CHALMERS
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Systematic approach to assembly system design

Designing an assembly system in a low volume, rapid growth scenario

Master's thesis in Master's Program Production Engineering

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Gothenburg, Sweden 2018
Report No. E2018:055

MASTER'S THESIS E2018:055

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Abstract

Arcam is a company that develops and manufactures additive manufacturing machines for production of metal parts. Production is planned to move to larger facilities, as to facilitate future increases in capacity requirements. There is existing theory on systematic approaches to production system design, which in this thesis has been adapted and applied in designing the mechanical assembly subsystem. Requirements on the assembly system were found to focus on handling uncertainty and gradual changes in product mix and production volumes. Analysis of current product and assembly system characteristics revealed a large work content and a high degree of complexity. A division of work into sequential work stations with a team-based organizational structure was found suitable to satisfy system requirements as well as prioritized metrics.

Designing assembly systems is complex, and acquiring sufficient knowledge of preconditions and requirements in a timely manner is difficult. The use of a systematic approach for assembly system design was found to be beneficial, as complexity was reduced and because structuring and planning of design activities was simplified.

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1

Introduction

Arcam is a Swedish company that develops and manufactures additive manufacturing machines for production of metal parts. Arcam has customers all over the globe, most of which are active in the orthopedic implant or aerospace industry. The manufacturing facility is comprised of two main parts, Area 1 which mainly consists of mechanical assembly, and Area 2 which consists of calibration, quality control and supplementary assembly of electronic components.

The company is facing gradually increasing production volume requirements over the coming years. Assembly in Area 1 has not changed dramatically since the start of production, and is not well suited for increased production volumes. The current production facilities are limited with regards to space, and a move to larger facilities is imminent. Before the move takes place a new assembly system for Area 1 that facilitates a gradual increase in production volumes must be designed.

1.1 Purpose

The purpose of the master thesis is to produce a design proposal for a new assembly system. The system should be easily reconfigurable to ensure short and long term assembly system performance.

1.2 Scope

The thesis includes investigations and design proposals specifically for the mechanical assembly system. The work focuses on the design of the assembly flows and processes, but does not include details such as assembly sequence or methods. Broader aspects such as material handling and work organization is also included, but only to the extent that can be considered to lie within the mechanical assembly system.

1.3 Problem Description and Research Questions

Many different departments and stakeholders are affected by the production system, where they all have their own set of expectations, requirements and requests. To produce a design that satisfies the stakeholders to as large extent as possible, all these aspects need to be taken into consideration. It will be of importance not only to define the strict requirements on the system, but also which are the most important performance measures. Accordingly, the first research question is:

RQ1: What are the production system requirements and which are the most important performance measures?

The many choices that have to be made when designing a production system leads to a high degree of complexity. There are many alternative design concepts, and trying to find the best possible solution is challenging but necessary. The solution is largely affected by the context and the current situation. To reduce complexity the number of possible solutions is narrowed down during the earlier stages of the process by settling with a conceptual design. The second research question is therefore:

RQ2: What system design concept best suits the context and system characteristics?

Before implementing major changes in the production system it is important that the design is specified at a sufficient level of detail. The different system aspects must be thoroughly planned and specified to ensure satisfactory results. To satisfy demands that are changing over time, the system reconfigurability must also be addressed. Thus, the third research question is:

RQ3: How should the future production system be designed in detail to handle increasing requirements on capacity and other production metrics?

2

Theoretical Framework

Defining a system model improves the ability to design and analyze the system and to understand its parts and their relations, which is important to increase quality of the system design [Bennett and Forrester, 1993, Bellgran and Säfsten, 2010]. This chapter therefore includes some systems theory, with a focus on constituent parts and aspects of production systems. Due to the future changes to production system requirements as well as the impending move to new facilities, particular focus is put on a life-cycle perspective and reconfigurability characteristics of production systems.

When designing a production system it is preferable to use a structured way of working. It simplifies the development process and maximizes the time spent on tasks related to the development of the production system, providing the prerequisites for a good system design [Bellgran and Säfsten, 2010]. Bellgran & Säfsten propose a systematic method for production system development that consists of eleven phases, see Figure 2.1.The initial phases related to management and control, as well as the final phases related to the implementation of the production system, all lie outside the scope of this thesis. Therefore, the last parts of this chapter contain detailed descriptions of phases A through E, related to preparatory design as well as design specification.

2.1 System Models in Manufacturing

Systems are commonly defined as a set of things working together to form a complex whole that is more than the sum of its parts [Checkland, P., 1999]. Systems can be described by a variety of system perspectives such as functional, structural and hierarchical perspectives [Rösiö, 2012]. A production system can be described as dependant on its environment and hierarchical in nature (see Figure 2.2), where different subsystems can be of different levels of importance to fulfilling the system goals [Bellgran and Säfsten, 2010]. A production system is also characterized by equifinality, meaning the desired goals of a system can be achieved in several different ways.

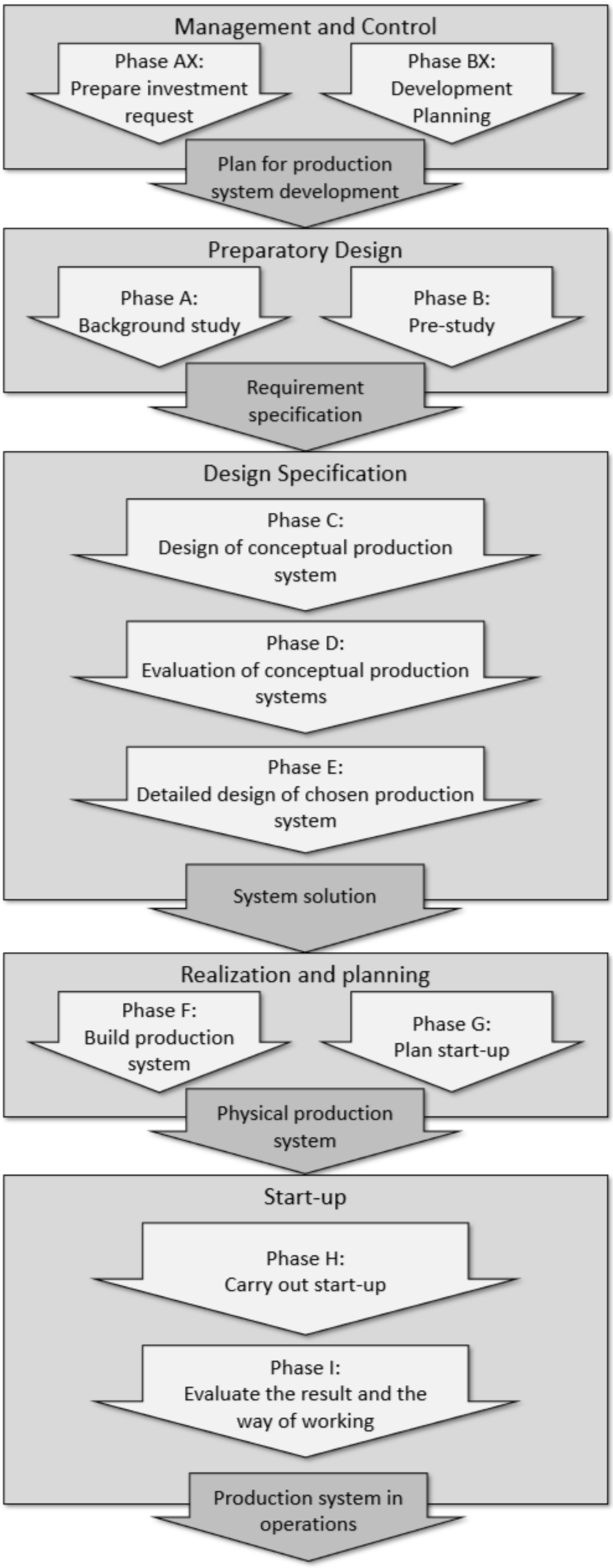

Figure 2.1: Systematic method for production system development based on [Bellgran, 1998].

