantry crane
3. Configuration 3: Jacket production using TKY welding robot and gantry crane

Based on the obtained results with this evaluation, Configuration 3 is proposed as a promising alternative. Additionally, throughout this research, the potential of a simulation-based approach to explore new configurations for offshore jacket production is suggested. Together with the morphological table, this results in a novel decision-making tool which can be used by fabrication companies to indigenously explore new alternatives.

# Samenvatting

Daling van de olieprijzen heeft investeringen in de verkenning van offshore olie en gas negatief beïnvloed. Om competitief te blijven in de industrie heeft dit offshorebouwers gedwongen om kosteneffectieve alternatieven te vinden om olieplatformen en jackets te fabriceren. Een jacket is een gelaste, torenachtige, stalen constructie die het olieplatform en de bijbehorende uitrusting ondersteunt. Specifieke technieken worden gebruikt om onderdelen te passen, lassen en hanteren tijdens het productieproces. Momenteel worden deze taken grotendeels uitgevoerd met behulp van conventionele methoden, bijvoorbeeld lassers voor het lassen en rupskranen voor het hanteren van onderdelen. In dit onderzoek, combineert een morfologische tabel deze taken en bijbehorende methodes om een gestructureerd overzicht te creëren dat vervolgens werd gebruikt om alternatieven voor deze middelen op te sommen.

Geïnspireerd door de bedrijfsstrategie van een productiebedrijf en van andere industrieën, worden voor elke taak de alternatieven verkend voor de gebruikte middelen. Bijvoorbeeld kan het handmatig lassen vervangen worden door gebruik te maken van een TKY-lasrobot. Tijdens de definitieve constructie kunnen ook portaalkranen gebruikt worden in plaats van rupskranen. De morfologische tabel in dit werk biedt de gebruiker de mogelijkheid om meerdere configuraties voor te stellen. Bij het onderzoeken van deze configuraties om de huidige productiemethodes te verbeteren zijn de effecten op productietijd en productiekosten belangrijke prestatie-indicatoren voor het productiebedrijf. De prestaties van deze configuraties werden geëvalueerd met behulp van een simulatiemodel dat is gemaakt in Simio®, een softwarepakket voor discrete-event modelleren.

Om de correctheid en toepasbaarheid van de resultaten te verbeteren is een gevalideerd simulatiemodel vereist. Belangrijk om op te merken is dat vereenvoudiging van bepaalde aspecten van de werkelijkheid tot grote verschillen in modeloutputs leidt. Deze variatie voorkwam dat het model grondig gevalideerd kon worden. Mogelijke geïdentificeerde oorzaken hielden verband met het aantal gedeelde hefmiddelen, utilisatie van de beschikbare fabricatie werkruimte van het beschikbare productiegebied en logistieke problemen bij levering van de onderdelen die worden gebruikt in de productie van de jackets. Binnen de beperkingen van het simulatiemodel werden drie alternatieve configuraties geëvalueerd:

1. Configuratie 1: productie van een jacket met behulp van de TKY-lasrobot
2. Configuratie 2: productie van een jacket met een portaalkraan
3. Configuratie 3: productie van een jacket met de TKY-lasrobot en een portaalkraan

Op basis van de resultaten uit deze evaluatie werd geconcludeerd dat Configuratie 3 een veelbelovend alternatief is. Bovendien werd via dit onderzoek het potentieel van op simulatie gebaseerde benaderingen om nieuwe configuraties voor offshore jacket productie te verkennen gesuggereerd. Samen met de morfologische tabel resulteert dit in een nieuw besluitvormingsinstrument dat door productiebedrijven kan worden gebruikt om op eigen initiatief nieuwe alternatieven te verkennen.

# Acknowledgement

I am here today, at the final footstep of my successful journey to become *Ingenieur* from Technische Universiteit Delft, only through the unwavering support and love of my family, and to them, I dedicate my work. Thank you for believing in me.

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*Pritish Bose*
*Delft, September 2018*

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# 1
# Introduction

This chapter, describes the background of the research and gives an overview of the jacket sub-structure. This is followed by identifying the problem statement. Then, the research area is established and the scope of the project is defined.

## 1.1. Background

Oil & gas sector holds a major share in the current global economy. With the economic downturn since 2008, the oil & gas industry has also suffered. In the slowly recovering oil sector, fluctuating oil prices and exchange rates are leading to instability in project revenues [12] [2]. Although the prices of crude oil are on an increasing trend, investors are holding back on oil explorations due to high uncertainties in forecasting future oil price. According to Oil & Gas UK, in the period between 2014 and 2016, investment in United Kingdom Continental Shelf (UKCS) went down from GBP 14.8 billion to GBP 9 billion [24]. This has resulted in a decrease in upcoming projects. Moreover, most exploration projects take a long time to conduct feasibility studies of the oil-well before drilling can be started. For oil companies, explorations are ongoing, however, for structural fabricators of oil platforms and jackets, such uncertainty is challenging. With fewer projects in the market, fabrication companies have to be competitive, both strategically and technologically.

Offshore structure fabrication companies, especially the ones related to large and heavy offshore structures, currently use conventional methods for production. Due to the low volume high risk nature of the industry, where a project typically takes almost year to complete and in a year only a few structures are produced, it is only understandable that why the companies are hesitant to explore alternative methods of production. Some companies, however, have a different outlook.

Heerema Fabrication Group (HFG) has been exploring ways to improve their fabrication process. To stay competitive in this market, it is imperative for HFG to maintain the quality of its services while reducing their price. In such scenario, one of the ways to maintain the cost efficiency of a project is to come up with better technological solutions to make the fabrication process more efficient. Heerema Innovation Centre (HIC), a division of HFG, is looking into various aspects of the fabrication procedures which can be improved. More specifically, they are investigating alternatives to their current jacket production methods.

Heerema was established in 1948 in Venezuela as a small construction company. With increasing oil & gas projects, they expanded their services to include fabrication of offshore modules and jackets for North Sea oil & gas industry in 1980s. Over the years, through such projects, they gained expertise in offering Engineering, Procurement, Construction and Installation (EPIC) or turnkey services to their clients. In 1990, Heerema Fabrication Group B.V. (HFG) was founded to manage all fabrication projects for Heerema Group. Currently, HFG is an international player in the engineering and fabrication of large and complex offshore structures for oil & gas and energy-related industries. To facilitate the fabrication of these structures, HFG has four fabrication sites: two in The Netherlands (Heerema Vlissingen and Heerema Zwijndrecht); one in Unite Kingdom (Heerema Hartlepool) and one in Poland (HFG Polska). Each of these facilities are equipped with large (pre)fabrication and assembly halls for indoor construction. Their portfolio of offshore structures includes platforms, jackets and topsides. The largest jacket built by HFG in terms of its weight was Gina Krog for Statoil, which weighed over 17,000 tonnes. The jacket was constructed within 17 months at Heerema Vlissingen.

## 1.2. Overview of jacket structure

A jacket is a welded, tower-like, steel structure which provides support to topsides, typically oil platform, offshore living quarters, wind turbine tower or generator sets for wind energy farms. Traditionally, a jacket structure is made up of four major components: Legs, braces, horizontal frames and vertical frames. A typical offshore jacket is shown in Figure 1.1, presenting the different structural components. The number of legs and braces can vary based on the weight of topside, its function and the depth of water at the location. Due to different numbers of legs and braces, the weight of a jacket also varies significantly. Typically a jacket consists of 3, 4, 6 or, in some cases, 8 legs. For different sub-structure types, there are different types of braces that can be used: K-braces, X-braces, and Z-braces, subdivided braces, rhombus braces and mixed-braces [11].

The legs and braces are constructed from tubular steel sections which are joined together by means of welds. These welds are critical because they must meet high quality standards and precision as they will be exposed to highly corrosive environment. To perform these specialized welding operations, highly skilled welders are required. Moreover, the parts of a jacket can weigh around 200 tons, and conventional assembly methods of these major parts require multiple heavy lifting and transport equipment along with highly trained personnel.

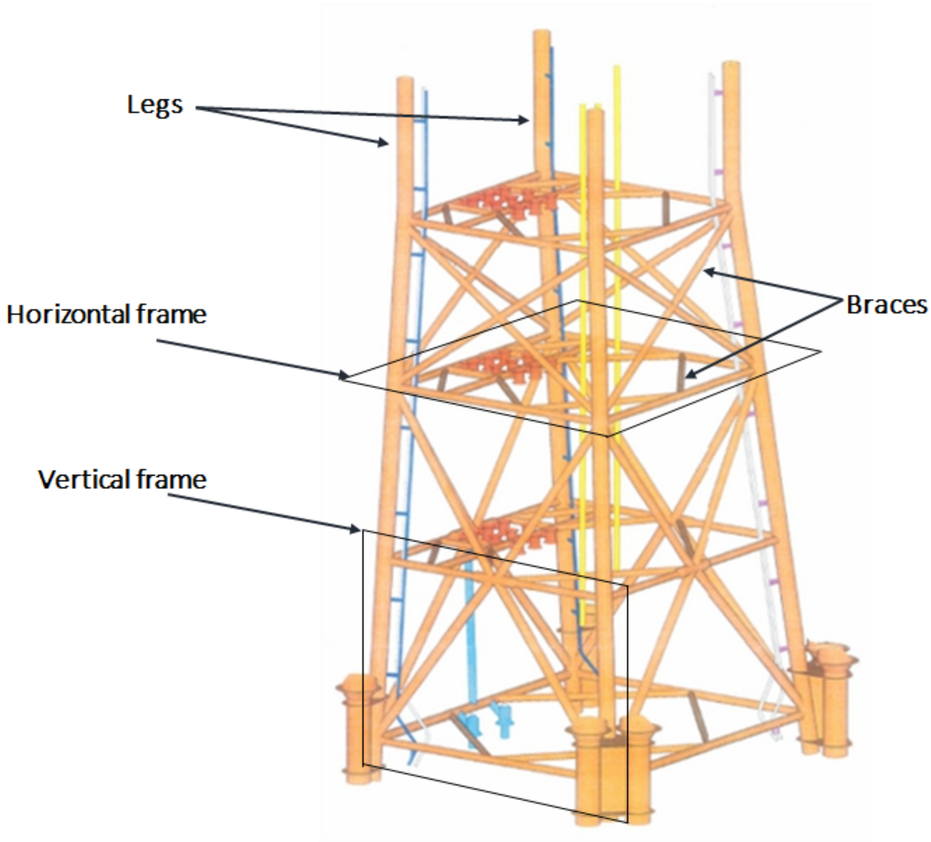


Figure 1.1: Representation of Babbage jacket substructure of SLP North Sea, fabricated by HFG, showing its major structural parts: Legs and braces.[10]

## 1.3. Problem statement

Conventional jacket construction methods have been in use for many years without any significant changes. HFG wants to explore alternative configurations to assemble a jacket which may lead to lower fabrication and construction costs, lower duration of production and safer working environment. With the increase in use of automation in other sectors, HFG is also exploring the use of a welding robot for. The main challenge is to explore and evaluate these options to understand their effects on the complete production process.

## 1.4. Research focus and scope

This research is conducted for TU Delft and supported by a case study at HFG. HFG is a jacket fabricator for both offshore oil & gas and wind energy sectors. Previously, a research was conducted at HFG to check the feasibility of transforming the current one-off production process to a batch production line. This research will be focusing specifically on the one-of-a-kind oil & gas jackets production methods.

The fabrication and construction of jacket involves many different processes of varying complexities and time span. Since the production of jackets is carried out both inside and outside the assembly hall, the processes are influenced by various external factors which can be categorized as quantitative and qualitative. Quantitative factors may include spatial availability of yard, availability of resources, availability of raw materials, weather forecasts (wind speed, rainfall) etc. On the other hand, qualitative factors such as client-contractor-supplier relationship, market fluctuations and morale of personnel also play a major role in completion of project on time and within allotted budget. Since, it is difficult to explore the effects of all such processes and factors, it is imperative to define the scope within which this research will be focused.

The scope is defined using the black box approach. The focus of this research is on the sub-processes involved in "Production process". In Figure 1.2, a grey box for shows the processes under the scope of this research.

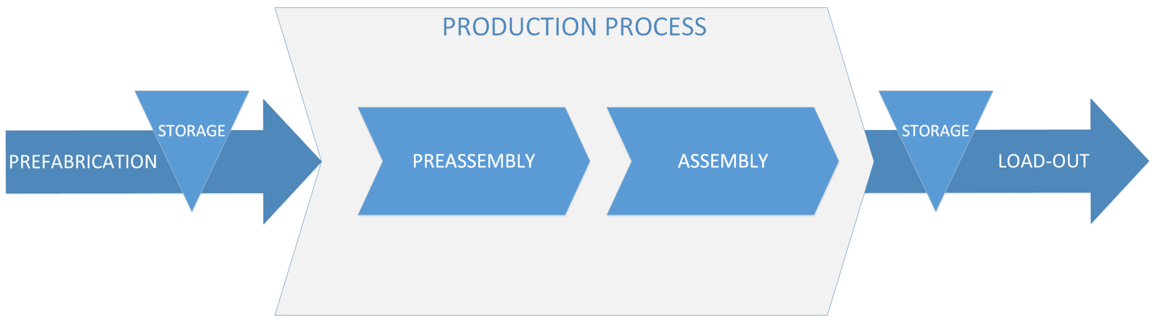


Figure 1.2: Scope of the research.

## 1.5. Research Question

Building on the problem statement and scope, the main research goal is to explore and suggest alternative configurations for the jacket production methods. The intent is to use a simulation model to evaluate the alternative configurations and study their effects on the peformance of production process. The research question can be formulated as follows:

***"What can be a possible alternative design to conventional assembly process of an offshore jacket substructure which is cost efficient?"***

The research question can be divided into the following sub-questions:

1. What are the main components, tasks and resources of the current production process?
2. What characteristics from the literature can be used to define and model the current production process?
3. Which challenges are identified in the present production process?

4. Which alternative configurations will be evaluated?
5. How is the performance of the production process defined?
6. What assumptions are taken to model the production process?
7. Is a verified and validated model achieved?
8. What are the causes of variation in simulation outputs?
9. Which alternative configuration performs better than the present production process?

## 1.6. Research Approach

The research begins with understanding the jacket production process. In Figure 2, starting first with the overall production process, the focus is narrowed on to two major sub-processes: preassembly and assembly. Within each sub-processes, major tasks which are common to all jacket types are identified and a thorough understanding of the resources used to perform these tasks is gained and a process flow model is constructed. Based on the tasks identified, in figure 4 one project, carried out by HFG in the past, is chosen as a Reference Project for further analysis. Additionally, the challenges faced during the production process are identified by interviewing and consulting experts from HFG. Using these challenges, a morphological table is presented that contains alternatives to the major features of a production process. Additionally it can be used to design new configurations for the production method. To analyze the Key Performance Indicators (KPIs) of these configurations, a conceptual model is designed in figure 5, which forms the basis of a simulation model in a discrete-event environment. However, before analyzing the configurations, it is important to verify and validate the model. Figure 6 explains the verification and validation methodologies and analyses the outcomes and challenges in validating the model. Finally, figure 8 summarizes the conclusion and recommendation of this research.

# 2
# The jacket production process

In previous chapter, the context of this research was established. This chapter will explain the jacket building process. To explore alternatives, it is imperative to understand the conventional methods employed at different stages of jacket production. First, the chapter will describe the production process from a high level of detail. Then, it will explain its two sub-processes: preassembly and assembly. This is followed by descriptions of major tasks, resources and building methods. Finally, a process flow model will be presented to represent the material flow identified in these sub-processes. The following research sub-questions will be answered:

1. What are the main components, tasks and resources of the current production process?

## 2.1. Overall production process

In figure 2.1, the fabrication facility of HFG, based in Vlissingen area of The Netherlands, is shown. The production process of a jacket begins at the earliest availability of prefabricated tubular steel sections. The prefabrication of steel sections is carried out in the *prefabrication* hall. The process terminates once the assembly of the jacket is complete. After assembly, preparations are made for load-out of the jacket and it is placed in the *Load-out area* until the sail-away.


Figure 2.1: Aerial view of the fabrication yard of HFG at Vlissingen, The Netherlands.Source: Google Earth©

A major part of the production process occurs in the *preassembly hall*, *Blasting & painting (B&P) shop* and *Assembly yard*. A large *Storage yard* is primarily used to store the raw materials required for prefabrication, but it is also used to store prefabricated and preassembled parts depending on the requirements of the project. Similarly, the *preassembly yard* is primarily used to store steel pipes for the main structure, prefabricated steel sections and preassemblies. Larger parts are sometimes prefabricated and preassembled in this yard, for example, cutting leg sections from approximately 20m long steel pipes. Some customers require the steel structure to be coated with anti-corrosive paints. For prefabricated items and preassemblies, this is performed at the blasting & painting shop located between preassembly hall and the assembly yard. prefabricated parts serve as the input for the jacket production process. preassemblies are constructed using these prefabricated parts which are finally assembled to build the jacket.

## 2.2. Sub-processes in jacket production

The jacket production process can be divided into two major sub processes: preassembly and Assembly. It is important to note here that the terms prefabrication and preassembly are not completely defined in the construction industry, and is often used interchangeably [19]. The following discussion of the above sub-processes will define these terms in the context of jacket production.

### 2.2.1. Preassembly sub-process

The steel tube sections that have been prefabricated, are welded together to produce preassembled parts, also called *preassemblies*. These preassemblies are modules for the final assembly of jacket. The concept of making preassemblies in the construction sector has been studied previously by various researchers through expert interviews and case studies [9]. It has been found that, in a majority of cases, the industries choose to make preassemblies citing improvements in time, quality and cost of projects [8].

The location where parts can be preassembled depends upon the area required to carry out this process. The size and orientation of the preassemblies determine the type of preassemblies that can be produced simultaneously, within the confinements of the preassembly hall.

### 2.2.2. Assembly sub-section

The final process of constructing the jacket using the preassemblies and prefabricated parts is referred to as *Assembly of the jacket*. It is also called erection of the jacket or building of the jacket. Generally, the final assembly is always carried out outside in the open near the load-out location of the yard. However, it varies depending on the dimensions of jackets, dimensions of preassemblies, available area for construction and available lifting and transporting equipment. Figure 2.2 shows a jacket being assembled at the Vlissingen fabrication yard of HFG.

Assembly of the jacket is the most complex and resource intensive sub-process. It also has the highest risk factor as it involves lifting of preassemblies that can weigh up to 350 tonnes and tasks being performed at heights of about 60 meters. In such conditions, the safety of workforce needs to be ensured.

To construct the jacket, engineers decide the sequence of steps in which the preassemblies will be joined during the initial phase of the project. Conventionally, industries follow a common procedure for jacket assembly which is called the *Roll up*. Figure 2.3 shows typical steps involved in the roll up method of building a jacket.

Figure 2.2: Assembly of Valemon jacket at Heerema Vlissingen yard. Source: www.hfg.heerema.com

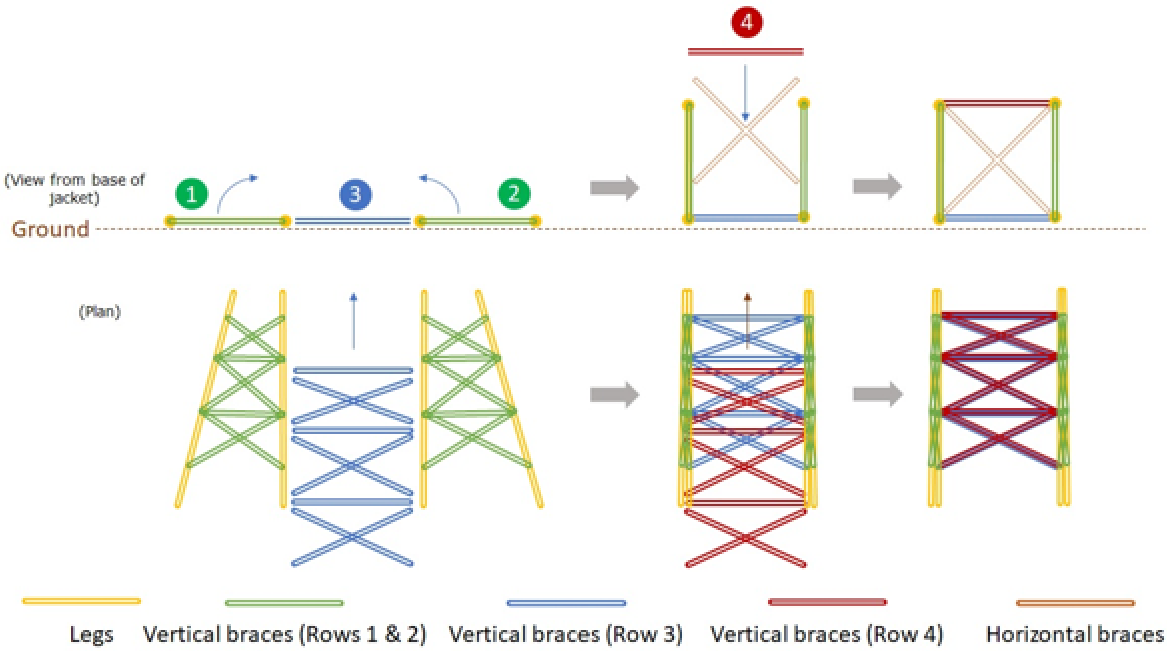


Figure 2.3: A typical roll up building method

## 2.3. Tasks involved in jacket production

Within the two sub-processes discussed in Section 2.2, multiple tasks are performed to finally produce the jacket. The major tasks performed during the production are:

1. Handling of parts
2. Fitting
3. Welding
4. Blasting and painting
5. Building temporary construction aids

### 2.3.1. Handling of parts

Material handling is a vital task in a fabrication process. In a fabrication process, the part has to be moved from one location to another so as to perform the required tasks on it. In some cases, the orientation of the part needs to be altered to complete a task. In jacket production process, the prefabricated and preassembled parts are required to be moved around from one place to another. Handling of these parts involves two tasks:

1. **Lifting:** To move the parts or to change its orientation, the part is first lifted using a suitable lifting equipment and then, the required operation is performed. Figure 2.4 shows lifting of jacket structure during assembly.

   **Transporting:** When a part is required to be transported from one location to another, then, a suitable transporting equipment is used. Figure 2.5 shows a Mammoet Self-propelled Modular Trailer (SPMT) transporting a pile sleeve cluster for jacket.

Figure 2.4: Cranes being used for lifting during jacket assembly. Source: www.hfg.heerema.com

Figure 2.5: Mammoet SPMT carrying a jacket part for Maersk Culzean jacket at Vlissingen yard. Source: www.hfg.heerema.com

### 2.3.2. Fitting

It is an operation of preparing the welding ends of parts prior to welding. It involves grinding, beveling and temporary fixing the welding ends using small, cylindrical steel pieces, called *bullets*, or welding temporary fit plates, in order to constrain the relative orientation of welding surfaces when welding is performed.

### 2.3.3. Welding

It is the major task performed in all sub processes. A jacket is constructed by welding different tubular steel sections with each other. Considering the main structure of the jacket, i.e., legs and braces, two types of weld joints are possible:

1. **Circular weld:** When the ends of steel tubes are welded together, such that the axes of both sections are coincident, then, it results in a circular weld.
2. **Branch (saddle) weld:** When end of a steel tube is welded on the surface of another steel tube, the geometry of the weld resembles the shape of a horse-saddle. Such a weld joint is known as a branch weld.

### 2.3.4. Blasting and Painting

A large portion of offshore jacket sub-structures installed is under the sea which is a highly corrosive environment. To inhibit corrosion in the structure, paint is applied on the outer surface of the jacket. In some cases, the top parts of jackets are also painted. Generally, whether the jacket requires painting or not, depends on customer requirements.

Blasting and painting of an offshore jacket requires a controlled environment to maintain the quality and standard of the paint. Once the parts are assembled, it becomes exceedingly difficult to blast and paint the steel surfaces in the open yard. For this reason, during the production process, it is preferred to have majority of the preassemblies painted in the paint shop before the final assembly. The number and size of parts that can be painted at a time is limited by the size of the shop.

However, not all painting tasks can be performed during preassembly. When the per-assemblies are joined together during final assembly, the welded areas need to be painted. The painting of these welded areas is then carried out by making temporary tents around the welds, to create a controlled environment.

### 2.3.5. Building temporary construction aids

The steel tubes used to make preassemblies have a diameter in the range of 2 meters to 5 meters or higher. In order to perform different tasks of joining the parts, welders and other personnel need to reach the location where those tasks have to be performed. To make those locations accessible to the personnel, a temporary construction aid is constructed around or on the structure. An example of such a construction aid is a scaffolding. Scaffoldings are widely used in construction industries and are the most traditional form of construction aids. Bridges are another form of construction aid that is attached to the jacket structure when the work is carried out at height and over long distances.

## 2.4. Resources

In order to perform the tasks explained in this section, suitable resources are required. Due to large and heavy assembly of steel pipes, jacket construction requires large, open areas and equipment that can handle these heavy parts. Non-uniformity of preassemblies and jacket structures increases the challenges involved in deciding the right resource to be used during jacket production. A particular task can be performed by more than one type of equipment. Their choice is often defined by, but not limited to, the capacity, weight to be handled, dimensional constraints and cost of investment. The type of equipment that is used differs within companies. However, there are certain typical choice of equipment which have been traditionally used due to their proven performance and traditional construction methods. Concentrating on HFG Vlissingen fabrication facility, Table 2.1 summarizes the various equipment used for jacket production within the scope of research.

