



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Evaluating the Production Capacity of the future Final Assembly Line at Heart Aerospace

A simulation study

Master's thesis in Quality and Operations Management

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Cover:

The cover illustrates an image of the ES-30 aircraft designed by Heart Aerospace. The image is collected from Heart Aerospace media library.

Gothenburg, Sweden 2023

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## Abstract

This research study focuses on investigating the capacity of Hearts' intended Final Assembly Line by examining its sensitivity to variation and differences in the average required man-hours to complete the assembly of one aircraft. The main objective is to understand how the FAL should be developed to achieve a given production output. This research is crucial because it enables informed decision-making during the design and implementation of the FAL, considering the multitude of factors involved. Currently, there is uncertainty surrounding the information related to these factors, and further investigations are needed. To accomplish the objectives of the study, various methodologies were employed, where the most prominent one was a discrete event simulation model. The findings revealed that the studied assembly line is highly sensitive to both the average man-hours required for aircraft assembly and variations within the system. Additionally, it was discovered that Hearts' previous calculation of required operators differs from the findings of the study due to several reasons. These findings hold great importance for multiple reasons. Firstly, they provide validation for the assumptions made by Heart. Secondly, they offer a new perspective on the capacity of the intended FAL, highlighting the areas where adjustments and improvements are necessary. Lastly, the findings act as a catalyst for stimulating discussions within the organization, encouraging further exploration and refinement of the FAL design and production planning processes.

Keywords: Aerospace, Final Assembly Line, Hybrid-Electric Aircraft, Simulation

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# 1. Introduction

The objective of this chapter is to introduce the research and its corresponding context. Moreover, it defines the purpose of the study and states the research questions that will be addressed in the study.

## 1.1 Background

Bellgran and Säfsten (2010) and Caggiano et al. (2016) argue that production system development is a crucial aspect of achieving competitive advantage for manufacturing companies. According to Bellgran and Säfstens' (2010) research, production system development enables companies to improve their processes, reduce costs, and enhance their product quality and flexibility, leading to better customer satisfaction and increased profitability. The authors also emphasize that the largest potential to achieve a competitive production system is during the development of new systems.

According to the authors, companies that prioritize the development of their production processes can attain a competitive advantage over their rivals through various means. Firstly, Bellgran and Säfsten (2010) argue that by analyzing and approach the planning of production systems at an early stage and from different directions, firms can improve their efficiency and minimize production costs, which, enables them to offer their products at a more competitive price point in comparison to their competitors. The authors continue by saying that to achieve customer satisfaction and loyalty, it is imperative for a company to be reliable in terms of fulfilling their commitments and delivering products as promised within the stipulated time frame. This can be achieved by undertaking a thorough analysis of production processes and ensuring that the promised delivery dates are feasible. By fulfilling commitments and delivering products within the promised timeline, customers develop a sense of trust and reliability towards the company. Such attributes serve to differentiate the company from its competitors, thereby strengthening customer loyalty.

Furthermore, Groover (2015) also emphasizes the importance of analyzing production systems and assembly lines and the significance of analyzing assembly systems to enhance production efficiency and quality. Moreover, Groover (2015) advocates that industries should endeavor to explore means of automating their production processes as a strategy to reduce production costs in the long run. Nonetheless, the author acknowledges that some industries, such as the automotive and aerospace industries, are inherently challenging to automate due to the intricacy of their production tasks, the exacting standards of quality, and the constraints of space, which Mas et al. (2013a) also states. In these industries, a critical aspect of production analysis involves determining the optimal number of operators required to manufacture high-quality products at the right time and quantity. According to Groover (2015), the analysis of the assembly should always involve a careful examination of various factors. According to Groover (2015), the analysis should always involve a careful examination of various factors. Firstly, the design of the product being manufactured should be analyzed

to determine how it can be efficiently assembled on the assembly line. This analysis should consider factors such as the size, shape, and weight of the product, as well as the number of components and the assembly sequence. Secondly, the production volume required for the product should be determined to select the appropriate assembly line layout, which also is emphasized by Kiran (2019). The production volume will influence the type of layout chosen and the level of automation that can be employed. Thirdly, the production requirements, such as the time required to assemble each component and the total assembly time, should be analyzed to determine the required capacity of the assembly line. This analysis should consider factors such as the availability of labor and the expected production rate. Lastly, the assembly line should be analyzed to identify potential bottlenecks that could slow down production and quality issues that could lead to defects. This analysis should consider factors such as the rate at which components are supplied to the assembly line, the availability of tools and equipment, and the skill level of the assembly line workers.

By carefully analyzing, manufacturers can design and optimize the assembly line that improves production efficiency and quality. This can result in reduced production costs, increased production rates, and improved product quality, which can provide a competitive advantage in the marketplace (Groover, 2015).

## 1.2 Case Company

Heart Aerospace, here from referred to as Heart, is a relatively new company established in 2019, that endeavors to have a 30-seater hybrid-electric airplane available for commercial use by 2028. To achieve this objective, the company must undertake several fundamental tasks, such as designing and developing the aircraft and establishing a production system for its manufacture. The aircraft's final assembly will transpire in a dedicated line, with the integration of various sub-systems and components sourced from suppliers across the world. Moreover, Heart will only conduct the final assembly operation themselves and all the sub-systems, such as wings, fuselage, and engines, will be manufactured by suppliers. Heart aims to have a production system capable of accommodating an annual production capacity according to a set Business Plan of a specific<sup>1</sup> number of aircraft, and thus, its design must account for several parameters that influence the system's throughput. The primary challenge for Heart lies in constructing a final assembly line (FAL) capable of delivering the required output in a region with limited experience and expertise in the aerospace industry. Hence, the manufacturing of an aircraft is a highly intricate operation that requires the consideration of multiple variables to establish an FAL that can satisfy all requirements. Furthermore, Heart will need to design and construct a completely new FAL from scratch without any limitations from existing buildings and distractions from ongoing operations. Although the design freedom is large, no real processes exist, and real-world data cannot be collected. However, the production department at Heart possesses a wealth of knowledge,

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<sup>1</sup> Confidential information

previous experience, and great success in this field, which will greatly contribute to ensuring the accuracy of the study.

Despite the early stage of this project, there is an urgent need for decision-making, and opportunities exist to validate and test various aspects of the assembly line. These validation and testing processes are crucial for gathering essential data and insights that will aid in the progression of the project. Moreover, Heart has been using static excel models up till now to determine, for instance, the necessary number of operators and the number of stations on the FAL to achieve the given production rate. These calculations have been based on estimates regarding required man-hours to complete a single aircraft from previous experience of the production department. However, due to the absence of stochastic elements in the results, further investigations regarding variation and sensitivity to misestimations is a valuable input to nuance the previous findings. Hence, it is necessary to validate parameter assumptions used in calculations to make sure the right decisions are taken to reach the outlined output without crossing reasonable limits regarding number of operators and number of stations on the line.

However, when creating a new business, novel opportunities arise to consider sustainability within it. By making informed decisions a lot can be done from a sustainability standpoint. Elkington (1998) asserts that organizations should strive for sustainability by adopting the triple bottom line approach, which emphasizes the simultaneous consideration of economic, ecological, and social aspects. In the context of designing a FAL, these aspects are significantly influenced by the information utilized in the development process. By making appropriate decisions regarding FAL dimensions, such as the number of stations and operators, optimal operational efficiency can be achieved, leading to economic sustainability. This aspect also contributes to ecological sustainability, as it enables careful utilization of resources during the construction and operation of the FAL. In addition, the design of the FAL directly influences the working environment and the nature of tasks performed by operators, thereby influencing the social sustainability aspect in a closely interconnected manner.

### 1.3 Aerospace industry characteristics

The main activity for aerospace companies is the final assembly since most of the components and sub-assemblies come directly from suppliers (Gagné, n.d.). Hence, the final assembly is the last stage in the manufacturing process and accounts for more than 50 % of the workload of the entire aircraft (Mei & Maropoulos, 2014). This is where all the various components of an aircraft are put together to form a complete, functioning, and safe product. The industry demands a notable level of precision and expertise in order to deliver products that are safe and reliable. It is recognized for its specialized and technologically advanced approach to manufacturing, encompassing the intricate processes of aircraft design, development, and production. This necessitates a meticulous attention to detail and a high level of proficiency to ensure the quality and reliability of the final products (Malm, 2013). Furthermore, the aerospace industry places the utmost priority on quality, as aircraft failures while flying would

be catastrophic and result in huge impacts on the business. The aircraft assembly industry poses a unique and formidable challenge due to the predominance of manual-intensive and complex tasks. As a result, it necessitates the employment of well-trained and highly skilled operators to successfully execute such tasks (A. Bogini, personal communication, January 23, 2023).

Just like most stages of the aircraft manufacturing process, the assembly is complex and contains highly specialized tasks that require good coordination of various teams of engineers and technicians (Mei & Maropoulos, 2014). Even though the assembly process is extremely complex, the aircraft OEMs often face significant cost penalties for delayed deliveries and dependability therefore becomes a vital part of the operation (Chao & Graves, 1998). Furthermore, before the customer receives the aircraft, it must go through exhaustive testing, which put strong emphasis on the safety and quality that the production system can provide (C. Wallace, personal communication, February 9, 2023). The procurement of an aircraft is a significant investment, and it is imperative that the product possesses the highest level of quality and reliability to ensure the safety of its passengers. The risk of failure is unacceptable and as such, quality is considered as the most critical factor in the production process (C. Wallace, personal communication, January 27, 2023).

To further highlight the importance of a well-working production system within the commercial aircraft industry, the basic model of how production volume and product variety affects the production system is used. On a general level, the production system's layout is decided based on the relationship between production volume and product variety (Bellgran & Säfsten, 2010). The common perception is, according to the same authors, to have a product layout, e.g., production/assembly lines, when products are produced in large quantities with small product variation and a fixed position layout, e.g., job shops, when the production volume is small, and the product variety is large. However, the commercial aerospace industry generally uses a product layout with an assembly line even though the produced quantity is relatively low (Bellgran & Säfsten, 2010). Companies within the aerospace industry, such as Boeing and Airbus deliver aircraft in the order of hundreds per year from the assembly line even though Groover (2015) states that assembly lines are preferred when the production volume is in the order of 100 000. Hence, the production system used in aircraft production does not follow the conventional logic described above and to design a completely new one therefore requires a lot of consideration.

Furthermore, the complexity of aircraft production affects the assembly line and its various tasks, as the aircraft is a product that is manufactured in collaboration with suppliers. The choice of suppliers and the specific components that are pre-assembled prior to arrival at the manufacturer's facility will dictate the necessary in-house tasks and production processes. To ensure that the finished product meets all quality requirements, the manufacturer must carefully consider its suppliers and the interplay between them and the production process (D. Simão, Personal Communication, February 9, 2023).

## 1.4 Purpose

As mentioned earlier, the aircraft production process is intricately complex and necessitates the implementation of a carefully designed FAL to guarantee the achievement of the targeted output. At present, Heart is in the initial stages of designing and planning their FAL, which gives rise to numerous uncertainties and inquiries regarding the operational scope of the assembly line. As part of their endeavor to determine the necessary capacity to meet the desired annual output, Heart has initiated preliminary calculations. This step has been taken to gain valuable insights into the feasibility and resource requirements of achieving the production target. Consequently, there is a pressing need for validated information to enable informed, meticulous decision-making pertaining to the FAL.

*Therefore, the aim of the study is to contribute to the development of the FAL for the ES-30 aircraft of Heart Aerospace by assessing the already acquired information and made-up assumptions. The results of the study will be used by Heart to make informed decisions regarding the FAL to achieve the targeted annual production rate, while minimizing the number of required operators.*

The results of this study will provide valuable insights for companies within the aerospace industry, particularly those involved in building a new FAL. However, the findings may also be relevant to other manufacturing companies operating within similar contexts.

## 1.5 Specification of issue under investigation

To fulfill the purpose of the study, four research questions have been formulated to put further nuance on the information possessed by Heart. By seeking answers to these questions, the aim is to shed light on critical aspects of the subject matter and contribute to the existing body of knowledge in the field.

First, it is important to understand what theories previous research states are important in an aircraft FAL in order to decide how the information possessed by Heart should be validated. Thus, resulting in the first research question.

*RQ1: What production system theory is important to consider in an aircraft FAL?*

Secondly, since Heart uses previous experience of similar aircraft programs to estimate the total required man-hours for the full assembly of the ES-30 aircraft. Using these estimates, they have determined the total number of operators needed to achieve their production target. However, due to the reliance on educated guesses from previous work, is crucial to validate the accuracy of the data and assess the impact of potential misestimations. Thus, research questions two to four are created.

*RQ2: How does the minimum number of operators required to achieve the desired output deviate from Heart's previous calculations?*

*RQ3: How does an error in estimation regarding required man-hours affect the number of produced aircraft?*

*RQ4: How does variation in the required man-hours affect the number of produced aircraft?*

## 2. Frame of reference

Creating and operating a new assembly line is a complex process that requires a comprehensive evaluation of multiple factors, as stated by Bellgran & Säfsten (2010). To fulfill the objectives of this study, it is crucial to conduct a comprehensive analysis of multiple factors influencing the performance of the assembly line as a holistic system. The efficiency, productivity, and reliability of the assembly line are significantly influenced by these various aspects. Neglecting this crucial step can lead to the development of an inefficient and ineffective assembly line, resulting in low productivity, high expenses, poor product quality, and delayed deliveries. Bellgran & Säfsten (2010) also mentions how the operators within a production system play a significant role, and therefore it is important to consider the human factor as well as the quality control for the system. Given the significance of Production System Design, Human Factors, and Quality Control and Training, the following section is divided into these three areas, facilitating a thorough examination of each aspect's importance and interplay within the aircraft assembly process.

### 2.1 Production System Configuration

When designing an assembly line, it is important to consider the tangible settings, which are physical parameters of the production system that can impact its effectiveness.

#### 2.1.1 Layout

A production system consists of several distinct flows, which refer to the transfer of materials, information, and labor within the plant (Bellgran & Säfsten, 2010). The plant layout should be designed with the aim to maximize the use of resources and minimize operating costs, with the goal of achieving smooth and efficient material flow (Kiran, 2019). This requires a systematic approach to planning, which integrates all movements in a logical pattern. The emphasis on the utilization of resources and cost-effectiveness highlights the crucial role that plant layout plays in the overall success of a manufacturing facility.

Bellgran & Säfsten (2010) explains that these flows also must be managed in a way that ensures that the subject of transfer reaches its intended recipient at the right time and in the right quantity. The flow of materials, information, and labor is unique to each manufacturing plant, with the A-shaped flow being a common representation in aircraft assembly plants, where the input of many components is transformed into a single product (Bellgran & Säfsten, 2010).

The physical arrangement of components within a workshop is known as the production system layout (PSL). There are various PSLs, with fixed-position and line-based layouts being the two extremes. In fixed-position layout, the product is fixed in place, while workers and equipment move around the product to complete the various stages of production (Kiran, 2019). According to Bellgran & Säfsten (2010), this approach is often used for large, customized, and complex products that cannot be moved during the production process. The

production process is labor-intensive, and assembly tasks are performed by highly skilled workers. However, due to the lack of repetition in the production process, there is low standardization, which results in limited learning by doing (Bellgran & Säfsten, 2010). Kiran (2019) also states that fixed-position layout mainly is used for big and complex products such as boilers, powerplant generators, aircraft, and ships.

In contrast, Bellgran & Säfsten (2010) explains that line-based layouts are structured in a way where the assembly of a product is done by moving it through a series of stations, each performing different tasks. The product moves continuously or intermittently from one station to the next, allowing for high-volume and high utilization production. With a continuous flow, there is no idle time for workers, and the more intense repetition of tasks leads to faster learning, leading to improved quality and less variation in process time. Bellgran & Säfsten (2010) also explains how the repetition of tasks reduces the need for highly skilled workers, resulting in lower labor costs.

In addition to what is presented above, there are several advantages and disadvantages with either a fixed position or a line layout. According to Kiran (2019), the advantages for the former layout option often presents itself as disadvantages in the latter option. For instance, if a machine breakdown occurs in the line layout, the whole operation is affected, sometimes even completely stopped, which is not the case for fixed-position layouts where the other work centers can continue working while the breakdown is fixed. Furthermore, a fixed-position layout offers greater flexibility and allows for a change in product mix, production volume, and product design whereas the flexibility in a line layout is strictly limited.

### 2.1.2 Number of Stations

According to Groover (2015), the number of workstations is a key differentiator between manufacturing system types, and it also has a strong influence on the system's performance in terms of production rate and reliability. Furthermore, the amount of work that can be achieved by the system increases with the number of workstations. However, Groover (2015) states that the stations need to have a synergistic effect in order for the performance to increase. This effect mainly comes from dividing complex and time-consuming tasks into sub-tasks that can be standardized and performed more efficiently. Due to the cycle time of the sub-tasks being reduced, the system becomes more efficient both by increased repetition and by fewer tasks for the operator to focus on. Nevertheless, in order to allocate tasks among a greater number of stations, it is imperative that the tasks possess the capability to be subdivided into more compact work-packages. Though a system with multiple stations might achieve a higher output, it will also be more complex and therefore more difficult to maintain and manage, potentially resulting in reliability problems (Groover, 2015).

Furthermore, the number of workstations in an assembly line is closely related to the cycle time for each station (Baudin, 2002). The cycle time can be defined as how long time it takes for one product to be processed by one workstation, i.e., the time interval between when one work unit begins assembly and when the next unit begins (Groover, 2015). To further put the

cycle time into context, takt time needs to be defined. The takt time can be seen as the interval that products need to leave the assembly line in order to satisfy demand, i.e., available capacity, in time, divided by the demand (Baudin, 2002). Moreover, to be able to produce according to the takt time, or demand, all workstations need to have a cycle time below the takt time. For instance, if a fixed number of tasks require X minutes to be completed and if all these tasks were to be performed by one station the cycle time and takt time would be X minutes. However, if it is possible to distribute the tasks to several workstations in a serial flow, each station will have to perform fewer tasks and the cycle time will be decreased, which further allows for a decreased takt time. Moreover, the number of workstations is closely related to the takt time achieved.