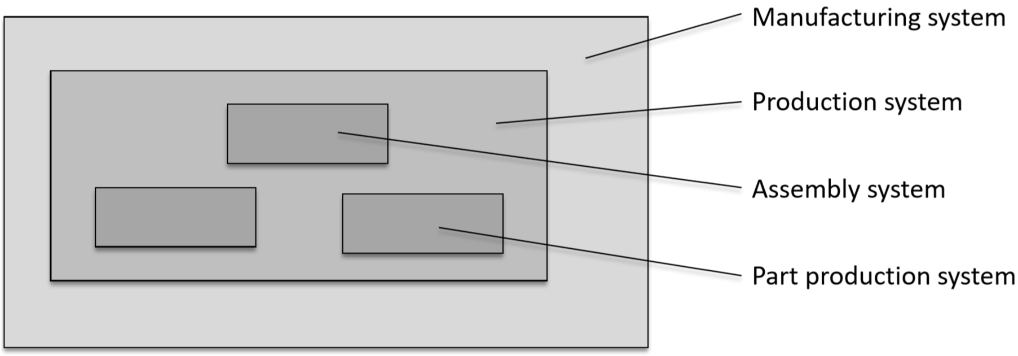

Figure 2.2: Hierarchical perspective of production systems based on [Bellgran and Säfsten, 2010].

2.1.1 Production Subsystems and Aspects

Descriptions of the production system vary with some focusing only on the division between the human system and the technical system, while others describe several more subsystems. Four subsystems can be considered common when describing a production system [Rösiö, 2012]:

- **Material handling system:** Hardware related to operations at or between stations (transport lines, fork lifts, pallets etc.)

- **Human system:** Direct and indirect labor (operators, supervisors, administrators etc.)

- **Computer and information system:** Hardware and software used to communicate information (work instructions, software programs, information boards, notebooks etc.)

- **Technical system:** Hardware directly related to the production process (tools, fixtures, machines etc.)

Furthermore, some descriptions include a fifth subsystem:

- **Building and premises:** Buildings and their premises (floors, ceiling, walls etc.)

These different subsystems as well as their interactions together comprise the production system, as illustrated in Figure 2.3. This view of the production system facilitates production engineering since different parts of the production system are taken into consideration. However, it might be of use to have a more detailed view of different production system aspects, as to not miss important aspects when making design decisions. Bellgran [Bellgran, 1998] suggests a thorough checklist when developing production systems, see Table 2.1.

System Aspects – Checklist

Production engineering
Production layout
Level of automation (dynamic)
Flexibility
Production volume
Product life-cycle
Number of product variants
Cycle time, lead time, change-over time
Availability, reliability
Separation of production processes
Disturbances
Modularisation
Operation sequences
Tolerances
Production process demands
Reliability – equipment
Spare parts
Tool supply
Follow-up system

Material handling
Control principle: push/pull
Work in progress, buffers
MRP-system
Information system
Handling equipment, handling volumes
Material and product flows
Queuing time
Transport, transport time
Inventory capacity, routines
Quality control

Plant and equipment
Plant characteristics: floor, ceiling, pillars, truck roads, etc.
Layout planning
Equipment
Stores
Media
Capacity
Personal premises

Financing
Investment level
Method of calculation
Pay-off time for machines/equipment
Offer inquiry
Staff turnover
Absence costs
Profitability demands
Life-cycle cost, Life-cycle profit

Work organisation and personnel
Type of work organisation, team work
Available personnel, personnel structure
Education, training
Competence, personnel flexibility
Information
Attitudes, creativity, adaptability for changes

Work environment
Physical environment
Man-machine, ergonomics
Safety
Noise, vibrations, light
Chemical health risks
Psycho-social work environment
Stress level related to work tasks
Cleaning routines
Work studies

Market – strategic level
New markets, market demands
Competitors, customers
Price level, stability, prognoses

Company – strategic level
Company strategy, future plans
Investment policy
Resources, competence
Core activities
Make or buy strategy

Product concept – strategic level
Price
Quality, design
Product mix, product complexity
Delivery time, delivery precision
Customer adaptation

Table 2.1: Checklist with system aspects to consider during production system development based on [Bellgran, 1998].

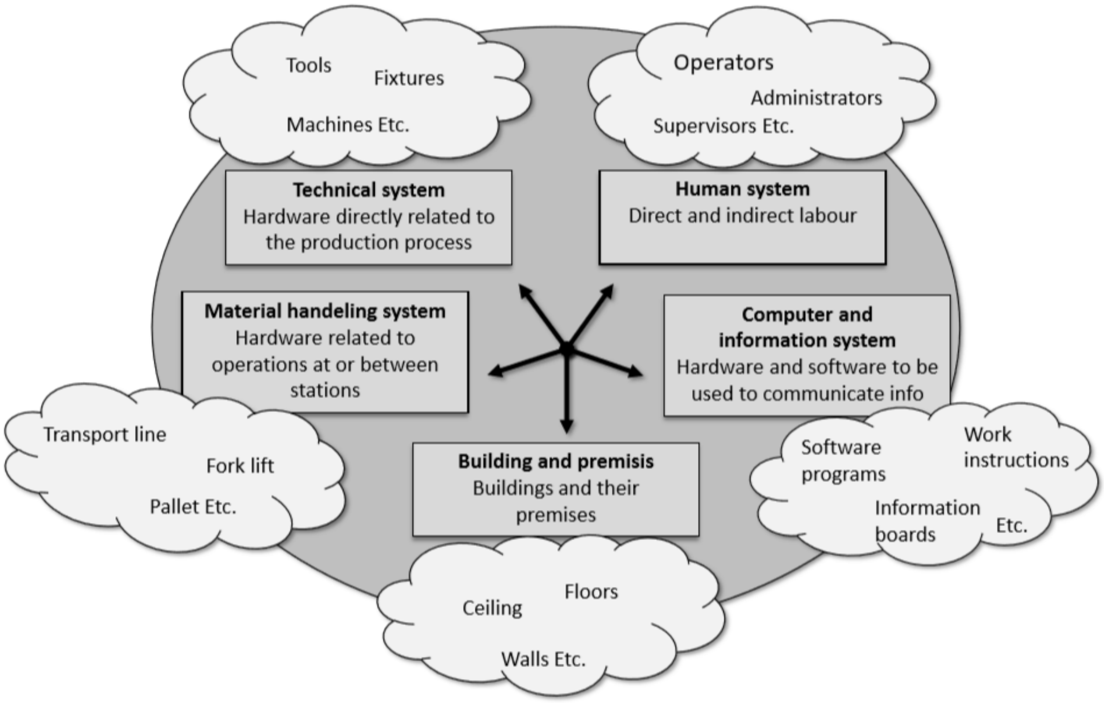

Figure 2.3: Constituent parts of production systems based on [Rösiö, 2012].

2.2 Reconfigurability in Production Systems

Manufacturing benefits from being able to adapt to changing requirements, such as changes in production volumes and mix, introduction of new product models or engineering change [National Research Council, 1998]. Depending on which new requirements arise, adaptation might be needed at different levels of the organization. This could mean anything ranging from strategical adaptations on a high level, to adaptations of specific work stations in production. This ability can be described as reconfigurability, which is connected to different production system characteristics, illustrated in Figure 2.4 [Rösiö, 2012]. Effectively utilizing reconfigurability in production system design requires an understanding of these characteristics, and how to handle different types of change. In this way, reconfigurability can serve as a tool to enable a flexible production [Rösiö, 2012]. Despite the potential benefits, reconfigurability is seldom considered in the production system design process.

Production systems can be seen from a life cycle perspective, where the system is created, used and retired [Wiktorsson, 2000]. Over the course of the lifetime of a production system the requirements on the system changes, for example with regards to production volumes and product mix. In general the production systems length of life is longer than the product and the production volumes that the system was designed for [Bellgran, 1998]. This results in a production system that isn't always suitable for the desired production. By improving reconfigurability the system can be adapted to better suit the context and requirements at any given time, while also improving the systems' length of life.