Table 2.1: Resources used for construction at HFG Vlissingen fabrication site.

| Sl. No | Resource | Task | Location | Description |
|---|---|---|---|---|
| 1 | Overhead crane | Lifting and transporting | Assembly hall | Remote controlled cranes to lift and transport parts in assembly hall. |
| 2 | Multi-wheelers | Transporting | Assembly hall, Blasting & painting shop, Assembly yard | Self-propelled multi-wheel trailers used to transport prefabricated parts and preassemblies. |
| 3 | Trailers | Transporting | Assembly hall, Blasting & painting shop, Assembly yard | Tractor pulled trailers used to transport prefabricated parts and preassemblies. |
| 4 | Crawler cranes, winches | Lifting | Assembly yard; Storage yard | They are extensively used during the assembly process to lift and orient preassemblies. |
| 5 | Fitters | Fitting | Assembly hall, Assembly yard | Fitters prepare the edge of steel pipes before they can be welded. This process is done manually. |
| 6 | Welders | Welding | Assembly hall, Assembly yard | Welders perform Flux-cored Arc Welding (FCAW) using hand-held FCAW equipment for branch and circular welds, and sometimes using semi-automatic track welding equipment for circular welds. |
| 7 | Scaffold | Temporary construction aids | Assembly hall, Assembly yard | Scaffolds are used to access the work locations which are at a minimum height of 2 meters from the working level. |

## 2.5. Process Flow model

The process flow model for jacket production system is represented by Figure 2.6. The prefabrication process acts as the input to the preassembly process. It provides the prefabricated steel sections which are transported to the preassembly hall. The transport method used for moving prefabricated steel sections is not considered. Once the steel section enters the preassembly hall, the first task of picking up the part and placing it on the workbench or supports at the fitting workstation, is performed. When the second steel section arrives, the two parts are fitted and prepared for welding. After the parts are welded, they are lifted from the workstation and transported to the desired location.

If the part requires blasting and painting, then, the transport equipment carries it into the blasting and painting shop otherwise it moves on to the next step. In both scenario, the painted or not painted preassembly is either taken to the assembly yard or is stored in a storage area. If the preassembly is not yet required, then, it needs to be stored in a storage are. In this case, the storage area also requires a lifting equipment to pick and place the preassembly on the storage yard. When the preassembly is required for assembly, it has to be picked and placed on a transport equipment which, then, brings it to the assembly yard. The task of transporting the preassembly is considered in the process of preassembly.

When the preassembly reaches the assembly yard, the part is lifted by a crane or similar lifting equipment. This completes the task of transport equipment. The lifting equipment is then engaged until the preassembly has been temporary fitted with the assembly and then the welding is performed. This process is repeated until all the preassemblies have been installed. After all the welds are completed, the respective weld joints are painted to prevent corrosion. After this step, the jacket is ready to be lifted and transported for final load out.

This process flow model simplifies the main tasks performed during the preassembly and assembly sub-processes during jacket production. There are also other tasks such as quality checks and replenishing resources that are performed during this process. By abstraction of the system, those processes become less relevant for the analysis of these processes.

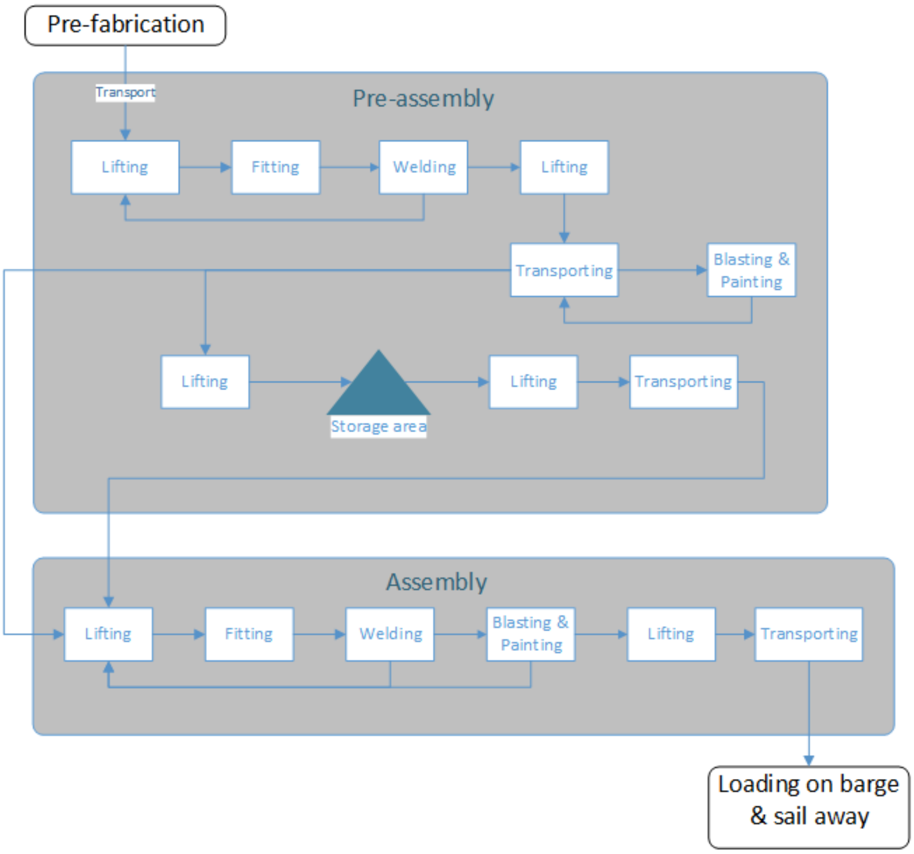


Figure 2.6: Process flow model representing the jacket preassembly and assembly sub-processes.

### 2.5.1. Conclusion

From this discussion, the major sub-processes are defined: Preassembly and Assembly. In addition to that, defining the tasks performed in these sub-processes and the choice of resources to perform them brings the research into context. Finally, the flow model gives a perspective to the material flow of this process and the interactions between the tasks. The next chapter will discuss the characteristics of the production process.

# 3 Literature Analysis

In the previous chapter, the research was introduced and a general overview of the jacket sub-structure and its production was given. The main challenge of exploring and evaluating alternatives to the conventional jacket production methods was presented. In this chapter, the theory needed to design the simulation model in for evaluation of options is discussed to answer the following research questions:

2. What characteristics from the literature can be used to define and model the current production process?

## 3.1. Previous research

HFG has been actively exploring ways to improve the jacket production process, for both offshore oil & gas and offshore wind energy sector. Previously, a research was conducted by Suzanne Kuijs [14] at HFG to design a batch production line for jackets exclusively for the offshore wind energy sector. Suzanne analyzed the scope of automation in transitioning from the current one-off jacket production process to batch production of 50 jackets a year. This was achieved by modifying the configuration of current production line.

To compare the performance of current and future production methods, Suzanne identified the key performance indicators as:

1. Makespan (in hours): The total duration required to complete the production of one batch of jackets.
2. Cost (in Euro): The total costs of resources used in jacket production, namely, investment cost for equipment, cost of workable area and cost of workers.

Then, Suzanne identified specific features in the production process which could be varied to design three different concepts for future production line. These features were as follows:

1. Weld profiles in preassembly and assembly sub-processes
2. Material savings during welding
3. Use of automated fitting and welding methods
4. Building sequence

The research concluded that, assuming modular jacket structure, automating the production process led to lower production times. Also, replacing joints with stubs in preassembly sub-process to ensure circular welds during the assembly sub-process led to more material savings.

It can be noted that the previous research was focused on a batch production line. For offshore wind jackets, modular designs can be achieved for a set of similar windmills. Jackets for oil & gas explorations are one unique in their structure and custom designed to suit the purpose of a particular project. The structure of the jacket depends largely on the depth it is installed at and weight of the topside it is supporting. Learning from Suzanne's research, a circular welds will be considered for assembly process when choosing a Reference Project and exploring alternative configurations.

## 3.2. Characteristic of jacket production process

Previous research explored a future scenario of a batch production of modular offshore jackets. As this research is focused on exploring alternatives for production method of unique jackets, it is required to understand the characteristics of the current production method.

### 3.2.1. One-off production process

In the manufacturing and fabrication sector, different types of production processes exist. Process characteristics vary on the basis of the product being manufactured. The graph in Figure 3.1 categorizes various process types based on the volume of product produced and the variety, or the randomness between two products. As per the underlying theory behind this graph, the author states that job, batch and line processes are used when the standard products are produced [5]. These processes produce a batch of products and at a certain volume. When the process produces high volumes of a repetitive lot of products, then, it is defined as a line process; if the volume is lower and some batches are made as per customer specifications, the process is termed as a batch process. In job production process, small lot sizes of different products are produced. When the product is highly customized and only one large and complex unit is the final product it is termed as a Project. According to the author, the project-type process is also termed as one-product line or one-off production line. The last process, as the name suggests, is used when the flow of the material is continuous. Project, job, batch and line processes have a discrete flow of material [5].

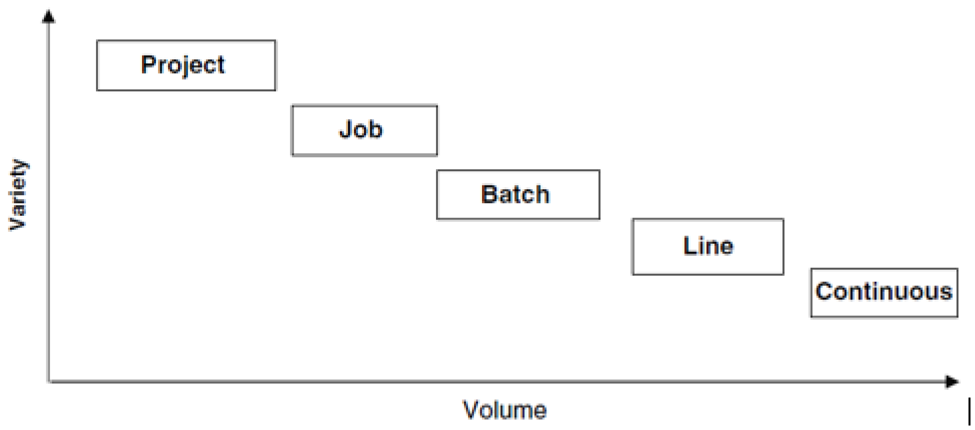


Figure 3.1: Process types based on the type of product(s) involved. [5].

As mentioned earlier, the offshore oil & gas jackets are custom made based on customer specifications. That means, a jacket produced for one project is one of its kind. Also, each sub-process follows a discrete material flow pattern. Comparing with the above theory, the jacket production method may fall under the category of a one-off production process.

### 3.2.2. Construction process

The production process is a combination of preassembly and assembly sub-processes. The material flow within the preassembly sub-process can be related to that of a one-off production, but for the assembly process it is not completely true. From a material perspective, one can argue that the material, or preassemblies, flow into the assembly process and a complete jacket is produced in the end, thereby making it a production process. But from a resource perspective, there are slight differences between the two sub-processes. In preassembly sub-process, the parts and workstations both can be moved around the preassembly hall to make space for forming new preassemblies. At the same time, the location of workstation for a part at a particular time is fixed and the parts *flow* through that workstation after being fitted and welded.

The situation at the assembly site is slightly different. Here, the assembly area is fixed and the resources are moved around to complete the task. Thus, it can be categorized as “fixed position manufacturing”, where the parts (preassemblies) are assembled to make the product (jacket) a whole [3]. In words of Ballard and Howell, “In the assembly process, the parts become too large to move through assembly stations, so the stations move through the emerging wholes, adding pieces as they move.” [3].

Preassembly sub-process being a one-off production process and categorizing the assembly sub-process as a construction process makes the overall jacket production process a combination of the two. Moreover, construction process brings with it its own peculiarities. Since the assembly is rooted to one location, the process is affected by the site conditions such as weather, location and soil [25]. During the construction process, some tasks require specific technological capabilities for which a specific resource needs to be mobilized [25]. This aspect of makes it difficult to plan all the tasks ahead and requires on site decision-making. To tackle these challenges, industries find ways to increase preassemblies because the material flow in the preassembly sub-process creates a job shop condition inside the preassembly hall which can be more efficiently managed [3].

The impact of this knowledge is on the technique to be applied when modelling the jacket production process. A theoretical framework needs to be decided to effectively model both types of production methods.

## 3.3. Theory on modelling techniques

In this section, literature review is presented as an underlying theoretical framework to decide the best suited simulation environment and technique for modelling the jacket production process.

### 3.3.1. Simulation environment

Halpin introduced simulation in the field of construction in 1973 by developing the CYCLONE methodology [21]. Since then simulation has been extensively used to model construction processes. Some of its applications reviewed in literatures include tunneling, earth moving and heavy construction and bridge construction [22]. However, depending on the abstraction level of the model and the application for which the model is used, the effectiveness of a simulation environment may vary [4]. From Figure 3.2 and Figure 3.3, it is clear that for this research, the process can be simulated either in *Discrete-event (DE) environment* or *Agent Based (AB) environment.*

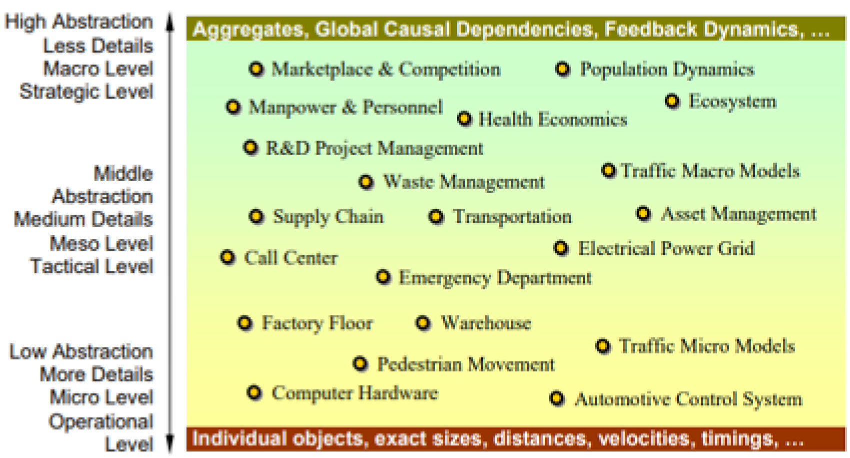


Figure 3.2: Application based on abstraction levels.[4]

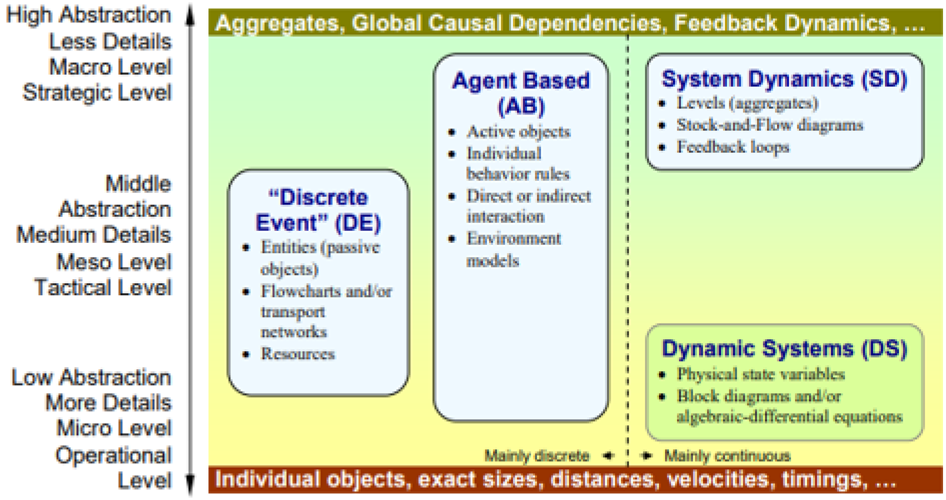


Figure 3.3: Simulation environments based on abstraction level.[4]

Many researchers strongly approve AB environment to be used for systems which are autonomous and have interacting agents [15] [18]. However, AB is still mostly used for research purposes [4]. The aim of this research is to design a model that can be commercially used. DE has been traditionally and successfully used to design and analyse production processes, and also construction processes [17] [16]. Thus, Discrete Event environment is chosen for modelling the jacket production process.

### 3.3.2. Simulation techniques

Different methods are available to model a production process using discrete event simulation. Through literature it is found that three main techniques exist: Process interaction (PI), Event scheduling (ES) and Activity scanning (AS).

In PI model, the focus is on entities (element of system that flows through a sequence of activities and get processed) and is used for systems where the entities have varying attributes but the processing servers have few attributes and have less interaction with each other [17]. This approach is more suited for manufacturing and job shop systems where the servers have few states. AS uses a more activity centric approach. The technique focuses more on the type of activity to be performed and the sequence in which each activity shall be executed. ES is used in both PI and AS modelling methods. It defines the start and end of an event but does not specify the activities that occur between these two states.

One other simulation approach, presented by Jingsheng and Simaan, is using the concepts of *Resource-Based Modelling (RBM)*, where smaller models, known as atomic models, define the operating processes of resources used for various activities during the simulation [21]. This way of modelling the resources gives users more flexibility to alter the resource characteristics to achieve a more realistic representation of reality.

## 3.4. Conclusion

This chapter discussed previous research, characteristics of different production processes, defined the characteristics of construction process and explored different simulation environments and techniques. It is found that the jacket production process shows the characteristics of a one-off process, but the assembly sub-process within it has the characteristics of construction process. It lacks a material flow which is present in the preassembly sub-process. The challenge is to find a suitable modelling environment and technique that can be effective in modelling this process. A discrete-event environment with an a combination of process interaction, activity scanning and event scheduling techniques event is chosen for modelling the production process.

# 4

# Morphological table and Alternative configurations

The jacket production process, described in Chapter 2, gives an understanding of different sub-processes and tasks performed by using various resources. In this chapter, first a project, completed by HFG in the past, is described which will be used as a Reference Project for evaluating alternatives. Through this reference project, major challenges in the production process will be defined and investigated. Next a morphological table is designed, which is constructed as a decision making tool for selecting these alternatives. This chapter will attempt to answer the following sub-questions:

3. Which challenges are identified in the present production process?
4. Which alternative configurations will be evaluated?

## 4.1. Reference Project

HFG has produced 21 offshore jackets for the oil & gas industry, each having a custom design and for varied purposes. Unique jacket designs and structures make the comparison of one project with others more complex. Moreover, the production process itself is adapted to suit a particular jacket production. In case of production of a jacket with similar design and structural complexities, some parts of the production process can be replicated, such as, type of building method, the building sequence, the number of resources and type of welds during preassembly and assembly sub-processes, to name a few. Often for jackets with lesser similarities, only few aspects of the process can be reproduced, usually the type of building method and the type of welds performed during the sub-processes. Table 4.1 compares some of these differences and similarities for three projects (out of 21) completed by HFG.

Table 4.1: Differences and similarities in some aspects of production process are compared for three projects successfully concluded by HFG.

| Sl. No | Item | Project 1 | Project 2 | Project 3 |
|---|---|---|---|---|
| 1 | Weight | 9150 MT | 8000 MT | 2600 MT |
| 2 | Dimension | Bottom: 46x46, Top: 28 x 30, Height: 163 | Bottom: 38x38, Top: 24 x 30, Height: 115 | Bottom: 31x31, Top: 17 x 17, Height: 91 |
| 3 | Building method | Half Roll-Up | Roll-Up | Roll-Up |
| 4 | Field weld | Circular & branch | Circular | Branch |

The commonalities among the projects lie in the tasks performed during the production process and the resources used to perform these tasks. Each of the five tasks and corresponding resources, explained in Sections

2.4 and 2.5, repeat for all projects. This means that alternatives to the conventional methods of performing these tasks can be explored by focusing on one project. After consulting with experts, it is observed that Project 2 is considered to have the most convenient production method due to the following factors:

1. **Circular field welds:** According to experts at HFG, due to a variable thickness of weld around the profile of branch weld, it requires more precision during fitting and welding of parts. On an open assembly yard with weather playing an important role in construction, aligning the parts is more challenging. In addition to this, performing a branch weld takes more time and is more labor intensive, which makes it less desirable for workers to perform such welds in the assembly yard, especially for parts at height above 10 m. For Project 2, all field welds are circular owing to the design of preassemblies.

2. **Design of preassemblies:** For Project 2, the preassemblies were designed such that all nodes (the junction where two steel pipes intersect non-coaxially producing T, K, Y junctions) were constructed inside the preassembly hall and at lower heights. Since, the construction of T, K, Y junctions consists mainly of branch welds, experts are exploring implementing a TKY welding robot to automate this task.

From the above factors, for this research, Project 2 is chosen the *Reference Project*.

## 4.2. Challenges in current production process

The next step is to gain information about challenges faced during execution of projects in general. These information are collected by conducting interviews with experienced personnel of HFG which include production engineers, project manager, asset manager, yard manager, innovation manager and welders. The following challenges are identified from these interviews which are summarized below:

1. Welding robots for both circular and branch weld are planned to be used in the fabrication process. This may be a factor in choosing the design of pre-assemblies.

2. Logistics challenges occur when pre-assemblies are carried from the assembly halls or blasting & painting shops to the yard due to spatial constraints.

3. Handling of parts is a time intensive process which the engineers believe is a major bottleneck.

4. Pre-assemblies are sometimes ready and blasted & painted before they are required in the assembly process. In such scenarios, the pre-assemblies are needed to be stored in the storage area outside the fabrication yard until it is required. This involves additional delays due to multiple transports and part handlings.

5. The crawler cranes used in the assembly of jacket have a long set-up and dismantling time.

6. It is desirable for managers and workers to have only circular welds in the assembly sub-process and, if possible, all branch welds in the preassembly hall.

7. The welds performed during assembly can be located even at heights of around 50 meters from the ground. Traditionally, scaffolds are used to allow workers to approach these locations. To construct a scaffold is a time intensive process. Moreover, the workers have to walk to and from the location of weld which also takes time.

8. There are approximately 50 trailers which are not completely utilized but need to be maintained nonetheless.

9. Sometimes the building methods change in middle of the assembly process and it becomes difficult to keep up with the planning schedule. This is attributed to the inaccuracy in considerations for choosing a building method.

Based on the above project analysis and expert opinions the following scope in improvements are identified:

1. Introducing welding robots in the production system to perform circular and branch welds.

2. Alternative design of pre-assemblies that can replace branch welds with circular welds during jacket assembly.

3. Introduce alternative fitting mechanisms that can reduce time of fitting task.

4. Innovative logistics system with reduced handling of parts.
5. Reducing the usage of crawler cranes to reduce cost and time of setting-up and dismantling of cranes and winches.
6. Alternatives to current building methods that uses less yard space and incorporates the above alternatives.

## 4.3. Morphological table

For the scope of improvements listed in the previous section, different set of alternatives can be possible. The resource identified with tasks in Table 2.1 are conventional set of resources that are used. Taking inspiration from different industrial practices and discussing with experienced personnel from HFG has shown that same tasks can be performed with different sets of equipment. These alternatives can be used to form a morphological table, as shown in

The morphological table enables the user to choose different combinations of alternatives and combine them to devise different design alternatives to produce jackets. The "Feature" column lists out those attributes of a jacket production process that have a major contribution in the cost of production and production time of jacket. Each feature is provided with a respective set of alternatives to choose from. The table serves as a generic decision-making tool that is expandable both vertically, to add more features to increase the level of details, and horizontally, to accommodate future alternatives and innovations for each feature.

Additionally, the morphological table is independent of the project variabilities discussed before and can be used to represent the production method for any project. In Figure 4.1 , the Reference Project is represented by the blue trajectory. The preassembly process involves production of braces and legs, which are formed by circular welds between steel sections. It also involves welding of parts of braces to the legs to form pre-assemblies. These pre-assemblies consist of branch welds. The assembly processes, however, contain a combination of both weld types. The fitting before welds is done in the traditional way by using chain clamps and bullets in both the processes. The welding equipment used is mostly hand held FCAW equipment. Additionally, for some circular welds in pre-assembly, track mounted remote controlled welding equipment is also known to be used. Although, during assembly, only manual welding is performed. The parts and pre-assemblies are transported using trailers and multi-wheelers. For transporting parts less than 100tonnes in weight, a telescopic crane is sometimes used. This crane also acts as lifting aid for smaller parts but for heavier lifts, crawler cranes are used. In order to perform tasks on the structures, traditional tubular steel scaffolds are used.