Worth mentioning, dispersing tasks onto more stations of an assembly line often requires the size of the factory to increase since more space is needed to accommodate more stations. Hence, Baudin (2002) states that more investment is needed to manage the larger factory. Furthermore, more stations also imply more work-in-process since several assembly objects can be worked on concurrently, resulting in an increase in tied-up capital.

### 2.1.3 Assembly Line Balancing

According to Jonsson and Mattsson (2009), assembly line balancing is the process of optimizing production efficiency in manufacturing environments by ensuring that each workstation along a production line has an equal workload. This is strongly affected by the number of stations in the system and the capability of the tasks to be divided into smaller work packages. An assembly line follows the theory of constraints (Jonsson & Mattsson, 2009). That is, a system cannot perform better than its weakest link, i.e., the bottleneck. If an assembly line has three stations with a cycle time of 4, 5, and 6 minutes respectively, the shortest takt time that can be achieved by the system will be 6 minutes. Therefore, it will bring no additional value to sub-optimize the system, i.e., improve the station with a cycle time of 4 minutes. Hence, the real added value will appear first when the line is balanced in a way that makes all processes have the same cycle time, e.g., 5 minutes each.

### 2.1.4 Material Supply

Another important consideration when designing an FAL is the material feeding strategies used to feed the line. According to Calzavara et al. (2022), these methods can be divided into direct and indirect methods, and both affect the performance of the assembly system. Furthermore, the direct feeding strategy, also called continuous supply by Hanson and Brolin (2013), uses a central warehouse where the material is delivered to the assembly line in bulky load units. The other strategy, indirect feeding, rely on several decentralized warehouses, often called supermarkets, located on strategic locations throughout the factory, where smaller kits with materials are prepared and delivered to the nearest assembly station in a more frequent manner. Hanson and Brolin (2013) further explain that the direct feeding strategy occupies more space on the assembly line compared to indirect feeding since more material in bulkier packages is presented to the operators on the line. Hence, the operators

need to have more part numbers presented to them at any given time, thus taking up more space at the station. If indirect feeding strategy such as kitting is used instead, smaller batches of material are delivered to the stations with each delivery, and less space is required for material presentation at the line. Although the indirect feeding strategy frees up space at the stations, Calzavara et al. (2022) states that this strategy requires space for the decentralized warehouses elsewhere in the factory. Moreover, the space freed up at the line will be traded for the space occupied by the decentralized warehouses. However, since the feeding strategies influence the space occupied at the line, decisions regarding feeding strategy can influence the number of assembly stations that is required and the layout of the assembly line (Calzavara et al. 2022).

Furthermore, indirect feeding has the possibility to facilitate the assembly work since operators will be presented with a standardized kit of components (Hanson & Brodin, 2013). Moreover, the operators do not need to put as much time into fetching components when they are presented in a standardized way. Consequently, by adopting this approach, the operator can allocate additional resources towards value-adding tasks, thereby directing less attention to other responsibilities. As a result, the assembly line can enhance its overall efficiency. Although kitting saves time at the assembly line, additional time is needed at the supermarkets where the kits are prepared. Hence, the assembly line can potentially operate with less operators, but more workers are needed in the logistics department (Hanson & Brodin, 2013). Thus, the overall number of workers in the factory might not change at all. Consequently, it is important to compare what the two different choices would result in total cost versus the chance to increase quality to make the appropriate decision.

Additionally, Hanson and Brodin (2013) argue for a quality increase when kitting is being used. The operators are being presented with a standardized kit with components that all belong to the same assembly object, hence reducing the risk of picking wrong components to the product. However, the authors' study showed that it is of high necessity for the kit preparer to assemble the correct parts into the kits, otherwise quality problems might be even more severe compared to using direct feeding strategy.

## 2.2 Human Factors

When designing an assembly line, it is beneficial to consider the human factor as the operators play a significant role in determining the efficiency, productivity, and quality of the system. Due to the manual-intensive and complex nature of aircraft assembly, in combination with the high number of operators involved, it may be even more important to consider the human factor when designing Heart's assembly line. Therefore, it is of outmost importance, in this context, to ensure that optimal conditions are in place to promote the performance of the assembly line.

### 2.2.1 Number of Operators

The number of operators in an aircraft assembly line can significantly impact its efficiency, productivity, and quality. Having too few operators can lead to delays and bottlenecks, as workstations may not be staffed when needed (Sivasankaran et al., 2014). This can cause other operators to be idle, reducing the overall output of the assembly line. Additionally, insufficient staffing can result in fatigue, which can compromise the quality of work and increase the risk of errors or accidents.

On the other hand, the authors also mention that too many operators can be problematic, mainly due to the limitation of space when operating at the same time on the same product and the hectic environment when a lot of people are in the surroundings. Consequently, it can lead to congestion, confusion, and decreased efficiency, as multiple workers may be attempting to access the same area or perform the same task simultaneously. This can result in delays, rework, and increased risk of accidents. This is one of the reasons, according to Groover (2015), to conduct an analysis of production systems in order to identify tasks or activities within the system that are suitable for automation.

Therefore, Sivasankaran et al. (2014) argue that it is necessary to carefully consider the number of operators for an efficient and effective assembly line. Determining the appropriate staffing level requires careful planning, considering factors such as the complexity of the assembly process, limited room, the type of aircraft being produced, the skill level of workers, and the required throughput.

### 2.2.2 Organizational Learning

The planning of a company's production capability involves a multitude of factors to consider. Beyond the physical characteristics of the assembly line or manufacturing plant and the necessary workforce, organizations must also consider the principle of "learning by doing" which suggests that repeated performance of tasks leads to an enhancement of organizational efficiency (Bongers, 2022).

The implications behind learning by doing are called "The learning curve" (Argote, 2013). This is critical in the aircraft assembly industry, as it helps companies understand the relationship between the time it takes for a worker to become proficient at a task and the cumulative number of units produced.

In the early stages of research on learning in production systems, the focus was primarily on the individual's learning process and the improvement in their performance as they gained experience in a specific task. However, in recent years, the focus of research on learning has shifted towards the organizational level, examining the learning process of the entire system or organization rather than just the individual. This shift in focus has been driven by the recognition that an organization's overall performance is the result of the combined efforts of many individuals and that the collective learning of the organization can have a significant impact on the final output (Argote, 2013).

The knowledge of this curve enables companies to make informed decisions regarding resource allocation, production scheduling, and workforce planning and is therefore crucial to consider when looking at an assembly process (Argote, 2013). In production, learning is an important factor in determining several things, like the time, required number of operators, costs, and efficiency of the production process. As a system or organization becomes more familiar with a task, it becomes more efficient in performing it. Hence, resulting in a decrease in the time it takes to complete a specific task. The organization also becomes better at completing the task by repeating it. The improved accuracy can result in better quality and fewer defects and rework, which can altogether reduce the cost of production. The rate at which performance improves can vary depending on the complexity of the task and how many times the task is completed, but learning typically levels off after a certain amount of experience (Argote, 2013).

### 2.2.3 Organizational Forgetting

Despite the widespread belief that the marginal costs of producing aircraft decrease over time due to pure learning, anecdotal evidence and discussions with industry executives suggest otherwise. An examination of the data presented in the study of Lainer (2000), indicates that there is a subset of the learning curve which involves forgetting. Organizational forgetting is the phenomenon of organizations losing knowledge, skills, and capabilities over time, resulting in a decline in organizational performance. This phenomenon arises when the knowledge or skills necessary to execute specific tasks or activities are no longer actively utilized or transmitted within the organization, or when individuals possessing the expertise to undertake such tasks or resolve crucial issues depart from the organization. One example of organizational forgetting may arise during a recession when a company receives no orders, while another more common scenario is when a large series of a specific model is completed, followed by the introduction and assembly of a new model for future production. This can result in forgetting the specific activities that were previously executed during the production of the prior model, leading to a reduction in production efficiency.

### 2.2.4 Experience spillovers and previous experience

Experience spillovers can be defined simply as the impact of the experience accumulated in the execution of one activity on the performance of another activity (Lainer, 2000). According to the author, there are two types of experience spillovers, namely external spillovers, which are often associated with previous experience, and internal spillovers, which are between products within the company. Regarding external spillovers, or previous experience, there is a lot of research regarding the effect it has on the learning for assembly related tasks. Cherrington et al. (1987) writes that a focus on the impact of prior knowledge and experience on the learning in industrial settings is beneficial for a more accurate production planning. The authors also contend that workers' prior knowledge and experience can significantly affect the time it takes for them to become proficient at a task. Similar in a case study by Cook et al. (2007), the author recommend that the level of experience should be reported as fully

as possible, in lieu of a better measure, more precisely the number of previously performed by each operator should be stated along with details of any prior training received for a more accurate prediction regarding performance improvement. These studies employ statistical analysis of data from several industrial processes to investigate the relationship between prior experience and the improvement in performance. The authors find that workers with prior experience tend to exhibit a faster learning, demonstrating a faster rate of proficiency acquisition, compared to workers with limited prior experience.

Regarding the internal experience spillovers, Lainer (2000) brings up an example of the aircraft production industry and how there is a difference between the fighter jet production and commercial jet production that needs to be considered. The author refers to the market for fighter jet as the “optimal control problem” due to the environment. The producer often receives a contract to produce a certain number of identical planes with a specific deadline for the last delivered aircraft. The commercial aerospace market is subject to a range of challenges that affect its operations and overall possibility to retain the possessed knowledge.

### 2.2.5 Task complexity & repetition

The study by Nembhard (2000) aims to assess the impact of task complexity on the performance in a production system. The authors of the study posit that the complexity of a task can greatly influence the learning, affecting both the rate at which workers attain proficiency and to what degree. To examine the relationship between task complexity and learning, Nembhard (2000) employs a field study that involves workers performing tasks of varying complexity. The findings of the study indicate that tasks of higher complexity result in slower learning, requiring workers to take more time to become proficient. In contrast, tasks of lower complexity tend to produce a steeper learning, enabling workers to attain proficiency at a quicker pace and therefore reduce the variation in time required, decreasing the quality issues and time required of completion.

It is noteworthy to observe that, because of the prolonged takt times in the aircraft assembly process, the operational tasks are not repeated at the same frequency as other industrial sectors, such as the automotive industry's assembly line. While an automotive assembly team may repeat their assigned duties multiple times per hour, workers on an aircraft assembly line may not perform the same task for several days having a negative impact on the rate of learning.

### 2.2.6 Flexible Workers

According to Malachowski and Korytkowski (2015), one of the essential principles of a well-functioning production system is the deployment of multi-skilled employees. The possession of a diverse set of competencies, experience, and knowledge by employees allows them to execute a variety of simple and complex tasks, thereby enhancing the production process' efficiency. The authors further explain that multi-skilled employees can avoid waiting for a specific task and instead proactively identify areas where support is needed and activities that

require attention. This approach minimizes bottlenecks, reduces idle hours, and consequently enhances overall productivity. Additionally, the authors explain that multi-skilled employees demonstrate greater receptivity to learning new methods and adapting to changes within the production environment, which translates into higher motivation and better retention rates.

In the pursuit of a more flexible approach to work, a FAL may employ the use of flexible crews, a concept that involves assigning multi-skilled workers to different stations within the FAL to address bottlenecks in the system (Heike et al., 2000). In contrast to the conventional practice of station-specific assignment of workers, flexible crews move to different stations as the need arises. A fully flexible crew is one in which all workers within a station can move to other stations to assist with bottlenecks, while flexible crews refer to a selection of workers within a station that can move to other stations to provide assistance. This approach improves the cycle time of the system by acting as a dynamic backup for the entire production.

### 2.2.7 Working Shifts

The idea of working shifts is to increase production without having to invest in additional manufacturing equipment or facilities (de Cordova et al., 2016). By doing so, a company can utilize their existing resources for a longer time each day and hence increase output. Another possibility when working shifts is to greater respond to changing customer needs or fluctuations in demand.

However, shift work, particularly nighttime shifts, can have significant negative effects on job performance and quality (de Cordova et al., 2016). A systematic review conducted by the authors found that shift work is associated with increased errors and decreased performance. This is believed to be due to disruptions to the body's circadian rhythm and reduced alertness during nighttime hours. To mitigate these consequences, the company can implement scheduling changes, such as implementing a rotating shift schedule (de Cordova et al., 2016)

## 2.3 Quality Control and Training

The aerospace industry is subject to strict regulations, and specific standards must be met to ensure the safety of passengers. By considering quality, control, and training for the operators, the chances to ensure compliance with these regulations and standards increase. A robust quality control process can aid in early identification and resolution of issues, thereby reducing the likelihood of delays and rework, and subsequently decreasing costs while increasing customer satisfaction by delivering on promises.

### 2.3.1 Supplier involvement

As mentioned in Section 1.3, the development of the aircraft and its components is a collaborative effort between the aerospace company and its suppliers. This makes the supplier's involvement a significant factor for the final assembly process.

According to Gagné (n.d.), organizations within the aerospace industry rely heavily on a global network of suppliers and subcontractors who provide a wide range of components and systems necessary for the assembly of the aircraft. Given that the development of the aircraft and its component is a collaborative effort between the manufacturer and its suppliers, a significant amount of attention must be dedicated to fostering and maintaining a strong relationship with the suppliers (Gagné, n.d.). Hence, to maximize efficiency, aerospace companies typically outsource most of the components or sub-assemblies, while focusing on the final assembly and integration of the aircraft. The authors explain how the limited degree of vertical integration distinguishes the aerospace industry from others, as it primarily involves the assembly of various components to create the final product.

Despite the benefits of outsourcing, there are also challenges associated with a low degree of vertical integration in the aerospace industry. These challenges stem from communication difficulties and organizational barriers which can negatively impact the reliability and quality of the end-product (Slack et al, 2013). To address these challenges and ensure high-quality products are delivered within the specified timeframe, aerospace companies must prioritize cultivating close relationships with their suppliers. However, even with close supplier relationships and careful planning, the production of complex and multifaceted aircraft products carries an inherent risk. Despite this unavoidable risk, the aerospace companies are aware of these challenges and employ various measures to minimize their impact. For example, regular follow-ups on deliveries and on-site supplier audits are conducted to ensure that production is proceeding according to plan. In the case of critical components, incoming inspections are conducted to confirm that quality requirements are being met. For highly complex parts, quality assurance personnel may be dispatched to monitor the production process and ensure that all specifications are met (D. Simão, Personal Communication, February 9, 2023).

Furthermore, aerospace companies implement a comprehensive Quality Requirements for Suppliers (QRS) document that outlines the necessary requirements for potential suppliers to meet. This document serves as a crucial tool in the selection process, as suppliers must meet the established quality standards in order to be considered as a viable source of components and materials for the aircraft production process. The QRS document helps ensure that the manufacturer's suppliers adhere to rigorous quality standards, contributing to the overall reliability and quality of the end-product (D. Simão, Personal Communication, February 9, 2023).

### 2.3.2 Variation's effect on the FAL

Holweg et al. (2018) present an important principle that states, "Variation is inherent in all process inputs, tasks, and outputs" (p. 83). Moreover, no matter how well-working a process is, it will always be prone to variation. Therefore, Holweg et al. (2018) argues for the importance of understanding the effect variation has on a system's performance. Furthermore, variation can occur in quality, quantity, and timing, and the resulting effect on

the system depends on which form of variation is present. Holweg et al. (2018) continues by describing two types of variation: common cause and assignable cause variation. Common cause variation is random and cannot be predicted, it appears like a noise surrounding the process, whereas assignable cause variation is non-random variation caused by one or more identifiable factors. Moreover, assignable cause variation can be controlled and managed, whereas common cause cannot.

The quality of a product is defined by Holweg et al. (2018) as “...to what degree its production conforms to predetermined specifications” (p. 84). Moreover, to replicate a product’s constituent parts perfectly. A product with bad quality may result in extra work in the form of re-work or scrap. Hence, it is important to reduce variation in product quality and to detect and eliminate all aspects of variation caused by assignable causes.

The aspect of variability in quantity and time within a production system has not been given as much attention as variability in quality, as noted by Holweg et al. (2018). However, both aspects can have a significant impact on the system's performance. For instance, the authors highlighted an example in which two workstations are linked directly to each other without any buffer in between. If there is a high degree of variability in the processing time for each station, the system may experience starvation and blocking. This occurs when the second station remains idle due to a lack of work objects, either because the first station has not yet completed their work at the same time, or because the second station takes longer to complete its work and the first station is therefore blocked, unable to send its work forward. How much less than the maximum output the system will produce depends on the degree of variation that is present.

### 2.3.3 Structure of training programs

According to Bell and Kozlowski (2008), the structure and processes of training in organizations have an impact on learning. The authors highlight two dimensions of training that are particularly significant for organizational learning. The first is whether the training is conducted on an individual or group basis, with the latter being deemed the more beneficial approach. The main advantage with group training is the possibility to create a sense of community among trainees, which can help to reinforce the learning process and foster a positive learning culture within the organization. The second dimension concerns the provision of opportunities for trainees to observe experts perform specific tasks. Through this, trainees can gain access to tacit, or difficult-to-articulate knowledge, while also internalizing norms of behavior that are relevant to the workplace.