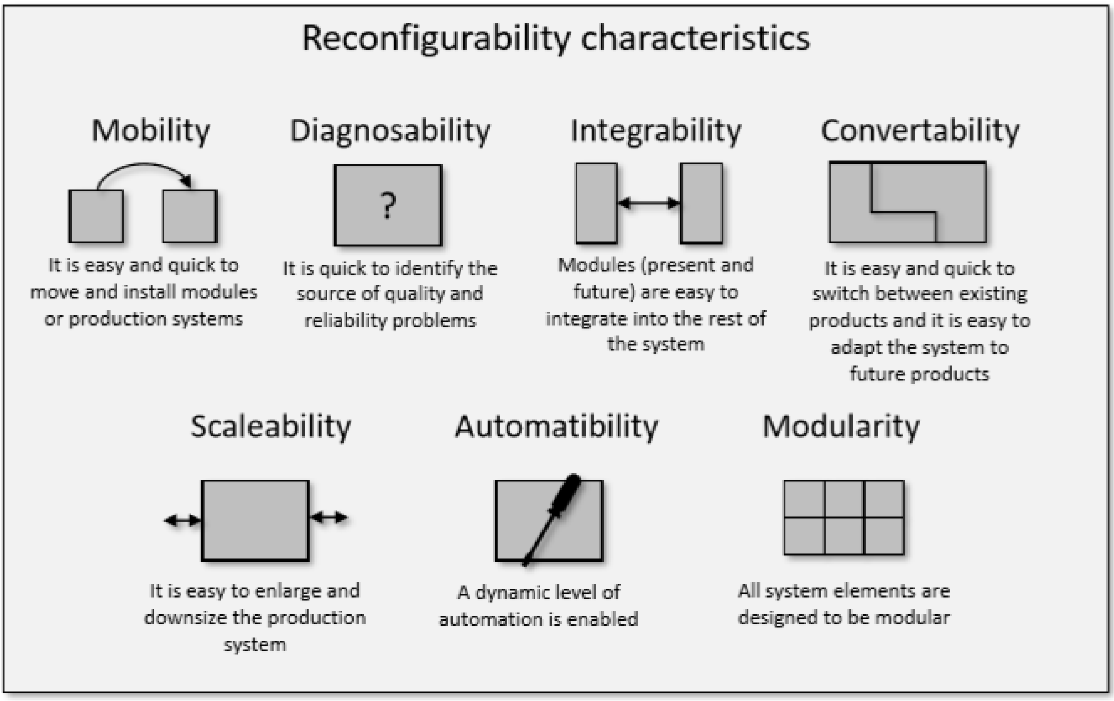

Figure 2.4: Reconfigurability characteristics based on [Rösiö, 2012].

The ability to effectively handle change is positive, but increasing flexibility can sometimes lead to increased costs. Customers do not want to pay for excess flexibility, and excess flexibility can make the system complex and ineffective. Thus it is important to not invest in more flexibility than necessary [Rösiö, 2012]. On the other hand, it is easier to calculate costs than the potential benefits of flexibility. Identifying which changes will be necessary in the future helps with determining which reconfigurability characteristics should be considered, and to what degree.

2.3 Preparatory Design

Producing a design specification requires some preparatory work. A background study should be performed, looking into the current production system. A pre-study should also be performed, that serves instead to look forward to what might be required of the production system in the future. These two studies are then used to create a requirements specification for the future design. The requirements specification is used to filter out any alternative solutions that do not reach the mandatory objectives. It's also of interest to touch upon desired objectives and performance measures, as it can help to distinguish solutions having an extra edge.

The level of detail of the requirements specification tend to vary depending on whether the system design process is performed in-house, by a supplier etc., as well as depending on the extent of the change. When larger changes to the production system are carried out the requirements specification tend to be rigorous, while requirements during smaller change projects often are communicated verbally. Even though the importance of the requirements specification has been shown to play a central part in production development efficiency, studies indicate companies often underestimate the value of thorough preparatory work [Bellgran and Säfsten, 2010].

2.3.1 Background Study

A background study serves to give insight into what has worked well in the current or similar production systems, and what hasn't. Apart from serving to gain knowledge that is useful for the future system design, a background study can also help facilitate change by involving different stakeholders early in the change process. This background work is often omitted, as many believe that their production system is unique, and that generalities and best practices do not apply in their specific case anyway. Instead it is common to go straight for the solution without properly evaluating the current situation and preconditions [Bellgran and Säfsten, 2010].

To gain insight into the current and previous states of the production system, different approaches can be used. Quantitative and qualitative data can be gathered through surveys or studies, or it can be extracted from already existing data management systems, and can be analyzed to draw conclusions about the production system. More formalized methods could also be used, such as Rapid Plant Assessment (RPA) or Value Stream Mapping (VSM). This has the benefit of being standardized methods, potentially reducing the impact of bias in the background study. Regardless, it is important to consider the validity of the data that is used. The data might not reflect reality accurately, as results could be reported in a way that makes them look better than what they actually are.

2.3.2 Pre-study

While the background study looks back at how things have worked before, including analysis of strengths and weaknesses in the current system, the pre-study instead looks forward into the future production system. By investigating the company strategies as well as the more concrete plans over the coming years, it is possible to specify in what way the system is expected to perform as well as the requirements and desires for the future system. An example of this could be that planned marketing and sales efforts mean production volumes are forecasted to increase a lot, resulting in improved requirements on capacity.

During the production development project as well as after the new production has been realized, the requirements on the production might change. This puts requirements on the design process, where the requirements specification might need to be intermittently updated during the project. It might also require the suggested design to be flexible to future changes in requirements of aspects such as capacity, level of technology or production lead times.

2.4 Design Specification

The design specification process serves to create a detailed description of a system design. In order to deliver a good and balanced system solution, first a conceptual design including several solutions to various problems has to be produced. The conceptual design is then revised in an iterative process including evaluation, comparison and redesign of the solutions until a satisfactory concept has been found. This concept is further refined and designed in detail to produce the final design specification. These three activities make up the design specification process, and are covered in more detail in this section. While the process might seem rather linear, in practice the different subprocesses interact with each other and are performed iteratively and to some degree in parallel.

2.4.1 Design of Conceptual Production System

When the requirement specification produced in the preparatory design is completed, the next phase is to produce a conceptual design for the assembly system. This includes solutions to the most crucial aspects, that in turn affect the rest of the design process. Beyond complying with the requirement specification, the conceptual design also has to include solutions to a number of dimensions or parameters. Exactly which dimensions and parameters that are considered part of the conceptual design will vary from project to project, but can for example be solutions to issues such as material planning, process flows, estimation of capacity need, level of automation, work organization etc. To reduce the complexity the system is often broken down into several subsystems.

2.4.2 Evaluation of Conceptual Production System

During and after the development of the conceptual design the solutions need to be evaluated. This is an iterative process where the solutions are redesigned or rejected based on the requirement specification. Evaluation could include making CAD drawings, layout proposals, cost estimations as well as using systematic evaluation and risk analysis tools. One way to get more input on the alternatives and at the same time gain acceptance of the design is to arrange workshops with people that will be affected by the solution.

2.4.3 Detailed Design of Chosen Production System

The goal of the design specification process is to deliver a detailed description of the production system, which is the purpose of this step. The level of detail can vary depending on if the design is seen as a proposal or as a final solution. It also varies depending on is responsible for the realization process, e.g. if it's an external supplier or if it's done in-house. The system solution could include things like detailed layouts, investigations of technical solutions, work place designs, work organizational and work environment solutions, operator training plans, line balancing solutions and more.

3

Method

In this chapter the method used during the research process is described. This is done by explaining the chosen research approach and strategy, as well as by detailing the different phases of the project. Furthermore, the way in which data was collected and analyzed is described. The final section contains a description of how quality was assured during the study.

3.1 Research Approach

When performing research, there is a distinction between inductive or deductive approach. A deductive approach is based on existing theories and knowledge within the area to formulate hypotheses or frame research questions. Observations or findings are then used to draw conclusions according to the theory [Bryman, A. and Bell, E., 2015]. An inductive approach on the other hand is more suitable when information or theory is lacking, and thus focuses much more on gathering information to build new theories on. While there is some criticism regarding lack of scientific justification for inductive inference, an inductive approach is of use when aiming to draw conclusions in fields where existing theory is lacking [Ormerod, 2010].

In the company studied in this case the production engineering focus has been mostly on operations, and less on overarching production development. As a result much of the relevant data for a production development project like this one is missing or of inadequate reliability. There is also existing theory on the topic of production system design in general, as well as assembly system design in particular. A deductive approach was therefore used, where existing theory served as a base for posing relevant research questions. Established methods were used to gather information to answer the research questions, as well as for analyzing data.

3.2 Research Strategy

Different research strategies can be categorized based on if they result in quantitative or qualitative data. Quantitative research methods are used to gather quantifiable data or measure a specific characteristic, while qualitative research methods are applied to investigate a phenomena in a more heuristic way. Quantitative methods include time studies or questionnaires with closed questions, while qualitative methods include interviews, observations and questionnaires with open ended questions [Blessing and Chakrabarti, 2009].

This thesis was primarily based on an application of the systematic method for assembly system design, as can be seen in Figure 3.1. A mix of research methods were used to achieve a degree of triangulation. Data collection was mainly done through qualitative methods, while quantitative methods were used where possible to reduce bias.