## 4.4. Alternative configurations

Based on the above morphological table and bearing in mind the challenges in learnt from the reference proect, following configurations are chosen as possible alternatives:

1. Configuration 1: Jacket production using TKY welding robot
2. Configuration 2: Jacket production using gantry crane
3. Configuration 3: Jacket production using TKY welding robot and gantry crane

### 4.4.1. Configuration 1: Jacket production using TKY welding robot

HFG envisages using an automated TKY welding robot for performing branch welds in preassembly subprocess of jacket production. Limitation of this robot is that it cannot perform circular welds, which will continue to be performed by workers. In *Configuration 1*, therefore, the inputs for only branch welding servers are modified to represent robot welding stations. The following parameters are changed:

1. **Number of branch welding servers**
   In the Reference Project, where branch welds are performed manually, four branch welding stations

| Feature | | Alternative | | | | |
|---|---|---|---|---|---|---|
| | | A1 | A2 | A3 | A4 | A5 |
| F1 | Type of Weld (Pre-assembly) | Circular | Branch | Combination of circular and branch | - | - |
| F2 | Type of weld (Assembly) | Circular | Branch | Combination of circular and Branch | - | - |
| F3 | Fitting equipment | Clamping with chains and bullets | Rim-type reforming clamp | Rim-type reforming clamp with consumable ring | - | - |
| F4 | Welding equipment (Pre-assembly) | Hand-held FCAW equipment and track mounted circular welding machine | Track mounted circular welding machine | TKY welding robot for branch welds; Track mounted circular welding machine for circular welds | Linear weld robot | Circular weld robot |
| F5 | Welding equipment (Assembly) | Hand-held FCAW equipment | Track mounted circular welding machine | TKY welding robot | Linear weld robot | Circular weld robot |
| F6 | Primary Transportation | Tractor trailer | Multi-wheeler | Tractor trailer and multi-wheeler | Mobile telescopic crane | Transfer car |
| F7 | Secondary Transportation | Tractor trailer | Multi-wheeler | Mobile telescopic crane | Transfer car | - |
| F8 | Primary Lifting equipment | Crawler crane | Mobile telescopic crane | Tower crane | Gantry crane | Electro-hydraulic jacks |
| F9 | Secondary Lifting equipment | Crawler crane | Mobile telescopic crane | Tower crane | Gantry crane | Electro-hydraulic jacks |
| F10 | Temporary construction aid | Scaffold | Container | Combination of scaffold and container | - | - |

Reference Project | Configuration 1 | Configuration 2 | Configuration 3

Figure 4.1: Morphological table showing alternatives to different features of jacket production process. The generic nature of this table represents the Reference Project and explores alternative configurations.

are considered in the preassembly hall. However, when the TKY welding robot is used, some aspects have to be taken into account. First, the welding robot system is stationary for all projects. Second, the fixed area of preassembly hall restricts the number of welding robots that can be accommodated in the hall, considering the area required for the inbound and outbound logistics for the parts. Third, HFG is more inclined to have only two TKY welding robots to automate their production process. Taking these three factors into account, two welding robots are considered for *Configuration 1*, which perform all the branch welds during the preassembly process.

2. **Welding rate for branch welds**
   According to the data obtained from HFG, the average welding rate for manual welding is 0.5 $kg/hr$. For TKY welding robot, the average welding rate used by HFG for calculating welding times is considered taken as 3.5 $kg/hr$. The welding times are calculated using the calculation sheet obtained from HFG, which is confidential.

3. **Number of workers**
   For automated welding robot, workers are used only to set up the part at the machine. The welding itself does not require any workers. Thus, it is assumed that two workers are required at the fitting server and then at the circular welding servers to perform the welds. As the part enters the branch welding server, only one worker is used to setup the part and then the worker is released.

### 4.4.2. Configuration 2: Jacket production using gantry crane

In *Configuration 2*, the primary focus is to find an alternative to leasing a heavy lift crawler crane. According to project experts in HFG, leasing of a heavy lift crane has a significant cost, which is kept confidential for the purpose of this research. Additionally, the cost of operation and maintenance is also the liability of the user. In reality, when using such a crane during the assembly process, the building sequence of the jacket is decided such that the duration of a heavy lift crane on-site can be reduced to save operational costs, which includes cost of leasing, operation and maintenance.

Here, a gantry crane is explored as an alternative to the heavy lift crane, as a primary lifting equipment. The crane is envisaged to be bought by the company and used in collaboration with smaller cranes which are used as secondary lifting equipment. For the evaluation, only operational cost of the gantry crane is taken into account because return of investment in buying the gantry crane depends on the business plan of HFG. The gantry crane is operated by one specially trained worker. Thus, the operational cost of a gantry crane is considered equivalent to the operational cost of smaller cranes that are used in the assembly process.

Another important factor to be considered in this configuration is the delay caused during travelling of crane. Heavy lift cranes and smaller cranes travel around the perimeter of jacket whereas the gantry crane can travel over the jacket, as shown in Figure 4.2. From this figure, it is clear that when the gantry crane travels over the jacket, it covers only half the distance than a heavy lift crane or a smaller crane. The delay for the two scenarios is then calculated using Equations 4.1 and 4.2:

For smaller cranes,

$$t_{delay,sc} = \frac{(2 \times l) + w}{v_{sc}} \tag{4.1}$$

For gantry cranes,

$$t_{delay,gc} = \frac{(2 \times l) + w}{v_{gc}} \tag{4.2}$$

where,

$t_{delay,sc}$ = Travel delay for smaller cranes, in hours.
$t_{delay,gc}$ = Travel delay for gantry cranes, in hours.
$l$ = Height of the jacket, in m.
$w$ = Width of the jacket, in m.
$v_{sc}$ = Travelling speed of crawler crane, in $m/hr$.
$v_{gc}$ = Travelling speed of gantry crane, in $m/hr$.

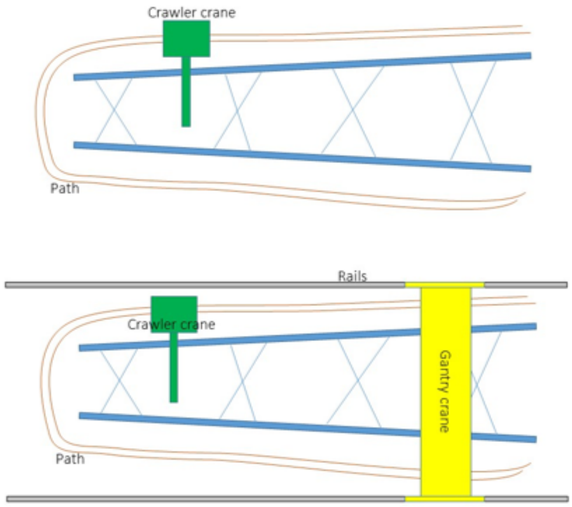


Figure 4.2: Path traversed by crawler cranes and gantry crane. The crawler cranes have to travel more distance along the perimeter of the jacket, whereas, gantry crane has to traverse only the length of the jacket.

### 4.4.3. Configuration 3: Jacket production using TKY welding robot and gantry crane

The third configuration is a combination of *Configuration 1* and *Configuration 2*. TKY welding robot and gantry crane are alternatives to resources used in preassembly and assembly sub-processes, respectively. *Configuration 3* is focused on analyzing the combined impact of these alternatives on the overall production process.

## 4.5. Conclusion

Through investigation of the past project and consulting with experts of HFG, the main challenges of of jacket production were found, which are as follows:

- Welding is a tedious and time consuming process. HFG envisages to automate the branch welding in the preassembly sub-process.
- The design of the jacket in the case study enabled only circular welds during the assembly stage. According to experts, circular welds are easier, faster and it saves more material than compared to branch welds.
- Assembly sub-process is found to be the bottleneck of the production process. The main reason are the slow movements of crawler cranes. According to an internal study conducted by HFG, they found reducing the use of crawler cranes reduces the cost and project duration.

Based on these three challenges the alternative configurations explored are:

1. Configuration 1: Jacket production using TKY welding robot
2. Configuration 2: Jacket production using gantry crane
3. Configuration 3: Jacket production using TKY welding robot and gantry crane

Next chapter will discuss the modelling of the production process.

# 5

# Modelling the jacket production process

In the previous chapter, a morphological table was prepared to explore alternatives to performing major tasks in jacket production process. In this chapter, a simulation model of the production process will be developed to evaluate and analyze the effect of different combinations of these alternatives on the performance of production process. After the chapter, following sub-questions will be answered:

5. How is the performance of the production process defined?
6. What assumptions are taken to model the production process?

## 5.1. Conceptual model

Modelling is defined as the representation and abstraction of a system. It incorporates the relationships between different elements of a system. In other words, it is a simplified depiction of the important relationships between different elements of a complex process.

According to Robinson, a conceptual model is a specific description of the simulation model, to be developed to represent the real system [20]. It should be independent of the software used to make the simulation model. Figure 5.1 and figure 5.2 together show the conceptual model for the jacket production process. To model a system, it is important to understand the material flow and the information flow in the process. The solid lines in the model represent material flow and the dotted lines represent the information flow. The conceptual model is based on the process flow diagram in Figure 2.6.

### 5.1.1. Model inputs and outputs

For experimentation in simulation using the conceptual model, the following inputs are considered:

1. **Bill of material:** It determines the number and type of materials required to make individual pre-assembly and assembly. It is a list of raw materials available and Leg sections and brace sections are the building blocks of the jacket structure. The number of these individual sections required is different for each jacket. Thus, to prepare the bill of material.
2. **Number of fittings:** It is the count of fittings to be performed prior to welding each section to produce a pre-assembly. For the assembly sub-process, it is the number of fittings performed in the field to connect pre-assemblies for one assembly.
3. **Number of welds:** It is the count of welds performed to connect each section to produce a pre-assembly. For the assembly sub-process, it is the number of field welds required to complete one assembly. It is equal to the number of fittings. The number of welds is a sum of number of circular welds and number of branch welds.

4. **Welding time and welding rate:** The time taken by workers (or machines) to complete a weld is called the welding time and it is determined by the welding rate, which is the amount of weld (in kg) consumed per hour for welding.
5. **Number of cranes:** In the assembly sub-process, two types of cranes are used based on the weight of part to be handled: small cranes for lifting parts weighing up to 200 MT and heavy cranes for handling parts up to 600 MT. The number of cranes is the individual count of small and heavy cranes used during the production process.
6. **Lifting time:** It is the time required for handling of part during which a lifting resource is considered busy.
7. **Cost of workers:** The hourly rate of the workers employed.
8. **Cost of cranes:** It includes the operating and lease or rental costs of cranes.
9. **Building sequence:** It determines the sequence in which the pre-assemblies are joined to in the assembly sub-process to construct the jacket.

To check the performance of the system, the following KPI's are selected:

1. Total time of production: It is the time at which the jacket is produced.
2. Total cost of production: It includes the operational and idle costs of all resources involved in the jacket production process.

### 5.1.2. Model assumptions

- **Number of workstations:** In pre-assembly sub-process, the location where a pre-assembly is being constructed is referred to as a workstation. The number of pre-assemblies that can be constructed inside the pre-assembly hall determines the number of workstations. Since, this number is dependent on the available are of the hall and the size of pre-assemblies, it is assumed that at a time 4 workstations are active in the pre-assembly hall.
- **Number of workers:**There are always sufficient workers to perform a task.
- **Welding rate:** It is the rate at which welding is performed. The welding rate for workers and machines are different. For welding robots, for instance, the welding rate can be obtained from the product specification or the manufacturer. However, the welding rates for workers can only be calculated through empirical studies. For this research, the welding rate for workers is assumed at 0.5 $kg/hr$ and for welding robot at 3.5 $kg/hr$.
- Setup and fitting time: The fitting time for each weld is assumed to be 25% of the welding time and the setup time to start the fitting process, which includes orientating and placing the parts in the right position, is assumed to take 20% of the fitting time.
- Capital expenditure on alternative equipment is excluded from this study.

### 5.1.3. Model simplifications

- A jacket comprises of many parts. In this model, only the main structural elements are considered to produce a jacket. This includes the tubular steel sections for building pre-assemblies, the constructed pre-assemblies and final assemblies. It excludes other structural elements like piles and mud mats, grillage, stairways etc.
- **Type of weld:** The type of groove weld, required to connect the structural elements, plays an important role in calculating the welding time. The type of weld determines the cross-sectional area of the weld and subsequently welding volume and the amount of weld required to fill the volume. Since the each weld has a different dimensions, calculating individual cross-sectional area for each weld is a time consuming process. For the sake of simplicity of this research, it is assumed that the circular welds in pre-assembly sub-process have a double V-butt weld profile and the in assembly sub-process, the circular welds have a single V-butt weld profile.

- **Blasting and painting time:** The time required to paint a surface depends on the surface area to be painted and the rate of painting. Calculating the surface area of pre-assemblies with varying dimensions and a time consuming process. Since, this research excludes the alternative to blasting & painting methods, the total time that the parts spend in the blasting and painting station is taken as 72 hours.

## 5.2. Simulation Model

Based on the conceptual model described in Section 5.1, the jacket production process is simulated using Simio, a discrete-event simulation software. Simio has an in-built library of object oriented elements that represent the physical components of the system. These objects are used as building blocks to simulate the information flow and the material flow of the conceptual model.

### 5.2.1. Information Flow

To initiate the simulation, the following information is imported by the software using data input files:

1. **Manufacturing orders:** For producing a jacket, two types of manufacturing orders are released during the simulation:
   (a) Assembly order – to initiate the assembly sub-process.
   (b) Pre-assembly order – to initiate the pre-assembly sub-process.

   The priority in which these orders are released is set by the building sequence followed in the Reference Project.
2. **Material information:** Three material types are used in the simulation: sections, pre-assembly and assembly. This input file contains the initial quantity of these material types, and the weight of each pre-assembly and assembly.
3. **Bill of materials (BOM):** The BOM is a list of materials required to be consumed in order to produce a pre-assembly or assembly. An entity remains within the sub-process until all required materials are consumed.
4. **Routing sequence:** The routing sequence determines the order in which an entity will visit the processing stations. It also contains the setup and processing times for each part at the stations it visits.

### 5.2.2. Material Flow

Looking at the material flow in the conceptual model, it is represented in the simulation environment within the following three categories:

1. **Materials:** Pre-assemblies and assemblies are modelled as Entity in the simulation environment. Each entity is a dynamic object instance that passes through various processing stations, representing the material used in the production process.
2. **Stations:** The four major tasks, fitting, welding, blasting & painting and handling of parts, are performed at designated locations called the stations. These are modelled using a server object where an entity is processed. The following servers are modelled in this simulation:
   (a) **Fit:** Fit servers represent fitting stations in the jacket production facility. It is assumed that the preassembly hall can accommodate four preassemblies at one time. The input buffer capacity, therefore, is set to 1 pre-assembly. For assembly yard, the input buffer capacity is not constrained because it has the capacity to hold all preassemblies and assemblies during the construction of jacket.
   (b) **Weld:** Welding servers represent the welding locations in preassembly hall and assembly yard. Within the preassembly hall, two different welding servers are modelled: one for circular welds and the other for branch welds. For the assembly process, all the welds are circular, according to the Reference Project.

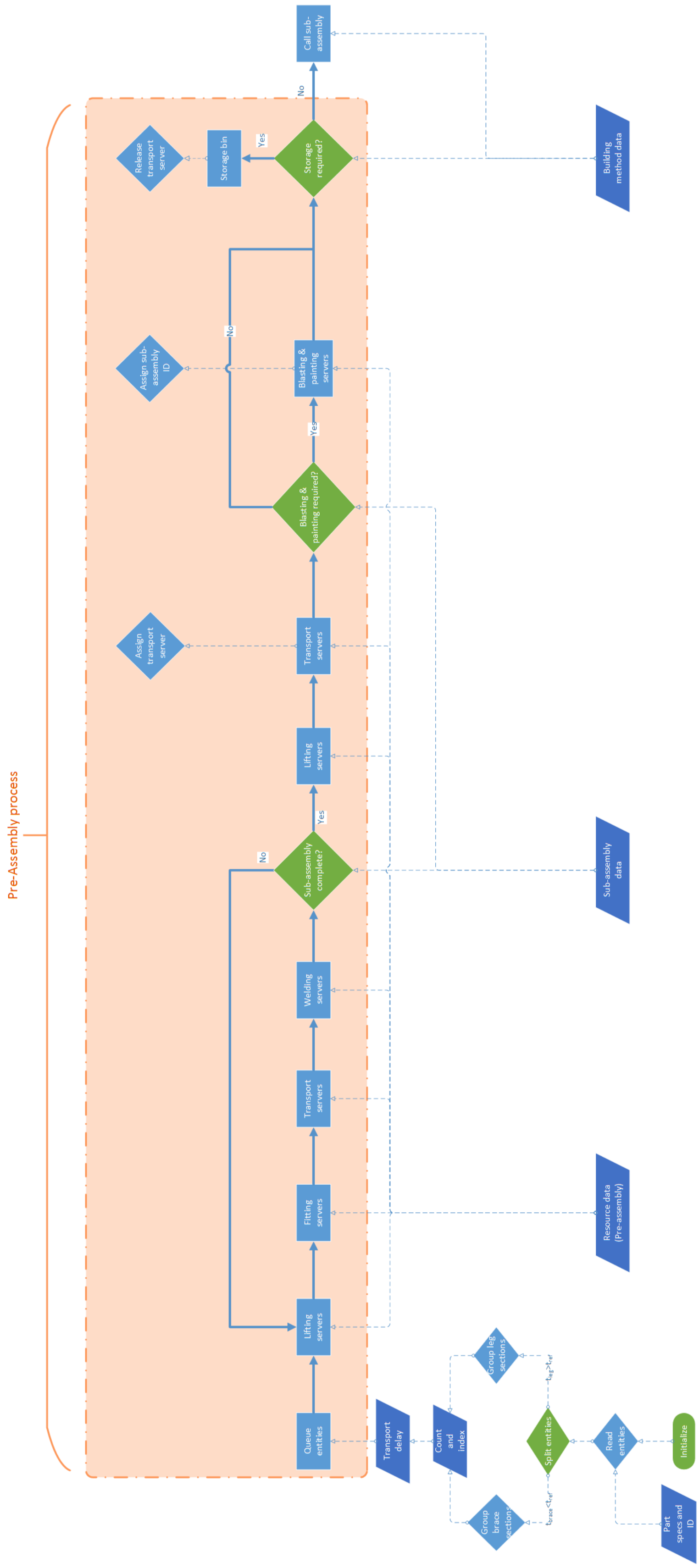


Figure 5.1: Conceptual model (Part-1): Pre-assembly process

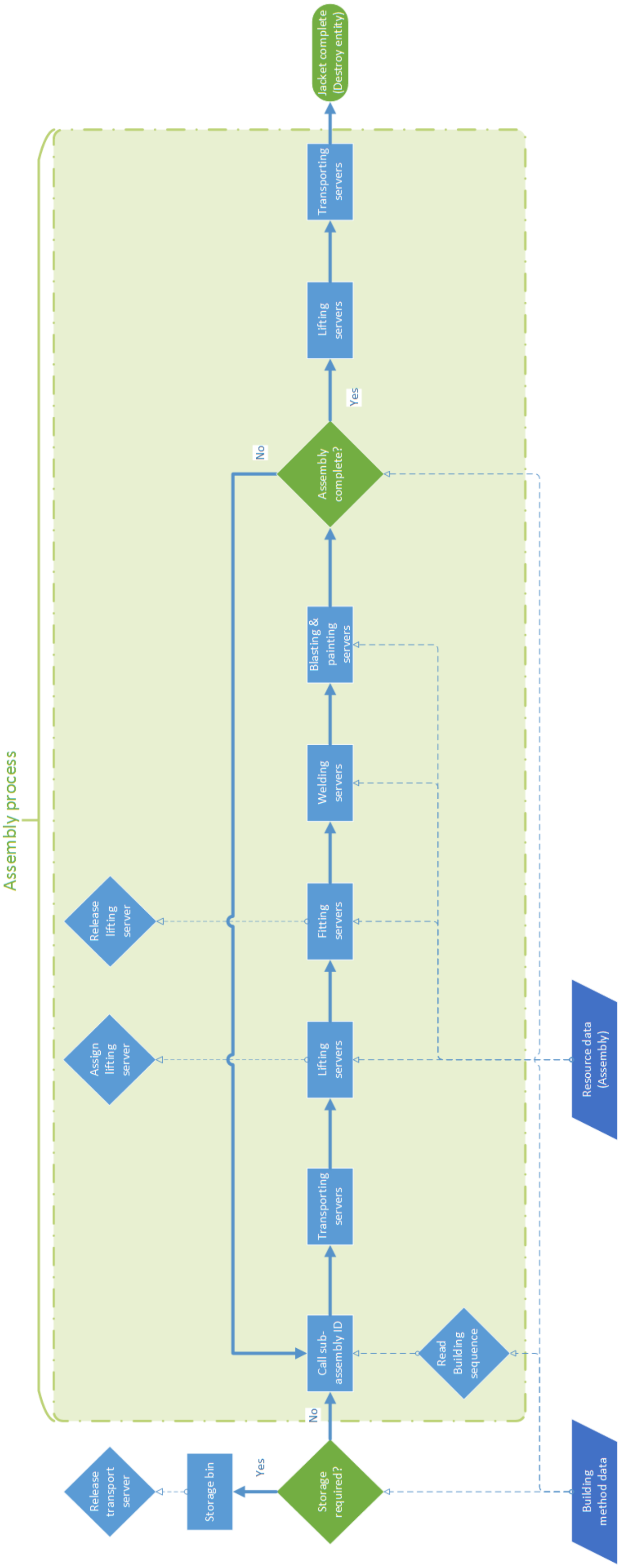


Figure 5.2: Conceptual model (Part-2): Assembly process

   (c) **Paint:** Blasting & painting of preassembly parts is done in a paint hall which can accommodate 2 parts simultaneously. This is performed at the 'Paint' server. In the assembly yard, after welding two assemblies together painting is performed only at the joints and on the location.
   (d) **Lift:** 'Lift' server is used to model lifting and handling task of the assembly parts in the yard.
   (e) **Storage:** Storage facility is used to temporarily store the preassembly and assembly parts. 'Storage' server is used to store the preassemblies until they are called by the Assembly Orders. Another storage server is used in the model, which is a representation of the assembly yard itself, where the constructed jacket is placed.

3. **Resources:** To perform the above tasks, the following resources are required at specific stations:
   (a) **Workers:** Workers are used by fitting, welding and painting servers to perform the tasks of fitting, welding and painting respectively, in both sub-processes.
   (b) **Heavy-lift cranes:** This resource represents heavy lift cranes which are used for assemblies weighing more than 400MT. This resource is used by Lift server. At least one such crane is available for use in the Reference Project
   (c) **Small cranes:** For parts weighing below 400MT, smaller cranes (2 numbers) are used to lift assemblies at the Lift server.

## 5.3. Conclusion

In this chapter, a conceptual model of the production method is presented. The inputs for the model can be altered to simulate any different jacket production, thus this model is fairly generic. To evaluate the performance of production, the following KPIs are used:

- Total production time
- Total production cost

The restriction of the model, however, stems from the assumptions and simplifications that are defined in this chapter. In the next chapter, verification and validation of the model will be attempte

# 6

# Model verification and validation

This chapter explains the methodology used to verify and validate the simulation model of jacket production process. Jacket production process is simulated using a discrete-event simulation software. First, the verification of the model is conducted by simulating the production of a simplified jacket. Then, the validation of the model is performed in two steps: validation of the overall production process and validation of the sub-processes. This chapter will answer the following question:

- Is a verified and validated model achieved?

## 6.1. Verification

Verification is defined by Davis as the process of determining whether the computer model has been constructed from the conceptual model with sufficient accuracy [6]. To check the fidelity of the simulation model, the model is used to construct a simplified jacket structure consisting of only leg parts.

Various methods are available to verify a simulation model. For jacket production process, the number of parts required for constructing the jacket is unique due to which only one quantity of each part is produced in both sub-processes. Quantity of each part produced in the pre-assembly sub-process, after processing at the Paint server, should be equal to the quantity consumed in the assembly sub-process, at the Lift server, thus, maintaining an equivalence in the simulation environment, as per Equation 6.1.

$$\sum_{i=1}^{N} n_{pa,i} = \sum_{i=1}^{N} n'_{pa,i} \tag{6.1}$$

where,
$n_{pa,i}$ = Quantity of a preassembly $i$ produced after the preassembly sub-process.
$n'_{pa,i}$ = Quantity of a preassembly $i$ consumed in the assembly sub-process.
$i \in 1, N$ = For pre-assemblies, $N = 12$.
$N$ = Number of preassemblies for legs in Reference Project.

Similarly, quantity of an assembly produced in the assembly process must be equal to the quantity of that assembly used in the construction of the jacket, which is represented by Equation 6.2

$$\sum_{j=1}^{N} n_{a,j} = \sum_{j=1}^{N} n'_{a,j} \tag{6.2}$$

where,
$n_{a,j}$ = Quantity of a preassembly $j$ produced after the preassembly sub-process.

$n'_{a,j}$ = Quantity of a preassembly $j$ consumed in the assembly sub-process.
$i \in 1, N$ = For pre-assemblies, $N = 12$.
$N$ = Number of preassemblies for legs in Reference Project.

Table 6.1 shows the part ID and the part types used in the construction of the simplified jacket. Jacket is also considered as an assembly part because it is also given as a manufacturing order of assembly type. The initial quantities of the preassemblies and assemblies are 0 and the required quantities are 1. The exact number of brace and leg sections required for the jacket constructions are 88 and 76 respectively. These sections should be completely consumed.

Table 6.1: Initial and required quantities of the different parts for the verification of simplified jacket production process.

| **Part ID** | **Part Type** | **Structural component** | **Initial Quantity** | **Constructed quantity** |
|---|---|---|---|---|
| Jacket_1 | Assembly | Jacket | 0 | 1 |
| Leg_A2; Leg_A4; Leg_B2; Leg_B4 | Assembly | Leg assembly | 0 | 1 |
| Legs_A2_1; Legs_A2_2; Legs_A2_3;<br>Legs_A4_1; Legs_A4_2; Legs_A4_3;<br>Legs_B2_1; Legs_B2_2; Legs_B2_3;<br>Legs_B4_1; Legs_B4_2; Legs_B4_3; | Preassembly | Leg assembly | 0 | 1 |
| Brace_sec | Section | Brace section | 88 | 0 |
| Leg_sec | Section | Leg section | 76 | 0 |

Using the above data, the simulation run shows the results depicted in Figure 6.1 . It can be observed that only 1 number of each preassembly and assembly are being produced ad consumed to final produce 1 jacket.