## 2.4 Synthesis

This section addresses the research question pertaining to the production system theory relevant to an aircraft FAL. The aim is to provide a comprehensive analysis of the theories that hold significance within the aerospace industry. By synthesizing knowledge from the existing body of research, the key production system theories that play a vital role in the context of

an aircraft FAL can be identified. Through this exploration, the objective is to elucidate the theories that bear relevance and offer valuable insights for optimizing the production process and achieving operational excellence in the aerospace sector.

#### 2.4.1 Number of stations and operators

The manufacturing industry has long sought to enhance efficiency and productivity through automation (Groover, 2015). However, in certain production systems, especially within the aerospace industry, the complexity involved has rendered full automation impractical. Consequently, the scope for automation is limited, necessitating careful consideration of the workforce allocation on the assembly line. Sivasankaran et al. (2014) highlight the significant role that the number of operators plays in determining the capacity of a FAL. Therefore, it becomes imperative to accurately assess and determine the required number of operators to meet the production demands and effectively increase the capacity of the FAL. Additionally, considering the constraints imposed by physical limitations, it is important to acknowledge that simultaneous work on an aircraft is not always feasible. Consequently, optimizing the number of workstations becomes crucial to ensure that the system's capacity is maximized, as elucidated by Baudin (2002). As a result, careful planning and consideration must be given to the number of operators and stations required to produce according to demand.

A challenge encountered in the aircraft industry relates to the absence of buffers between the various workstations. Holweg et al. (2001) note that such a configuration renders the system acutely susceptible to difficulties arising from variations in processing times, particularly in the context of complex tasks. One potential solution to this problem entails leveraging the benefits of flexible workers. As explained by Malachowski and Korytkowski (2015), flexible workers possess the capacity to execute diverse tasks within the production system, thereby impacting the number of operators required for the assembly line. The integration of flexible work teams can potentially diminish the number of operators necessary for an assembly line while concurrently sustaining production capacity. This is achievable by flexible workers providing a dynamic balance among workers, empowering them to engage in multiple tasks and adapt to changes in the production process. Consequently, the workforce becomes more flexible, and the system can function efficiently even with a decreased number of operators. Nonetheless, the employment of flexible workers may necessitate supplementary training and supervision and could potentially increase the likelihood of bottlenecks or delays if one station encounters complications. Thus, the use of flexible workers should be thoughtfully considered when planning and optimizing the assembly line.

#### 2.4.2 Learning

Since the aerospace industry is subject to long cycle times, in Heart's case a matter of days, each task is performed with low repetition compared to the automotive industry where the cycle time can be as low as one minute. Moreover, the learning effect of an aircraft production system is much slower compared to an automotive factory. As stated by Anzanello and

Fogliatto (2010), Wright's Law posits that the marginal cost for the next aircraft reduces with a certain percentage after doubling the cumulative numbers the system has produced. Whereas an automotive factory can produce the same number of cars in a couple of hours as an aircraft factory can do in an entire year, the rate of learning therefore differs a lot. Learning is therefore a dilemma for the aircraft industry, and it needs to be considered when designing and developing the FAL.

An additional aspect that warrants attention in the context of learning pertains to the insights brought to light by Nembhard (2000). His research findings underscore that the attainment of proficiency in long and complex tasks requires a longer duration compared to less complex counterparts. Moreover, the learning process is significantly hindered when considerable intervals elapse before the subsequent execution of the same task. These findings further indicate that the complexity of a task plays a substantial role in shaping the learning process, influencing not only the rate at which workers acquire proficiency but also the level of proficiency attained. As a result, it may prove advantageous to strategically decompose tasks into smaller, more manageable processes, adopting a standardized approach. This approach aims to streamline the learning process by simplifying tasks, thereby potentially enhancing workers' ability to acquire the necessary skills and knowledge in an effective manner.

Finally, Cherrington et al. (1987) emphasize the influential role of workers' prior knowledge and experience on the learning process and the duration required to achieve proficiency in a given task. Considering this, Heart could potentially benefit by seeking to recruit operators who possess experience in the aerospace industry, or at the very least, individuals with expertise in complex and quality-demanding manufacturing environments. Such a strategic approach to hiring may facilitate a smoother learning curve and expedite the development of necessary skills and competencies among the workforces.

Hence, addressing and managing the challenge of the learning effect in an aircraft FAL is of utmost importance. One potential strategy for addressing this challenge, as posited by Hanson and Brolin (2013), is the utilization of kitting. This method streamlines the learning process by freeing operators from the task of searching for the appropriate parts, thereby allowing them to focus on the precise assembly of the aircraft and consequently accelerating their acquisition of knowledge. Additionally, reducing staff turnover is an essential consideration, as it takes a significant amount of time to acquire proficiency in the aerospace industry. Maintaining personnel within the organization is therefore crucial to prevent the loss of competence and skills. It may be in the firm's interest to make some provision for recurring laid-off workers in the future. Another strategy to overcome the learning challenge is to implement effective training programs for personnel within the company. According to Bell and Kozlowski (2008), such programs and group training foster knowledge and skills sharing, expediting the learning process for individuals involved in aircraft production.

The issue of forgetting is a significant concern in manufacturing industries (Lainer, 2000), and particularly in the aviation manufacturing industry due to the long cycle times and learning involved in producing unique airplane models with customizations. After completing a large

order for a specific airplane model, the company may switch production to a new order with different customizations. Given the size and complexity of these orders, the completion time for each order can be lengthy. Consequently, by the time a large order has been completed, knowledge about how to assemble certain components for the model may have become obsolete or forgotten since the last production run.

### 2.4.3 Supplier involvement

Supplier involvement in the FAL planning process is critical for several reasons. Gagné (n.d.) explains that the aerospace industry exhibits a distinctive feature of minimal vertical integration and primarily relies on its broad network of suppliers. In this context, multiple components are collaboratively designed and produced in conjunction with suppliers, underscoring the need to determine the extent of assembly operations that must be performed at the FAL versus those that can be executed by the suppliers. This decision, in turn, has implications for identifying the specific tasks that must be integrated at the FAL, as well as the requisite number of operators needed to accomplish them.

Moreover, ensuring early and intensive supplier involvement can help to ensure that the FAL is designed to accommodate the specific needs and requirements of the components being supplied. By working closely with suppliers, manufacturers can both leverage this expertise to optimize the layout and design of the FAL, resulting in a more efficient and effective production process and identify potential bottlenecks or inefficiencies in the production process and develop solutions to address these issues before they become a problem.

The selection of suppliers is also known to exert a profound influence on the overall performance of the aircraft. Given this, the choice of supplier must also encompass a meticulous evaluation of their quality control standards as mentioned by D. Simão (Personal Communication, February 9, 2023). Furthermore, an aerospace company must also thoroughly assess the supplier's ability to meet delivery schedules, ensuring the timely and appropriate provision of the requisite quantity of supplies.

### 3. Methodology

To answer the first research question, a literature review has been conducted alongside discussions with Heart employees, resulting in the Frame of Reference chapter found above. Furthermore, since an aircraft FAL is a complex and intricate process that contains randomness, simulation is according to Chung (2003) the best analysis method to use. Especially when the system to be studied is dynamic in real time. In contrast, Chung (2003) states that before simulation software existed, more complex systems could only be studied through a static point of view.

Hence, to answer the remaining research questions having a dynamic nature, a simulation model has been built to quantitatively test different scenarios and to see what effect different factors have on the FAL's capacity. Moreover, Chapter 3 outlines the methodology adopted for the study and it is greatly inspired by Banks et al.'s (2001) model for simulation studies. The chapter starts with a short description of which research strategy is adopted, followed by how the literature study was conducted, and how Banks et al.'s (2001) methodology has been utilized.

#### 3.1 Research Strategy

The study has a quantitative research strategy where the fundamental logic stems from deduction. Moreover, different theories regarding important variables used for designing an FAL are tested against Heart's calculations and assumptions through the simulation model to answer the research questions. Banks (1998) puts great emphasis on quantitative data when performing a simulation study, which resulted in the selection of a quantitative research strategy. However, since a literature study has been conducted to find out important production system parameters that need to be considered when designing a new FAL, the study has a small portion of a qualitative strategy as well.

#### 3.2 Literature study

Since this research has a deductive position, the literature study was concluded in the early phase of the study to build up the Frame of Reference acting as a foundational body of knowledge regarding production system development. When the research moved forward, the theoretical areas were continuously expanded, and new ones were added. The literature took its departure from the book *Production Development: Design and Operations of Production systems* written by Bellgran and Säfsten (2010), and the book *Automation, Production Systems, and Computer-Integrated Manufacturing* written by Groover (2015). From these books and discussions with Heart, keywords could be formulated and later used to search the academic databases of Google Scholar, Scopus, and Chalmers' library. Frequently used keywords were, *Aerospace, Aerospace industry, Production system, Final Assembly Line, Aircraft assembly, Automation, Variation in manufacturing, and Organizational learning* in different combinations. In addition to exploring academic

databases, industry publications and relevant websites for information on aircraft assembly processes were examined.

Furthermore, to find more relevant articles, snowball sampling was applied based on the publications found using the initial keywords. The purpose of utilizing snowball sampling in the literature search is to expand the understanding and knowledge of the base subject. This methodology operates on the principle that references to previous studies can lead to the identification of additional relevant sources, and thereby creating a cumulative, also known as a snowball effect (Bell et al., 2018). The outcome of this process is the establishment of a comprehensive reference framework that encompasses multiple perspectives on designing an FAL.

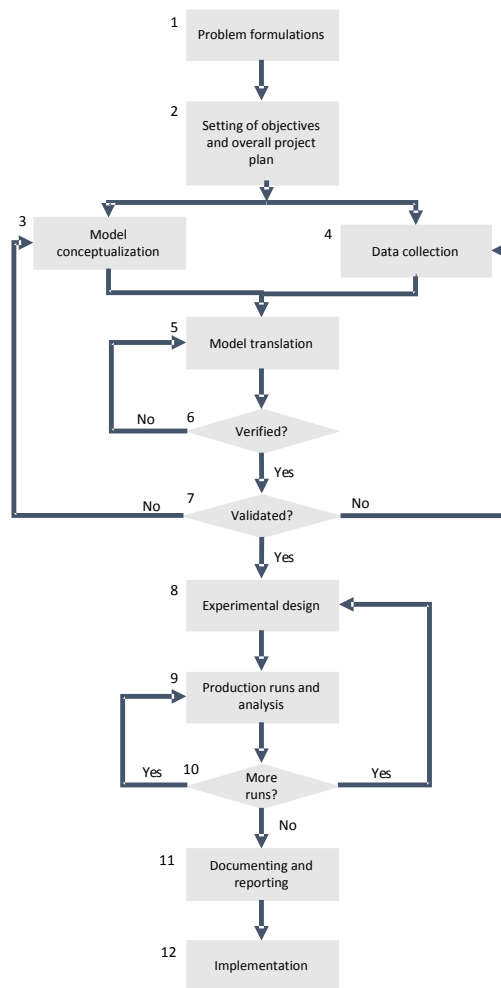
### 3.3 Simulation methodology

To question and contrast the information possessed by Heart, a discrete event simulation model representing the intended FAL was created using the software Simul8. In the software, Heart's intended FAL was constructed on an aggregated level that allowed for testing different scenarios and its effect on the output of the system. According to Banks et al. (2001), a simulation study should follow the steps presented in Figure 1 below.

These twelve steps can be categorized into four phases with the first one containing step 1 (Problem formulation) and 2 (Setting of objectives and overall project plan). Here, the modeler explores the system and builds up basic knowledge of the system and its context to formulate a problem statement. However, Banks et al. (2001) argue that the problem statement might change during the consecutive phases when more knowledge has been gathered and objectives have shifted.

Furthermore, the second phase contains steps 3 (Model conceptualization), 4 (Data collection), 5 (Model translation), 6 (Verification), and 7 (Validation). In this phase, the focus is to model the system, both on a conceptual level and in the simulation software, and to collect necessary data (Banks et al., 2001). A key objective is also to make the operational model, i.e., the simulation, to work properly without any error messages etc., i.e., verification, and to make sure that the conceptual model is an accurate representation of the real or intended system, i.e., validation.

The third phase includes the steps 8 (Experimental design), 9 (Production runs and analysis), and 10 (Additional runs). Here, Banks et al. (2001) states that the experimental design is decided, which is to decide what variables to vary to reach the objectives and find a solution to the problem statement. After that, focus is on running the model according to the experimental design to study how the input variables are affecting the output variables. Furthermore, to be able to draw any conclusions, it is often important to utilize statistical analysis.



**Figure 1**

*Steps in a simulation study*

**Note.** *Figure reproduced from Banks et al. (2001).*

Finally, the last phase involves steps 11 (Documenting and reporting) and 12 (Implementation). This step is crucial to make the decision makers understand the results of the simulation and how the results can be used in the organization. Though, this phase is not further explored in the study.

### 3.3.1 Problem formulation & setting of objectives and overall plan

In the initial phase of the study, the goal was to formulate the problem to be investigated, set up the objectives to be achieved, and formulate an overall plan. These aspects are argued by Banks (1998) to be a fundamental part in achieving a thorough and sound simulation study.

Therefore, the initial time was used to build up as much knowledge of Heart and the aerospace industry as possible. By participating in general meetings with personnel from the production department at Heart in combination with dedicated conversations regarding the study, watching videos of aircraft FALs, and doing literature searches provided us with fundamental knowledge and an understanding of the aerospace industry and the company's current situation, presented in Chapter 1.

Furthermore, the problem under investigation was initially derived from extensive discussions with Heart and their production department with many years and successful work within the aerospace industry, complemented by a review of manufacturing and aerospace literature. This process facilitated the acquisition of foundational knowledge and comprehension of the company's set objectives. By doing that, the challenges faced by the company could also be identified. Furthermore, the problem formulation (the purpose) and the objectives (the research questions) decided upon are described in more depth in Chapter 1.

### 3.3.2 Model conceptualization

According to Banks (1998), conceptual modelling is used to abstract a real-world system into a model built up of a series of mathematical and logical relationships concerning the components and the structure of the system. However, since Heart was underway with designing their FAL there was no real-world system to study. Therefore, it could be argued that the construction of the FAL was initiated with the development of the conceptual model. To do this, multiple workshops were conducted together with Heart to decide on which abstraction level the system should be studied and together it was decided to include the 41 main operations needed to assemble an aircraft and their dependencies into the conceptual model. However, these grouped activities together contain approximately 300 sub-activities, but since the aircraft is not yet fully developed and all suppliers are not selected, it would have been too uncertain to model the system on that level and a more aggregated level was chosen. Given the absence of an actual system for examination, determining the appropriate location within the system for each activity posed a significant challenge. Fortunately, the production department at Heart had already started to plan for a certain number of stations within the FAL, and together with their experience from previous programs, we could decide where along the FAL each activity should be performed, with consideration taken to the precedence constraints. Precedence constraints refer to the relationships between tasks or activities that dictate the order in which they must be performed, i.e., the wings cannot be installed before the fuselage is joined. These constraints help to ensure that an assembly object is completed in the correct sequence and that one task is not started until its predecessor has been completed.

Moreover, upon devising a rudimentary conceptual model, it was presented to the production department at Heart for their critical evaluation and scrutiny of the underlying rationale. This deliberation was facilitated by providing a tangible model, which enabled the production department to uncover novel insights. For instance, the transportation logistics between stations were deliberated upon through this approach. Additionally, it came to light

that certain activities in the model were executed by an excessive number of operators. This could be illustrated with an example. Let's say one activity was assigned 20 operators, but after deeper review and when taking the physical limitation into account, a more reasonable maximum number of operators was six.

To summarize, the conceptual model was created through intense discussions with well experienced individuals at Heart, but also through more standardized workshops where everyone had the opportunity to bring up their thoughts and opinions, which later were discussed by the whole production department to come up with final decisions for all comments.

### 3.3.3 Data collection

Banks et al. (2021) put large emphasize on collecting data with good quality. Garbage-in, Garbage-out is a basic concept in computer science and it applies to the area of discrete event simulation as well. Hence, it does not matter how well-operating and aligned the simulation model is to the real system if the input data is of bad quality since the simulation is driven by the data used for input. Furthermore, since there was no existing FAL to study it was impossible to collect observable data. Therefore, the simulation was heavily based on data from knowledge of experts in the field. To validate this data, it was decided to check the sensitivity of the results. These assumptions were made by the production department at Heart based on engineering data, expert opinion, previous experience, and physical or conventional limitations and later discussed in various workshops, which is further explained in Banks et al. (2001) and utilized in Mas et al. (2013b).

To initiate the data collection process, the production department at Heart commenced by employing the anticipated dimensions of the ES-30 aircraft as a benchmark. Specifically, they conducted a comprehensive analysis of various parameters including wingspan, total fuselage length, fuselage radius, manufacturing procedures, materials used, overall aircraft weight, and the kind of systems considered in the ES-30. The primary objective of this exercise was to estimate the total man-hours that would be necessary to complete the assembly of the entire aircraft by comparing all these metrics with previously assembled aircraft. This estimation was based on the production department's experience regarding completion time for several other aircraft of similar size. Consequently, the assembly process was estimated to require X man-hours, while the painting process, including preparation for painting and painting, was expected to require approximately Y man-hours, resulting in a total of Z man-hours required to assemble a complete aircraft when the system is fully learned. A system is considered fully learnt when the marginal improvement in processing time of producing one more aircraft is close to zero, which is further explained in Section 2.2.2. The reason for using a top-down approach for estimating the man-hours needed is because the aircraft is not yet fully designed and therefore not all the processes neither. Moreover, the bottom-up approach, e.g., doing time studies for all the required activities along the FAL, was not possible.

To determine the most feasible layout for the assembly process, several factors were considered, such as the required takt time, the size of the assembly facility, and the physical space available for operators. Eventually, it was decided by Heart that a total of 9 stations, including the paint shop, would be the most viable option to further investigate.