Phase A and B of the method in Figure 3.1 that are related to preparatory design were used to formulate a requirements specification, answering the first research question of the thesis. Phase C and D related to conceptual system design, and phase E related to detailed system specification were used to answer the second and third research question respectively.

3.3 Data Collection

Using multiple data collection methods has the advantage of reducing subjectiveness [Yin, R. K., 2014]. A common way to categorize data is into the categories primary and secondary data [Bryman, A. and Bell, E., 2015]. Data which has been collected for the sole purpose of the study is considered to be primary data. This type of data collection is time consuming and potentially very expensive, but has the advantage of being tailored for the specific purpose of the study, including details or context that would otherwise be impossible to find. Secondary data on the other hand is data that has already been collected in other research, or for other purposes than the study. Such data has the potential to be of very high quality, while requiring little to no effort to procure. The biggest downsides are related to unfamiliarity with the data, data complexity and a lack of control over the quality of the data. This study used interviews and on site observations as primary data collection methods, and internal documentation and performance data as secondary data.

3.3.1 Primary Data

The main purpose of data collection in this study revolved around getting an understanding of the current system, its strengths and weaknesses as well as what requirements there are on the future production system. For this purpose,

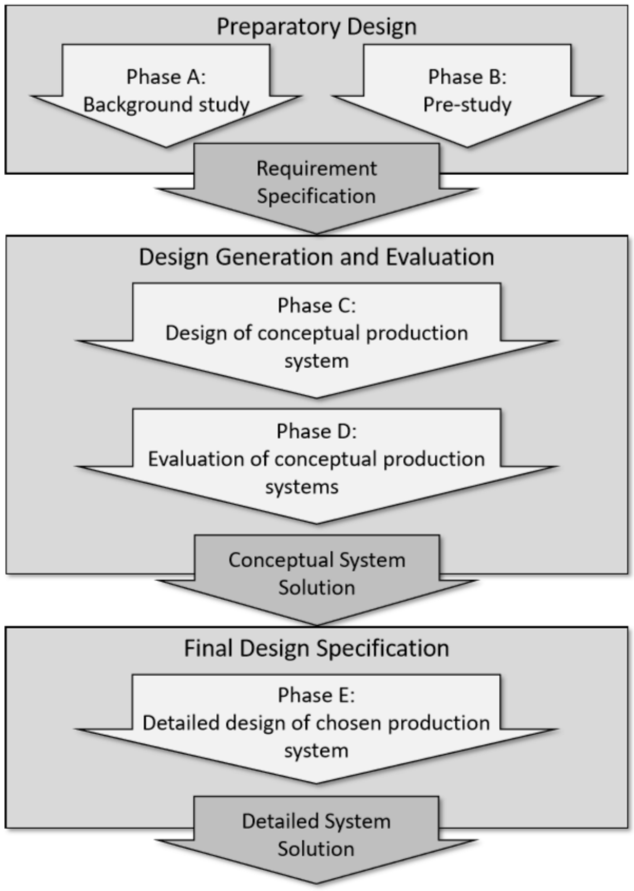

Figure 3.1: Adaptation of the systematic method for production development originally suggested by Bellgran [Bellgran, 1998]. Parts of the original method related to investment and development planning, realization and start-up have been omitted as they fall outside of the scope of the thesis.

interviews were used as the main data collection method. Interviews were held in a semi-structured manner, where a set of interview questions were prepared in advance. During the interviews follow-up questions could be added, ordering of questions could be changed, or questions that were deemed irrelevant could be omitted or changed, depending on the answers of the interviewee [Bryman, A. and Bell, E., 2015].

Interviews were conducted internally at the company, and included one set of interviews with 3 different operators, as well as another set of 3 interviews with managerial and support functions. The interviewed operators were of varying levels of experience, and worked in different areas of the production. The other interviewees had the positions of VP of Product Supply, Production Manager and Manufacturing Engineer. The main purpose of interviews with operators was to gain insight into the current production system and its strengths and weaknesses. This was done by asking questions about the current system based on key aspects from the theoretical framework, such as the system aspects checklist. Interviews with managerial and support functions also served to gather information on requirements and wishes for the future system. Questions about the future production system requirements were therefore included, based also on the theoretical framework. All interviews were held in Swedish, on site and face to face, using interview guides customized for the interviewee's position. The interviews typically took between 30 and 60 minutes.

In addition to interviews, the current operations at the company were observed. This too was done to gain understanding of the current system and its characteristics. Material supply to Area 1 as well as assembly in Area 1 was observed by following along during the process, continuously asking questions to clarify how things work. Work sampling of the assembly processes was also done as a case study for the assembly of one product, to find how time was distributed throughout the work day. In addition to this, different meetings related to production were observed. This included daily pulse meetings, bi-weekly production planning meetings, weekly production staff meetings and bi-weekly improvement meetings. Daily meetings were attended nearly every day throughout the thesis, while the other meetings were attended 2-5 times each. Daily meetings were 15 minutes long, while the other meetings were roughly 30 minutes long.

Finally, study visits were conducted at 2 other companies with similar types of manufacturing. This was done to learn from others what could work and what solutions might be best avoided. The study visits included observations from guided tours as well as interviews with Production Technicians or similar.

3.3.2 Secondary Data

Some secondary data was used in addition to the primary data. This consisted mainly of quantitative performance data from the company's data management system, as well as internal documentation such as work instructions, standards and certifications. The secondary data helped gain an understanding of the current production system.

3.4 Data analysis

The literature study was used to build a theoretical framework, centered around system models and a systematic method for production system design. The theoretical framework served as a base for structuring and analyzing the data throughout the project. In addition to the topics covered in the theoretical framework, a wide variety of theories regarding things like material handling and process flows were used in analysis. Referencing and explanations of these different topics was done in conjunction with analysis throughout the thesis, as to keep the scope of the theoretical framework manageable. Analysis was done iteratively and in parallel to other activities throughout the project, so that findings could help guide the project going forward.

As the data analysis involved some degree of judgment and interpretation, the results of analysis had to be verified continuously. This was done through workshops with different groups of employees, as well as through meetings and presentations. This meant knowledgeable persons could verify or reject the conclusions that were drawn at different stages of the project. Two workshops were held, where the first one was conducted roughly half way through the thesis. The workshop hosted 8 people, of which half were assemblers and half were industrial engineers and a manager. The second workshop took place towards the end of the thesis, and included 4 industrial engineers. In addition, 5 meetings were conducted with one production engineer throughout the thesis. Both workshops, as well as the meetings with the production engineer, included some presentation of findings followed by discussion and feedback from participants.

3.5 Quality Assurance

A common way to increase reliability and validity of a study is by increasing the number of data points in data collection. This is particularly relevant in qualitative studies such as interviews, as interviewees might exhibit bias in their answers. There is also the issue of bias of the interviewer, since there is always a degree of interpretation. A method to reduce this is member checking, where participants are asked for feedback on the results from the study [Buchbinder, 2011]. In this way participants are more actively involved as collaborators in the study, thus enhancing the authenticity and weight of the results. Member checking was used throughout the project through several means; results were subjected to feedback through workshops and respondent validation after interviews, as well as during more formal meetings with university and company supervisors.

A common way to increase accuracy of a study is by using a mix of several research methods through so called triangulation [Denscombe, M, 2014, Bryman, A. and Bell, E., 2015]. Triangulation usually refers to the combination of quantitative and qualitative methods, but can include other methods such as literature studies as well. This thesis consisted mostly of qualitative data collection and literature studies, however some quantitative methods were used where applicable as well to achieve triangulation.

4

Preparatory Design

This chapter describes the result from the first phase of the study, namely the preparatory design phase [Bellgran and Säfsten, 2010]. The first section of the chapter includes a description of the current state of the production. The second section then discusses the different requirements and priorities that were found. To cover all relevant aspects of the production system the checklist by [Bellgran, 1998] seen in Table 2.1 has been used as a guide, omitting some aspects that were considerd to lie outside of the scope of the thesis. Furthermore, the first research question formulated as "What are the production system requirements and which are the most important performance measures?" will be answered.

4.1 Background study

This section includes study and analysis of the current state of the assembly system, including activities based on suggestions by Bellgran & Säfsten [Bellgran and Säfsten, 2010]. The different system practicalities and attributes are analyzed to get a better understanding of the current system, as well as its strengths and weaknesses. The system is also compared to other similar assembly systems.