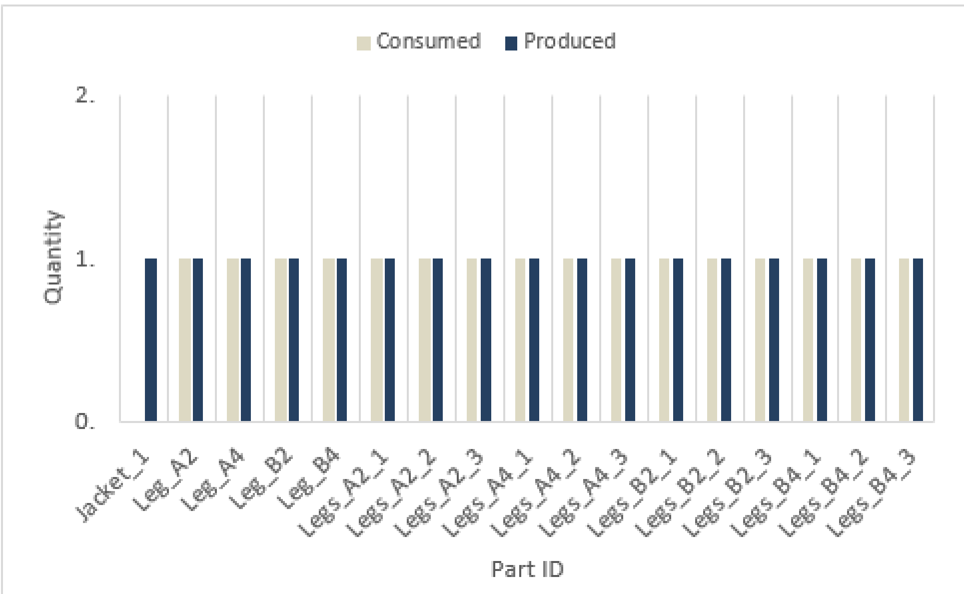


Figure 6.1: Quantities of parts produced and consumed when sufficient tubular steel sections are available

However, when the number of available brace sections is reduced to 87, it can be seen in Figure 6.2, that the preassembly *Legs_B4_3* is not produced due to insufficient brace sections. Subsequently, the assembly part *Leg_B2* is also not produced as it requires *Legs_B4_3* for its construction. Due to a missing assembly part, the final jacket is also not produced which is as expected. Thus, from this analysis, the model is verified.

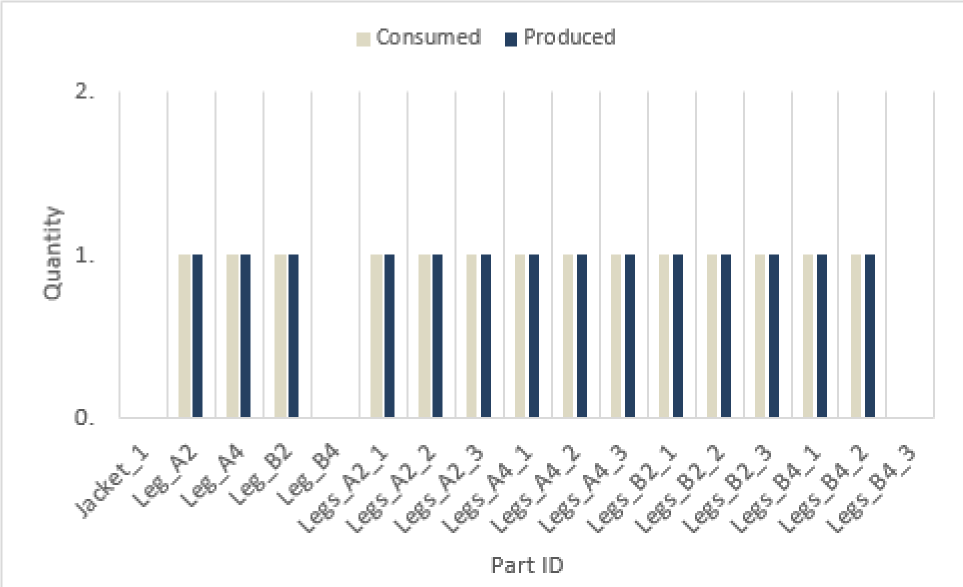


Figure 6.2: Quantities of parts produced and consumed when lesser tubular steel sections, than required to complete all preassemblies, are available

## 6.2. Validation of Reference Project output

The process duration's of the Reference Project are obtained from a project schedule document, which was prepared by HFG using a commercial project planning software package before the start of the Reference Project. To increase the confidence of accepting the output from this scheduling document for validation, the start and end dates of Reference Project in the project schedule should be in accordance with dates of realization of these events, which is found in an official document released by HFG.

Table 6.2: Start and end date of Reference Project as estimated in planning compared with actual duration of realization

| **Supporting document** | **Output Type** | **Start of Production** | **End date** | **Production Time (Days)** | **Total lead time (Days)** |
|---|---|---|---|---|---|
| Project schedule | Planning | 04 Jan. 2016 | 02 June 2017* | 318 | 516 |
| Official dates | Realization | 01 Jan. 2016** | 28 JUne 2017*** | NA | 545 |
| * Jacket is loaded out and is ready for sail away. | | | | | |
| ** Start date of construction is not specified, so it is assumed to be 01 January, 2016. | | | | | |
| *** Actual date when jacket sailed away. | | | | | |

The lead time of the jacket production is given by Equation 6.3:

$$Leas\ time = Production\ time + Load\ out\ time \tag{6.3}$$

From the data in Table 6.2, it is observed that the expected duration of jacket lead time from project schedule has an error of 5.32% from the actual date when the jacket sailed away. Load-out refers to that stage of project when all structural elements required to construct the jacket are assembled and temporary structures are mounted for it transportation through a barge. When all these temporary structures have been mounted, the jacket is loaded out on to a barge where it waits for transportation to begin, called the sail away, the permission for which is given by the port authorities. Since, the project end date in the schedule refers to the date of completion of jacket and ready for sail away, this difference is acceptable. Thus, project schedule complies with the actual dates of occurrence of these events. In conclusion, the outputs from project schedule can be used as an acceptable reference for validation of simulation model.

## 6.3. Methodology

The focus of this research is to find alternatives to the current equipment used for different tasks in jacket production. The production comprises of two sub-processes, namely *preassembly* and *assembly*. Tasks performed in each sub-process are also within the scope of this research. Therefore, it is important to validate the overall production process as well as the preassembly and assembly sub-processes.

### 6.3.1. Cycle time and experiments

Cycle time is chosen as the measure of comparison for validating this simulation model. It is defined as the time take to complete a process, including both processing times and waiting times. From the data available in the project schedule, cycle times of the overall production and the sub-processes are calculated.

Furthermore, the assembly sub-process uses cranes to lift the preassemblies and carry out the construction of jacket. During this process, at least two small cranes are used in tandem to safely lift the parts. Depending on the weight of the parts, an additional heavy-lift crane may be used. However, in the whole assembly sub-process, the total number of small cranes and heavy-lift cranes used may vary depending on the following factors:

1. To match the project schedule, the number of cranes might be increased to decrease the production time.
2. If more than one jackets are being assembled simultaneously, the process is optimized by sharing the cranes instead of keeping them idle.

From the data available, it is difficult to determine the exact numbers of lifting resources used. Therefore, considering different configuration of lifting equipment, three experiments are designed. Table 6.3 shows the experiments that are conducted to validate the simulation model.

Table 6.3: Different scenarios considered for validating the simulation model by taking into account the order release dates and lifting resources.

| **Experiment ID** | **Experiment 1** | **Experiment 2** | **Experiment 3** |
|---|---|---|---|
| Configuration | 3 Smaller cranes and 1 Heavy crane | 4 Smaller cranes and 1 Heavy crane | 6 Smaller cranes and 1 Heavy crane |

### 6.3.2. Validation of overall production process

The black box validation method is used as the primary test for the validation of the overall jacket production. In this method, the cycle time of jacket production from simulation model and Reference Project is compared. The system under consideration is as shown in Figure 6.3. The production process begins with the release of order and at completion, a jacket is produced.

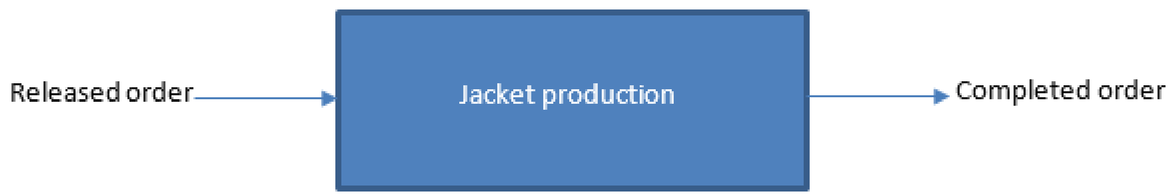


Figure 6.3: Black box representation of order flow in the jacket production process.

Cycle time of production is calculated using the expression:

$$T_{cp} = (Date)_{End} - (Date)_{Start} + 1 \tag{6.4}$$

Where,
$T_{cp}$ = Time required for producing a jacket, in *days*.
$(Date)_{End}$ = The date when the order for jacket production is completed. Alternatively, the date when a jacket is produced.
$(Date)_{Start}$ = The date when the order for jacket production is released. Alternatively, the date when jacket production begins.

However, using black box validation alone is not a reliable method as it fails to show the relationships of the processes within the system and their effects on complete system.

### 6.3.3. Validation of sub-processes

As a secondary test, white box validation is used to judge if the simulation model is sufficiently similar to the real world. Looking at the sub-processes of jacket production, the cycle times of preassembly and assembly sub-processes from the simulation is compared with the project schedule.

Figure 6.4 shows the system under consideration. *Released order* enters the preassembly sub-process, from where it moves on to assembly process. Once the assembly of jacket is complete, it exits the system as a *Completed order*.

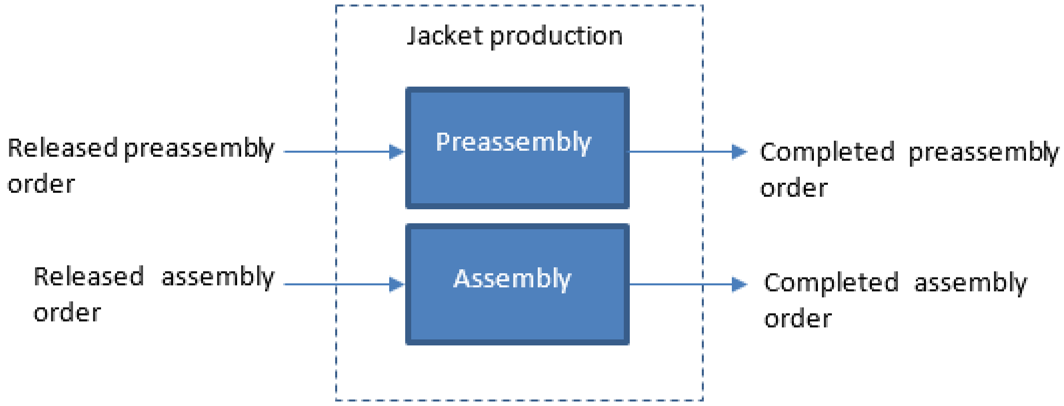


Figure 6.4: White box representation of jacket production, showing preassembly and assembly sub-processes.

The cycle times for both sub-processes are compared in this method. They are calculated using the following expressions:

$$(T_{cpa})_i = (Date)_{End,i} - (Date)_{Start,i} + 1 \tag{6.5}$$

$$(T_{ca})_j = (Date)_{End,j} - (Date)_{Start,j} + 1 \tag{6.6}$$

Where,
$(T_{cpa})_i$ = Number of days required for producing a preassembly i, in days.
$(T_{ca})_j$ = Number of days required to complete an assembly, in days.
$(Date)_{Start,i}$ = The date when the order for a preassembly i is released.
$(Date)_{End,i}$ = TThe date when the order for a preassembly i is completed.
$(Date)_{Start,j}$ = The date when the order for a assembly j is released.
$(Date)_{End,j}$ = TThe date when the order for a assembly j is completed.

$i \in 1, N$ = For pre-assemblies, $N = 24$.
$j \in 1, N$ = For assemblies, $N = 4$.
$N$ = Number of preassembly and assembly orders in Reference Project.

## 6.4. Comparison of outputs

### 6.4.1. Comparison of overall production process

Using the black box validation method, explained in Subsection 6.3.2, the cycle times of overall production process from the simulation model are compared with the times calculated from project schedule of the Reference Project. Figure 6.5 shows the cycle times for the Experiments 1, 2 and 3. From the trend it can be observed that increasing the number of smaller cranes significantly decreases the cycle time of overall production. Looking at Table 6.4, it can be seen that Experiment 3 has a 4% lower cycle time for simulation model when compared to that of the Reference Project. In this comparison, the model closely represents the real world only in Experiment 3. It can be concluded that Experiment 3 is the closest representation of the Reference Project.

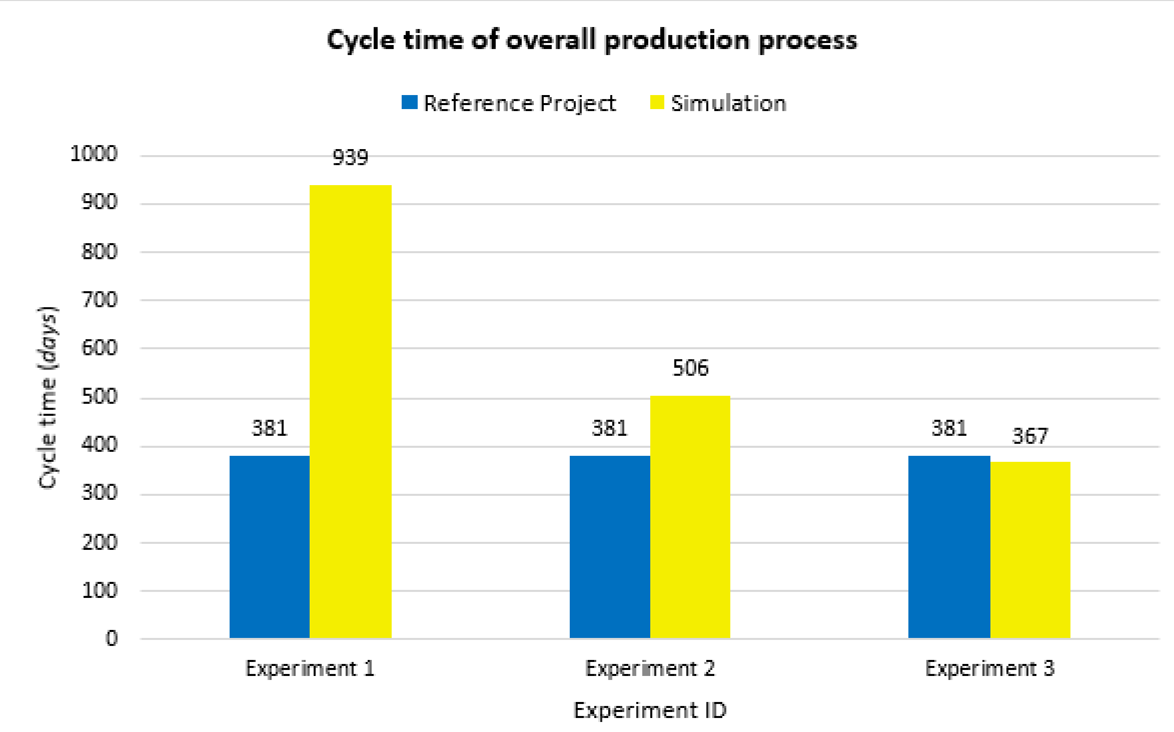


Figure 6.5: Comparison of cycle times of overall production process.

Table 6.4: Percent error between cycle times of overall production process for Reference project and Simulation model.

| Experiment ID | Cycle times of overall production process (days) | | Error % |
|---|---|---|---|
| | Reference projects | Simulation Model | |
| Experiment 1 | 381 | 939 | 146 |
| Experiment 2 | 381 | 506 | 33 |
| Experiment 3 | 381 | 367 | 4 |

### 6.4.2. Comparison of sub-processes

To compare the cycle times of preassembly and assembly sub-processes, the white box validation method is used (Figure 6.4).

**Comparison by mean cycle times**

Jacket produced in the Reference Project comprises of 24 preassemblies and 4 assemblies. Equations 6.5 and 6.6 give the cycle times for individual parts. As a comparative measure, mean cycle time for each sub-process is chosen, which is calculated using Equations 6.7 and 6.8.

$$\mu_{cpa} = \frac{\sum_{i=1}^{N} (T_{cpa})_i}{N} \tag{6.7}$$

$$\mu_{ca} = \frac{\sum_{i=1}^{N} (T_{ca})_j}{N} \tag{6.8}$$

Where,
$\mu_{cpa}$ = Mean cycle time for preassembly sub-process, in days.
$\mu_{ca}$ = Mean cycle time for assembly sub-process, in days.

Figure 6.6 shows the comparison of mean cycle times of pre-assembly process for the three experiments. Here, the values are equal for all experiments because the configuration of equipment in each experiment is changed only for the assembly sub-process. It can be seen that the cycle time from simulation model are comparable to the Reference Project within an acceptable error of 4.25%, as shown in Table 6.5.

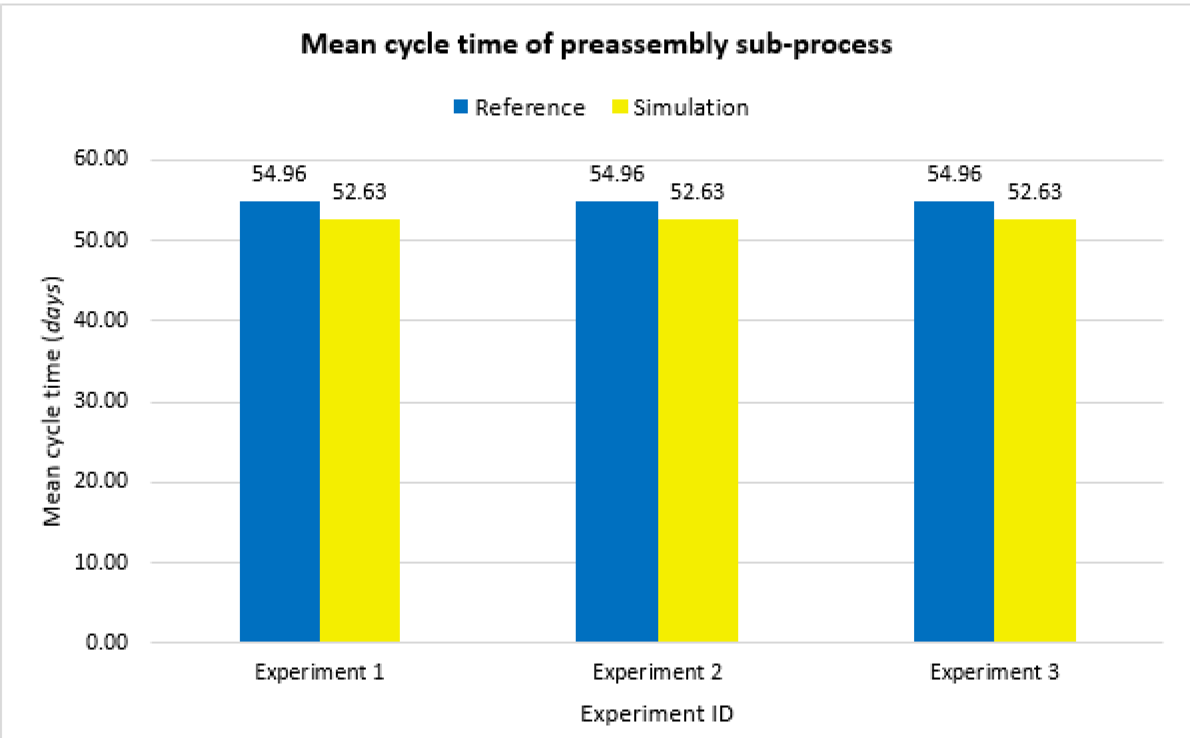


Figure 6.6: Comparison of mean cycle times of preassembly sub-process ($\mu_{cpa}$) for Reference Project and Simulation model.

Table 6.5: Percent error between mean cycle times of preassembly sub-process ($\mu_{cpa}$) for Reference project and Simulation model.

| Experiment ID | Cycle times of overall production process (days) | | Error % |
|---|---|---|---|
| | Reference projects | Simulation Model | |
| Experiment 1 | 54.96 | 52.63 | 4.25 |
| Experiment 2 | 54.96 | 52.63 | 4.25 |
| Experiment 3 | 54.96 | 52.63 | 4.25 |

Looking at the mean cycle time of assembly sub-process for the experiments in Figure 6.7, a decreasing trend can be observed as the number of smaller cranes are increased. The cycle times decrease significantly which can be observed from the error values in Table 6.6. It can also be observed that the lowest error of 1.35% is achieved for Experiment 2, i.e. by using four smaller cranes in assembly process. It can be inferred that Experiment 2 is the closest representation of the Reference Project

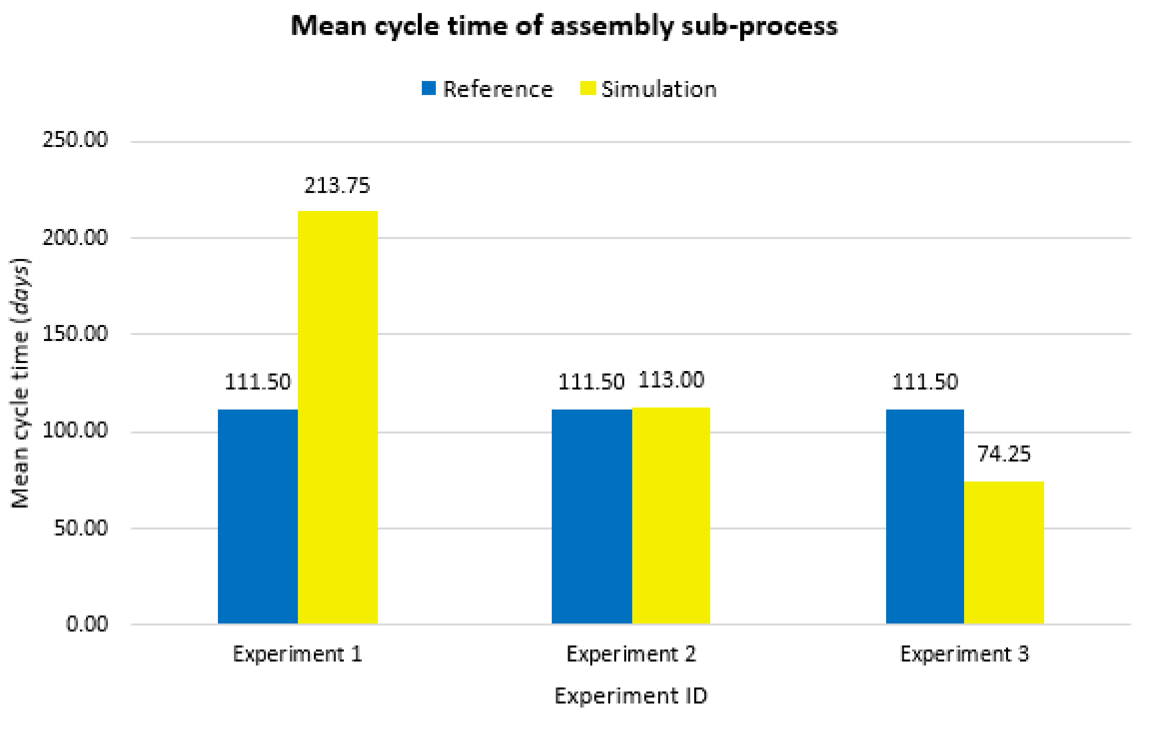


Figure 6.7: Comparison of mean cycle times of assembly sub-process ($\mu_{ca}$) for Reference Project and Simulation model.

Table 6.6: Percent error between mean cycle times of assembly sub-process ($\mu_{ca}$) for Reference Project and Simulation model.

| Experiment ID | Cycle times of overall production process (days) | | Error % |
|---|---|---|---|
| | Reference projects | Simulation Model | |
| Experiment 1 | 111.50 | 213.75 | 91.70 |
| Experiment 2 | 111.50 | 113.00 | 1.35 |
| Experiment 3 | 111.50 | 74.25 | 33.41 |

From above comparisons of mean cycle times of the two sub-processes, it can be observed that Experiment 2 is a good representation of the real world scenario. However the discussion in Section 6.4.1, shows that cycle time of overall production for this experiment is higher than that of Experiment 3 and, thus, not acceptable. This discrepancy arises because multiple preassemblies and assemblies are produced in preassembly and assembly sub-processes respectively, having high variation in their individual cycle times.

**Comparison by coefficient of variation in cycle times**

*Coefficient of variation (CV)* has been used extensively in many areas of biological and medical sciences, as a measurement tool for quantifying the degree of variability in a population with relative to the mean [13]. Its use is common in the area of biochemistry as well, where it is used to measure the reliability of an assay [1]. The use of CV as a measure of reliability and system's precision also extends to other research fields such as engineering, agricultural economics, archaeology and financial management [7].

As explained by Rohlf and Sokal, CV is used in systematics to compare the variability in a particular characteristic in two different populations [23]. In order for the populations to be compared using CV, the variable being compared must be proportional. For example, if a variable X has to be compared for population 1 and population 2, where, the variable has a value of $X_1$ and $X_2$, respectively, then,

$$X_2 = kX_1 \tag{6.9}$$

Where, k is the constant of proportionality.