The time required for each station was derived by considering the previous experience of the production department. According to Heart's production department, there exists a phenomenon called "The S-curve" in aircraft assembly, which refers to the workload at different stages of the assembly line. The term is derived from the shape of the workload for the assembly line, which initially increases, reaches a peak point, decreases to a minimum, and then increases again to form an S-shape. Following this principle, the X man-hours were allocated among the 8 stations, excluding the paint shop, which itself was estimated to require Y man-hours.

In addition to calculating the total man-hours required for the assembly and painting processes, the production department also identified a diverse range of activities that were necessary to fully complete the aircraft. Drawing on their previous experience, the production department identified approximately a total of 300 activities. However, given the exploratory nature of the study and the model being too complex for this early stage, it was deemed unnecessary to consider each of these activities in detail. As such, the activities were consolidated and grouped to represent higher-level tasks. For instance, all the activities required for joining the aft and mid fuselage were consolidated under the higher-level activity named "Joint of aft and mid fuselage." This grouping yielded 41 higher-level activities, which were then assigned to the stations by Heart, according to the inherent precedence and the S-curve.

Subsequently, the assigned man-hours required and activities for each station were combined, and the aggregate hours required were apportioned among the activities specific to each station. In cases where certain activities were deemed to require a longer time or greater effort than others, which were discovered through discussions, the hours were not simply divided equally between them. Instead, a rational approach was adopted whereby the hours were assigned proportionately based on the estimated effort required for each activity. The manufacturing engineering department undertook a deeper examination of the first station, the Joint Hangar, to assign the hours more accurately for each activity. This was due to the processes within this station being less uncertain than the other stations along the assembly line.

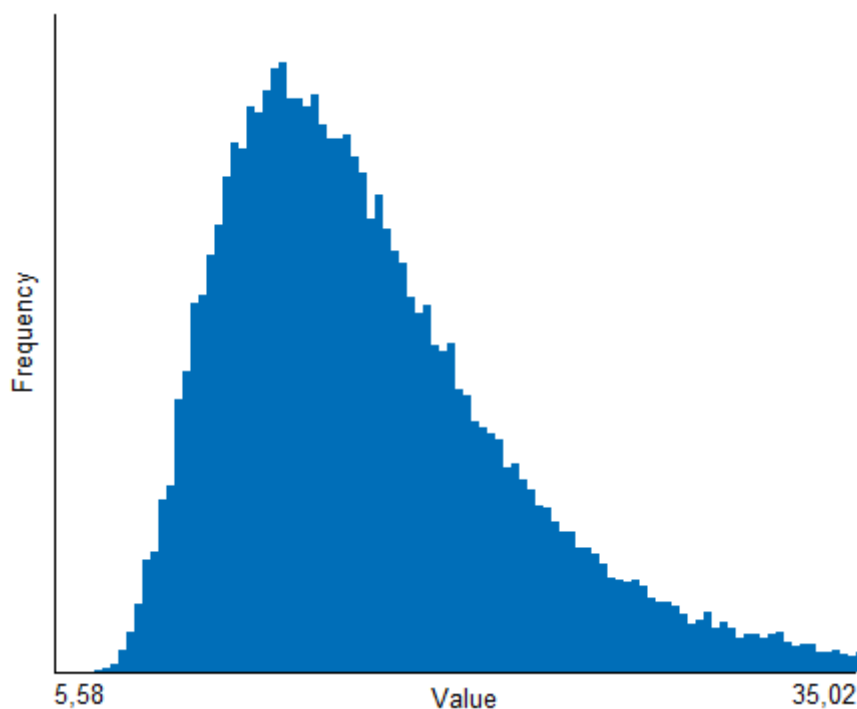
Furthermore, the production department engaged in a discussion regarding the time required to move the aircraft from one station to the next. Transport was determined to be a stable and secure process that did not require significant time investment. As such, a decision was made to allocate one hour for transportation time.

Since activities in the model consists of several sub-activities and the fact that Heart provided the average man-hours required for each activity, the flaw of averages became prominent.

This term was coined by Dr. Sam Savage (Savage, 2000) and states that: “Plans based on the assumptions that average conditions will occur are usually wrong.” (p. 1). To correctly capture the impact of having variation within a system, it is important to consider each data point possible. Though, to represent the reality more precisely, it was decided to incorporate variations in the time required for each activity. After consulting with the supervisor at Chalmers, who possessed extensive expertise in production systems and manual assembly processes, and the well experienced production department at Heart it was concluded that the average man-hours required was allowed to vary +/- 10% for 95% of the instances. To incorporate this into the model, a log-normal distribution was utilized to represent manual assembly activities and the variation. The choice of distribution was informed by several factors, including the desire for an offset that reflects the minimum time required to complete a task, since an activity has a minimum time that cannot be exceeded, as well as an average time that reflects the typical duration of most tasks. Additionally, we sought a distribution that was rightly skewed, which would allow for the inclusion of instances where unexpected events such as errors, missed parts, or machine breakdowns led to a significant increase in the time required for a given task. Although the Weibull and Gamma distributions were also considered, we ultimately decided to employ the log-normal distribution, shown in Figure 2.

**Figure 2**

*Log-normal distribution*



**Note. Only for illustrative purposes. The figure is an example of a log-normal distribution with the lowest value of 5, standard deviation of 2.5, and an average value of 10. Moreover, the figure clearly states how required man-hours for each activity is allowed to vary.**

Through the adoption of a process-oriented approach and by tackling the challenges arising from the complex, uncertain, and dynamic nature for this early stage regarding the assembly line, an operating model that can enhance the conceptual design of an aircraft assembly line has been created. While the present study has incorporated various methodologies to capture diverse perspectives, it is important to recognize that certain variables may pose difficulties in their precise quantification, requiring the use of conjecture and approximation. Thus, a comprehensive understanding of the industry and relevant theory is crucial to support the development of evidence-based data.

### 3.3.4 Model translation

Numerous software applications are available for simulation, each endowed with distinctive merits and demerits. The present study employed Simul8, as it was deemed suitable since Chalmers University already possessed the requisite licenses, coupled with the presence of expertise within the academic institution. Furthermore, the operationalization of the conceptual model was executed via Simul8, wherein all system activities and underlying logic previously mapped out, were incorporated into a functional simulation model.

### 3.3.5 Verification and Validation

The goal of having a verified model is, according to Banks (1998), to have the operational model working as intended. That is, the operating model can be run without any errors and warnings and all components intended are included. This was a continuous process performed together with the supervisor from the University, mainly through using Simul8's built in debugging tool and by incorporating animations in the model to see if entities were flowing as intended when at the same time advancing the simulation clock manually. Also, a sign was included in the model to signal when a station performs work on the assembly object, which was used to see if the transportation between stations was executed correctly. Furthermore, to facilitate the verification process, a technique called "Divide and Concur" explained by Chung (2003) was used. That is to have a model containing several smaller sub-models that are put together once each is verified.

To have a validated model implies that the conceptual model is an accurate representation of the real system (Banks, 1998). Without a validated model it is impossible to make a proper analysis and draw conclusions that are representative for the real system (Chung, 2003). Furthermore, Chung (2003) argues that two types of validation can be achieved, face validity and statistical validity. Face validity implies that the model, at least on the surface, represents reality and statistical validity involves quantitative comparison between the output of the model and the actual system. However, since there was no real system to compare with, the

statistical validity was impossible to achieve. Moreover, the validation process was relying on achieving face validity through discussions with experts from Heart. Chung (2003) emphasizes the significance of maintaining a current list of assumptions for the purpose of validating the model. This catalogue was presented to the personnel of Heart and deliberated upon to reinforce its connection to actuality. During these discussions, it was revealed that certain assumptions were inaccurately articulated and subsequently rectified, whereas others could be excluded from the list owing to the obtainment of information concerning those facets. Furthermore, in parallel to the development of the simulation model, several workshops were conducted with Heart to align the logic in the model with reality. Moreover, when a new subsystem was included in the model, it was presented to Heart to make sure the model operated as intended, i.e., that the entities in the model flowed correctly. Another tool used to validate the model was to perform sensitivity analysis. By increasing the process times for some activities or reducing the number of operators for others, the entities flow in the model could be studied better and faults could be detected.

### 3.3.6 Analysis of the system

The following section puts emphasize on what Banks (1998) refers to as “Experimental design”, “Production runs”, and “More runs?”, here from referred to as Analysis of the system.

The experimental design adheres to the guidelines established by Banks (1998) with regards to determining the appropriate duration for each simulation run, how many runs should be done, and what initialization values the model should have, i.e., how the model should look when a new simulation run starts. Additionally, Banks (1998) highlights the importance of deciding a suitable analysis method. After that, production runs are performed, i.e., experiments are conducted in the software according to the design previously chosen. Lastly, if the results are not satisfactory, more runs might be necessary to get valid results.

For this simulation study, a full factorial experimental design was chosen. To answer the research questions six different factors in the model were chosen to vary between two different levels, one optimistic level and one pessimistic. In a full factorial design, all the different factors are tested in all combinations possible and the performance measure, in this case the output of the FAL, for each test is documented. Since all combinations need to be tested, six factors having two levels each, results in 64 (two to the power of six) combinations that need to be tested. The rationale behind using a full factorial design is, according to Bergman and Klefsjö (1995), that all the different main effects and interaction effects can be studied. In addition, by using a full factorial design, sub-optimizations can be avoided which is a prevalent problem in other experimental designs. Although the number of tests to perform might be enormous, it is beneficial when no factors are deemed to have a bigger effect on the system beforehand (Bergman & Klefsjö, 1995).

Furthermore, the main effects are described by Bergman and Klefsjö (1995) as how each factor affects the response variable, i.e., the output of the system, when varying between the

optimistic and pessimistic settings. In addition to main effects, interaction effects between factors can also be prevalent. The interaction effects are described by the same authors as how the factors together affect the system. For instance, if two factors each give the system a 5 percent increase in output when varied from pessimistic to optimistic level tested individually, but the sum of both only gives 8 percent, then the interaction effect is -2 percent. Bergman and Klefsjö (1995) state that the interaction effects easily is captured with a full factorial experimental design.

Additionally, after the experimental design is chosen and before all 64 tests can be performed, the length of each run and number of replicates for each run needs to be decided (Banks, 1998). The length of each run was initially set to be 251 days since it is the average amount of working days in one year in Sweden. Moreover, the results could easily be compared, translated, and explained for Heart. Furthermore, the number of replicates was initially set to five and it was later shown to be enough to get a satisfactory uncertainty interval for the experimental error, i.e., small enough to capture the required details.

Furthermore, the determination of initialization values for the simulation was imperative. As stated by Chung (2003), disparate systems exhibit unique behaviors, whereby certain systems commence each day in a completely empty state, while others operate continuously throughout the year. In the present simulation model, the system is initialized as completely empty, although this does not align with the actual operation of the system. Consequently, the establishment of a warm-up period became necessary. This warm-up period allows for the system to accommodate its initial empty state, requiring the passage of time before meaningful results can be collected from the simulation.

Additionally, to ascertain the appropriate duration of the warm-up period, various starting points for result collection were tested. It was observed that as the starting point was pushed further into the simulation, the output no longer exhibited any significant variations. This signified the attainment of a steady state within the system. Based on this criterion, a warm-up period of 1000 hours was determined.

### 3.4 Ethical considerations

According to Bell et al. (2018), researchers must address four key areas pertaining to research ethics in order to ensure a robust research project. These four areas encompass the topics of *Harm to participants*, *Lack of informed consent*, *Invasion of privacy*, and *Deception*. The ethical considerations discussed by Bell et al. (2018) primarily revolve around safeguarding the well-being of the study's participants. In the present simulation study, external participants were not involved, and the sole participant that necessitates consideration is the case company, Heart Aerospace.

For instance, the aspect of *Harm to participants* underscores the importance of ensuring that no harm is inflicted upon the respondents involved in the study, be it physical, societal, psychological, or in other ways. To safeguard Heart Aerospace from any harm arising from

this study, necessary data has been anonymized and omitted from this report to prevent the leakage of confidential information to competitors and other entities.

Concerning *Lack of informed consent*, the objective is to provide comprehensive information to enable respondents to make an informed decision about their participation in the study (Bell et al., 2018). Given that the master's thesis was a suggested proposal from Heart, they were fully aware of the nature of their involvement, rendering this aspect negligible during the study.

The third aspect to consider is *Invasion of privacy*, which pertains to the protection of participants' privacy (Bell et al., 2018). In compliance with this standard, all information included in the report has been reviewed by Heart themselves, and necessary measures have been taken to anonymize or withhold sensitive information.

Lastly, *Deception* refers to the scenario where the researcher presents the research as something other than its true nature (Bell et al., 2018). However, since this thesis has been conducted based on Heart's explicit request, they have defined the objectives, and the authors of the research have not deviated from this understanding.

## 4. Modelling the assembly line

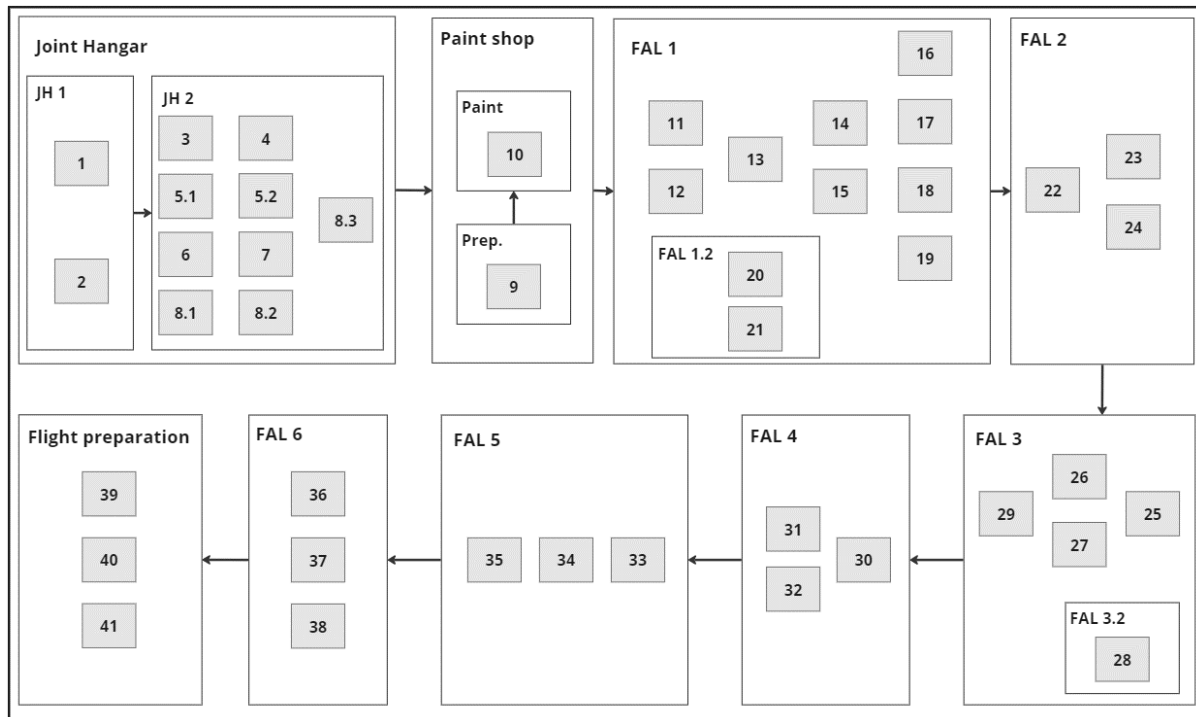
The primary objective of the aircraft assembly line is to integrate various structural components and advanced technologies into a fully operational aircraft, with the goal of ensuring timely delivery to customers. To achieve that objective, the assembly line must undertake approximately 300 activities, which are distributed across several stations. Each station comprises a distinct number of activities, each with varying degrees of complexity. Due to the high complexity of modeling 300 different activities, particularly during the early stages of production system development, when Heart or their suppliers have not yet determined exactly which activities to perform, similar activities have been grouped within each station for simplicity, as explained further in Section 3.3.3. Consequently, the model contains 41 activities instead of approximately 300 separate ones. Each activity within a group has a corresponding processing time that denotes the required number of man-hours to complete. For example, an activity that necessitates 10 man-hours will need 10 operators to finish it within a single hour. Additionally, the order in which the activities are executed is subject to precedence constraints, which are determined by the production department at Heart.

As most of the activities on the assembly line are manual or semi-manual, they require the involvement of operators. The production is organized around a three-shift schedule, with a specified number of operators assigned to each station. It is anticipated that each operator will perform 6.5 man-hours of work within each shift, when breaks and other non-value adding time are deducted. Furthermore, since all structural components and parts will be sourced from multiple suppliers in combination with the fact that all suppliers are not selected yet, forecasting the potential impact of delayed or defective deliveries has been challenging. Consequently, the model always presumes that all materials are available in stock and that it meets the required quality standards to prevent any delays or bottlenecks.

The stations are organized from left to right and consist of the Joint Hangar, the Paint Shop, FAL stations 1-6, and Flight Preparation. A conceptual view of the assembly line is shown in Figure 3 below.

**Figure 3**

*Conceptual model containing all modeled activities*



**Note.** The figure presents all modeled activities within each station and where transportation is conducted (represented by arrows). The U-shaped FAL is only for illustrative purposes.

The allocation of parts, tools, and operators is exclusive to each station. Importantly, only one aircraft can be processed at any given time across each station on the assembly line, except for the Joint Hangar, the Paint Shop, and the Flight Preparation where two aircraft structures are processed at the same time in the first two, and three can be processed in the Flight Preparation. Any delay in a single station will result in a holdup across all stations since physical buffers between stations are absent.