4.1.1 Production engineering analysis

The production system at the company is divided into two main parts, Area 1 and Area 2. The process starts in Area 1 with most of the mechanical assembly. During the assembly in Area 1 the product stays at one fixed position until it is ready to be moved to Area 2. In Area 2 the product is complemented with the electronic cabinet and components which enables further calibration and assembly, thus making the product ready for final testing. Figure 4.1 shows the flow on a conceptual level while Figure 4.2 shows the actual flow through production.

Area 1 currently consists of four parallel fixed position assembly stations. The assembly is manual, and is primarily performed by 2 assemblers that are specialized towards Area 1. Depending on the production plan, multi-skilled assemblers otherwise working in Area 2 will occasionally come and assemble a product in

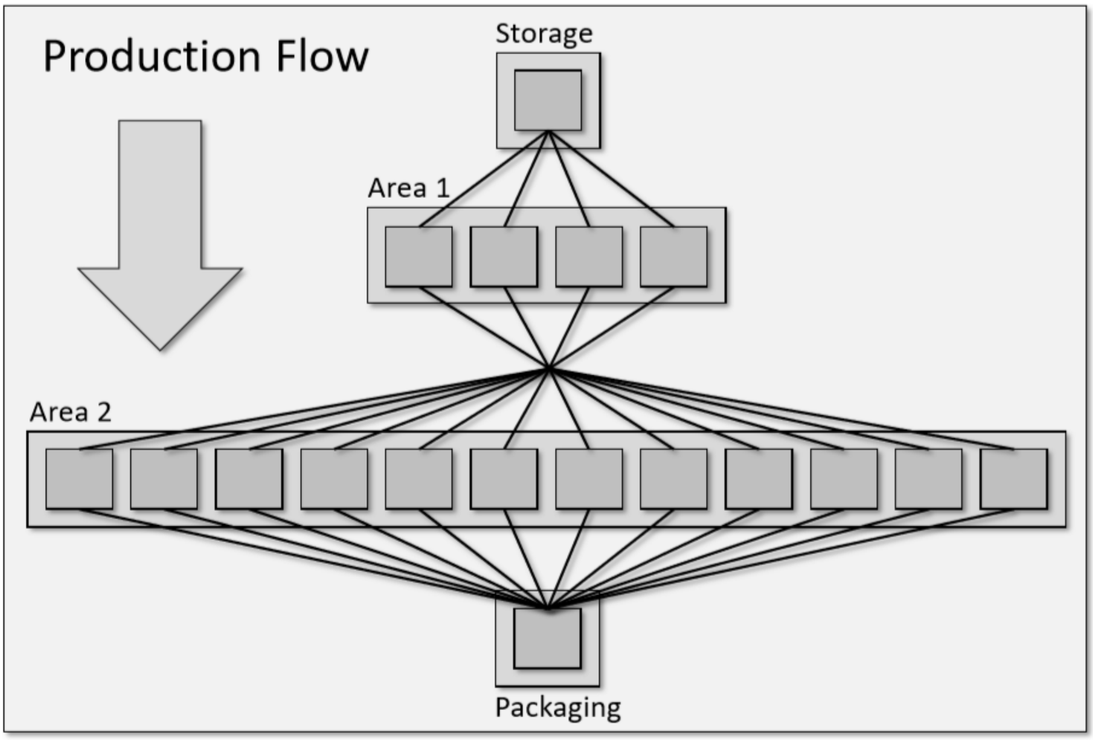

Figure 4.1: Conceptual illustration of the current production flow. The large difference in number of work stations between Area 1 and Area 2 is due to a larger work content and longer lead times in Area 2.

Area 1. In this way the number of occupied work stations in Area 1 vary from 2 to 4, averaging around 3 actively used work stations. The fixed position combined with the generalized and flexible assemblers contribute to a high degree of flexibility in the assembly system. Unused work stations are used as temporary buffers for products that are finished before Area 2 can accomodate them, or for components such as frames and chambers that arrive too early. This flexible use of Area 1 is by Arcam considered a necessity due to somewhat unstable material quality and delivery, and to some extent also due to the unstable production processes in the production system as a whole.

There are three main product models in production today, with one more being launched later this year. The goal has been to replace older models with the new ones, as to keep the number of models in production low. However, since the customer side validation process of the product can take up to a few years and be very costly, customers are not willing to perform this process for new product models if they can instead buy the older, validated ones. This results in a significantly increased product life-cycle, and consequentially a higher number of product models in production than what was originally intended. The general hope and conjecture is that these older models will be phased out sooner rather than later, which has resulted in fewer improvements being made to these models and their production processes.

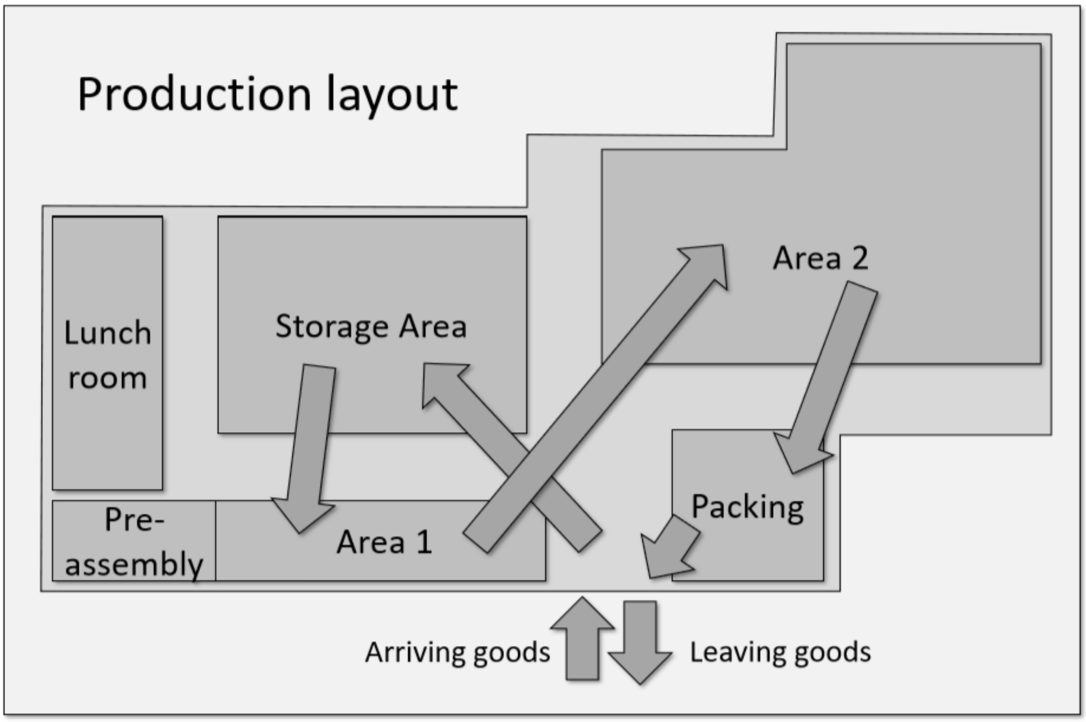

Figure 4.2: Layout of the current production facility. Arrows indicate the flow through the production system, from the arrival of central components such as chambers and framework to the final packaging and departure of finished products.

Table 4.1: Operations and process times in Area 1. This table is based on the most advanced and time consuming model.

OpNr	Name	Process time [min]	Acc. Time [min]	Extremely heavy lifting	Elevated assembly	Heavy lifting	Large components
10	Framework and vacuum chamber in framework	21	21	X			Vacuum chamber, framwork
20	Z-actuator assembly	51	73	X			Z-actuator
30	Vacuum parts assembly 1	9	81	X			
40	EB-unit assembly	9	90	X	X		Electron beam unit
50	Rake actuator assembly	21	111				Rake actuator
60	Vacuum parts assembly 2	34	146		X		
70	Light and shutter assembly	26	171		X		
80	Cable ladder assembly	9	180				
90	Cooling liquid assembly	34	214		X	X	Cooling system, metal sheets
100	Helium system assembly	17	231				
110	Pneumatic valves assembly	26	257				
120	Main stand assembly	41	291		X	X	Metal sheets
130	Exterior design assembly	26	317		X	X	Metal sheets, heat exchanger
140	Protection shield assemby	21	339			X	Metal sheets
150	Build unit assembly 1	26	364				

The production volume is currently 525 products in a year, with a relatively even mix between the three product models (161/189/175). The time required to assemble the different models has never been measured, and is therefore uncertain. Production is instead planned according to estimated assembly times for different product models. Currently these estimates range from 4,6 hours for the simplest model to 6 hours for the most advanced one, and there are no estimates for the coming product launches. A detailed description of the operations performed in Area 1 when producing the most advanced model can be seen in Table 4.1. These process times are based on the current situation where assemblers work alone on one machine at a time. The resulting lead times take into consideration things like meetings and administrative work, and assemblers are expected to spend 6,5 hours per day on assembly. Lead times can however be considerably higher in case of deviations. Such deviations are fairly common, largely due to unstable processes and deviating, damaged or missing components. Faulty materials or process deviations often result in an hour of extra work, while more severe situations where material runs out sometimes cause products to be delayed for days or even weeks. Such disturbances are somewhat offset by the current over-capacity in fixed position work stations in area 1, as work can often be done on another machine at another work station instead.