In this research, due to high variation in the cycle times of preassemblies and assemblies produced during the jacket production process, a comparative study of variability of cycle times for simulation model and Reference Project needs to be carried out. Here, the cycle time of preassembly and assembly sub-processes are the variables to be compared for the Reference Project and the simulation. Ideally, the cycle time of each part should be equal in both real situation and simulation. The cycle times, then, conform to the form in equation 5.9, as shown by Equations 6.10 and 6.11, for $k = 1$.

$$(T_{cpa})_{i,Simulation} = (T_{cpa})_{i,Reference} \tag{6.10}$$

$$(T_{ca})_{i,Simulation} = (T_{ca})_{i,Reference} \tag{6.11}$$

*CV* is calculated as a fraction of mean and standard deviation of the population and expressed in percentage, as shown in Equations 6.12 and 6.13. The values from these equations are compared by finding the percent difference in terms *Percentage points (pp)*.

$$CV_{pa} = \frac{\sigma_{cpa}}{\mu_{cpa}} \times 100 \tag{6.12}$$

$$CV_a = \frac{\sigma_{ca}}{\mu_{ca}} \times 100 \tag{6.13}$$

Where,
$CV_{pa}$ = Coefficient of variation for cycle times of preassembly sub-process, in %.
$CV_a$ = Coefficient of variation for cycle times of preassembly sub-process, in %.
$\sigma_{cpa}$ = Coefficient of variation for cycle times of preassembly sub-process, in days.
$\sigma_{ca}$ = Coefficient of variation for cycle times of preassembly sub-process, in days.

As can be observed from Table 6.7 and Figure 6.8, the variation in cycle times is higher for preassembly sub-process in simulation model as compared to that of the Reference Project, by 14.25 pp. For assembly sub-process, the trend in Figure 6.9 shows that increasing the number of cranes reduces the variation in simulation output. Looking at the difference in Table 6.8, Experiment 3 shows the least variation with a value of 21.44 pp. This shows that calculating the mean cycle times for these sub-processes is not reliable for validating the simulation model.

Table 6.7: Difference between Coefficient of variation of preassembly sub-process ($CV_{pa}$) for Reference Project and Simulation model.

| Experiment ID | Cycle times of overall production process (days) | | Error % |
|---|---|---|---|
| | Reference projects | Simulation Model | |
| Experiment 1 | 35.15 | 49.64 | 14.49 |
| Experiment 2 | 35.15 | 49.64 | 14.49 |
| Experiment 3 | 35.15 | 49.64 | 14.49 |

Table 6.8: Difference between Coefficient of variation of assembly sub-process ($CV_{pa}$) for Reference Project and Simulation model.

| Experiment ID | Cycle times of overall production process (days) | | Error % |
|---|---|---|---|
| | Reference projects | Simulation Model | |
| Experiment 1 | 11.03 | 34.72 | 23.69 |
| Experiment 2 | 11.03 | 33.81 | 22.78 |
| Experiment 3 | 11.03 | 32.47 | 21.44 |

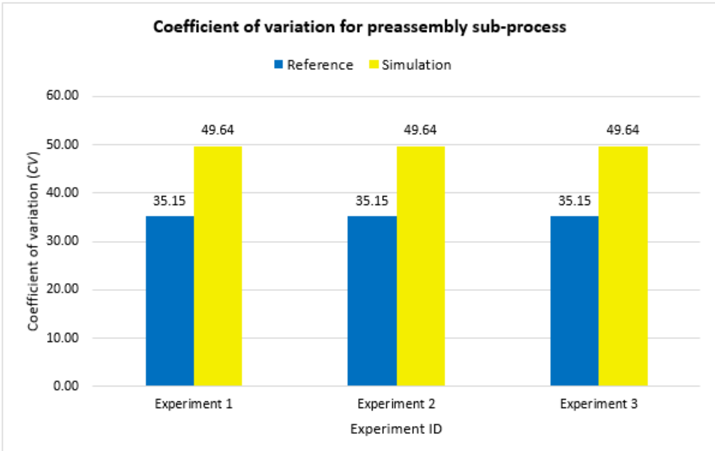


Figure 6.8: Comparison of Coefficient of variation ($CV_{pa}$) of preassembly sub-process for Reference Project and Simulation model.

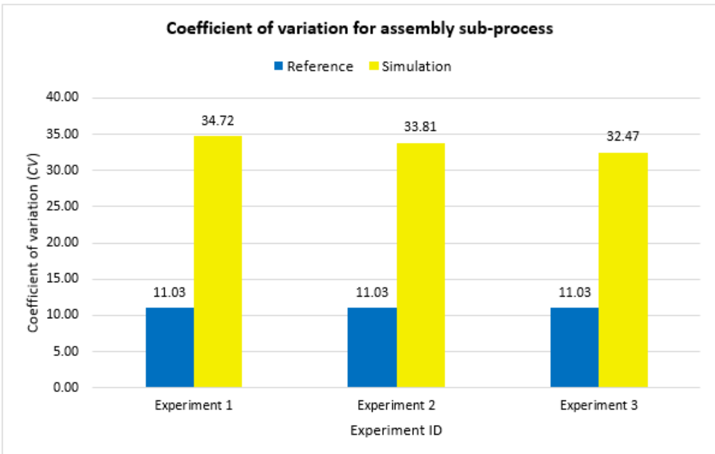


Figure 6.9: Comparison of Coefficient of variation ($CV_a$) of preassembly sub-process for Reference Project and Simulation model.

Although, the *CV* for Experiment 3 is the lowest, the difference in values for both preassembly and assembly sub-processes is significantly higher compared to the Reference Project values.

## 6.5. Conclusion

Using black box validation method, *Experiment 3* is found to be a significantly accurate representation of Reference Project. In the next step using white box validation method, conflicting results are obtained. On comparing the mean cycle times, *Experiment 2* shows higher resemblance to the Reference Project, however, a comparison of variability in the outputs shows that mean cycle times is not an accurate measurement of comparison because of high variation in the individual cycle times of the sub-processes and has to be discarded. Moreover, *Experiment 3* has the lowest variation in its output among the other experiments. But due to significantly high variation compared to the Reference Project, it cannot be accepted as a validated model.

# 7
# Further Analysis

From the previous chapter, it was concluded that high variation in cycle times of production sub-processes makes it difficult to validate the simulation model of jacket production process. Using coefficient of variation (CV) as a statistical tool to measure the variability shows that further examination of the processes is required to understand the causes behind these inequalities. This chapter explains the possible effects of assumptions, which have been considered in the simulation model to simplify the reality, on inducing variations in cycle times. To further show the potential of this simulation model as a comparative tool for exploring alternative production methods, three alternative configurations are evaluated. In the last section, the KPIs for each configuration are compared and recommendations are made for choosing the best design alternative. This chapter attempts to answer the following sub-questions:

8. What are the causes of variation in simulation outputs?
9. Which alternative configuration performs better than the present production process?

## 7.1. Effect of simplifying reality

Validation of the simulation model largely depends on the level of detail of the model itself [20]. Observing from Subsection 6.4.1, the simulation model represents reality when comparing the overall production process. However, comparison of the variations in sub-processes, in Subsection 6.4.2, gives rise to ambiguity in conclusively validating the model.

A validated model can be achieved by reducing the variation in the cycle times of pre-assembly and assembly sub-processes. As speculated earlier, these variations might be a result of oversimplification of the simulation model, resulting in higher variation in simulation outputs. Certain aspects of the production process need to be modelled in more detail to represent the process in a more realistic nature, which are explained as follows:

1. **Effect of order release date**
   In the simulation model, the orders for preassemblies and assemblies are released simultaneously at the start of simulation. The tubular steel sections required for producing preassemblies are assumed to be available from the start. These orders, then, follow the sequence of tasks depending on the availability of processing stations within the sub-processes and, task resources. Due to this, initial preassemblies are produced faster but eventually a queue forms at the stations which affects the processing times. However, in Reference Project, the parts are released on dates estimated using the project planning schedule. Project scheduling takes into account the availability of steel sections, which are produced during the prefabrication process, before they can be used in the preassembly sub-process. This reduces the waiting time of orders in the sub-process and, thus, reduces the variation in cycle times.

2. **Effect of number of workstations**
   In the preassembly workshop, the number of locations at which preassemblies are produced depends

upon the available area. Also, depending upon the size of the preassembly and the availability of tubular sections, number of processing stations may vary depending on number of parts being preassembled at one time. In reality, this dynamic optimization of the available area reduces the cycle times of preassembly sub-process. In this simulation model, however, based on the available data on the Reference Project, four processing stations are assumed where tasks are performed simultaneously. As a result, cycle times are lower than the real world when less than four stations are required and higher when more than four stations are in use.

3. **Effect of number of cranes**
In each experiment, the number of cranes used in the assembly sub-process is fixed. As the number of cranes is increased, the waiting time of assembly orders decreases significantly, resulting in lower cycle time per assembly. But the decrease in variation of cycle times is not very significant. When the cycle times of the four assemblies from the simulation model is compared with that of the Reference Project, it is observed that constructing *Assembly 3* takes significantly longer time than others, as shown in Figure 7.1. Among the four assemblies, *Assembly 3* constitutes of 26 preassembled parts whereas *Assemblies 1*, *2* and *4* are made of 12, 12 and 14 parts respectively. The combination of higher input volumes and fixed lifting resources culminates in increased waiting times and, consequently, increased cycle time for *Assembly 3*. When the number of lifting resources are increased, it improves the cycle times for all four assemblies and, thus, it does not have a significant effect on the variability. For Reference Project, the number of cranes used were not fixed. They were mobilized or demobilized, depending on the project requirements. Additionally, next to Reference Project, another jacket was being constructed on the yard. The resources between them were shared. Thus, the variation in cycle times for Reference Project is significantly lower than the simulation model.

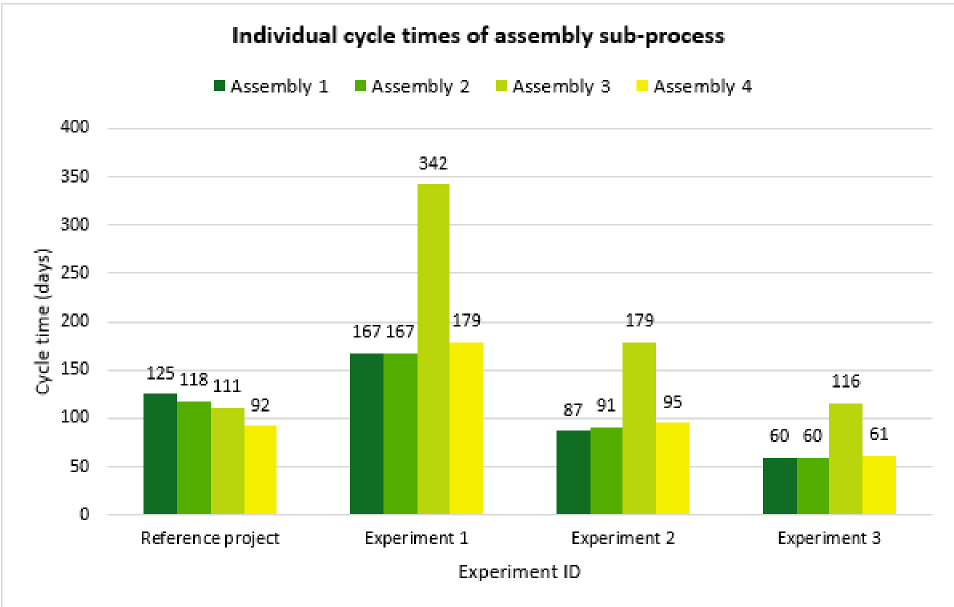


Figure 7.1: Comparison of individual cycle times of four assemblies in assembly sub-process for Reference Project and Simulation model.

## 7.2. Alternative configurations

In Section 4.3, three alternative configurations were considered using the morphological table shown in Figure 4.1. The configurations are:

1. Configuration 1: Jacket production using TKY welding robot
2. Configuration 2: Jacket production using gantry crane

3. Configuration 3: Jacket production using TKY welding robot and gantry crane

To evaluate and compare these design alternatives, the simulation model of the jacket production process is used. The evaluation is based on the following KPIs:

1. Total production time

2. Total operation cost

Although, the simulation model presented here requires a more detailed modelling before it can be used for more accurate analyses of alternatives, the following experiments are conducted to demonstrate the benefits of using this concept. For this evaluation, Experiment 2 described in Table 6.3 is considered as the Reference Project.

## 7.3. Comparison of total production time

Comparing the jacket production time for the Reference Project and the three configurations shows that using gantry crane reduces the production time by 17%. Using the TKY welding robot in the pre-assembly sub-process alone, reduces the production time by only 2%. However, when both, the welding robot and gantry crane, are used together for jacket production, production time is decreased by 16%.

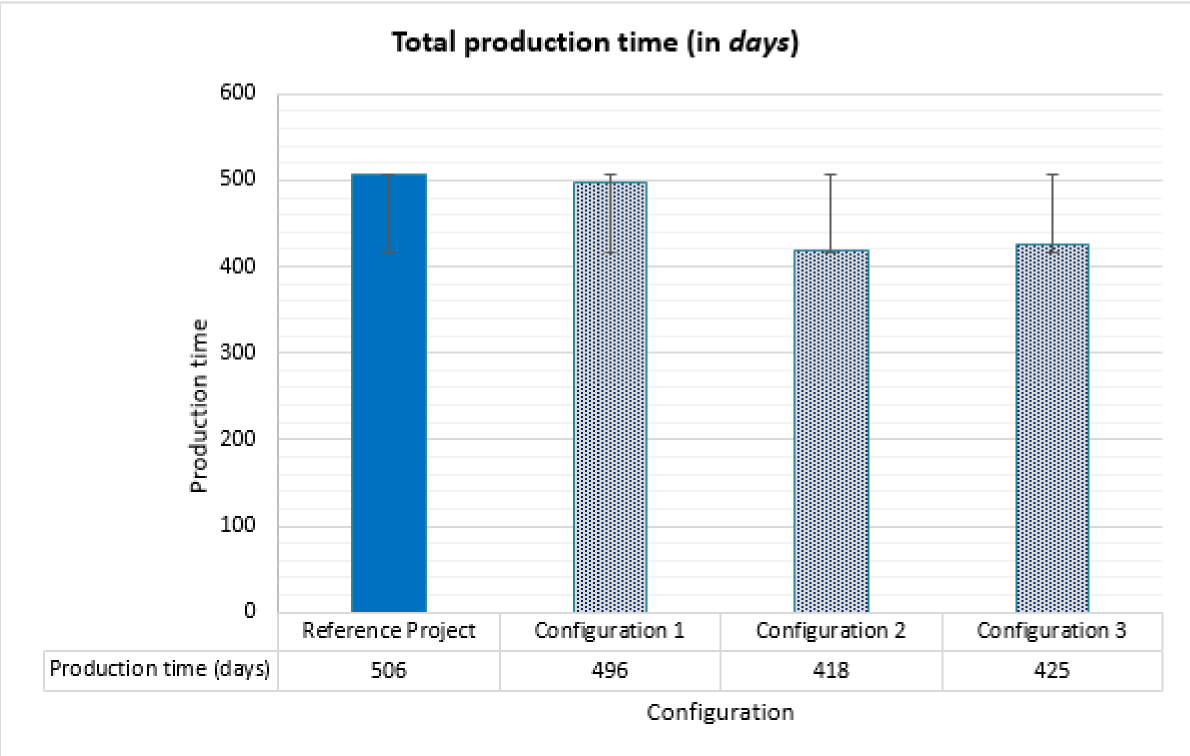


Figure 7.2: Comparison of total duration of production, in days, for *Configurations 1*, *2* and *3* with respect to Reference Project.

Table 7.1: Difference in production times for *Configurations 1*, *2* and *3* with respect to Reference Project.

| Configuration | Production time (in Days) | Difference (in Days) |
|---|---|---|
| Reference Project | 506 | - |
| Configuration 1 | 496 | 10 |
| Configuration 2 | 418 | 88 |
| Configuration 3 | 425 | 81 |

## 7.4. Comparison of total production cost

Observing the trend in operational cost of jacket production for different configurations shows that automating the preassembly process can reduce the production cost by 32%. Welding is a time intensive task and using a welding robot reduces the number of workers engaged to perform welding, thus, having a significant effect on its operational cost. Using a gantry crane during the assembly process has comparatively lesser impact on the production cost, with a reduction of 3%. The slight decrease owing to reduced travel distance which decreases the operational time. Using both configurations together has the highest impact on production cost with a decrease of 35% from the actual value.

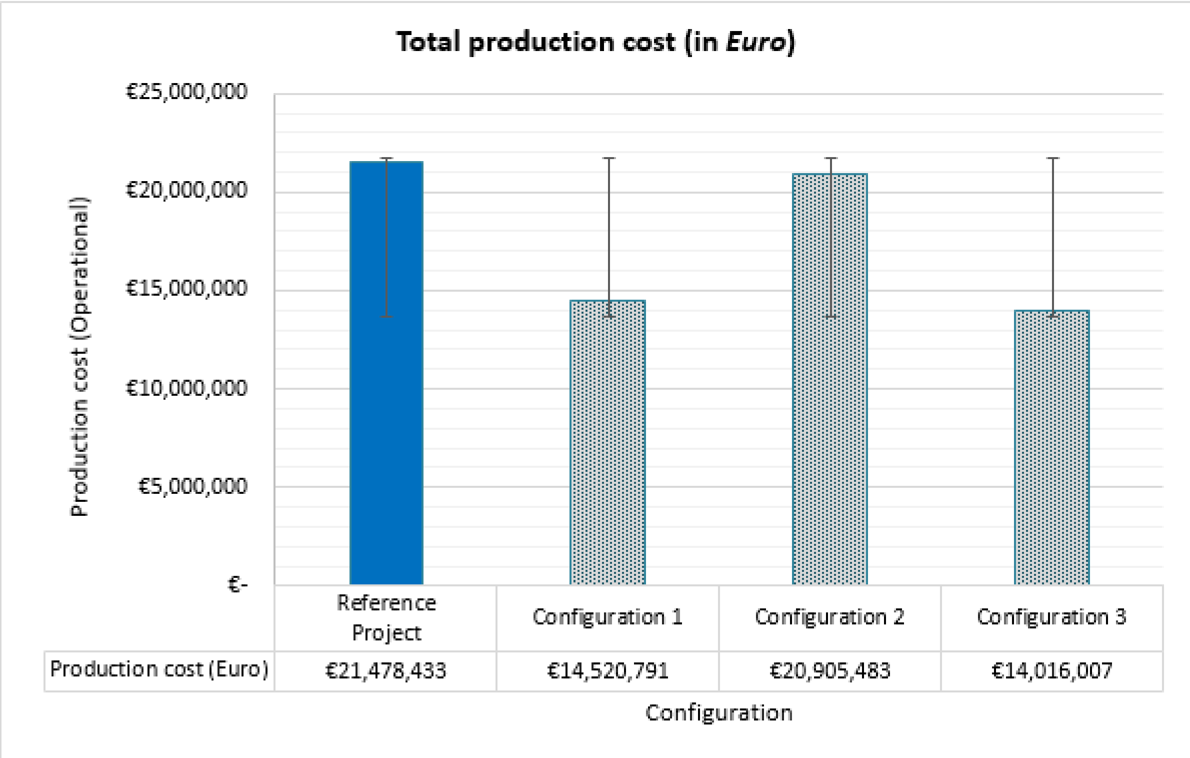


Figure 7.3: Comparison of total cost of production, in Euros, for *Configurations 1, 2* and *3* with respect to Reference Project.

Table 7.2: Percentage difference in production costs for *Configurations 1, 2* and *3* with respect to Reference Project.

| Configuration | Production time (in Euro) | Percentage Difference |
|---|---|---|
| Reference Project | €21,478,433 | - |
| Configuration 1 | €14,520,791 | 32% |
| Configuration 2 | €20,905,483 | 3% |
| Configuration 3 | €14,016,007 | 35% |

## 7.5. Conclusion

This chapter identified release date of orders, number of workstations in preassembly hall and number of shared resources used in the assembly sub-process as probable causes of high variation in simulation outputs with respect to the real production process. Incorporating these aspects of reality in the model could lead to a validated simulation model. Depending on the accuracy of results required, more aspects can be included in the simulation model to represent the reality to a higher level of detail.

The proposed simulation showed promising results when different configurations were analyzed in Sections 7.3 and 7.4. Improved production times and costs were observed for all of the three configurations evaluated in this research. Deciding the cost efficient configuration among the three depends on HFG's future investments and business strategy, however, in view of the objective of this research the following conclusions drawn from these experiments:

1. TKY welding robot reduced the production cost significantly by 32%, without any considerable reduction in the production time. This alternative could be useful for HFG to reduce the operational cost of production and stay competitive in the offshore industry.

2. Using a gantry crane decreased the production time from by 88 days or by 17%. Lower jacket production time could help HFG to free its resources earlier, like assembly yard, than it would take in the present configuration. Free resources can be reallocated to other projects thereby increasing the throughput of the yard.

3. Unlike the previous configurations, which showed significant decrease only in one of the two KPIs, *Configuration 3*, using both TKY welding robot and gantry crane, reduced both the production time and operational cost by 16% and 35%, respectively. Although, the capital investment for this configuration may be higher than the previous *Configuration 1* and *2*, the significant reduction in production time and cost can improve the overall jacket production process for HFG.

# 8

# Conclusion and Recommendations

This chapter presents the conclusion, recommendations and discussions for the research.

## 8.1. Conclusion

The main research question that needs to be answered is:

"*What can be a possible alternative configuration to the current offshore jacket production method which is cost efficient*?"

Based on the results from the proposed simulation model, and taking its limitation into consideration, all three alternative configurations proposed in this research show lower production time and cost. However, *Configuration 3* which incorporates the TKY welding robot and gantry crane in the production method, shows significant decrease in both performance aspects. The production cost of this alternative is significantly lower than the configuration using gantry crane alone. On the other hand, its cost is comparable to the production cost incurred by employing only welding robots. Moreover, the production time of jacket using *Configuration 3* is only marginally higher than the one with gantry crane, and significantly higher than the configuration with welding robot. Thus, a production method using two TKY welding robot and one gantry crane is proposed as a possible alternative to the present one-off offshore jacket production method.

The main research question was answered by answering the sub-questions, which can be grouped into following sub-aspects of the research:

1. Defining characteristics and elements of jacket production process:
   Jacket for offshore oil and gas sector follows a one-off production process. The production process comprises of two sub-processes: preassembly and assembly. In preassembly process, tubular steel sections are welded together to form preassemblies. The preassemblies are then lifted and transported to the assembly yard where the jacket is erected. Preassembly process resembles shop process where the material flows in and out and gets processed at the workstations. For assembly sub-process, the whole part stays at a single location and smaller parts are joined to the same structure. Eventually it becomes too big to be moved around freely which is categorized as fixed position manufacturing. Thus, an assembly process follows a construction process. In production process, certain tasks are identified which are performed in each sub-process: Fitting, welding, blasting and painting, handling of parts and building construction aids. Suitable resources are used to perform each task.

2. Exploring alternative configurations
   To represent the current production process, a previously finished project is chosen for the case study. This Reference Project is a four legged oil and gas jacket which was constructed in 2017. This Reference

Project is studied and information regarding the challenges faced in executing this project are gathered. Based on this information, Welding and lifting tasks are found to cause delay and bottlenecks in the process. To determine possible improvements, the tasks and their resources are presented in a morphological table. Since the improvement is focused on welding and lifting, the options include automation of the welding task and using a different kind of crane for lifting and handling. Similarly, alternatives for other tasks can be listed by the user in the table. The Reference Project is represented on the morphological chart and taking that as reference three alternative configurations are proposed. First configuration uses only TKY welding robot, a robot that can perform only branch welds on a jacket preassembly. The second configuration uses a gantry crane as the primary lifting crane, replacing the crawler crane. The third configuration uses both, the welding robot and the gantry crane.

3. Modelling the production process
For fabrication companies, cost and duration are the key drivers of a project. Thus, in this research, the production time and production cost are the key performance indicators for the process evaluation. For evaluation, a simulation model is designed with certain assumptions and simplifications.

4. Verifying and validating the proposed model
The jacket follows a bill of material which signifies the number and type of parts that are required to construct the jacket. Verification of the model is achieved by analyzing the number of parts entering and exiting the system. All parts in the bill of materials that enter the system must be consumed to form the jacket. Also, if one part is not produced, the jacket production stalls. Validation of the model is attempted in two steps. In the first step, the cycle time of the overall production system obtained from project schedule of Reference Project is compared with the simulated outputs. The second step compares the real and simulated mean cycle times of each sub-process. However, a discrepancy is observed in the results from these two steps. Hence, the variation in real values and simulated outputs are compared. It is found that the variation in the simulated output is significantly higher than in the real values, which prevents the simulation model from being validated.

5. Analysis and evaluation
Further analysis into the reasons behind the high variation in simulation output shows that simplification of the reality significantly affects the cycle times of individual parts by creating bottlenecks in the simulated process. Possible causes are identified which relate to the number of shared lifting resources, workspace utilization of the available fabrication area and release dates of orders of parts used in jacket production. It is expected that modelling the process in more detail to address these causes will make the simulation more accurate. Nevertheless, the simulation model is used to evaluate the alternative configurations. It is found that all three configurations decrease the production time and cost of the project, thereby, showing the potential of the simulation model.