Although buffers are absent between stations on the FAL, buffers exist for smaller components within the stations, but since all materials are assumed to be available in the model and small components are not included, these are excluded. Furthermore, the transportation of the aircraft between stations on the assembly line employs diverse methods such as overhead cranes, tow-trucks, and air skates. However, since the mode of transportation is not yet decided, all transportations activities are modeled to take exactly one hour based on discussions with Heart.

## 4.1 Overview of the Assembly line

It is important to note that the aircraft is stationary within each station and that Figure 3 only displays which activities are to be performed in what order by the operators, not the movement of the aircraft within each station. Each rectangle containing a number represents an activity that needs to be performed for the aircraft to be completed. These differ across all stations, however, due to uncertainties surrounding the limited flight time for electric aircraft and the behavior of the technology when fully assembled, three rectangles have been included within the Flight Preparation to represent the same activities, i.e., activities 39, 40, and 41 represent the same activity performed in parallel. Furthermore, activities placed in a vertical line can be performed simultaneously and the activities placed afterwards can only be performed once all preceding activities are done, i.e., precedence constraints.

As can be seen from Figure 3, FAL station 1 and 3 are being fed by one sub-assembly station each, FAL 1.2 and FAL 3.2. In reality, all stations are to be preceded by a sub-assembly station, but for now, the details of what to include in those are too vague and therefore cannot be included in the model. To account for this, all activities are modeled to take place within the station, even though some are to be performed in a sub-assembly. Concerning the rectangles that include a dot, specifically activity 5.1, 5.2, 8.1, 8.2, and 8.3, it should be noted that they depict a single activity that has been partitioned for the purpose of accommodating physical constraints and adhering to the logical structure of the model. Due to the limited number of operators who are able to perform activity 5, due to limited space, it has been partitioned into two precedence states to enable the collection of valid data. Similarly, activity 8 is subject to analogous constraints, wherein the final step is contingent on the completion of all preceding activities and is thus carried out as an independent task at the conclusion of the process. Each activity is subject to a required number of hours to complete, which is distributed under a log-normal variation, chosen after discussion and research as explained in Section 3.3.3. Additionally, the arrows in Figure 3 represent the movement of the aircraft between stations.

### 4.1.1 Joint Hangar

The first station on the assembly line is called the Joint Hangar. The Joint Hangar constitutes two positions where the first one, JH 1, performs the fuselage joining. Here, the fuselage is being joined together from three separate parts, aft, mid, and front fuselage. This is an intricate operation performed by operators that requires precision in alignment with laser measurement tools. When that is complete, the fuselage is moved to the second position, JH 2, where all doors are installed at the same time as some activities for fuselage completion are performed. Moreover, two fuselages are always being worked on simultaneously in the Joint Hangar. As previously explained in Section 3.3.3, the time required to perform all activities within the Joint Hangar stems from how the S-curve is distributed, and the required time for each separate activity has been estimated by the production department at Heart.

#### 4.1.2 Paint Shop

The process of painting various components and parts of the aircraft is a labor-intensive task that necessitates the involvement of multiple operators. However, the process is currently quite uncertain. Prior to painting, the parts must be subjected to preparatory procedures such as cleaning, masking, and chemical treatment. While different parts may follow distinct routes through the Paint Shop, the current lack of firm decisions has necessitated a simplification in the model. Therefore, all processes have been aggregated and the Paint Shop has been modeled with two distinct positions, Preparation (Prep.), which handles the preparatory stage for all components, and Paint, which is responsible for the actual painting process. Between these two positions all parts need to be transported.

#### 4.1.3 FAL station 1

Upon arrival of the painted fuselage at the initial FAL station, the primary objective is to attach the wings. To achieve this, the wings are prepared at a sub-assembly station one takt time prior to the arrival of the fuselage, in order to facilitate their prompt attachment. Once the wings have been installed onto the fuselage, a series of structural supports for the wings are put in place, alongside preparatory activities for the subsequent attachment of electrical engines later in the FAL process. In addition to this, certain mechanical and electrical pre-equipage components, such as harnesses and air ducts, are also installed onto the aircraft.

#### 4.1.4 FAL station 2

The second station of the FAL entails numerous uncertainties; however, its principal objective is to install the landing gear. Given the substantial degree of uncertainty encompassing this station, all its activities have been consolidated into three key blocks. The initial block involves the implementation of various mechanical systems, including the main and nose landing gear installations. The subsequent blocks pertain to the installation of certain electrical systems, predominantly featuring COAX cables that facilitate communication between diverse systems integrated later in the process.

#### 4.1.5 FAL station 3

The third FAL station is dedicated to the installation of the aircraft's empennage or the rear section. The empennage is assembled by joining the vertical and horizontal tail planes in a sub-assembly station one takt time prior to the aircraft's arrival. However, certain mechanical and electrical systems must be installed before the empennage can be attached to the fuselage. Moreover, while the empennage is being prepared for the subsequent aircraft, the present aircraft simultaneously undergoes system installations upon entering the third FAL. Once the various systems are installed, the empennage is raised and mounted onto the fuselage.

#### 4.1.6 FAL station 4

The fourth FAL station is mainly designated for the installation of the aircraft's four electric motors onto its wings. While the installation of the motors at this station is certain, the precise installation procedure has yet to be definitively determined by Heart. Thus, the station is structured with three primary activities, including the implementation of a mechanical system installation, specifically, the installation of electric motors, as well as two electrical system installations incorporating various systems essential for flight control, among other things. The mechanical system installation is carried out before the subsequent electrical systems can be integrated onto the aircraft.

#### 4.1.7 FAL station 5

Upon reaching the fifth FAL station, the exterior of the aircraft looks like a real aircraft. Nevertheless, the aircraft's internal section remains barren, thereby mandating the fifth station's solitary commitment to the installation of the entire interior components. The interior components are segregated into three primary activities that encompass the seating, overhead bins, lavatory, galley, and other relevant features. After the operators conclude the installation of a specific activity, they proceed to the subsequent activity until all three are comprehensively implemented.

#### 4.1.8 FAL station 6

When reaching the sixth FAL station, a few of the most expensive systems remain absent from the aircraft, notably the battery packs and turbo generators. This deliberate strategy to defer the installation of these components until later in the assembly process serves to minimize tied-up capital. The sixth station also encompasses the installation of other electrical systems and some interior features. Of particular note is the intricate nature of the battery installation process, which presents an unprecedented challenge and may require revision of existing estimates. Upon successful completion of this stage, the entire assembly process concludes, and the aircraft undergoes testing.

#### 4.1.9 Flight Preparation

The final stage prior to the delivery of the aircraft to the customer is the flight preparation phase. Here, the aircraft undergoes extensive testing, with all its systems rigorously scrutinized against a checklist. Upon successful completion of this stage, the aircraft takes off for in-air testing, during which its handling and performance are evaluated to ensure optimal functioning. This stage presents significant uncertainties, primarily because the conventional aircraft typically requires approximately three hours to complete all in-air checks, whereas the ES-30 is an electric hybrid aircraft with a significantly shorter airtime. As such, it may require multiple battery recharges to complete a full test cycle, resulting in the time required for this stage being subject to revision in the future. To accommodate this uncertainty, the

Flight Preparation station features three positions for the concurrent testing of multiple aircraft.

## 4.2 Assumptions and model simplifications

In practical settings, a production system is subject to several different factors, prompting the need to make assumptions in the modeling process to avoid being bogged down by details. When considering the individuals responsible for executing the various tasks, it is important to note that the model operates under the assumption that the number of operators available to perform a given task is not constrained by spatial or environmental factors, except for the Joint Hangar, and activity 13 and 29 where physical constraints are considered. Additionally, the operators do not experience diminishing marginal returns when performing tasks together. Lastly, all operators in the system can perform all tasks and equally good within their assigned activity.

Moreover, the current report underscores the limitation of real-life data, rendering it unfeasible to analyze variations across different components and estimated operations within the system. In light of this constraint, and the fact that the study does not specifically focus on activity-specific features, an approach was adopted to simplify the model by consolidating activities that encompass multiple distinct tasks. This simplification addresses uncertainties related to the delineation of responsibilities between suppliers and Heart.

Furthermore, the allocation of required hours for completing activities at all stations in the model adheres to the S-curve phenomenon expounded upon earlier in this report. To model the diverse activities involved in the assembly line, all are present to variation of log-normal distribution, decided after research and discussion with the supervisor at Chalmers. The utilization of the log-normal distribution was deemed appropriate given the limited availability of comprehensive data for conducting a more exhaustive analysis.

Given that the system in question is not an assembly line with a conveyor belt mechanism, the transportation of aircraft between different stations is a necessary consideration. This model assumes that the time required for each transport movement takes exactly one hour for each station pair, commencing after the completion of transport for the preceding station.

The supply of materials is a critical element to consider in assembly line planning, as it significantly impacts the system's ability to function effectively. However, in this particular model, material supply is not considered.

In addition, the principle of learning by doing is of considerable significance in the planning and analysis of assembly lines. This report pertains to a later phase of the production process, where maximal output serves as the foundation and the system has been in operation for a substantial duration, yielding numerous aircraft. Consequently, the system can be regarded as having achieved full proficiency and be treated as fully learned. As a result, the process times remain constant throughout the simulated year, owing to the attenuated effects of the learning by doing observed in proficient systems.

For Heart to reach the desired output from the assembly line, it is necessary to implement three shifts. Despite potential variability in efficiency, quality, and productivity among these shifts, the model assumes their equivalence in all aspects, owing to a lack of industry-specific information.

Since the study investigates the maximum output given a certain number of operators, there are no limitations in orders received by Heart. Moreover, the model assumes an infinite order backlog wherein the initiation of production for a new aircraft is immediately started upon the availability of an unoccupied station. Additionally, it is also assumed that only one aircraft model is produced and the level of customization between orders is low. Consequently, uniformity ensures that all aircraft are manufactured following identical procedures.

The assembly line encompasses various tasks that differ in complexity, potentially influencing the variation of process times and the quality of activities performed. However, the model assumes equal complexity for all activities, as uncertainty regarding the extent of Heart's involvement and outsourcing precludes the identification of variations in complexity and the fact that the activities in this model are several of smaller activities grouped together.

In high-quality production industries such as aerospace industry quality-related problems in the assembly line can be a prevalent issue. However, the introduction of new technology and electrical components in this product introduces substantial uncertainty regarding the occurrence of quality issues. Therefore, the model assumes that no quality-related challenges will occur on the assembly line, since no data regarding this is available.

## 5. Test Scenarios and Results

The following chapter will encompass the presentation of findings pertaining to Research Questions 2, 3, and 4. The chapter commences with an exposition on the development of the baseline model and the determination of the necessary number of operators. Subsequently, Section 5.2 elucidates the tested scenarios intended to address Research Questions 3 and 4, followed by Section 5.3, where the outcomes of the conducted experiments are presented.

### 5.1 The baseline model

Following the comprehensive overview of the model, the production department at Heart provided the pertinent data regarding the allocation of man-hours to each activity within every station, which were subsequently incorporated into the model. Upon the successful integration of all relevant values, the determination of the required number of operators for each station was made based on the corresponding man-hours associated with those activities. Subsequently, by conducting a simulation employing the production department's provided figures, the assembly line achieved a production output of 89 % of the intended output within a year. Moreover, all results presented in this chapter corresponds to how the required number of operators deviates from Heart's previous calculations.

To determine the minimum number of operators required to achieve the target output, a bottleneck analysis was conducted. Since a system cannot perform better than its weakest link (Jonsson & Mattsson, 2009), it is reasonable to start improving the bottleneck first. Looking at the results from the initial simulation-run, it could be determined what station had the highest utilization, and therefore was seen as the bottleneck of the system. Due to the characteristics of the model, adding operators to specific tasks within the specific station will contribute to a faster completion time and consequently lowering the utilization. After adding one operator to the station with the highest utilization, the simulation was run again, and the new results analyzed. The same process was repeated and subsequently, the new main bottleneck was identified, and one operator was added to that station. This iterative process continued until the assembly line was able to deliver according to the business plan. Once the goal was met, the station with the lowest utilization was identified, and a test was performed by removing one operator to investigate the potential to reduce the number of operators. The simulation was run again, and the output was analyzed to assess if the assembly line continued to deliver as intended aircraft. Like the iterative process of adding operators, the iterative process of removing operators continued until removing one additional operator led to a reduction in output.

Upon comparing the number of operators required according to the production department at Heart and the simulation results, the simulation necessitated an increase in number of operators with 2.6 % to achieve the target output. The deviation from what Heart previously calculated can be found in Table 1.

**Table 1***Distribution of required operators to produce according to the Business Plan per year*

Station	Deviation from Heart's calculations	Station	Deviation from Heart's calculations
JH	+20 %	FAL 4	0 %
Paint	0 %	FAL 5	0 %
FAL 1	+9 %	FAL 6	12.5 %
FAL 2	0 %	FP	-5 %
FAL 3	0 %		

**Note.** *The table displays the deviation in number of operators needed per station to produce the decided number of aircraft per year. I.e., +20 % represents an increase in operators.*

The balanced model was used as the baseline model for further experiments presented in the following sections.

## 5.2 Tested Scenarios

To further analyze the assembly line and to answer the research questions, different scenarios were discussed. After balancing the model, the final run was analyzed to identify what stations had the highest utilization. In order to find out how an error in the estimated process times would affect the output of the system, the average required man-hours provided by Heart became a factor to vary. However, since changing the input for the stations with relatively low utilization will most likely not have a considerable effect on the output of the assembly line since there exist extra capacity, the stations with the highest utilization, all over 90%, were chosen for further analysis. According to the baseline model, FAL station 2, 3, 4, and 6 had the highest utilization and was therefore chosen. Through discussion with the production department at Heart it was decided that a reasonable value for a miss estimation of man-hours required could be an increase of 10% across all the activities within a station. A bigger underestimation than this was not seen as reasonable.

Beyond these stations, it was decided, through discussion, that the Flight Preparation should be further analyzed. This is due to the uncertainties regarding this specific station and how, for now, the limited knowledge about, e.g., electric aircraft regarding certifications, tests to be done, and weather conditions affecting the tests. Just like the stations mentioned above, it was decided through discussion that a misestimation of 10% was reasonable.

Lastly, it was decided to further analyze what impact a bigger variation than 10% could have on the output, due to how little Heart knows about what processes will be required, their complexity and rework-rate, a variation of 30% was used. This number comes from an article written by Wild (1975), where the author indicates that a bad performing assembly line in the automotive industry could be working under variations as high as 30%. Comparing the

complexity of the tasks, the amount of repetition, and the possibility to standardize the work in the two different industries, it was reasonable to choose the increased level of variation to 30% as well. Therefore, the last factor was decided to be a change in variation across the whole system from 10% to 30%.

In summary, six distinct factors have been selected to vary between two levels, see Table 2, to analyze the system. These factors encompass the average man-hours required for stations FAL 2, 3, 4, 6, and FP with the objective of exploring variations between the estimates of the required man-hours provided by Heart and an increase of the value with 10%. Additionally, the variation across the entire system was modified from 10% to 30%. It is important to note that a full factorial experimental design has been adopted, entailing six factors with two levels each. As a consequence, a total of 64 tests are necessary to comprehensively analyze all the potential combinations arising from the varying factors.

**Table 2**

*Description of the factors tested*

<b>Factor - Location</b>	<b>Description</b>	<b>- (optimistic)</b>	<b>+ (pessimistic)</b>
A – FAL 2	Required man-hours	Data from Heart	Increase with 10%
B – FAL 3	Required man-hours	Data from Heart	Increase with 10%
C – FAL 4	Required man-hours	Data from Heart	Increase with 10%
D – FAL 6	Required man-hours	Data from Heart	Increase with 10%
E – FP	Required man-hours	Data from Heart	Increase with 10%
F – Whole system	Variance	10%	30%

**Note.** *The letters in the first column will be used to facilitate the presentation of the results further on, instead of writing out the full name. The second column describes what is being changed for each factor, and the last two ones describe between what levels the factors will vary.*

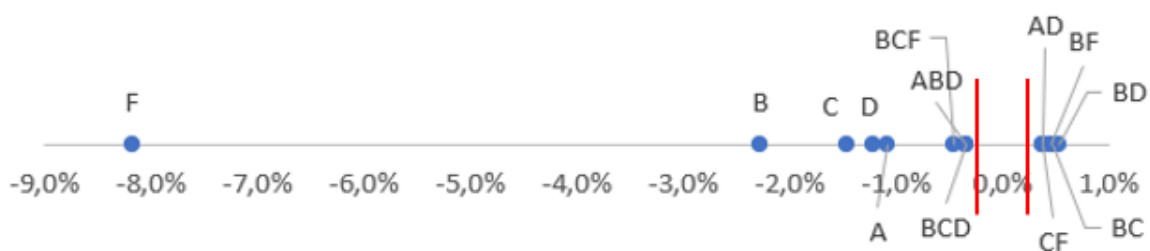
### 5.3 Results from the experiments

Upon completion of all tests, the calculation of 63 main effects and interaction effects became possible. Notably, each test was executed with five replicates, thereby enabling the computation of the average system output and the variance associated with each test configuration. A total of 32 tests were conducted for each factor at both the optimistic (-) and the pessimistic (+) levels. The difference between the average output obtained at the optimistic and pessimistic levels, divided by 32, provides the average effect of a single factor on the system, commonly referred to as the main effect. In this section, all percentage represents to what degree the system fulfills the output set in Heart’s Business Plan.