Although the time per product spent on assembly in Area 1 is uncertain, heuristics have been used to give a picture of the current situation. The box plot in Fig-

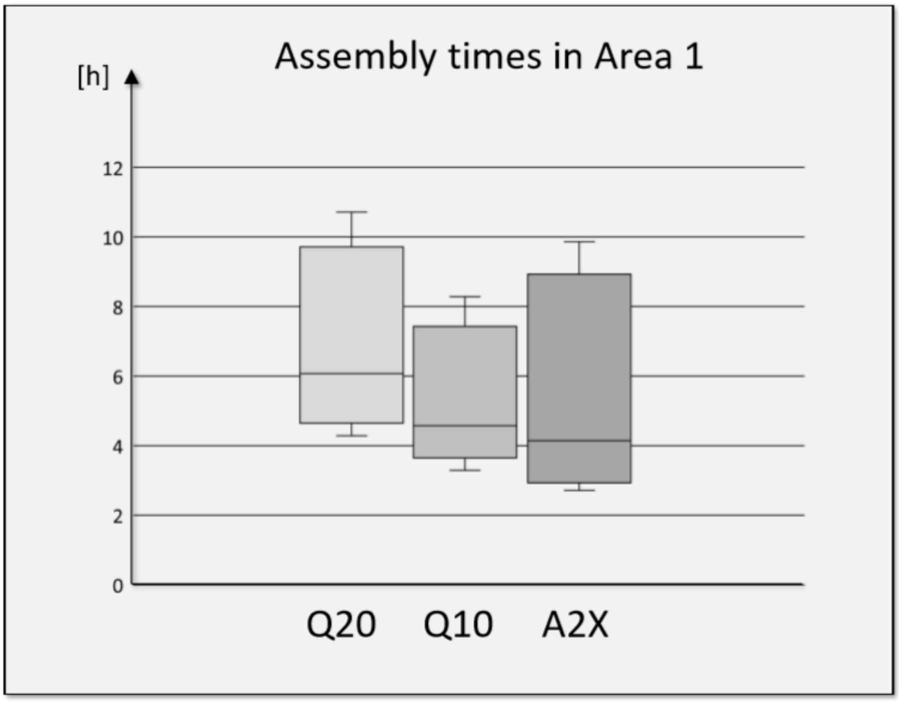

Figure 4.3: Estimated assembly times in Area 1 for different product models. Times are based on a small and imprecise data set, which is why they are only considered to be estimates.

ure 4.3 shows an estimate of how the assembly times in Area 1 of the different models vary.

The different models are similar with regards to subsystems such as pneumatic systems including valves, blocks, tubes etc, or rake systems including different motors, sprockets and chains. These subsystems have been used when structuring different assembly operations, in conjunction with grouping assembly tasks by where on the product they are performed. This roughly means assembly related to subsystems placed at the bottom of the product are grouped into one operation, subsystems and assembly at the top are grouped into another etc. Even though the subsystems are similar between models, they vary quite a bit in design. Consequently, there are large differences between models in the corresponding operations, both with regards to work content and time consumption.

There is a general lack of data describing the performance of the current processes, and the little data that can be found is unreliable due to the way that performance data is logged. For instance, the data concerning time consumption is supposed to be entered by all assemblers after each operation step. In reality however, approximately half of the products produced last year lack time data completely. In addition, the ones that actually have data on how long operations took were found to be inaccurate. When following an assembler through the process it became obvious that the time for each operation was not tracked, and the entered time was only a guess which was often exaggerated to reduce the risk of

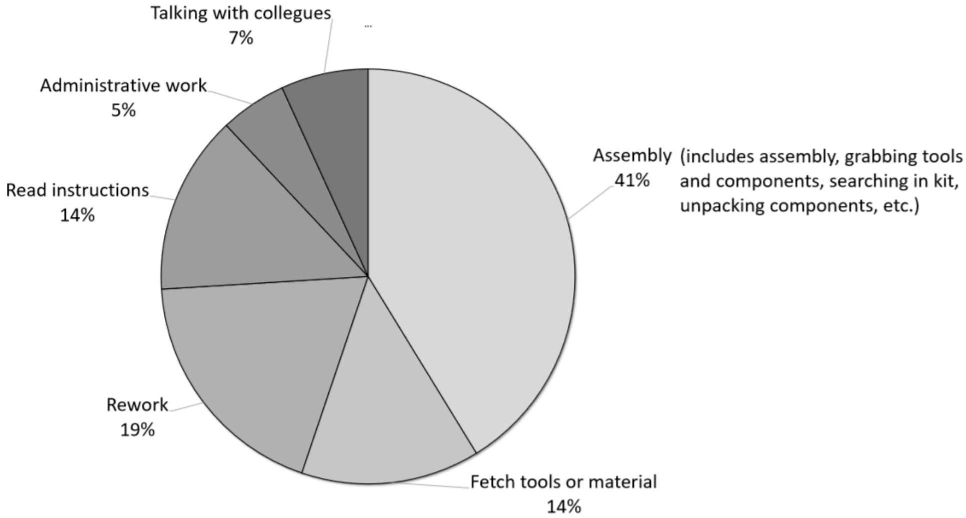

Figure 4.4: Time distribution between different activities in Area 1. Work sampling was performed throughout the assembly of one product. The time distribution shown might therefore not be representative of what is typical. It does however give some indications of how time is spent.

stricter demands on the assembly time. When asked, assemblers verified times are always just estimates, which is also apparent as all times are entered with the resolution of whole or half hours. Observations showed that data collection concerning time consumption as a result of deviations was similarly inconsistent, both with regards to actually reporting data as well as the precision of the data. This general lack and inaccuracy of data makes production engineering efforts uncertain, as they rely mostly on estimates and assumptions.

To get better understanding of what the assembler spent time on a case study was performed. One machine was followed through Area 1 and every 5 minutes the current activity was logged. The distribution between activities can be seen in Figure 4.4. It is hard to know if the data is representative of an average machine since there is no data to compare with, and the time it would take to gather more data is too great.

4.1.2 Material handling analysis

The products are produced according to a production plan developed by production management every other week. This plan is based partially on orders and partially on forecast. The quantity produced each week is based on forecast but the product mix is adjusted to the current order book. If there are not enough orders to cover the quantity to be produced, the rest of the product mix is based on forecast. This is not an unusual scenario since the average lead time on a machine is between 2,4 and 3,7 working days depending on the model, resulting in products often being produced before they are ordered. The finished machines