## 8.2. Recommendation and further research

Based on the results from validation, the proposed model is not very accurate for making a final decision to implement the alternative configuration. However, the model suggests its potential to give a preliminary idea about the possible effects of alternative configurations on the production time and cost of producing a jacket. From this research it is found that a production method with TKY welding robot and gantry crane can significantly reduce both production time and production cost. However, the capital investment required on acquiring two TKY welding robot and one gantry crane can be speculated to be high. For choosing the next best alternative from the remaining two, using gantry crane for the assembly should be considered by HFG. Although the production cost for this option is considerably higher than the configuration with welding robot, the production time for this option is fairly low. For a project, this means that it can be finished at an earlier date. This in turn will make the assembly yard available again for starting the next project. Long term benefits is speculated to be higher for this configuration.

For HFG, it is also recommended to validate the proposed simulation model by modelling the simplified aspects in more detail. Simulation models to analyze and improve the production process are not extensively used in offshore fabrication sector. New innovations and equipment are introduced in sub-process of the production with a vision of production improvement. However, in reality, the effects of such modifications in one-off production lines is not very straightforward, as suggested in this research. As the sub-processes depict slightly different forms of process characteristics, modelling the production process with a helicopter view would give you better information to make a decision. Together with the morphological table, this results in a novel decision-making tool which can be used by HFG to ingeniously explore new alternatives.

Further scientific research can be extended in the following directions:

1. Further research could be carried out on validating the current model by modelling shared resources in assembly area and introducing dynamic optimization of resources in the discrete event environment.
2. It would be interesting to see what other configurations can be proposed from the morphological table and evaluate its effect on the production process.
3. Currently the construction process is simulated in a discrete environment which limits the interactions between different actors on the construction yard. It would be interesting to see how this kind of hybrid production processes can be modelled in Agent Based environment. Agent Based Simulation is gaining speed. Currently it is being used mostly for academic purposes because of its high computational times, but it is expected to be used for commercial purposes in some years.
4. The morphological table proposed in this research does not account for cross-contingency assessment of the alternatives. A research could be focused on making a cross-contingency matrix for the presented morphological table, wherein incompatible set of alternatives will not be selected.

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# A

# Research Paper

# Exploring alternatives to offshore jacket production methods

Pritish Bose[1], Mark B. Duinkerken[2], Rudy R. Negenborn[3]

*Abstract*— **Decrease in oil prices have negatively affected the investment towards offshore oil and gas explorations. This has in turn compelled offshore structure fabricators to find cost effective ways of fabricating oil platforms and jackets, to stay competitive in the industry. In this research paper, three alternative configurations to the conventional jacket production process are explored. The configurations are derived from a morphological table that is designed to include major tasks and resources of the production process. To evaluate the effects of these options on performance of the production process, in terms of production time and cost, a simulation model is presented. During the validation of this model through cycle time of the preassembly and assembly sub-processes, high variations are observed. On further analysis, these discrepancies are attributed to the number of shared lifting resources, workspace utilization of the available fabrication area and release dates of orders of parts used in jacket production. To increase the accuracy of the model, these aspects must be modelled in more detail. However, to show the potential of the simulation model, the previously proposed configurations are evaluated and a possible alternative is proposed as a promising solution. Additionally, throughout this research, the potential of a simulation-based approach to explore new configurations for offshore jacket production is suggested. Together with the morphological table, this results in a novel decision-making tool which can be used by fabrication companies to indigenously explore new alternatives.**

*Keywords*— **Offshore jacket; Oil and gas; Morphological table; Simulated one-off production; Automation**

## I. INTRODUCTION

Since the dip in oil prices in 2008, the oil and gas industry has been struggling to recover. Although the prices of crude oil are on an increasing trend, investors are holding back on explorations. According to Oil & Gas UK, in the period between 2014 and 2016, investment in United Kingdom Continental Shelf (UKCS) has gone down from GBP 14.8 billion to GBP 9 billion [1]. Moreover, most exploration projects take a long time to conduct feasibility studies of the oil-well before drilling can be started. For oil companies, explorations are ongoing, however, for structural fabricators of oil platforms and jackets, such uncertainty is challenging. With fewer projects in the market, fabrication companies have to be competitive, both strategically and technologically.

Offshore jacket fabrication companies use conventional methods of production. Understandably, considering the high risks involved with such large construction processes, fabricators are not willing to explore new alternatives, to mitigate the risk of unproductive investment.

Some companies, however, have a different outlook. Heerema Fabrication Group (HFG) has been exploring ways to improve their fabrication process. They are investigating alternatives to their current jacket production methods.

This research focuses on understanding the jacket production method and identifying the challenges within. From there, it moves on to exploring and evaluating alternative configurations to the present production methods. Finally, a simulation model is proposed which attempts to evaluate the effect of these alternative configurations on performance of the current production method.

## II. JACKET PRODUCTION PROCESS

In this section, we begin with a brief overview of the jacket structure, then, introduce the jacket production process and identify the major tasks performed in it. As shown in Fig. 1, the main structural parts of a typical 4-legged oil & gas jacket are legs, braces, vertical frames and horizontal frames. These parts are constructed by welding tubular steel sections which are obtained from cutting standard steel pipes in a process called prefabrication.

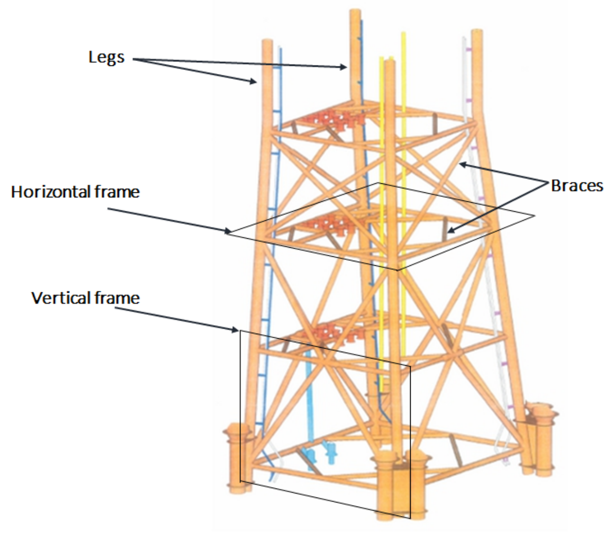


Fig. 1. Representation of Babbage jacket substructure of SLP North Sea, fabricated by HFG. Shown here are a jacket's major structural parts are: Legs and braces. Source: www.hfg.heerema.com

This research focuses on the production process of the jacket which starts at the earliest availability of the steel sections after prefabrication. These sections serve as an input

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for the production process, at the end of which a jacket is produced. Within the production process, two major sub processes are identified:

1) Preassembly sub-process: The prefabricated parts, are welded together to produce the preassembled parts, also called preassemblies. These preassemblies are modules for the structural parts.
2) Assembly sub-process: The preassemblies are welded together in this process to construct the construct the jacket.

The produced jacket is then transferred on to a barge for transportation; this process is called the load-out. The complete production takes place in a large fabrication yard. Fig. 2 shows the fabrication yard of Heerema Fabrication Group at Vlissingen. It highlights the locations where different parts of jacket are constructed.

Fig. 3 is a schematic representation of the jacket production process.

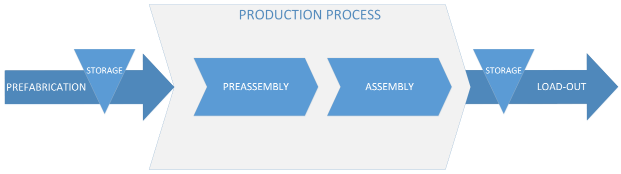



Fig. 3. Processes involved in jacket production.

In each sub-process, multiple tasks are performed. The following major tasks are identified in this research:

1) Handling of parts (Lifting and transporting)
2) Fitting
3) Welding
4) Blasting & painting
5) Building temporary construction aids

For each task, there are specific resources such as cranes and multiwheelers for handling the parts, welders for fitting and welding, workers for painting and scaffolds for construction aids. In addition to resources, jacket construction on assembly yard follows a sequence of steps, called building method, which also also affects the production process. Typically, jackets are constructed using the roll-up method which is represented in Fig. 4

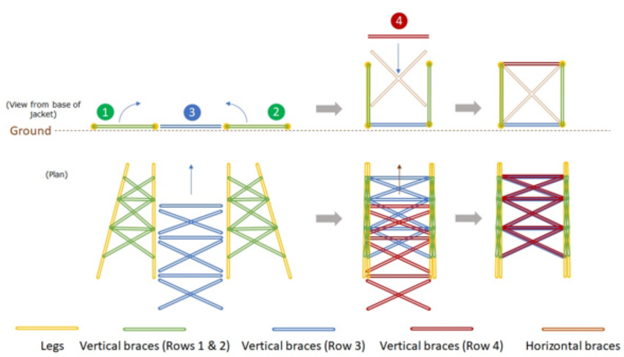



Fig. 4. A typical roll up building method.

## III. Literature Overview

In this section, characteristics of the present jacket production method is defined. Subsequently, a theoretical framework is established by comparing simulation environment and techniques available in literature.

### A. *One-off production process*

Process characteristics vary on the basis of the product being manufactured. The graph in Fig. 5 categorizes various process types based on the volume of product produced and the variety, or the randomness between two products. As per the underlying theory behind this graph, the author states that job, batch and line processes are used when the standard products are produced [2]. These processes produce a batch of products and at a certain volume. When the process produces high volumes of a repetitive lot of products, then, it is defined as a line process; if the volume is lower and some batches are made as per customer specifications, the process is termed as a batch process. In job production process, small lot sizes of different products are produced. When the product is highly customized and only one large and complex unit is the final product it is termed as a Project. According to the author, the project-type process is also termed as one-product line or one-off production line. The last process, as the name suggests, is used when the flow of the material is continuous. Project, job, batch and line processes have a discrete flow of material [2].

### B. *Construction process*

The production process is a combination of preassembly and assembly sub-processes. The material flow within the preassembly sub-process can be related to that of a one-off production, but for the assembly process it is not completely true. From a material perspective, one can argue that the material, or preassemblies, flow into the assembly process and a complete jacket is produced in the end, thereby making it a production process. But from a resource perspective, there are slight differences between the two sub-processes. In preassembly sub-process, the parts and workstations both can be moved around the preassembly hall to make space for forming new preassemblies. At the same time, the location of workstation for a part at a particular time is fixed and the parts flow through that workstation after being fitted and welded.

The situation at the assembly site is slightly different. Here, the assembly area is fixed and the resources are moved around to complete the task. Thus, it can be categorized as fixed position manufacturing, where the parts (preassemblies) are assembled to make the product (jacket) a whole [3]. In words of Ballard and Howell, In the assembly process, the parts become too large to move through assembly stations, so the stations move through the emerging wholes, adding pieces as they move. [3].

Preassembly sub-process being a one-off production process and categorizing the assembly sub-process as a construction process makes the overall jacket production process a combination of the two. Moreover, construction process


Fig. 2. Aerial view of the fabrication yard of HFG at Vlissingen, The Netherlands. Source: Google Earth

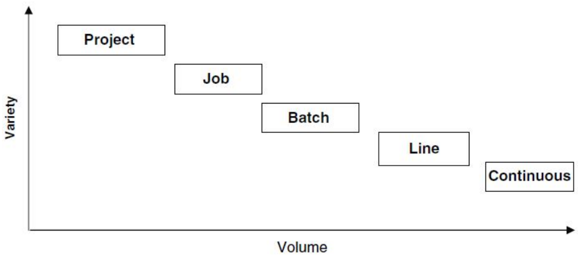
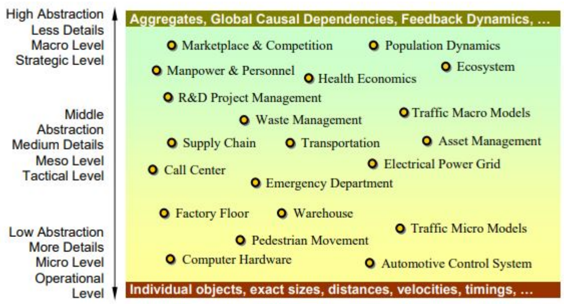
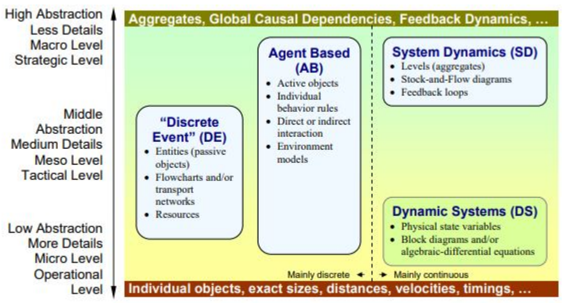



Fig. 5. Process types based on the type of product(s) involved [2]




(a) Application based




(b) Simulation environments based

Fig. 6. Abstraction level [7]

brings with it its own peculiarities. Since the assembly is rooted to one location, the process is affected by the site conditions such as weather, location and soil [4]. During the construction process, some tasks require specific technological capabilities for which a specific resource needs to be mobilized [4]. This aspect of makes it difficult to plan all the tasks ahead and requires on site decision-making. To tackle these challenges, industries find ways to increase preassemblies because the material flow in the preassembly sub-process creates a job shop condition inside the preassembly hall which can be more efficiently managed [3].

### *C. Simulation environment*

Halpin introduced simulation in the field of construction in 1973 by developing the CYCLONE methodology [5]. Since then simulation has been extensively used to model construction processes. Some of its applications reviewed in literatures include tunneling, earth moving and heavy construction and bridge construction [6]. However, depending on the abstraction level of the model and the application for which the model is used, the effectiveness of a simulation environment may vary [7]. From Fig. 6, it is clear that for this research, the process can be simulated either in Discrete-event (DE) environment or Agent Based (AB) environment.

Many researchers strongly approve AB environment to be used for systems which are autonomous and have interacting agents [8] [9]. However, AB is still mostly used for research purposes [7]. The aim of this research is to design a model that can be commercially used. DE has been traditionally and successfully used to design and analyze production processes, and also construction processes [10] [11].

### *D. Simulation techniques*

Different methods are available to model a production process using discrete event simulation. Through literature it is found that three main techniques exist: Process interaction (PI), Event scheduling (ES) and Activity scanning (AS).

In PI model, the focus is on entities (element of system that flows through a sequence of activities and get processed) and is used for systems where the entities have varying attributes but the processing servers have few attributes and have less interaction with each other [18]. This approach is more suited for manufacturing and job shop systems where the servers have few states. AS uses a more activity centric approach. The technique focuses more on the type of activity to be performed and the sequence in which each activity shall be executed. ES is used in both PI and AS modelling methods. It defines the start and end of an event but does not specify the activities that occur between these two states.

One other simulation approach, presented by Jingsheng and Simaan, is using the concepts of Resource-Based Modelling (RBM), where smaller models, known as atomic models, define the operating processes of resources used for various activities during the simulation [13]. This way of modelling the resources gives users more flexibility to alter the resource characteristics to achieve a more realistic representation of reality.

### *E. Determining characteristics of the present production process*

The offshore oil and gas jackets are custom made based on customer specifications, which means that a jacket produced for one project is unique in nature. Also, each sub-process follows a discrete material flow pattern. Comparing with the above theory, the jacket production method is determined as a one-off production process, wherein the assembly process depicts the characteristics of a construction process. Furthermore, this production process can be modelled in a discrete-event environment by using a combination of activity based and event scheduling techniques.

## IV. Alternative Configurations

To further understand the challenges of the production process in real world, a Reference Project is chosen for case study. The jacket in Reference Project was constructed by Heerema Fabrication Group (HFG) in 2017. This jacket was chosen because it is a typical 4-legged jacket that are more often required by companies for shallow water explorations.

During the case study, information was collected on challenges faced during the production of this jacket. Based on these challenges and through interviews with production experts, the following scope of improvements in the process are identified:

1) Introducing welding robots in the production system to perform and branch welds.
2) Introducing alternative fitting mechanisms that can reduce time of fitting task.
3) Innovative logistics system with reduced handling of parts.
4) Reducing the usage of crawler cranes to reduce cost and time of setting-up and dismantling of cranes.

Building on the above information, a morphological table is designed, as shown in Fig. 7. The morphological table includes different features and tasks defined in the production process. On the right, the alternatives are listed for each task. Using the morphological table and the information on scope of improvements, three alternative configurations are proposed:

1) Configuration 1: Jacket production using TKY welding robot
2) Configuration 2: Jacket production using gantry crane
3) Configuration 3: Jacket production using TKY welding robot and gantry crane

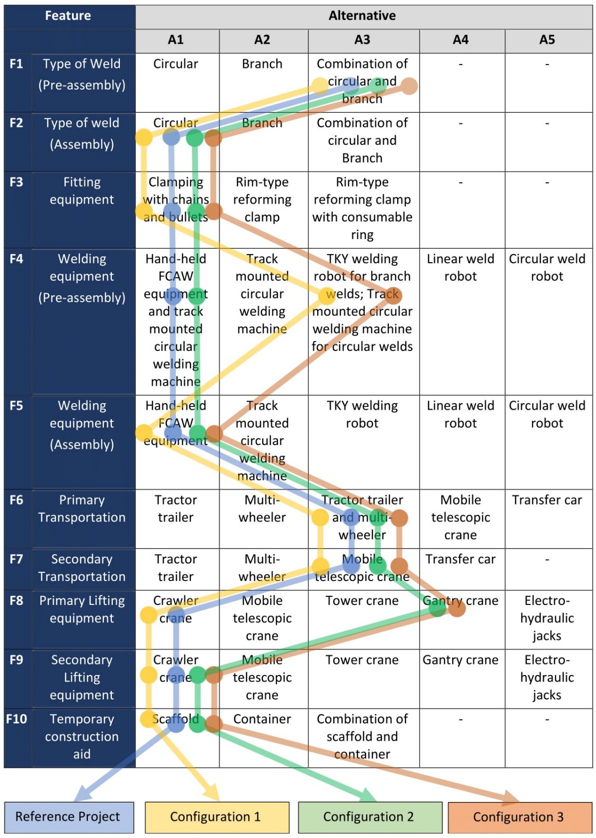



Fig. 7. Morphological table showing the Reference Project and exploring alternative configurations.

## V. Modelling of the Production Process

Based on the process flow model in Fig. 3, a conceptual model is designed. Fig. 8 presents the conceptual model. Main assumptions and simplifications made to model the process are:

- Number of workstations: Depending on the availability of area the number of workstations in preassembly hall dynamically changes. Here, 4 workstations are assumed.
- Number of workers: There are always enough workers available.
- Number of cranes: During construction, the number of cranes being utilized changes depending on the building method. Sometimes the cranes are also shared if a second jacket is being constructed simultaneously.

Due to lack of data specifying this number, for this simulation, it is assumed that three smaller cranes and 1 heavy cranes are deployed for the Reference Project.
- Capital expenditure on alternative equipment is excluded from this study.

For fabrication companies, cost and duration are the key drivers of a project. Thus, in this research, the production time and production cost are the key performance indicators for the process evaluation.

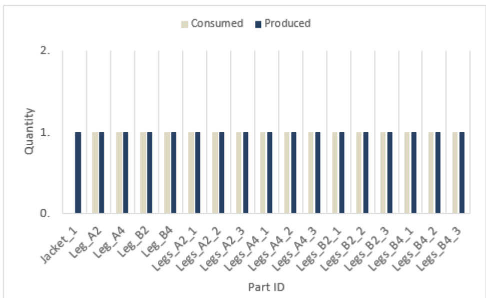
- Total time of production: Time it takes to produce a jacket.
- Total cost of production: It includes the operational and idle costs of all resources involved in the jacket production process.

## VI. Verification and Validation

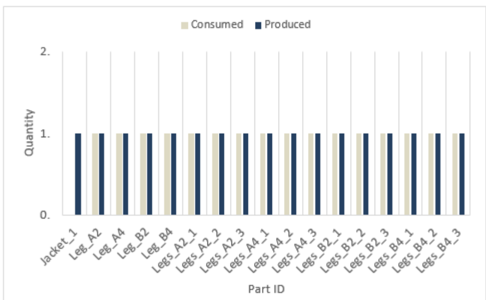
In this section the verification and validation methodology of the simulation model is explained.

### A. *Verification*

Jacket production in the simulation model follows a bill of material of the parts from which it is constructed. Verification of the model is achieved by analyzing the number of parts entering and exiting the system. All parts in the bill of materials that enter the system must be consumed to form the jacket. Also, if one part is not produced, the jacket production stalls.




(a) Quantities of parts produced and consumed when sufficient tubular steel sections are available.




(b) Quantities of parts produced and consumed when lesser tubular steel sections, than required to complete all preassemblies, are available.

Fig. 9. Verification of simulation model

### B. *Validation*

Validation of the model is attempted in two steps - First by validating the overall production process and, then, by validating each sub-process. To validate the model, the cycle times of processes from the simulation outputs are compared from cycle times calculated from the project schedule of Reference Project. Moreover, since the number of cranes in the assembly process is not known, 3 experiments are conducted with different number of cranes with the idea that the experiment with the least deviation from the real output will be used for further analysis.

TABLE I
Different scenarios considered for validating the simulation model by taking into account the order release dates and lifting resources.

| **Experiment ID** | **Experiment 1** | **Experiment 2** | **Experiment 3** |
|---|---|---|---|
| Configuration | 3 Smaller cranes and 1 Heavy crane | 4 Smaller cranes and 1 Heavy crane | 6 Smaller cranes and 1 Heavy crane |

As shown in Fig. 10, on comparing the cycle times of overall production process for Reference Project and simulated outputs, Experiment 3 shows the closest resemblance to the real world scenario with an error of 4%.

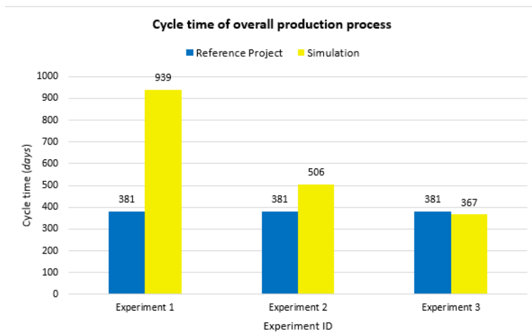
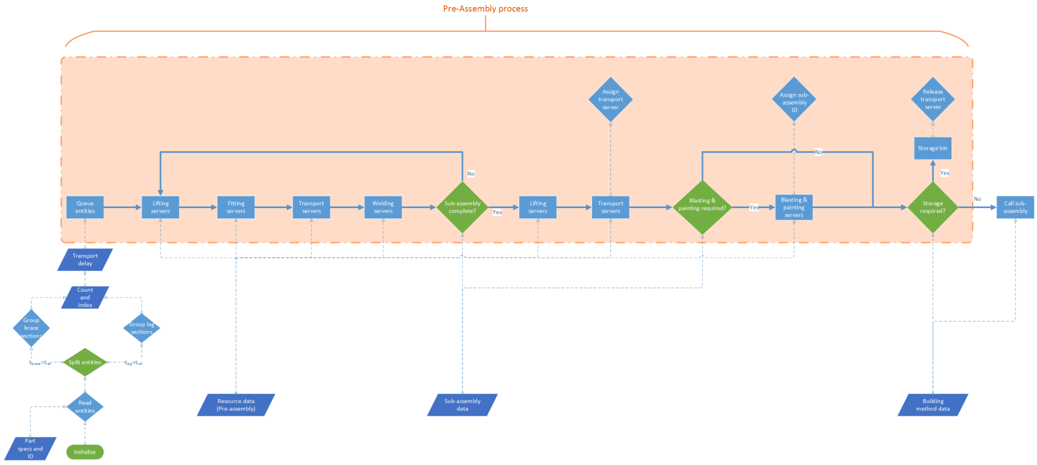
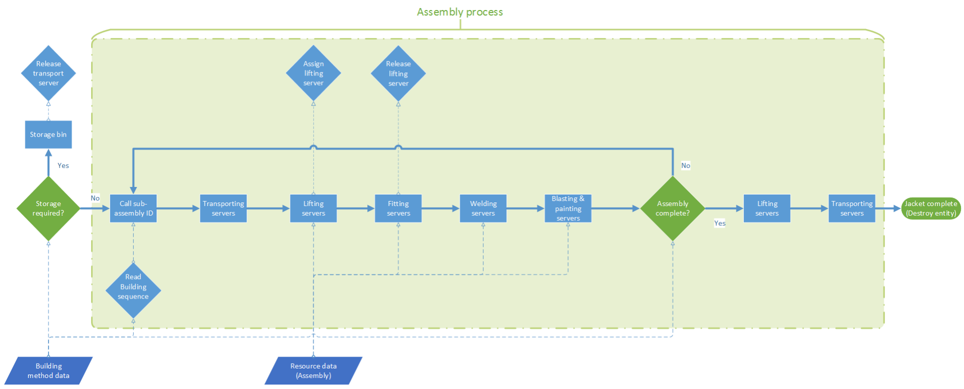



Fig. 10. Comparison of cycle times of overall production process.

For the sub-processes, 24 preassemblies and 4 assemblies are constructed. So, mean cycle time is calculated for each sub-process and compared with data from Reference Project. Since, in all experiments, only the number of cranes in assembly sub-process is varied, the mean cycle times of preassembly for all experiments remain same. From Fig. 11, it is observed that the mean cycle times falls within an acceptable error of 4.25% , however, for assembly process, Experiment 2 shows the least error, 1.35%

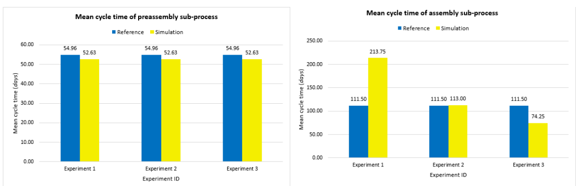



(a) Preassembly sub-process




(b) Assembly sub-process

Fig. 8. Conceptual model for sub-processes in jacket production




(a) Preassembly sub-process (b) Assembly sub-process

Fig. 11. Comparison of mean cycle times of sub-processes.