However, in order to determine whether the observed effect is a result of common cause variation or if it possesses a significant impact on the system, it is necessary to assess the uncertainty inherent in the test results, as outlined by Bergman and Klefsjö (1995). This involves calculating the uncertainty interval for the experimental error, where the experimental error is measured in standard deviations of the response variable, i.e., the output of the system. Moreover, the experimental error was 0.17 % of the targeted output and the 95% confidential interval for the experimental error became +/- 0.33 % of the targeted output, subsequently resulting in the same uncertainty interval. The uncertainty interval determines the level of precision with which the study can differentiate between common cause variation and effects that have a statistically significant impact on the system. Any factors demonstrating effects falling within this interval cannot be discerned from the common cause of variation, that is, nothing can be said about these factors' effect on the system, see Figure 4.

**Figure 4**

*Significant factors falling outside of the uncertainty interval*



**Note.** *The figure presents all 13 main effects and interaction effects having a significant impact on the system. The rest of the effects falls inside the uncertainty interval represented by the two red lines. The percentage represents the deviation from the targeted output.*

The present study displays the outcomes of a full factorial test that involved 64 runs, each of which tested different combinations of the six factors. For the purpose of clarity, all main effects and the 8 interaction effects that exhibit outcomes outside the uncertainty interval, and thus are considered to have a statistically significant impact on the output, are presented Table 3.

**Table 3***All main effects and all interaction effects having a statistically significant impact*

<b>Factor - Location</b>	<b>Effect</b>	<b>Factor</b>	<b>Effect</b>
F – Whole system	-8.18 %	BF	0.45 %
B – FAL 3	-2.27 %	BCF	-0.45 %
C – FAL 4	-1.46 %	CF	0.39 %
D – FAL 6	-1.22 %	AD	0.37 %
A – FAL 2	-1.07 %	BCD	-0.34 %
BD	0.53 %	ABD	-0.34 %
BC	0.48 %	<b>E – FP</b>	<b>-0.16 %</b>

**Note.** All factor's effects presented in the table have a significant impact on the system, except for the effect factor E colored in red. The percentage represents how the target output is affected of having different factors active.

After the completion of the test, it was possible to evaluate the effects of the different factors by themselves and in combination on the output, as demonstrated in Table 3. All main effects except one were active and had a statistically significant impact on the output. The variance of the system, factor F, had the most prominent effect on the output, with an average of -8.18 % when shifted from the optimistic to the pessimistic level. That is, the output of the system is on average reduced with 8.18 % per year when the variation increases from 10% to 30%. The effect of factor F is followed by factors B, C, D, and A, which also exceeded the uncertainty interval values. However, factor E fell within the uncertainty interval, and its effect on the output cannot be determined.

Looking at Table 3, it becomes evident that the two factors F (variation within the system) and B (average required man-hours for FAL 3), stand out from the others. Factor F has the biggest effect on the output, an average decrease of 8.18 % per year when shifted from optimistic to pessimistic level. The second most influential factor is factor B, which, on average, reduces the output by 2.27 % per year. Moreover, to have a system with a variation of 30 % instead of 10 % would have a considerable impact on the system, and an underestimation of the required man-hours for FAL station 3 would also have that.

Since the uncertainty interval of the experimental error in the result is +/-0.33 % of the targeted output, each effect presented in the aforementioned table contains an uncertainty.

For instance, factor F is indicated to have an effect of -8.18 % on the system. However, considering the uncertainty in the study, it is equally plausible for the effect to fall within the range of -8.51 % to -7.85 %. Consequently, drawing definitive conclusions regarding the relative magnitude of impact between different factors becomes challenging and inconclusive.

The three factors, C (-1.46 %), D (-1.22 %), and A (-1.07 %), have all been found to exert a statistically significant effect on the output. However, due to the aforementioned uncertainty, it is infeasible to rank them in order of magnitude. To elaborate, suppose that the effect of factor A is subjected to the experimental error of -0.33 % and factor D to the experimental error of 0.33 %, then their values would become A (-1.4 %) and D (-0.89 %), respectively, and consequently their order, based on magnitude, would differ from the values presented in Table 3. The same reasoning holds true for factor C as well. Moreover, the ranking in order of magnitude is inconclusive between these three factors.

The following interaction effects, with BD being the one with the biggest impact of 0.53 %, and the combination of A, B, and D (ABD in Table 3) having the least, 0.33 %, also have a statistically significant effect on the system. However, the relatively small disparity between all interaction effects and with consideration taken to the uncertainty interval precludes any definite ranking of the combinations.

Furthermore, to more accurately see how the factors' different levels affect the output, a regression model has been created from the results, see Equation 1. By taking the average output from all 64 tests and adding or subtracting each statistically significant main effect and interaction effect, the output will be given based on what factors are considered. For instance, if the output is of interest when factor A and B are on the pessimistic (+) level and the rest of the factors are on the optimistic (-) level, all A's and B's are substituted to +1 whereas the rest of the letters corresponding to factors are substituted to -1. Then a simple calculation provides the output of 90 % of the production goal. Worth noting is that all terms represented in the equation below contain uncertainty of +/- 0.33 %, and it is therefore the output from the equation differs from the same run in Table 4. To account for this, an error term ( $e$ ) is included in the equation.

### **Equation 1**

*Regression model deducted from the simulation*

$$\begin{aligned}
Output = & 89.5\% + \frac{-1.07\%}{2} \times A + \frac{-2.27\%}{2} \times B + \frac{-1.46\%}{2} \times C + \frac{-1.22\%}{2} \times D \\
& + \frac{-8.18\%}{2} \times F + \frac{0.37\%}{2} \times A \times D + \frac{0.48\%}{2} \times B \times C + \frac{0.53\%}{2} \times B \times D \\
& + \frac{0.45\%}{2} \times B \times F + \frac{0.39\%}{2} \times C \times F + \frac{0.48\%}{2} \times B \times C + \frac{-0.33\%}{2} \times A \times B \\
& \times D + \frac{-0.34\%}{2} \times B \times C \times D + \frac{-0.45\%}{2} \times B \times C \times F + e
\end{aligned}$$

**Note.** *e* represents the uncertainty in the model. The percentage represents how the system deviates from the targeted output.

Another advantage of having a regression model is the possibility to interpolate. By substituting the letters with values between -1 and 1, the output can be estimated for factor values in between the two levels. Moreover, the equation given above can be used as a substitute for the simulation model when that is not available.

### 5.3.1 Tests runs

As previously explained, 64 runs have been conducted and are showcased in Table 4. Some of these cases are worth extra attention. First of all, the worst-case scenario, run 64, found in the experiments yields 82.5 % of the targeted output, a decrease of 17.5 % from the targeted value. This scenario occurs when all six factors are on their respective pessimistic level. Furthermore, since increasing the variation from 10 % to 30 % throughout the system has the biggest impact on the output, it is interesting to see how the worst case would look like if the variation is kept at 10 %. This set-up, run 32, demonstrates an output of 91.3 % from the target value, a decrease of 8.7%. Additionally, by studying Table 4, it can be found that the average output from the system having 10 % variation is 93.7 % of what was originally planned. Whereas a system with 30 % variation only reaches an average output of 85.4 %. The difference between these two numbers is the main effect for factor F.

Looking at Table 4, a distinct factor emerges that sets certain runs apart. It is evident that all 16 runs exhibiting the highest average output correspond to FAL 3 configured in its optimistic setting. Conversely, the eight runs with the lowest average output correspond to FAL 3 configured in its pessimistic level. Furthermore, it is noteworthy that all 32 runs exhibiting the lowest average output align with the system variance set to its pessimistic level.

Among all the analyzed total runs, only two of them exhibit an average output that meets or surpasses the production target. The first case is with all factors on their optimistic (- 1) level (run 1), and the second one is with all factors on their optimistic level except the Flight Preparation (run 17). As previously mentioned, the Flight Preparation is not considered to have a statistically significant effect on the output.

**Table 4**

*Output achieved from all 64 runs*

Factor	A	B	C	D	E	F	Output
Run	FAL 2	FAL 3	FAL 4	FAL 6	FP	Variance	Percentage of baseline output
1	-1	-1	-1	-1	-1	-1	100%
17	-1	-1	-1	-1	-1	-1	100%
2	1	-1	-1	-1	-1	-1	95,3%
18	1	-1	-1	-1	1	-1	95,3%
9	-1	-1	-1	1	-1	-1	95,0%
25	-1	-1	-1	1	1	-1	95,0%
26	1	-1	-1	1	1	-1	94,7%
10	1	-1	-1	1	-1	-1	94,5%
5	-1	-1	1	-1	-1	-1	94,2%
21	-1	-1	1	-1	1	-1	94,0%
6	1	-1	1	-1	-1	-1	93,3%
13	-1	-1	1	1	-1	-1	93,3%
22	1	-1	1	-1	1	-1	93,3%
29	-1	-1	1	1	1	-1	93,3%
14	1	-1	1	1	-1	-1	93,0%
30	1	-1	1	1	1	-1	93,0%
3	-1	1	-1	-1	-1	-1	92,8%
11	-1	1	-1	1	-1	-1	92,8%
19	-1	1	-1	-1	1	-1	92,8%
27	-1	1	-1	1	1	-1	92,8%
4	1	1	-1	-1	-1	-1	92,3%
20	1	1	-1	-1	1	-1	92,3%
28	1	1	-1	1	1	-1	92,3%
12	1	1	-1	1	-1	-1	92,2%
23	-1	1	1	-1	1	-1	92,2%
7	-1	1	1	-1	-1	-1	92,0%
15	-1	1	1	1	-1	-1	91,8%
8	1	1	1	-1	-1	-1	91,7%
31	-1	1	1	1	1	-1	91,5%
16	1	1	1	1	-1	-1	91,3%
24	1	1	1	-1	1	-1	91,3%
32	1	1	1	1	1	-1	91,3%
33	-1	-1	-1	-1	-1	1	88,5%
49	-1	-1	-1	-1	1	1	88,5%
37	-1	-1	1	-1	-1	1	87,4%
34	1	-1	-1	-1	-1	1	87,2%
53	-1	-1	1	-1	1	1	87,0%
50	1	-1	-1	-1	1	1	86,7%
41	-1	-1	-1	1	-1	1	86,5%
38	1	-1	1	-1	-1	1	86,2%
51	-1	1	-1	-1	1	1	86,2%
35	-1	1	-1	-1	-1	1	86,0%
57	-1	-1	-1	1	1	1	86,0%
42	1	-1	-1	1	-1	1	85,5%
54	1	-1	1	-1	1	1	85,5%
61	-1	-1	1	1	1	1	85,4%
36	1	1	-1	-1	-1	1	85,2%
45	-1	-1	1	1	-1	1	85,2%
58	1	-1	-1	1	1	1	85,2%
39	-1	1	1	-1	-1	1	85,0%
43	-1	1	-1	1	-1	1	85,0%
55	-1	1	1	-1	1	1	85,0%
52	1	1	-1	-1	1	1	84,7%
59	-1	1	-1	1	1	1	84,7%
46	1	-1	1	1	-1	1	84,5%
62	1	-1	1	1	1	1	84,2%
40	1	1	1	-1	-1	1	84,0%
47	-1	1	1	1	-1	1	84,0%
44	1	1	-1	1	-1	1	83,9%
56	1	1	1	-1	1	1	83,9%
60	1	1	-1	1	1	1	83,7%
63	-1	1	1	1	1	1	83,5%
48	1	1	1	1	-1	1	83,0%
64	1	1	1	1	1	1	82,5%

**Note. The table describes what output all 64 runs achieved and which setting each factor had. The runs are ordered from the highest to lowest output.**

## 6. Discussion

The discussion is divided into two sections where the first one contains the discussion regarding the validity of the study's method and the second section discusses the results previously presented.

### 6.1 Methodological considerations and analysis

The study is undertaken during the initial phase of Heart's development of their FAL, with the objective of achieving an annual production capacity according to the Business Plan. At present, numerous critical decisions need to be made, and various regulatory and certification processes must be successfully navigated prior to the initiation of aircraft production. Heart's target is to commence production of their first aircraft by the year 2028. However, this study primarily focuses on analyzing the projected scenario that Heart will encounter several years after 2028. Given the speculative nature of this analysis, the report heavily relies on conjectures and approximations. In order to avoid misinterpretation of the results, it is imperative to provide thorough commentary and discussion concerning the various assumptions incorporated within the model. Furthermore, it is crucial to acknowledge and consider the potential impact of simplifications used in the simulation model.

#### 6.1.1 Required man-hours

First and foremost, the current model adheres to the data and assumptions made by the highly skilled and experienced production department at Heart. The production department has determined the required time for all activities involved in the assembly and painting of one aircraft based on a top-down approach i.e., an educated estimation of the total time from start to finish. However, given that the suppliers for all the necessary components have not yet been finalized, the production department at Heart is uncertain about all the procedures and activities that will be implemented and what will be done by the suppliers, due to this being a totally new product. Although the department is very experienced in manufacturing aircraft of similar sizes, the uncertainty regarding new systems, technology, and the fact that this aircraft is hybrid electric powered will affect the procedures in the future assembly line. Consequently, the data regarding the required man-hours are based on conjecture and informed assumptions based on similar sized conventional aircraft.

Moreover, simulation conducted in this study is based on the fundamental assumption of the S-curve phenomenon prevalent in the aerospace industry. While no relevant literature was identified to support this approach, the well experienced production department at Heart asserts that this is a realistic representation of actual industry practices. The S-curve represents an observed pattern whereby the distribution of required man-hours along an aircraft assembly line follows an initial increase, reaches a peak, and then gradually decreases before exhibiting a subsequent increase towards the end. This assumption serves as a foundational principle in capturing the overall resource allocation and work distribution dynamics in the simulation model, hence, this assumption significantly influences the

outcomes obtained in the simulation as it serves as a pivotal factor in accurately representing the dynamics of resource allocation and work distribution within the simulation model. However, the S-curve basically decides how many man-hours each station requires, when, in reality, that is decided by the sum of each activity's required man-hours within a station. Hence, a wrongly estimated S-curve will have a huge impact on the system and requires careful consideration.

The distribution of required man-hours within each station entails allocating them among the grouped activities. As the S-curve phenomenon influences the allocation of hours for each station, it subsequently affects the activities within those stations. By considering the sum of hours for each station, the most complex and demanding activity is subjectively assigned a higher portion of these hours compared to activities deemed less complex. Therefore, the modeling of the FAL is based on the total estimated man-hours required, rather than deriving the total man-hours from the model itself. In other words, the model utilizes the predetermined estimates of man-hour requirements to shape the FAL, ensuring that the allocation of man-hours aligns with the overall information.

Another more accurate method would have been to estimate the required man-hours based on a bottom-up approach where all the required man-hours for the individual activities are summed up to establish the total number of man-hours required. Through the top-down approach, the model basically states that each activity should take a specific amount of time to satisfy the estimation of the total man-hours required, instead of being based on the man-hours required in reality. Therefore, the accuracy of the data of the total man-hours required, the S-curve, and the complexity of the grouped activities are the most critical assumption on which the model is based, and the results need to be interpreted with caution.

To further problematize the assumptions regarding the required man-hours, it is crucial to consider the attainment of a fully learned system. Achieving such a system is a task influenced by various factors. Typically, a significant number of repetitions are necessary, and due to the aircraft industry's takt time, which operates on a scale of days rather than minutes as observed in the automotive industry, the time is prolonged. Additionally, as Heart Aerospace has yet to construct their FAL, operations will gradually scale up until reaching the targeted production capacity, further hampering the establishment of a fully learned system. During the ramp-up phase, all the operators required to produce according to the Business Plan will not be present initially, they will gradually be hired as the production rate increases. Consequently, a considerable number of new operators will require training and repeat their activities to achieve proficiency, potentially resulting in the assumption of a fully learned system inconsistent when producing as intended. In such a case, the model must be reassessed, and a learning factor incorporated. Moreover, the applicability of the model's results relies, among other things, on the achievement of a fully learned system, which presently remains uncertain.

### 6.1.2 Grouping of activities

Connected to what is mentioned above and due to the lack of knowledge, information, and data about the processes required to complete the ES – 30, sub activities have been grouped together. The decision to group activities within the assembly line simulation was driven by the desire to simplify the modeling process, particularly due to the lack of data or knowledge to accurately model each individual activity. However, it is important to recognize that grouping activities can have implications for capturing and understanding the effects of variation within the system. When activities are grouped together, variation that occurs within the individual smaller activities can become hidden or diluted according to the principles of the law of averages. For instance, let's consider a case of grouping eight linear activities, under precedence of constraints, into a single entity. In a situation where the activities are assessed individually, it is conceivable that four of them may experience variation while the other four remain stable. However, when these activities are grouped together, the impact of variation tends to decrease, resulting in a more binary outcome. Consequently, the grouping of activities leads to a more binary outcome, where the overall activity is characterized by either significant variation or relative stability. By grouping activities, there is a possibility that the visibility and comprehension of fluctuations, as well as their specific causes and impacts, may be reduced. This can limit the ability to accurately identify and address the root causes of delays or variations within the production process. As a result, the presence of fewer intermediate possibilities within the grouped activity may deviate further from the reality of the production process. Consequently, it becomes more challenging to implement targeted improvement measures and optimize the efficiency of the assembly line. This aspect assumes significance in the model, as it highlights the potential impact of grouping on the realism and fidelity of the simulation.

To fully capture and understand the impacts of variation within the assembly line, it is essential to model the individual smaller activities separately. This allows for a more detailed analysis of the specific sources of variation and their effects on the overall system performance. By maintaining the granularity of the activities, the assembly line simulation can provide insights into the causes and magnitudes of variation, facilitating the identification of potential bottlenecks, inefficiencies, and opportunities for improvement.

While grouping activities may be a practical approach in the absence of detailed data, it should be viewed as a temporary solution. As more information becomes available, it is important to reassess the modeling decisions and consider transitioning from grouped activities to individual ones. By refining the simulation model and incorporating the specific sources of variation, a more accurate representation of the assembly line can be achieved, enabling a comprehensive analysis of variation, and supporting effective decision-making.