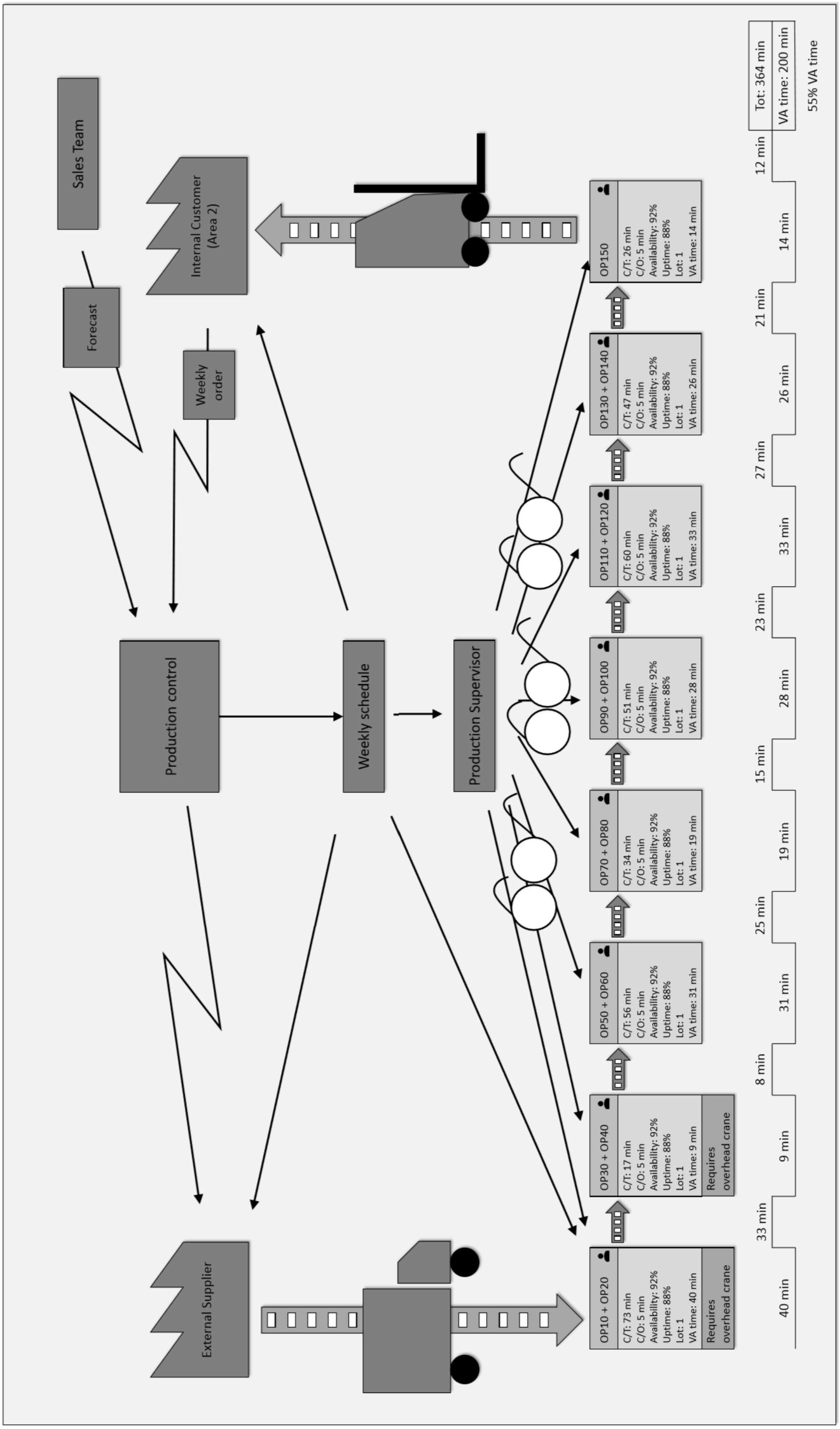

Figure 4.5: Value stream map of Area 1. The value stream map shows how a chamber was moved through Area 1 and its processes. [Hines, 1997]

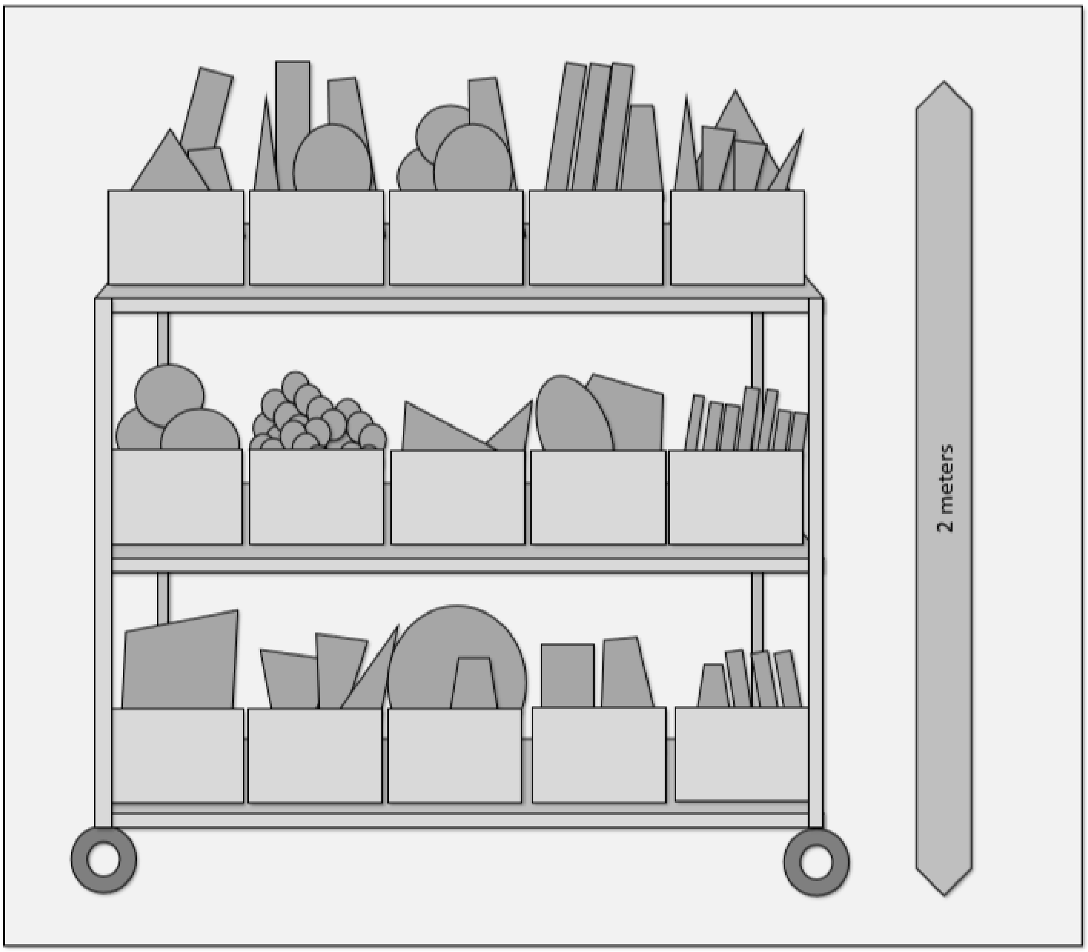

Figure 4.6: Kit cart for assembly in Area 1. Different boxes contain components for individual assembly operations. The contents of the boxes are unstructured.

are either delivered to customers or to an off-site stock of finished goods. The production plan includes start dates which are communicated to suppliers of the two largest components of the product, the frame and the vacuum chamber. These central components are delivered directly to Area 1, and from there the product is pushed through the system. The production plan includes a set time and date when the product is planned to be finished in Area 1. This is adjusted as progress goes along, and the last adjustment is usually made about a day before the product is finished in Area 1. The finish date in Area 1 is necessary for the electronics cabinet to be able to be delivered Just-In-Time and thereafter connected to the machine by the supplier.

Components for Area 1 is provided mainly through one large kit cart which contains several smaller kits with the components for each of the 15 operations performed in Area 1. Smaller parts such as screws and brackets are supplied through a shared stock placed by the work stations. Line stocked components are re-stocked by the logistics department when it is needed or when they have time, while kits are produced based on the production plan and placed near Area

1. The kit carts are not delivered Just-In-Time, but rather produced and placed in a buffer one or two days before the actual assembly starts. Each of the 15 smaller kits are based on the manufacturing bill of material for each operation step, but are placed on one big cart for the whole work content of Area 1 (see Figure 4.5). Each operation contains several tasks and the estimated time consumption varies a lot between operations, with the shortest operation taking about an hour and the longest about six hours. The logistics personnel pick the components for each of the 15 operations and place them in separate boxes which are later moved to the larger kit cart (see Figure 4.6). The smaller kits are unstructured, and to some degree even mixed with each other on the kit cart since a few of the components are too big for the boxes. There are also some components such as a cooling system pre-assembled by the supplier, two large modules pre-assembled in-house and several metal sheets for the exterior of the machine, which are not delivered to the work station. This is because the status of the assembly progress is of too low resolution to be able to deliver the components Just-In-Time, and the components are too large and bulky to keep at line side. These components are instead stored in different storage areas located 10 to 30 meters away, and are fetched by assemblers when they need them. Materials that are bought in bulk, such as cable ladders, hoses and pipes are fetched, measured and cut into a variety of lengths for the different products by the assemblers.

4.1.3 Plant and equipment analysis

The current production layout is a tight fit. It is a result of an organic increase of production volumes, and a consequential increase in allocated space. The increase in demand both for production and logistics capabilities has resulted in storage and production being placed nearly on top of one another. There are forklift roads next to assembly, and there is a fair amount of traffic through production to and from the company lunch room.