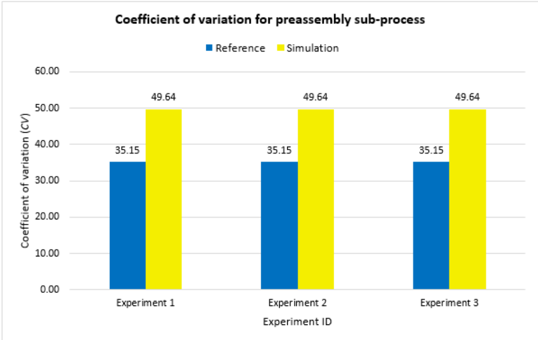
Since, the conclusion of validation from overall process is different from sub-process, the process is further analyzed for the variation within the cycle times by using *Coefficient of Variation (CV)*, which is calculated by Eq.1 and Eq.2.

$$CV_{pa} = \frac{\sigma_{cpa}}{\mu_{cpa}} \times 100 \quad (1)$$

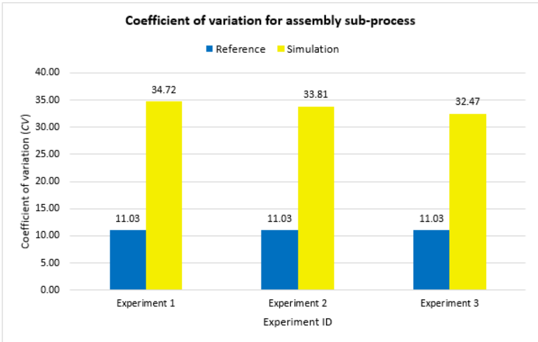
$$CV_{a} = \frac{\sigma_{ca}}{\mu_{ca}} \times 100 \quad (2)$$

Where,
$CV_{pa}$ = Coefficient of variation for cycle times of preassembly sub-process, in %.
$CV_a$ = Coefficient of variation for cycle times of preassembly sub-process, in %.
$\sigma_{cpa}$ = Coefficient of variation for cycle times of preassembly sub-process, in days.
$\sigma_{ca}$ = Coefficient of variation for cycle times of preassembly sub-process, in days.
$\mu_{cpa}$ = Mean cycle time for preassembly sub-process, in days.
$\mu_{ca}$ = Mean cycle time for assembly sub-process, in days.

The comparison of CV, as shown in Fig.12, shows that indeed there is high variation in the cycle times of parts in preassembly and assembly sub processes. For preassembly sub-process, the variation is 14.49 percentage points (*pp*) higher than the Reference Project. Variation in the assembly process is even higher, with the least difference of 21.44 *pp*. This shows that comparison with mean for a one-off production process, where each part is different, is not reliable. Instead, comparison of variation gives a more realistic results. Due to high variation in the cycle times of simulation model, it can be concluded that the model is not validated.




(a) Preassembly sub-process




(b) Assembly sub-process

Fig. 12. Comparison of Coeff. of variation in cycle times of sub-processes.

## VII. Further Analysis

Looking further into possible causes for high variation in cycle times of simulation model as compared to the Reference Project, the following aspects should be modelled in more detail:

1) Effect of order release date The dates at which orders for processing of parts are released can affect the material flow of the process. In the simulation model, the orders for preassemblies and assemblies are released simultaneously at the start of simulation. Since, at start of the simulation, processing stations are available, the initial preassemblies are processed faster and eventually a queue is formed. In reality, the release of orders is controlled by project schedule, which takes into account the availability of processing stations and the raw materials. Thus, the waiting time of orders is reduced in the sub-process and the reduces the variation in cycle times.
2) Effect of number of workstations Four workstations are assumed in preassembly hall. In reality, the number of workstations, or the number of preassemblies producing inside the hall, depends on the available area. The available area in turn depends on the size of preassemblies and the availability of raw materials. The workplace is dynamically optimized to accommodate more preassemblies which reduces cycle time of parts. In simulation model, the number of workstations is assumed and fixed at four locations. As a result, cycle times are lower than the real world when less than four stations are required and higher when more than four stations are in use.
3) Effect of number of cranes Due to uncertainty in exact number of cranes used in Reference Project, simulation was carried out considering 3 scenarios. When individual cycle times of the four assemblies are compared for these scenarios, it is found that constructing one of the assemblies takes a significantly longer time in simulation. This particular assembly is made of 26 parts whereas the other consists of 12, 12 and 14 parts, in that order. It is possible that the combination of higher input volumes and fixed lifting resources culminates in increased waiting times and, consequently, increased cycle time for this assembly.

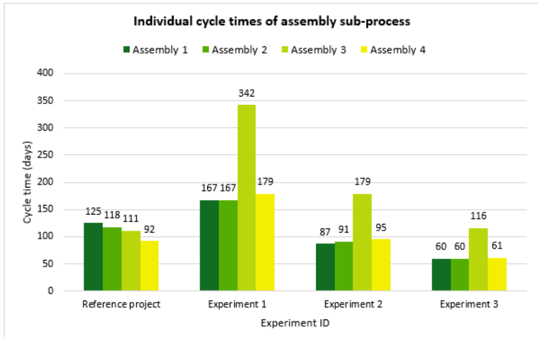
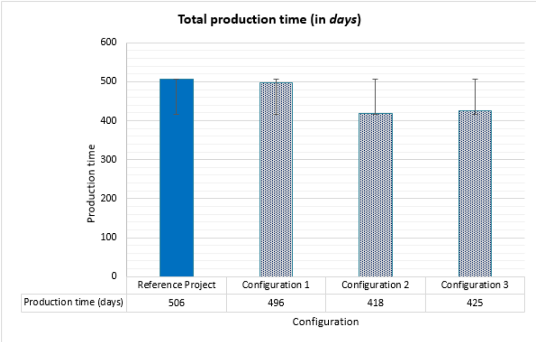


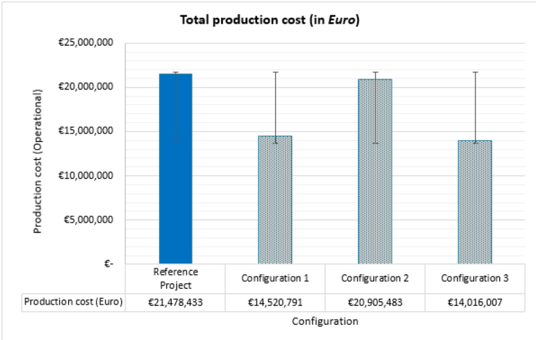

Fig. 13. Comparison of individual cycle times of four assemblies.

Based on the above analysis, it is clear that to increase the accuracy of the simulation model, these aspects need to be modelled in more detail. However, within the limitation of the model, the alternative configurations explored in Section IV are evaluated to evaluate their effects on production time and cost. For this evaluation, the simulation experiment with 4 small cranes and 1 heavy crane is taken as the new Reference Project

The evaluation results, in Fig. 14, show that the performance of the production process increases for all three configurations with respect to the Reference Project. Configuration 1 has the least effect on production time because it increases the throughput in preassembly process, but in the assembly process, the conventional cranes cause delay. However, it saves 32% of production cost by reducing the number of manual welders. Configuration 2 speeds up the assembly process by 88 days. This may be caused because, since it travles over the jacket, it covers half of the distance thant the crawler cranes. Among them, Configuration 3 is found to have a comparatively better effect on the both KPIs, by decreasing the production time by 81 days and production cost by 35% which is expected when the two configurations are brought together.




(a) Total production time




(b) Total production cost

Fig. 14. Evaluation of alternative configurations.

## VIII. CONCLUSION

The main objective of research is to suggest a possible alternative configurations to the conventional jacket production methods. By modelling the present jacket production process in a discrete event environment, three alternative configurations are evaluated. From the results, a configuration of TKY welding robot in preassembly sub-process and gantry crane in assembly sub-process is found to increase the overall performance of the production method. This configuration can be proposed as a possible solution to the present production process. However, the user should also consider the capital investment required for this configuration and business strategy of the company, which is beyond the scope of this research. Moreover, the simulation model lacks in accuracy because high variation in cycle times of sub-processes were observed during validation. Possible causes related to the number of shared lifting resources, workspace utilization of the available fabrication area and release dates of orders of parts used in jacket production are suggested. Nonetheless, the simulation model has indicated the potential of using a simulation model for improving the production facility. Simulation models to analyze and improve the production process are not extensively used in offshore fabrication sector. New innovations and equipment are introduced in sub-process of the production with a vision of improving production. However, in reality, the effects of such modifications in one-off production lines is not very straightforward, as suggested in this research. In coming years, the industry is expected to take an upward turn but the highly competitive nature of this industry would lead to companies finding better ways of producing offshore jackets.

## ACKNOWLEDGMENT

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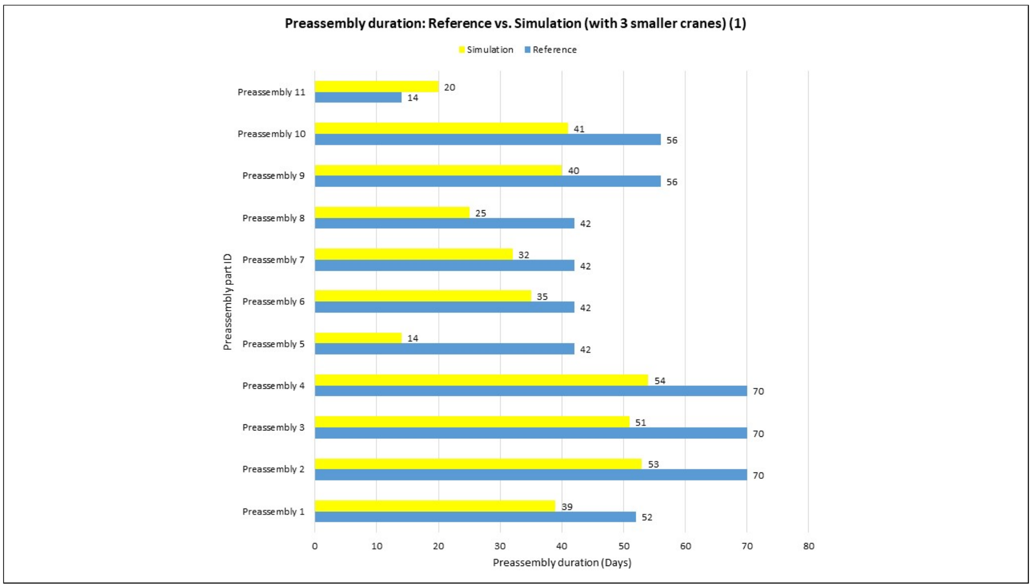
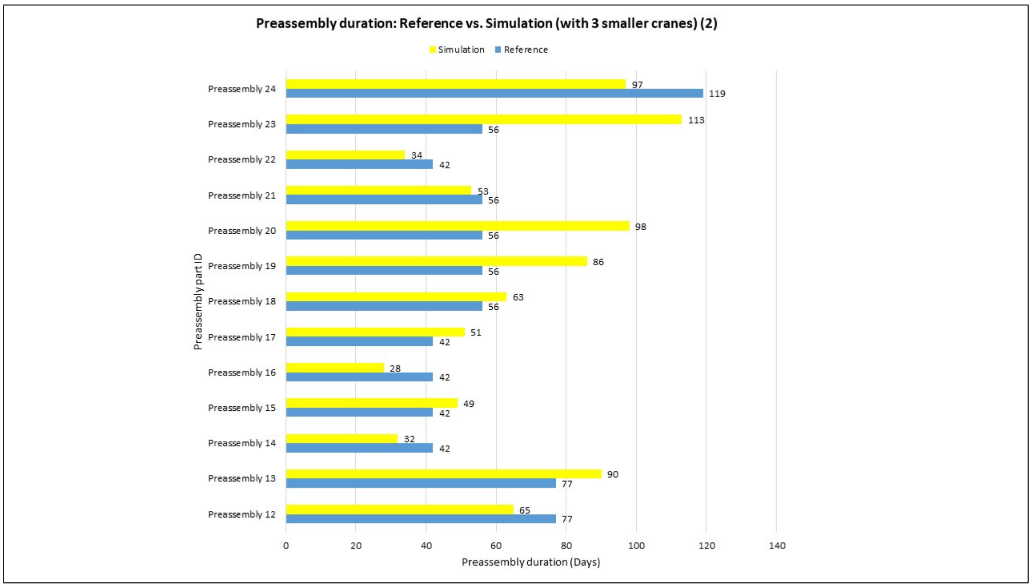
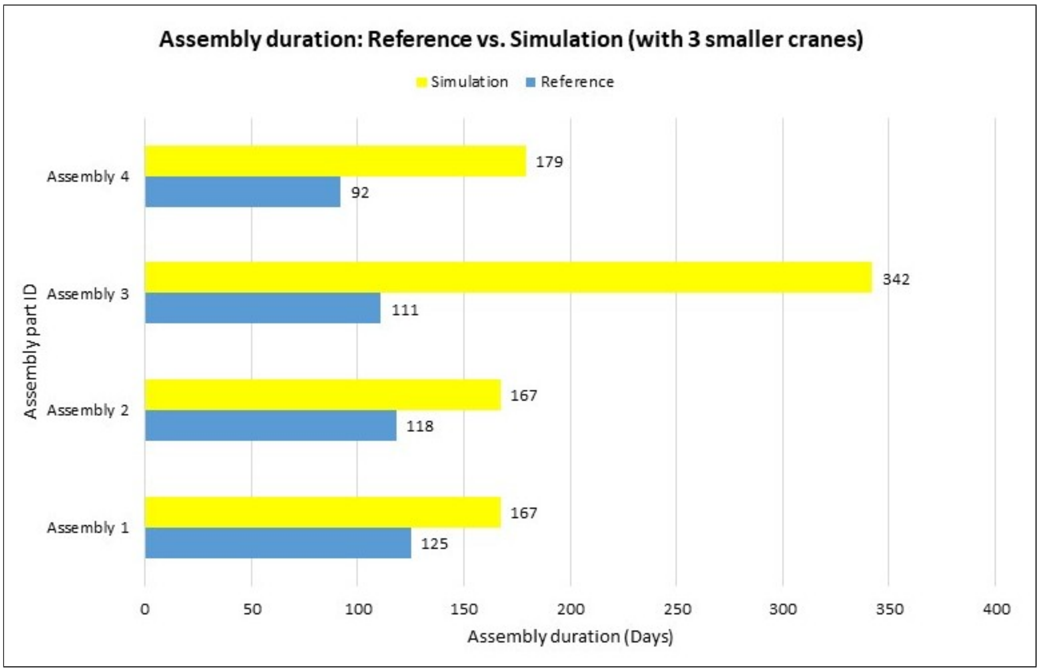
# B

# Comparison of Individual cycle times

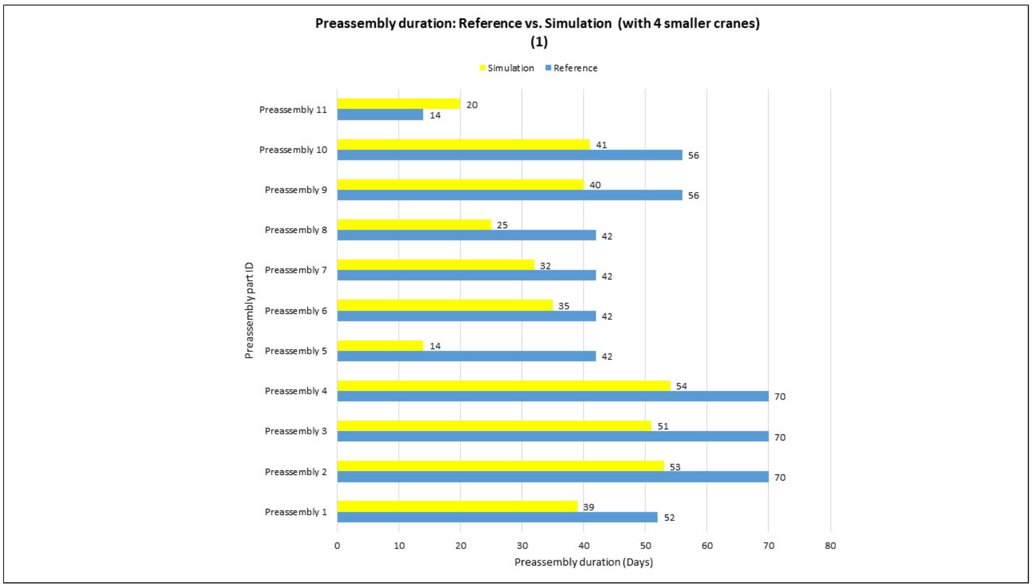
## Reference Project Vs. Experiment 1

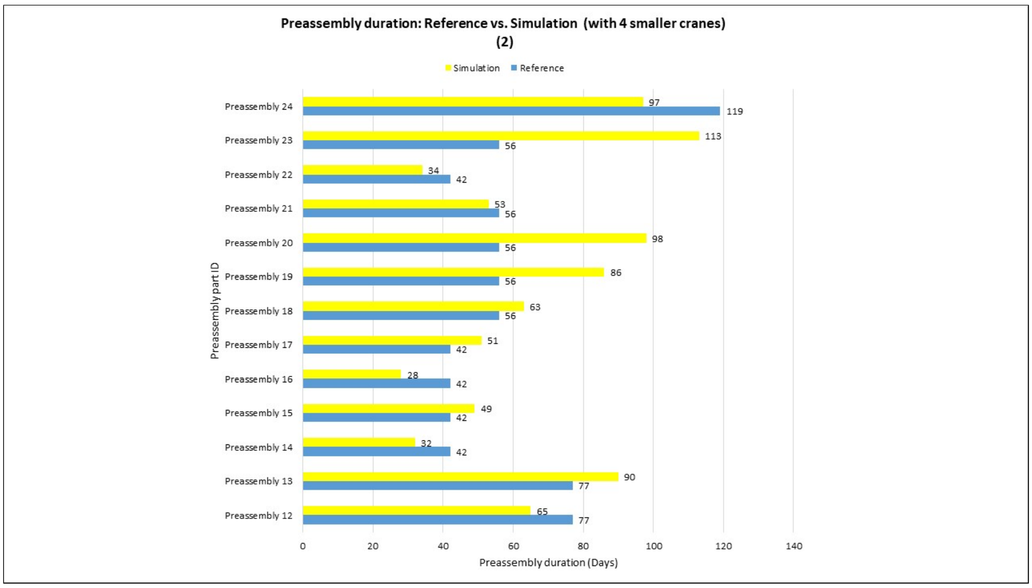


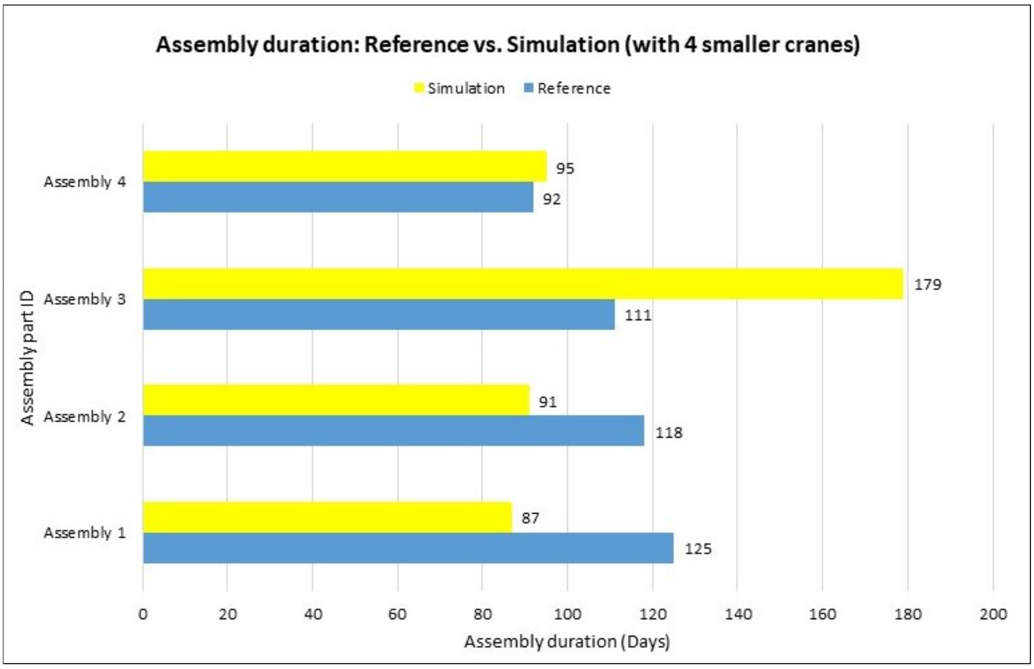

Preassembly duration: Reference vs. Simulation (with 3 smaller cranes) (2)
Simulation
Reference
Preassembly part ID
Preassembly 24
Preassembly 23
Preassembly 22
Preassembly 21
Preassembly 20
Preassembly 19
Preassembly 18
Preassembly 17
Preassembly 16
Preassembly 15
Preassembly 14
Preassembly 13
Preassembly 12
97
119
113
56
34
42
53
56
98
56
86
56
63
56
51
42
28
42
49
42
32
42
90
77
65
77
0
20
40
60
80
100
120
140
Preassembly duration (Days)


Assembly duration: Reference vs. Simulation (with 3 smaller cranes)
Simulation
Reference
Assembly part ID
Assembly 4
Assembly 3
Assembly 2
Assembly 1
179
92
342
111
167
118
167
125
0
50
100
150
200
250
300
350
400
Assembly duration (Days)