Another notable drawback of employing grouped activities lies in the neglect of precedence constraints within the assembly line. When multiple sub-activities are grouped together and represented as one single activity, it assumes that all these sub-activities can be performed simultaneously, without considering their interdependencies or the inherent order in which

they need to be executed. This oversimplification overlooks the critical aspect of sequencing and the potential time gaps required between certain activities to ensure smooth workflow.

Moreover, the results from the simulation model need to be considered with caution since the grouping of activities most likely resulted in a higher output compared to what the real system can achieve given the same number of operators.

### 6.1.3 Behavior of the operators

Another huge part of the system is the operators. Within the model, it is assumed that the inclusion of an additional operator at a given station, irrespective of the number of operators already present, will lead to a consistent increase of precisely 6.5 hours of work per shift. This assumption hinges on three factors. The first being that all operators possess equal abilities, a supposition that is unlikely to hold true given the likely discrepancies in skill levels between newly hired and experienced operators. Secondly, this model allows, e.g., 12 people to perform an activity when in reality it may not be possible. All 12 operators will contribute equally in terms of workload and maintain consistent quality standards. This is unreasonable since at some point the marginal benefit of adding one operator will start to decrease due to, for example, physical constraints. For instance, 20 operators cannot physically be present at the door installation since the space is limited. Thirdly, it assumes that each operator performs value-adding work to the product during exactly 6.5 hours per day, which may not be the case if problems and other special-cause events happen. Moreover, in order for each operator to effectively perform 6.5 hours of value-added work, it is imperative that the tasks within the stations are divided in a manner where each task requires an equal amount of time for completion. This division of work is essential to maintain the premise of equal work distribution among operators. By ensuring that tasks are balanced in terms of time requirements, the potential for each operator to perform the designated amount of work can be realized.

In order to mitigate the issue of an excessively high number of operators at a station, consultations have been conducted with Heart in an effort to improve the model's validity. Nevertheless, there remain certain stations where the reasonableness of the number of operators required cannot be definitively determined, even by Heart. This dilemma is extra prevalent when the activities are grouped since the operators' movement and work within the sub-activities cannot be controlled. Moreover, further investigations are required to correctly model these aspects of the system and strengthen the validity.

### 6.1.4 Shifts

The assumption of equal efficiency across all three shifts in the model has notable implications for the simulation outcomes. In real-world production environments, it is widely recognized that the shifts outside of the day shift do not perform at the same level as the day shift. This discrepancy arises due to various factors, such as fatigue, reduced staffing levels, and lower levels of supervision during non-day shifts. Consequently, the output and productivity during

these shifts tend to be lower compared to the day shift, resulting in a potentially lower number of assembled aircraft during a given period.

However, despite the acknowledged disparity in shift performance, the simulation model does not account for these variations in efficiency. This omission is primarily due to a lack of available information on what would be considered reasonable variations in efficiency among the three shifts in the aerospace industry. Without a clear understanding of the extent to which efficiency levels differ between shifts, it becomes challenging to incorporate this aspect into the simulation model effectively.

The absence of differentiated shift efficiency levels in the simulation may impact the realism and accuracy of the capable output of the model. The model's outputs, such as the number of assembled aircraft, could potentially overestimate the production capacity or fail to capture the actual challenges and bottlenecks that arise during non-day shifts. Consequently, decision-makers relying on the simulation outcomes may not have a comprehensive understanding of the operational dynamics and potential areas for improvement specific to each shift.

#### 6.1.5 Non-conformance and missing parts

The aerospace industry is widely acknowledged to be prone to quality issues, including challenges related to shortages of parts and non-conformance. These issues can significantly impact the efficiency and productivity of the assembly line, leading to delays, rework, and ultimately a decrease in output. However, in the current simulation model, these factors have not been explicitly considered due to the unavailability of relevant data and the lack of information regarding which suppliers are to supply what.

The model assumes an ideal scenario in which there are no shortages of parts and a 100% conformance rate, meaning that all components and processes align perfectly with the prescribed standards and specifications. While this assumption provides a simplified framework for the simulation, it has been recognized as unrealistic upon consultation with the production department. In real-world aerospace manufacturing, it is highly improbable to achieve perfect conformance and avoid shortages or discrepancies entirely.

#### 6.1.6 Baseline model

It is worth noting that the baseline model was derived from sequential tests, thereby potentially imparting subjective characteristics to the resulting model. In other words, it is plausible that alternative distributions of operators among the stations could yield equivalent outputs. Additionally, an essential factor to consider is the level of utilization attained in the baseline system. Apart from flight preparation, all stations chosen for further analysis exhibited a utilization rate surpassing 90%. This high level of utilization is attributable to the tight balancing of the system to minimize the number of operators employed. Nonetheless, it is crucial to recognize that such a degree of utilization may be impractical or unachievable within a real-world operational context. It should be noted that introducing an additional

operator to a specific activity or implementing other modifications within the simulation would yield divergent outcomes in the study. Given the absence of an existing system to replicate and a corresponding definitive model to adhere to, the absence of an established benchmark further compounds the complexity of the study. It is worth noting that the exploration of the remaining research question was carried out utilizing the baseline model. Consequently, it is crucial to emphasize that the outcomes of the study are greatly influenced by the outlook of the baseline model.

An illustrative instance within the model that exemplifies this can be observed in the domain of Flight Preparation. In practice, the Flight Preparation station entails inherent uncertainties, rendering it a highly unpredictable component of the overall assembly process. Consequently, to mitigate the potential disruptions stemming from fluctuations in the average time required to accomplish flight preparation, the production department at Heart allocated extra resources in the form of three parallel positions. This strategic decision resulted in that the overall system remained unaffected even in scenarios where the average required man-hours of Flight Preparation escalated by 10%.

As previously mentioned, the baseline model is characterized by stations with relatively high utilization. This is particularly evident in those stations that underwent further investigation. With this said, it should be noted that the outcomes are derived from a model where the level of utilization of four stations may not align with practical expectations. The presence of such heightened utilization exposes the system to increased vulnerability in the face of various disturbances, including quality issues, workforce limitations, non-conformances, and other related factors increasing the variation. Considering the industry's inherent complexity and susceptibility to disruptions, it is important to recognize that an excessively elevated utilization level may not accurately mirror real-world conditions. Consequently, caution is advised when extrapolating the findings to practical operational scenarios, as the model's intensified utilization may not faithfully reflect the realities of day-to-day operations. Nevertheless, the quest to complete was to find out how the number of operators deviate from what Heart previously thought to produce according to the Business Plan, and the model clearly shows that it is possible with a slight increase even though the utilization might lean towards the extreme end of the spectrum.

The assumption of having one aircraft model holds true for the moment. However, as the company grows, more models and customization options might be available, affecting the level of standardization the FAL can obtain. Which, furthermore, affects the variation inherent in the system. Moreover, it is important to consider if the FAL is to be used for several different aircraft in the future.

Despite the inherent uncertainty associated with simulations, particularly at the current stage of development of the Heart project, it is imperative to employ this approach in order to advance the analytical process beyond its initial findings. Simulations enable the consideration of factors such as the dynamic nature of the assembly, precedence constraints,

and stochastic behavior. Moreover, the primary objective of this study is not to obtain precise numerical values and outcomes, but rather to gain insights into the response of the planned system under various scenarios that deviate from the intended plan.

## 6.2 Interpretation of the results

The complexity and limitations inherent in simulating this system necessitate a cautious approach when analyzing the results. Relying on past experiences underscores the need for meticulous examination to prevent misinterpretations. Therefore, it is crucial to provide additional commentary on the results, offering potential explanations for their observed characteristics. Initially, attention is directed towards addressing uncertainties, followed by an examination of errors related to the estimated number of hours required. Subsequently, detailed commentary is provided for factors yielding particularly interesting findings, including variations across the system, station FAL 3, and the Flight Preparation.

### 6.2.1 Baseline model

Initially, it is pertinent to acknowledge that all the gathered results and conducted analyses have been derived from simulations utilizing a singular, predetermined baseline model. As the primary research question pertained to determining the minimal number of operators necessary to achieve the desired output, the resulting model was subsequently employed for investigating the remaining two.

As presented in Section 5.1, the study concludes that an increase of 2.6% in the number of operators are required in order to produce according to the target. The observed disparities between our model and the calculations performed by the company can be attributed to several crucial factors. Firstly, the model incorporates the precedence of constraints, meaning that certain tasks necessitate the completion of others before they can commence. This consideration accounts for the interdependencies and sequential nature of activities within the production process. In contrast, the company's calculations solely divide the required hours by the product of the number of operators and the work provided by each shift, thereby overlooking the hierarchical relationships between tasks and their respective dependencies.

Secondly, the model considers the element of transportation within the production process. By considering the movement of the aircraft between stations, a more realistic representation is captured of the overall workflow. Conversely, Heart's calculations do not incorporate transportation, thereby omitting a crucial aspect that can impact the required number of operators.

Furthermore, the model contains variations in process times for different activities, acknowledging the inherent variability that exists in real-world production environments. This enables to account for fluctuations and deviations in task durations, ultimately affecting the overall manpower requirements. However, Heart's calculations do not account for such variations, potentially leading to a discrepancy in the required number of operators.

Lastly, the model takes into consideration the physical limitations associated with specific tasks. By acknowledging and incorporating these limitations, the model is designed to accurately represent the practical constraints that may affect the production process. Conversely, Heart's calculations do not account for such physical limitations, potentially resulting in an underestimation of the required number of operators.

Collectively, these differences in modeling approach, considering precedence of constraints, transportation, variation in process times, and physical limitations, contribute to the disparities observed between our model and the calculations performed by the company. By addressing these crucial factors, our model provides a more comprehensive and realistic assessment of the required number of operators to achieve the desired output within the production process.

### 6.2.2 Required man-hours

Another important finding relates to the impact on system output when assuming an underestimation of the required man-hours. Specifically, by increasing the necessary man-hours for FAL stations 2, 3, 4, 6, and the Flight Preparation station by 10%. Furthermore, this configuration, in combination with a variation level of 10%, gives an output of 91.5 % indicating an 8.5% decrease from the target value. Conversely, if the variation were to escalate to 30%, the output would result in only 82.7 %, signifying a decrease of 17.3% from the target output. Moreover, depending on the system's inherent variation, a 10% increase in required man-hours for the five chosen out of the total nine stations in the FAL would lead to an output reduction ranging from 8.5% to 17.3%. Thus, it can be argued that the system exhibits notable sensitivity to underestimations in the overall required man-hours, whereby a 10% increase in required man-hours for all FAL stations, is likely to yield a decrease in output exceeding 10% from the target output. However, it is important to note that sensitivity is dependent on how the system is balanced. For instance, the Flight Preparation station's lack of statistically significant impact on the system may be explained by it being not as tightly balanced as the other stations in the tests. Moreover, to account for wrongly estimated required man-hours, Heart should consider designing the FAL to accommodate more operators compared to what the balanced model suggests, especially in stations having high utilization. Nevertheless, based on the conducted experiments, it is evident that underestimations of the required man-hours have an impact on the system, emphasizing the criticality for Heart Aerospace to review estimated values promptly upon the availability of more accurate data and knowledge about the processes to be conducted.

### 6.2.3 Variation of 30 %

Based on the conducted experiments, it can be concluded that the future FAL is exceedingly sensitive to variation in the man-hours required for each activity. Notably, when the variation increased from 10 % to 30 %, the system's average output decreased with 8.18 % per year. This phenomenon is emphasized by the findings presented in Table 4, which reveal that all 32 instances exhibiting the most unfavorable outcomes exhibit a variation factor of 30%. This

finding aligns with the observations made by Holweg et al. (2018), wherein emphasize is put on the absence of buffers between interconnected stations. Considering that the automotive industry in a worst-case scenario experiences variations of up to 30% in its processes (Wild, 1975), it is plausible that Heart Aerospace, alongside other companies within the aerospace industry, may encounter even greater levels of variability due to the inherent complexity in the sector and the aircraft itself.

Although this discovery may not come as a surprise, it is of utmost significance for Heart to account for this factor during the design of the intended FAL. It is imperative to develop operational procedures and processes that mitigate the potential impact of substantial variation permeating the FAL. Furthermore, establishing standardized procedures for operators and suppliers could be instrumental in minimizing variations. Additionally, the implementation of well-designed training programs for operators, focusing on proper task execution, could prove to be a valuable approach.

#### 6.2.4 FAL 3

One notable finding from the analysis is that the FAL station 3, represented by factor B, demonstrates the most substantial influence on the assembly line's output when compared to the other station's settings under investigation. The high impact can be attributed to the limitation on the number of operators assigned to activity 3.2 within that station. Since this activity is balanced with a single operator, any increase in the average completion time significantly affects the overall performance of the station. In order to address this issue within our simulation model, the option of assigning an additional operator to the FAL 3 station was considered and resulted in a higher output. Nevertheless, the implementation of an additional operator in the respective station was unfeasible since the test was conducted using the model with the minimum number of operators. Consequently, a bottleneck situation arose during the simulation, where the FAL 3 station became a limiting factor in the overall performance of the assembly line.

Additionally, FAL 3 is in its optimistic setting in all the 16 runs with the highest average output and is in its pessimistic setting in all the eight runs with the lowest average output. It is also noteworthy that all combinations involving three factors deemed statistically significant in influencing the assembly line's output include factor B, representing the FAL 3 station. The consistent inclusion of factor B in these combinations can be attributed to the previously mentioned limitation on the number of operators within station 3.2, reinforcing its influential role in determining the system's performance.

These findings shed light on the critical importance of optimizing resource allocation and capacity planning within the FAL 3 station. Future investigations should explore alternative strategies to mitigate the bottleneck effect, such as process re-engineering, workflow redesign, or exploring technological advancements that may help overcome physical space constraints. By addressing this challenge, the overall efficiency and output of the assembly line can be enhanced.

### 6.2.5 Flight Preparation

The Flight Preparation is the only one out of the six tested factors that lacks statistical significance on the average output of the system. The one run that accomplishes delivering the desired output that does not have all the factors in their optimistic level is the one where all activities are in their optimistic, but the Flight Preparation. Despite the simulation results indicating that factor E, representing the flight preparation, lacks statistical significance on the output of the assembly line, the flight test presents unique uncertainties. While the assembly activities involved in constructing the fuselage, wings, and other components are anticipated to in some degree resemble those of conventional turboprop aircraft, the flight test phase introduces a substantial level of unpredictability. Even though each station within the model presents distinct challenges and uncertainties, an argument can be made that the process of flight preparation, in this case, possesses an even greater degree of complexity and intricacy. The nature of flight testing for this particular aircraft, powered by new technologies and differing from conventional turboprop aircraft, raises several uncertainties. Factors such as the impact of new technologies on the flight test process, varying weather conditions affecting test procedures, the required duration of airborne testing, and the number of landings and recharges necessary before resuming flight tests all contribute to the complex and evolving nature of the flight test phase and likely an increase in required time spent in that station.

Currently, the estimation of time allocated to the flight test station is based on experience gathered from previously assembled aircraft, primarily those utilizing turboprop and jet engines, following the previously mentioned S-curve. As more information becomes available, a deeper understanding of the unique requirements and intricacies associated with flight testing of this novel aircraft will be gained leading to even more accurate data.

### 6.2.6 Synthesis discussion

An aerospace FAL shares commonalities with a generic FAL, signifying that the theoretical principles deemed significant for the latter also hold relevance for the former. However, owing to the distinctive characteristics of the aerospace industry, it is noteworthy to reiterate certain aspects that require extra consideration.

Looking at the characteristics of the produced aircraft, there are authors, Kiran (2019), and Bellgran and Säfsten (2019), arguing for aircraft fitting the theory of fixed-position assembly. The authors mention several product characteristics for an aircraft, for example regarding small order sizes, low volumes, low ready to stock, low labor cost, and level of specialist being high. Even though all these are correct and fit the production to be fixed position, all the big companies in the aerospace industry, like Airbus and Boeing, have chosen to go with an assembly line instead. This has a lot to do with the characteristics of the required processes within the industry.

The aerospace industry is characterized by intricate tasks that often take place in confined spaces and involve awkward angles. Groover (2015) indicates that these factors pose

significant challenges to the automation of processes, as machines are not currently capable of performing the diverse range of tasks required. Consequently, the aerospace industry heavily relies on manual labor, with operators playing a crucial role in the FAL operations.

Therefore, to increase the capacity of the assembly line, an augmentation in the number of operators is necessary. However, due to physical constraints, there is a practical limit to the maximum number of operators who can effectively work on an aircraft simultaneously. As a result, it becomes necessary to increase the number of workstations to distribute the workload among more stations, allowing more individuals to perform work to the aircraft assembly process.

The expansion of workstations does not only allow more people to work in the FAL, but also leads to a reduction in the number of tasks and activities assigned to each station since the same number of activities are now distributed across a greater number of stations. Consequently, operators find themselves repeating the required tasks more frequently and dealing with a reduced number of simultaneous responsibilities. The reduced task load per station facilitates the standardization and optimization of each workstation, tailoring them to their specific purpose in the assembly process. Hence, utilizing several stations in an assembly line facilitates learning, which is a subject within the aerospace industry that is challenging.

However, assembly lines do not only simplify learning, but it can also be beneficial for quality and control. In an assembly line configuration, each station is dedicated to a specific task or assembly stage. Compared to a fixed position layout, there are fewer activities to perform at each station and inspectors and quality control personnel can therefore focus their attention on a narrower set of tasks. This focused approach enables a more detailed and thorough examination of components, assemblies, and workmanship, reducing the likelihood of defects or errors going unnoticed. As a result, the assembly line provides a controlled environment where consistency and uniformity in the assembly process can be maintained.

Due to the limited vertical integration in the aerospace industry (Gagné, n.d.), the selection of suppliers assumes a vital role and holds substantial influence over the FAL. With product development in the aerospace sector being a collaborative endeavor between companies and suppliers, the choice of suppliers directly impacts the specific processes adopted by the aerospace company. As a result, careful supplier selection becomes imperative to gain a more comprehensive and insightful understanding of the assembly line. Without supplier involvement, a deeper exploration of the assembly process would be characterized by uncertainty and lack of essential details required for accurate planning and analysis.

Furthermore, the selection of suppliers in the aerospace industry holds a crucial influence in determining the activities and tasks carried out by the aerospace company on the assembly line. Different suppliers have the potential to offer varied products, subsystems, or services, resulting in variations in the assembly requirements. These disparities may arise from factors such as component designs, manufacturing processes, or the level of integration provided by the suppliers.

For instance, one supplier may offer a pre-integrated subsystem, effectively simplifying the assembly process and reducing the number of tasks required on the assembly line. This

streamlined workflow has the potential to require fewer stations and operators to achieve the desired output. Conversely, another supplier might provide individual components that necessitate additional assembly steps and specialized tasks, leading to a more complex assembly process. Consequently, this may require an increased number of stations and operators.

Therefore, when selecting suppliers, aerospace companies must meticulously consider the implications for the assembly process. The characteristics of the supplied components, subsystems, or services should align with the desired production goals and optimize the overall efficiency of the assembly line. By choosing suppliers whose offerings are in line with the desired assembly approach and integration requirements, aerospace companies can effectively manage the number of stations, operators, and activities needed on the assembly line. Ultimately, this enhances productivity while reducing potential bottlenecks and inefficiencies.

### 6.3 Sustainability discussion

This master's thesis, conducted at Chalmers University of Technology, places emphasis on considering sustainable aspects within the study. Thus, a brief discussion on sustainability is warranted. While the primary objective of our thesis was to validate the numbers used in planning Heart Aerospace's future assembly line, it is crucial to acknowledge the limitations of our research. The simulation employed in our study was based on several assumptions and remains in its early stages, rendering it challenging to provide definitive assessments regarding economic, environmental, and social considerations.

Nevertheless, by providing information used to design and develop an FAL as efficient as possible, economic sustainability can be affected by the study. However, since there is a lot of uncertainty within the results, it is hard to exactly quantify what economic effects findings from the simulation will have.

Although our validation process aimed to prevent the construction of an assembly line with insufficient capacity, thereby avoiding subsequent rebuilding and associated greenhouse gas emissions, the inherent uncertainties within the simulation introduce a level of unpredictability. Consequently, quantifying the precise environmental benefits that could be achieved becomes challenging.

Additionally, in order to reach the desired output, one can read from the results of the study that the utilization for some of the stations is high (over 90%). This could potentially lead to demanding work conditions for operators that surpass reasonable expectations. However, due to the uncertainties involved, drawing definitive conclusions regarding the social aspects and their impact on operators' workload becomes difficult.

In summary, while striving to validate the information of the assembly line, it is important to recognize the limitations of our research. The uncertainties inherent in the simulation and the multifaceted nature of real-world implementation necessitate continued exploration to fully comprehend the economic, environmental, and social implications of the proposed assembly line configuration.



## 7. Conclusion

The aim of this master thesis report was to evaluate the capacity of the FAL of Heart Aerospace. The purpose of this evaluation was to validate the data possessed by the production department at Heart and contribute to the development of the FAL. However, it should be noted that due to the absence of an assembly line to collect data from and no predetermined processes along the assembly line, the research project faced unique challenges.

In light of these challenges, the research study focused on assessing the data provided by the production department. The findings of the study revealed significant insights that are crucial for the development and optimization of the FAL. Specifically, the study demonstrated that the output from the FAL is highly sensitive to increases in variation and increases/decreases of the average required man-hours. This highlights the importance of accurate data and effective management of resources for the successful operation of the FAL.

Moreover, the study indicated that the FAL requires a greater number of operators than previously assumed. This finding has substantial implications for the planning and staffing of the assembly line, as well as the overall efficiency and productivity of the FAL. It underscores the need for careful consideration and adjustment of the manpower requirements to ensure smooth operations and maximize output.

Considering the significance of these findings and their potential impact on the development of the FAL, we strongly argue for the fulfillment of the thesis' purpose. The research project has successfully provided valuable insights into the capacity evaluation of the FAL and shed light on critical factors that affect its performance. By addressing the limitations and challenges faced during the research, this study has contributed to the knowledge base and can guide future decision-making and improvements in the development of the FAL. Lastly, to summarize this master thesis, the answers to the research questions are presented below.

*RQ1: What production system theory is important to consider in an aircraft FAL?*

The assembly line in the aerospace industry is influenced by several key factors. The number of stations and operators is determined by the complexity of tasks, with more operators and stations allowing for increased standardization. The manual-intensive and complex nature of the assembly process limits the potential for automation, resulting in operators being a significant part of the system. While there may be low repetition of tasks, continuous learning remains crucial, prompting the need to explore innovative approaches. Additionally, supplier involvement plays a significant role in determining the tasks performed on the assembly line, highlighting the importance of effective collaboration and decision-making with suppliers.

*RQ2: How does the minimum number of operators required to achieve the desired output deviate from Heart's previous calculations?*

By incorporating the estimated man-hours for aircraft assembly, the model was balanced by adjusting the number of operators present at the FAL. The efforts resulted in a daily requirement of 2.6 % more operators than previously thought. However, the system's

sensitivity to misestimations and inherent variation suggests the potential benefit of adding more operators to reduce sensitivity.

*RQ3: How does an error in estimation regarding required man-hours affect the number of produced aircraft?*

The impact of misestimating the required man-hours on the output of the FAL was assessed by introducing a 10% increase in the stipulated requirements for specific stations. Analyzing the consequences of this 10% increase in required man-hours on the FAL's output revealed substantial effects on the production system. Individual or combined tests of the required man-hours for stations 2, 3, 4, and 6 led to a reduction in the number of aircraft produced. However, when the required man-hours were increased for the Flight Preparation station, no statistically significant impact on the output was observed. In the most unfavorable scenario, involving a 10% increase across all five stations, the resulting output ranged from 82.7 % to 91.5 % of the targeted output, depending upon the level of system variation considered.

*RQ4: How does variation in the required man-hours affect the number of produced aircraft?*

From the experiments it can be concluded that increasing the variation of the system to 30% from 10% has a negative effect on the system. The results showcase an average decrease of 8.18 % from the targeted output, with a worst-case scenario resulting in a decrease of 17 %. Moreover, the system is sensitive to changes in variation and Heart needs to consider this when designing the FAL.

## 7.1 Recommendations

While this report has provided a comprehensive analysis of the current situation and proposed recommendations, there are several areas that warrant further investigation.

Since this study uses a top-down approach for data collection, we recommend Heart to nuance these findings with results from bottom-up data as well. A bottom-up approach can prove invaluable in the planning of an assembly line, specifically when determining the optimal number of stations and operators. By starting at the individual task level and gradually building up to the entire assembly process, this approach ensures a comprehensive understanding of the system's requirements and constraints. Through careful analysis of each task's duration, complexity, and resource utilization, a bottom-up approach allows for a more accurate estimation of the number of stations and operators needed. This method facilitates the identification of potential bottlenecks, optimization opportunities, and resource allocation strategies, and therefore could be a good complement to the top-down approach. Ultimately, a bottom-up approach enhances the planning process by providing a detailed and data-driven perspective on the assembly line's requirements.

As previously mentioned, this report uses the information and knowledge that is available for now. To do a similar study, or at least update the model with time when new information and knowledge is attained, would give a more representative result that replicates reality more

fairly. However, this requires Heart to acquire simulation knowledge and licenses in order to utilize the simulation model further.

This study focuses on only one layout of the assembly line. Since there are still decisions to be made regarding the layout of the FAL, it would be beneficial to study several other layouts to gain a more comprehensive understanding of the assembly line. For instance, doing the same study for assembly lines with ten, eleven, and 12 stations, both in parallel and series.

The report did not delve further into the implementation of flex crews as a theory for consideration. The implementation of flex crews could offer several potential benefits worth exploring in future investigations. Firstly, it allows for a more efficient utilization of human resources by enabling the workforce to be dynamically allocated to different tasks or stations based on real-time demand. Such flexibility can help in optimizing the overall productivity and reducing idle time or bottlenecks that may arise due to imbalanced workloads.

## 8. Epilogue

Although our model is built upon various assumptions that may deviate from the intricacies of real-world conditions, it is important to recognize the potential value the simulation study can bring to the production department at Heart and other manufacturing companies operating within similar contexts. Despite the uncertainties and limitations, our study offers valuable insights and benefits that can aid in decision-making and process optimization.

Firstly, the simulation provides a platform for exploring different scenarios and what-if analyses, allowing the production department to assess the potential impact of various factors and decisions on the assembly line. While the model's assumptions may not perfectly align with reality, they serve as a starting point for understanding the dynamics and interdependencies within the production process. By systematically evaluating different scenarios, the production department can gain valuable insights into potential bottlenecks, resource allocation strategies, and areas for improvement.

Secondly, the simulation study serves as a catalyst for discussions and knowledge sharing within the organization. By presenting the model's outcomes and assumptions, we encourage critical thinking and engagement from the production department. Such collaborative environment fosters a deeper understanding of the assembly line dynamics and allows for the identification of overlooked factors or alternative perspectives that can enhance the decision-making process.

Furthermore, the simulation study provides a foundation for data-driven decision-making. While the model's assumptions may not capture every nuance of the assembly line, they are based on available information and expert knowledge. By aligning the simulation outputs with real-world observations and data, the production department can refine and validate the model over time, enhancing its accuracy and applicability.

Lastly, the simulation study serves as a starting point for further research and exploration. By acknowledging the assumptions and limitations, it opens the door for future investigations and data collection efforts that can enhance the model's validity. As new information becomes available and as the production process evolves, the simulation can be refined and expanded to provide even more valuable insights.

## 9. References

- Anzanello, M., & Fogliatto, F. (2010). Learning curve models and applications: Literature review and research directions. *International Journal of Industrial Ergonomics*, 41(5), pp. 573-583. <https://doi.org/10.1016/j.ergon.2011.05.001>
- Argote, L. (2013). *Organizational Learning* (2<sup>nd</sup> ed.). Springer. ISBN: 9781461452515
- Banks, J. (1998). *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practices*. Wiley & Sons, New York, pp. 3-30.
- Banks, J., Carson, J.S., Nelson, B.L., & Nicol, D.M. (2001). *Discrete-Event System Simulation* (3<sup>rd</sup> ed.). Prentice-Hall, New Jersey.
- Baudin, M. (2002). *Lean Assembly: the nuts and bolts of making assembly operations flow*. Productivity Press, New York.
- Bell, B. S., & Kozlowski, S. W. J. (2008). Active learning: Effects of core training design elements on self-regulatory processes, learning, and adaptability. *Journal of Applied Psychology*, 93(2).
- Bell, E., Bryman, A., & Harley, B. (2018), *Business research methods*, Oxford university press.
- Bellgran, M., & Säfsten, K. (2010). *Production Development: Design and Operations of Production Systems*. Springer-Verlag London Limited.
- Bergman, B. and Klefsjö, B. (1995). *Kvalitet från behov till användning*, Studentlitteratur, Lund.
- Bongers, A. (2022). Learning by doing, organizational forgetting, and the business cycle. *Bulletin of Economic Research*, 75(1), pp. 141-150. <https://doi.org/10.1111/boer.12346>
- Caggiano, A., Marzano, A., & Teti, R. (2016). Resource efficient configuration of an aircraft assembly line. *Procedia CIRP*, 41, pp. 236-241. <https://doi.org/10.1016/j.procir.2015.12.130>
- Calzavara, M., Finco, S., Battini, D., Sgarbossa, F., & Persona, A. (2022). A Joint Assembly Line Balancing and Feeding Problem (JALBFP) considering direct and indirect supply strategies. *International Journal of Production Research*, 60(19), pp. 5727-5745. <https://doi.org/10.1080/00207543.2021.1968527>
- Chao, J.S., & Graves, S.C. (1998). Reducing flow time in Aircraft Manufacturing. *Production and Operations Management*, 7(1), pp. 38-52. <https://doi.org/10.1111/j.1937-5956.1998.tb00437.x>
- Cherrington, J., Lippert, S., & Towill, D. (1987). The effect of prior experience on learning curve parameters. *International Journal of Production Research*, 25(3), 399-411. <https://doi.org/10.1080/00207548708919849>
- Chung, C.A. (2003). *Simulation Modeling Handbook: A practical Approach* (1<sup>st</sup> ed.). CRC Press, Boca Raton.

- Cook, J., Ramsay, C., & Fayers, P. (2007). Using the literature to quantify the learning curve: A case study. *International Journal of Technology Assessment in Health Care*, 23(2), pp. 255-260. <https://doi.org/10.1017/S0266462307070341>
- De Cordova, P. B., Bradford, M. A., & Stone, P. W. (2016). Increased errors and decreased performance at night: A systematic review of the evidence concerning shift work and quality. *Work*, 53(4), pp. 825-834. <https://doi.org/10.3233/WOR-162250>
- Elkington, J. (1998). Accounting for the Triple Bottom Line. *Measuring Business Excellence*, 2(3), pp. 18-22. <https://doi.org/10.1108/eb025539>
- Gagné, P. (n.d.) Latest Trends in Aerospace Supply Chain Management. *Global Partner Solutions*.  
<https://www.gpsi-intl.com/blog/latest-trends-in-aerospace-supply-chain-management/>
- Groover, M.P. (2015). *Automation, Production Systems, and Computer-Integrated Manufacturing* (4<sup>th</sup> ed.). Pearson. ISBN 13: 978-0-13-349961-2.
- Hanson, R., & Brolin, A. (2013). A comparison of kitting and continuous supply in in-plant materials supply. *International Journal of Production Research*, 51(4), pp. 979-992, <https://doi.org/10.1080/00207543.2012.657806>
- Heike, G., Ramulu, M., Sorenson, E., Shanahan, P., & Moinzadeh, K. (2000). Mixed model assembly alternatives for low-volume manufacturing: The case of the aerospace industry. *Int. J. Production Economics*, 72(2), pp. 103-120. [https://doi.org/10.1016/S0925-5273\(00\)00089-X](https://doi.org/10.1016/S0925-5273(00)00089-X)
- Holweg, M., Dacies, J., De Meyer, A., Lawson, B., & Schmenner, R. (2018). *Process Theory: Principles of Operations Management*. Oxford: OUP Oxford.
- Jonsson, P. & Mattsson, S.A. (2009), *Manufacturing Planning and Control*. McGraw-Hill Education. ISBN 0077117395
- Kiran, D.R. (2019). *Production Planning and Control, A Comprehensive Approach*. BSP Books Pvt. Ltd.
- Lainer, C. (2000). Learning and Forgetting: The Dynamics of Aircraft Production. *The American Economic Review*, 90(4), pp. 1034-1054. <https://doi.org/10.1257/aer.90.4.1034>
- Malachowski, B., & Korytkowski, P. (2015). Competence-based performance model of multi-skilled workers. *Computer & Industrial Engineering*, 91, pp. 165-177. <https://doi.org/10.1016/j.cie.2015.11.018>
- Malm, A. (2013). Important factors in the transfer to aircraft production. *Linköping University*. <https://www.diva-portal.org/smash/get/diva2:625149/fulltext01.pdf>
- Mas, F., Ríos, J., & del Valle, C. (2013a). A Glimpse into Aircraft Assembly Lines. *Enterprise AI*. [https://www.enterpriseai.news/2013/09/09/a\\_glimpse\\_into\\_aircraft\\_assembly\\_lines/](https://www.enterpriseai.news/2013/09/09/a_glimpse_into_aircraft_assembly_lines/)

- Mas, F., Ríos, J., Menéndez, J., & Gómez, A. (2013b). A process-oriented approach to modeling the conceptual design of aircraft assembly lines. *Manufacturing Technology*, 67, pp. 771-784. <https://doi.org/10.1007/s00170-012-4521-5>
- Mei, Z., & Maropoulos, P. G. (2014). Review of the application of flexible, measurement-assisted assembly technology in aircraft manufacturing. *Journal of Engineering Manufacture*, 228(10), pp. 1185-1197. <https://doi.org/10.1177/0954405413517387>
- Nembhard, D. (2000). The Effects of Task Complexity and Experience on Learning and Forgetting: A Field Study. *The Journal of the Human Factors and Ergonomics Society*, 42(2), pp. 272–286. <https://doi.org/10.1518/001872000779656516>
- Peña, C., Romero, D., & Noguez, J. (2022). Workforce Learning Curves for Human-Based Assembly Operations: A State-of-the-Art Review. *Applied Sciences*, 12, pp. 9608. <https://doi.org/10.3390/app12199608>
- Savage, S. (2000). The flaw of averages. *Sunday*. <http://www.inescc.fe.uc.pt/~ewgmcda/ForSavage.pdf>
- Sivasankaran, P., & Shahabudeen, P. (2014). Literature review of assembly line balancing problems. *Int J Adv Manuf Technol*, 73, pp. 1665-1694. <https://doi.org/10.1007/s00170-014-5944-y>
- Slack, N., Brandon-Jones, A., & Johnston, R. (2013). *Operations Management* (7<sup>th</sup> ed.). Pearson. ISBN: 978-0-273-77628-4
- Wild, R. (1975). On the selection of mass production systems. *International Journal of Production Research*, 13(5), pp. 443-461. <https://doi.org/10.1080/00207547508943015>



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