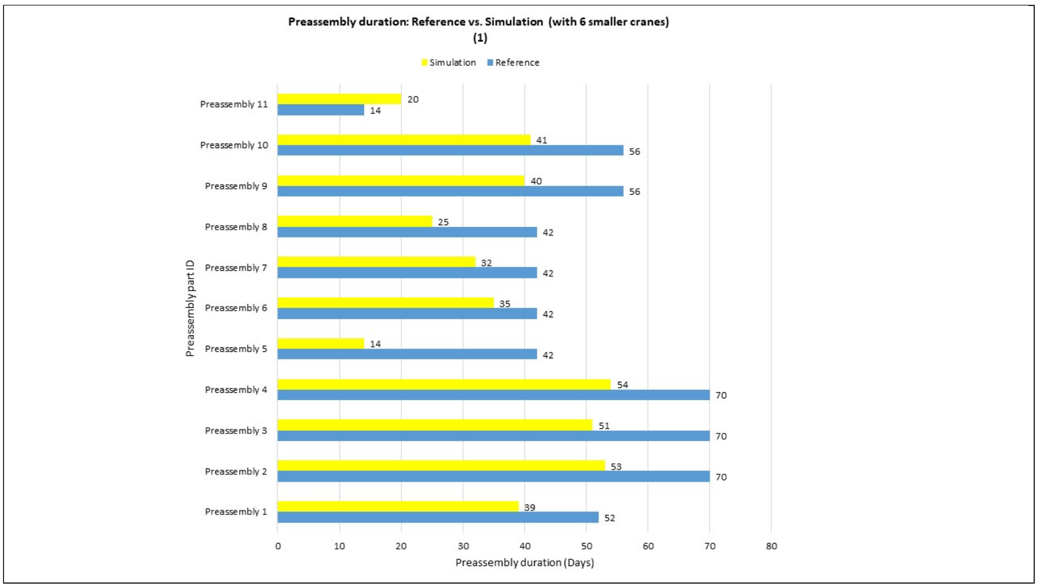
# Reference Project Vs. Experiment 2

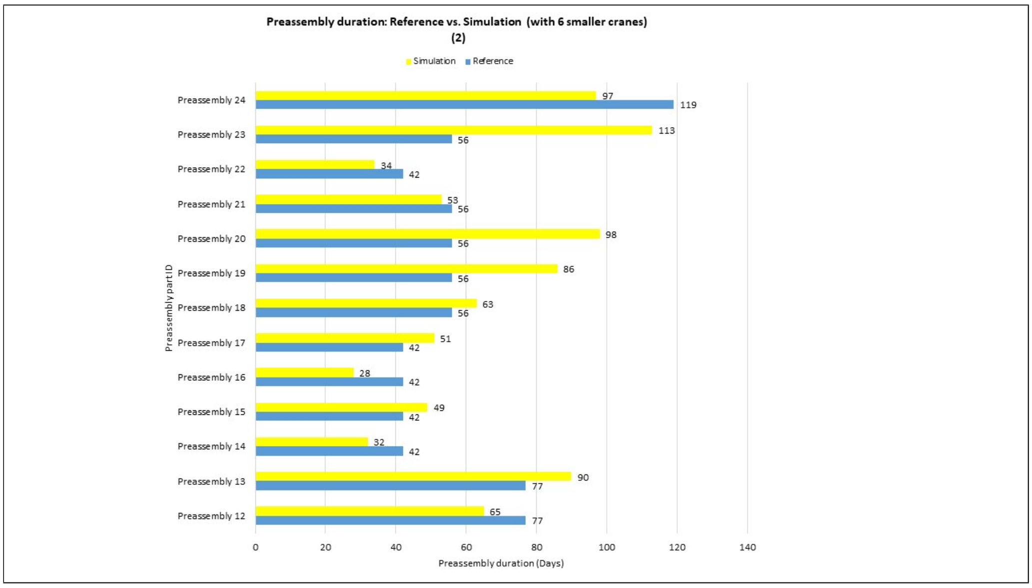


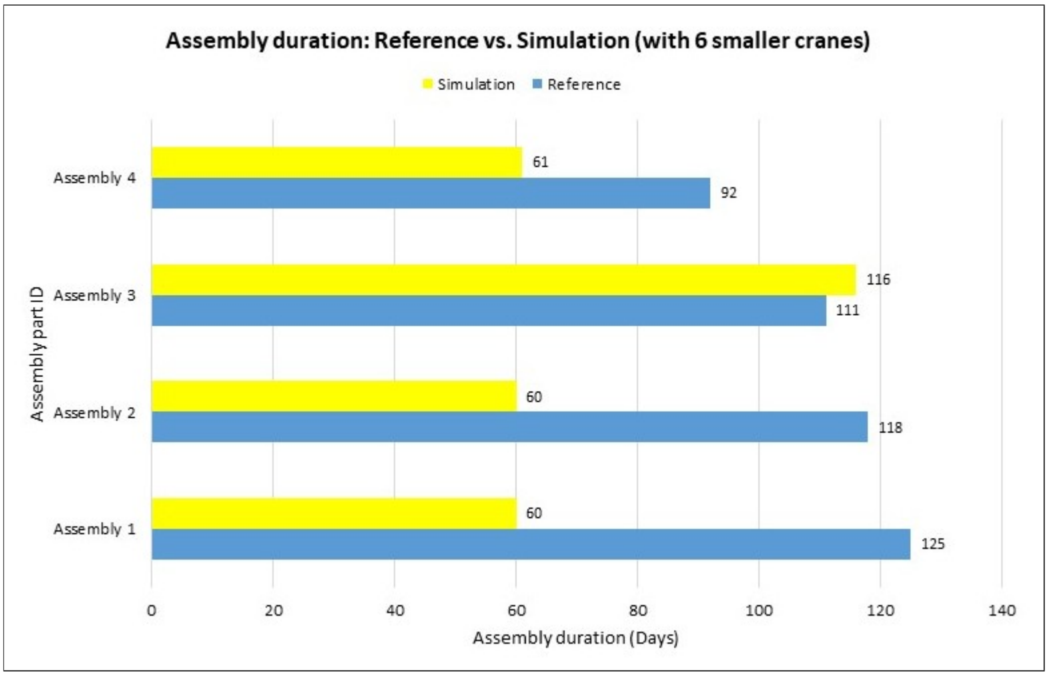






## Reference Project Vs. Experiment 3



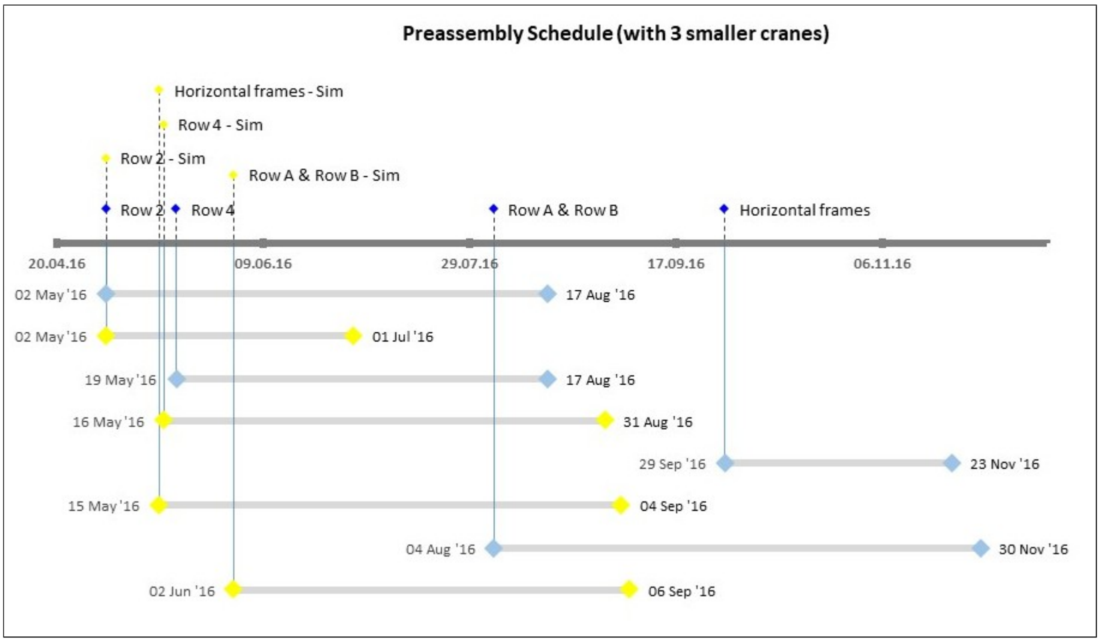

Preassembly duration: Reference vs. Simulation (with 6 smaller cranes) (2)
Simulation
Reference
Preassembly 24
Preassembly 23
Preassembly 22
Preassembly 21
Preassembly 20
Preassembly 19
Preassembly 18
Preassembly 17
Preassembly 16
Preassembly 15
Preassembly 14
Preassembly 13
Preassembly 12
97
119
113
56
34
42
53
56
98
56
86
56
63
56
51
42
28
42
49
42
32
42
90
77
65
77
0
20
40
60
80
100
120
140
Preassembly part ID
Preassembly duration (Days)

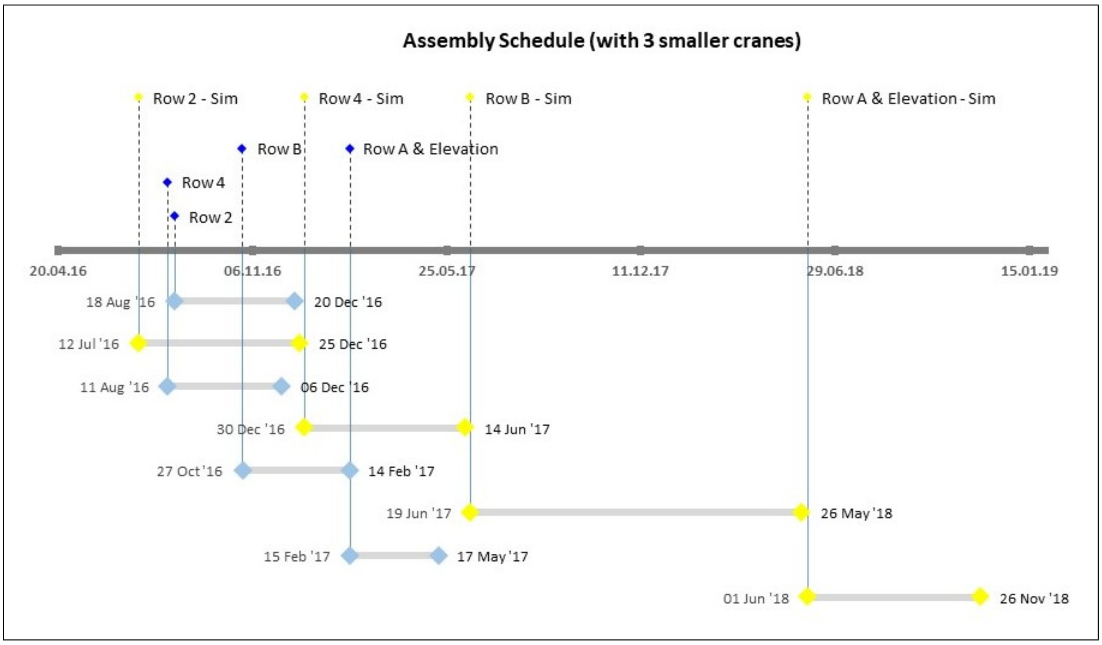

Assembly duration: Reference vs. Simulation (with 6 smaller cranes)
Simulation
Reference
Assembly 4
Assembly 3
Assembly 2
Assembly 1
61
92
116
111
60
118
60
125
0
20
40
60
80
100
120
140
Assembly part ID
Assembly duration (Days)

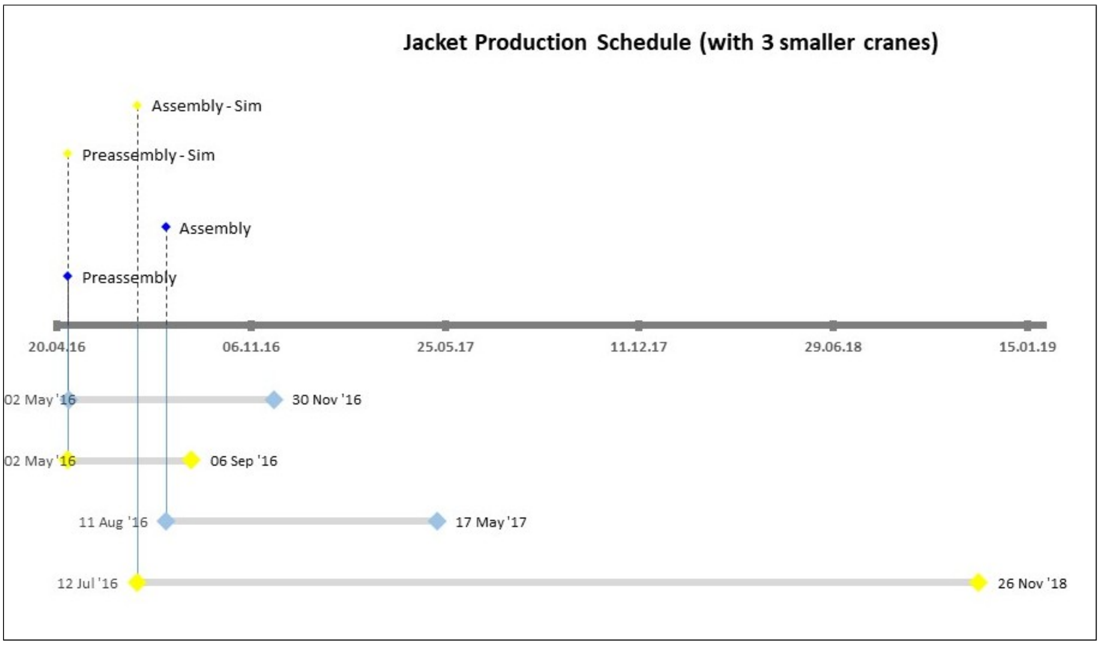
# C

# Comparison of project schedules

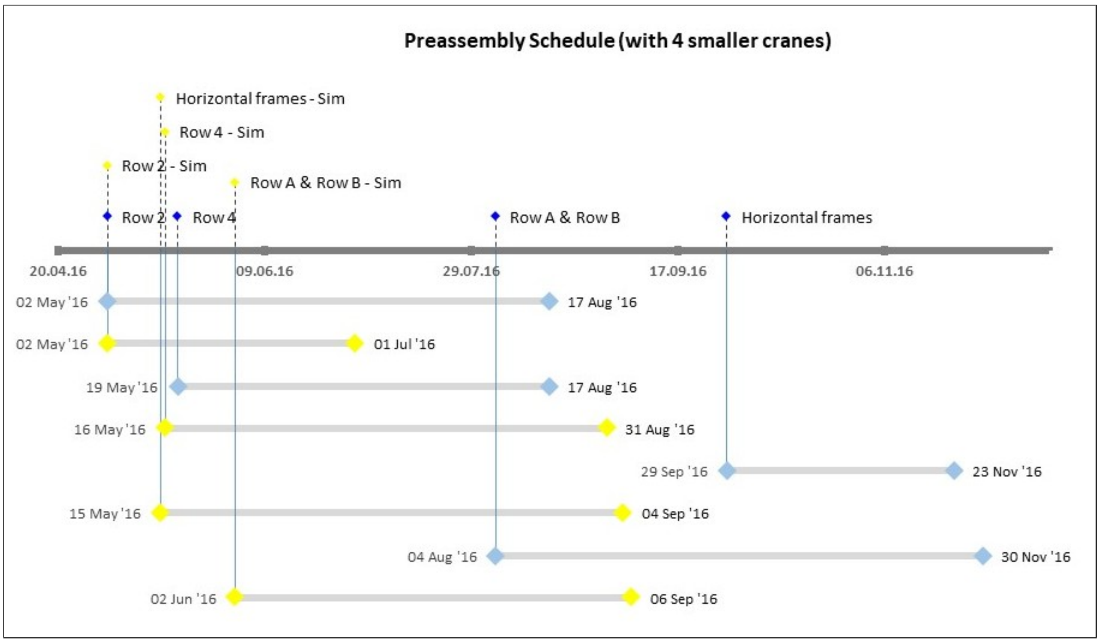
## Reference Project Vs. Experiment 1

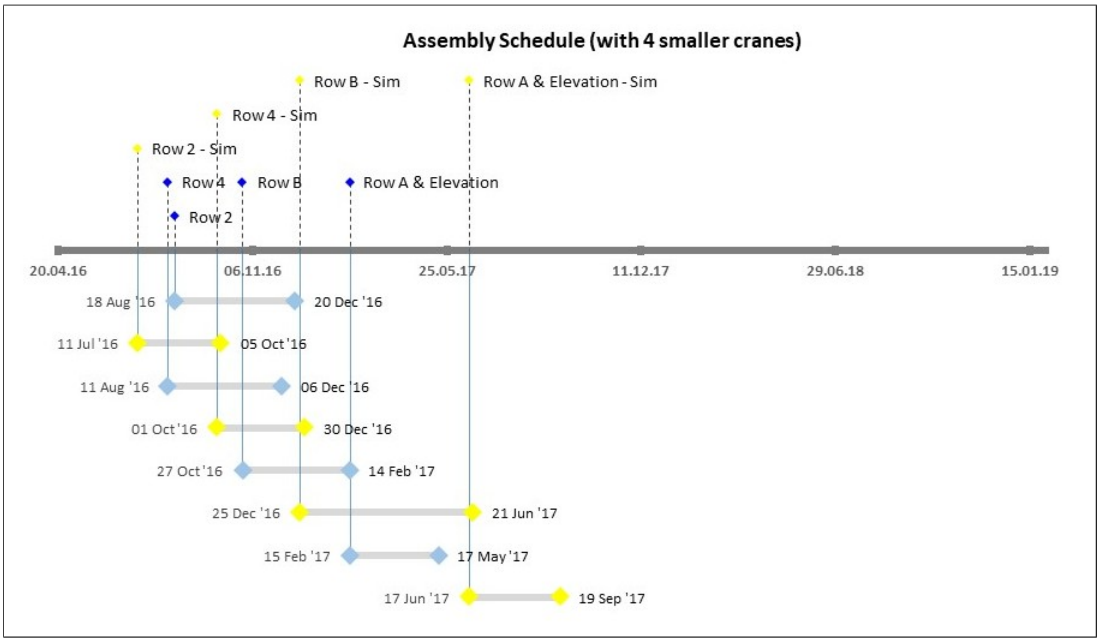


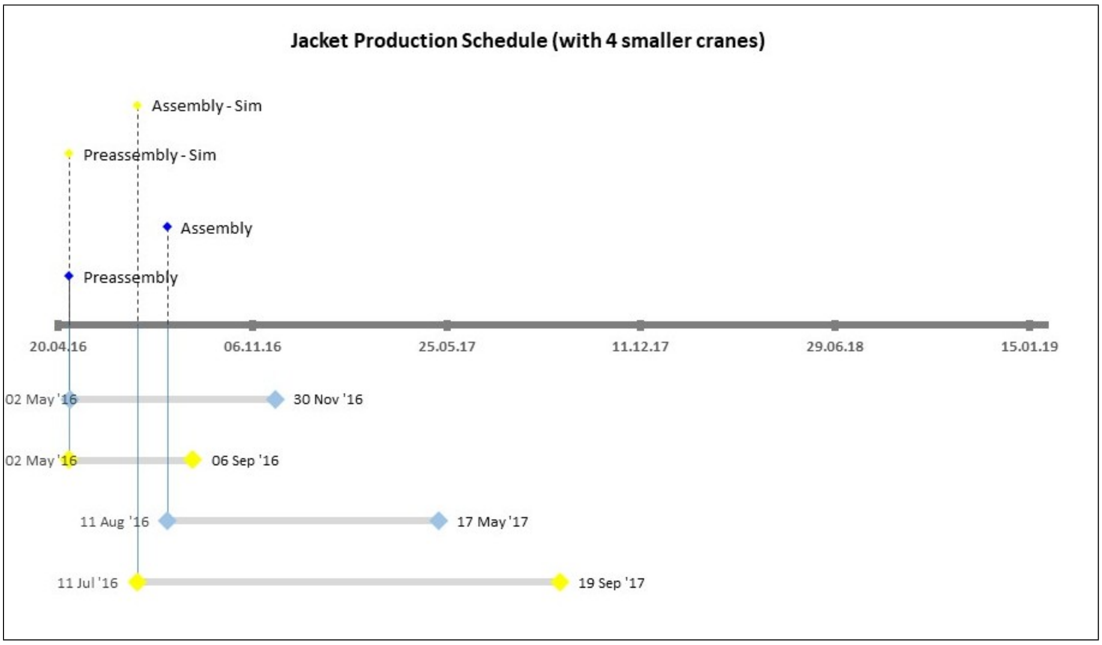

Assembly Schedule (with 3 smaller cranes)
Row 2 - Sim
Row 4 - Sim
Row B - Sim
Row A & Elevation - Sim
Row B
Row A & Elevation
Row 4
Row 2
20.04.16
06.11.16
25.05.17
11.12.17
29.06.18
15.01.19
18 Aug '16
20 Dec '16
12 Jul '16
25 Dec '16
11 Aug '16
06 Dec '16
30 Dec '16
14 Jun '17
27 Oct '16
14 Feb '17
19 Jun '17
26 May '18
15 Feb '17
17 May '17
01 Jun '18
26 Nov '18


Jacket Production Schedule (with 3 smaller cranes)
Assembly - Sim
Preassembly - Sim
Assembly
Preassembly
20.04.16
06.11.16
25.05.17
11.12.17
29.06.18
15.01.19
02 May '16
30 Nov '16
02 May '16
06 Sep '16
11 Aug '16
17 May '17
12 Jul '16
26 Nov '18

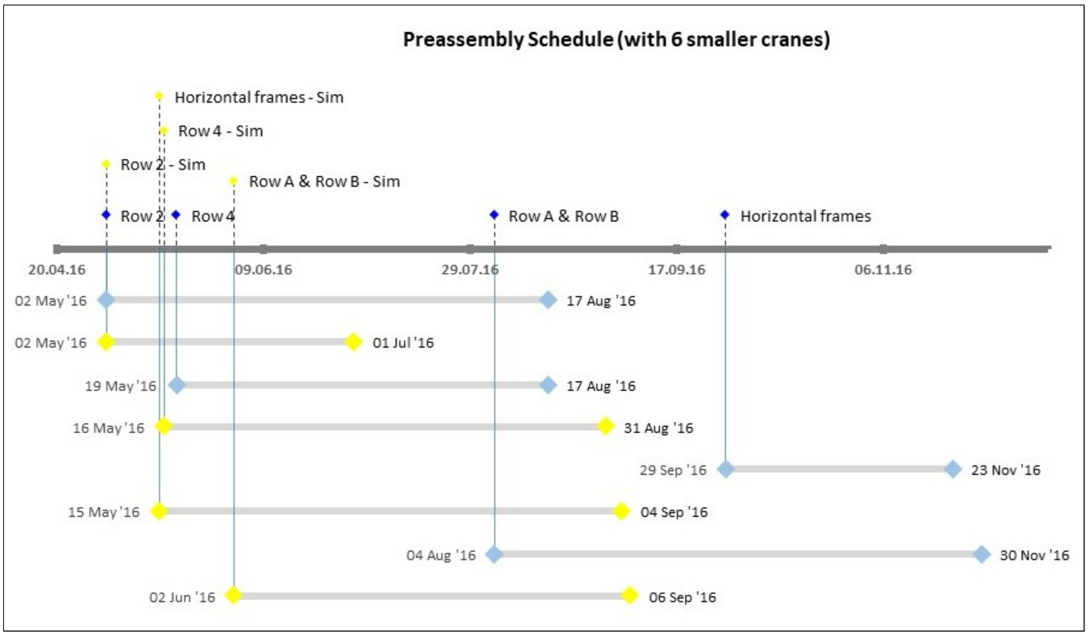
## Reference Project Vs. Experiment 2

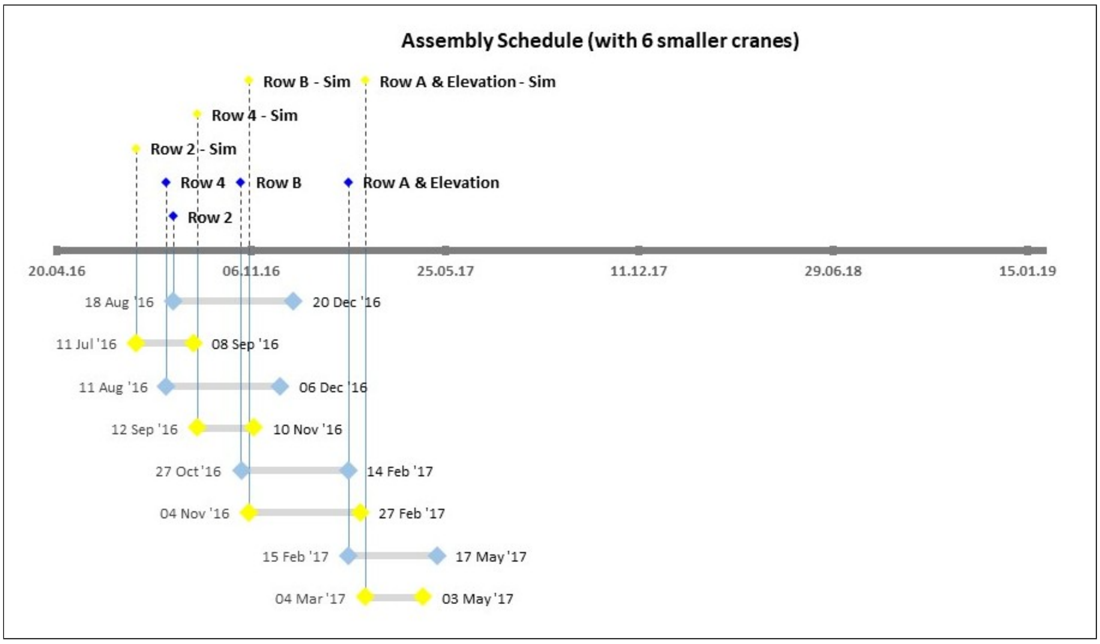


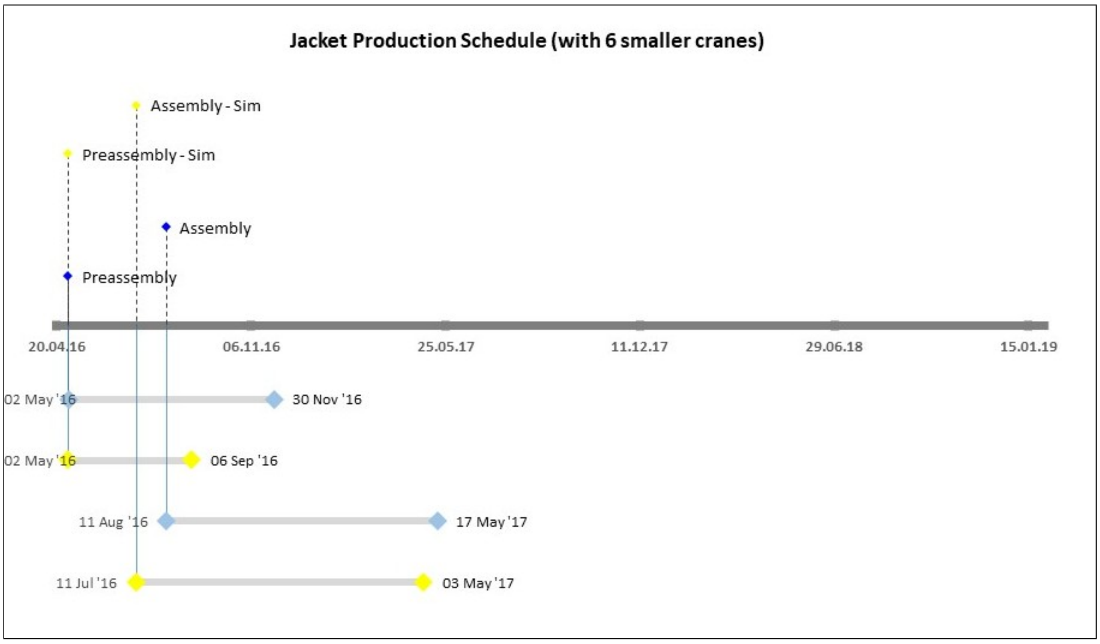






## Reference Project Vs. Experiment 3




Assembly Schedule (with 6 smaller cranes)
Row B - Sim
Row A & Elevation - Sim
Row 4 - Sim
Row 2 - Sim
Row 4
Row B
Row A & Elevation
Row 2
20.04.16
06.11.16
25.05.17
11.12.17
29.06.18
15.01.19
18 Aug '16
20 Dec '16
11 Jul '16
08 Sep '16
11 Aug '16
06 Dec '16
12 Sep '16
10 Nov '16
27 Oct '16
14 Feb '17
04 Nov '16
27 Feb '17
15 Feb '17
17 May '17
04 Mar '17
03 May '17


Jacket Production Schedule (with 6 smaller cranes)
Assembly - Sim
Preassembly - Sim
Assembly
Preassembly
20.04.16
06.11.16
25.05.17
11.12.17
29.06.18
15.01.19
02 May '16
30 Nov '16
02 May '16
06 Sep '16
11 Aug '16
17 May '17
11 Jul '16
03 May '17