Area 1 in itself is outfitted with a overhead crane unit, that has access to all the different work stations. This is shared between assemblers to lift and maneuver large and heavy components such as the vacuum chamber, one of the modules pre-assembled in house as well as the entire product. This works very well in general, though some components such as metal sheets for the exterior are too heavy to lift ergonomically alone while also being difficult to lift with the overhead crane, so these are instead either lifted with the help of a co-worker or lifted alone despite the risks. There are also steel fixtures which the product is placed on top of to raise the product up from the floor for easier access, and a specialized lift cart used during the assembly of another module pre-assembled in-house. These lifting aides are essential for effective and ergonomical assembly in area 1, as some components weigh several hundred kilograms.

Area 1 is also outfitted with a cabinet that contain some seldomly used tools such as electrical screw drivers and torque wrenches, which are shared between

	Employee A	Employee B	Employee C	Employee D	Employee E	Employee F	Employee G	Employee H
Task 1	2		1	0		1		1
Task 2	2	2	2		2		0	2
Task 3	1		2	0	0	2	1	1
Task 4	2	1	1	1	2	1	2	0
Task 5	2	0	0	2		0	1	0
Task 6	2	1			2		0	
Task 7	2		0			2		1
Task 8	1	2		2				1

Skill level
Blank: No training
0: In training
1: Basic knowledge
2: Proficient

Figure 4.7: Competency matrix example. The figure illustrates how work competencies of different employees can be structured.

the assemblers. In addition each assembler has their own personal work table that is outfitted with a personal set of simple tools, such as wrenches and hex keys. Whenever an assembler moves from one part of the production to another, such as when an assembler first works in Area 1 and then moves with a machine to Area 2, they take their work table with them.

4.1.4 Workplace analysis

The production's current work competencies are structured around a competency matrix that maps which assembler is proficient in which tasks. An example of a competency matrix can be seen in Figure 4.7. The current competency matrix is rather general and not very detailed, and does not correspond to the current work division into Area 1, Area 2 etc. However, a new competency matrix is currently being developed, which is more detailed and structured according to the actual work tasks within different areas. The work is mostly organized around working in a certain zone, such as Area 1, and being able to handle all different work tasks and product models within that zone. In addition, production management has stated that the ambition is to always have some redundancy in work competencies as to ensure a degree of flexibility in the work force.

The staff is educated in the basics of the product's subsystems and functions, as to get a better understanding of what is important in different assembly steps. Training in performing actual assembly is ideally done by following a more senior assembler, though this is not always the case - some assemblers instead have to start assembly work themselves straight away, learning as they go. While the assembly work in Area 1 in itself isn't very complex, the work content is large and much of the work isn't very well documented. This means the assembler must learn a lot of details by doing assembly work with support from other assemblers

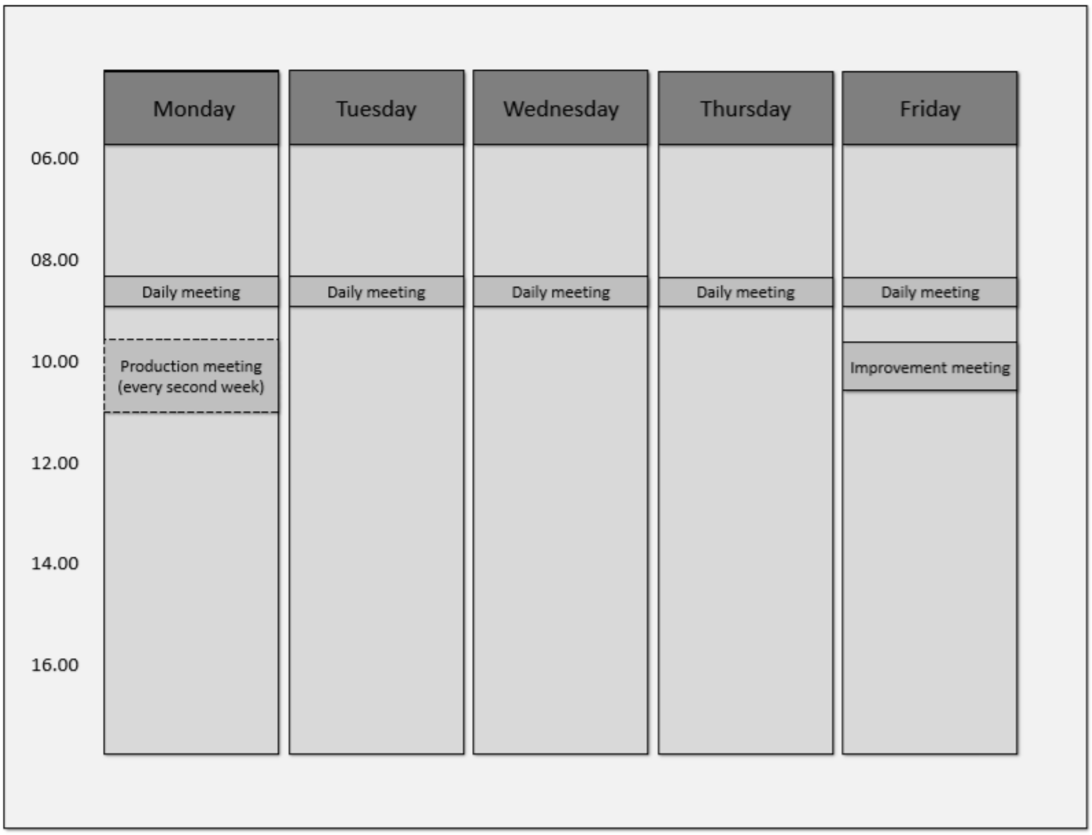

Figure 4.8: Scheduled meetings for production personnel.

before they become self sufficient. Even though there is no clean cut time for how long it takes before an assembler is proficient in the mechanical assembly of Area 1, assemblers state it would take at least 2 months.

Some cognitive support is provided through work instructions and assembly protocols. At Arcam this is used as a way to standardize the assembly work and thereby enable continuous improvements of the processes. They also strive for a well documented standard as a means to simplify learning, thereby making it possible for new assemblers to work independently early on. However, the work instructions are still relatively new, and one of the product models lack work instructions altogether. The assembly process as a whole is also rather undeveloped, with much time spent on non-value adding activities such as fetching tools and materials, doing administrative work or reading work instructions.

There are some efforts to continuously standardize, evaluate and improve the current assembly process. Whenever an issue is encountered, the person encountering it should file a deviation report. These deviation reports are then followed up, discussed and escalated at different meetings depending on the nature of the issue. Daily meetings are held each morning with all 20-25 people working in production, as well as an additional 5-10 people responsible for support functions such as purchasing and industrial engineering. This meeting acts as a first line where deviation reports are spontaneously analyzed and escalated to relevant persons or departments. Every other Monday there is a production meeting where current company happenings are discussed, and where general production issues are handled. Finally, every Friday there is an improvement meeting which focuses on improvement work, and act as more in-depth meeting about deviations and improvement projects. The status of all ongoing projects is reported and there is also the possibility for the personnel to lift problems or improvement potential which might lead to new projects. The issues that are escalated to people not directly working in production result in things like investigations with suppliers into material issues, or requests for engineering change when material specifications are insufficient. The production meetings and the improvement meetings are attended by at least the 20-25 people working in production, and sometimes also a few supporting functions. An overview of the meetings during a week can be seen in Figure 4.8

One problem is that far from all issues are reported. There are several possible reasons for why employees would choose to not report deviations. There could be a lack of understanding as to why reporting should be done, or there could be actual distrust or lack of acceptance of the concept of standardized work, leading to a belief that reporting deviations isn't a priority anyway. Another reason might be that assemblers consider their issue minor compared to others', and because of this they might not want their deviation report "competing" with others for time during improvement meetings. Observations and interviews with assemblers confirmed that reporting deviations wasn't a priority for most assemblers. One reason that was mentioned by assemblers was that they didn't notice any changes when pointing out issues, or that changes took a very long time to implement. In the end, the current lack of reporting of deviations results in a number of issues not being investigated and solved.

As seen in Figure 4.9 the work stations in area 1 each take up a relatively large area, as the products themselves are rather large and access is required from all sides of the product at some point. An open area without any workbenches or other stationary objects of roughly 4 by 4 meters is required to access the product from all sides. There is a permanent assembly table and a kit cart at each station, as well as the assemblers personal mobile assembly table including their personal tools. The work stations are also outfitted with stools for easier assembly on the lower parts of the product, as well as step ladders for assembly on the higher parts.

The most extreme working positions are the ones on the top or at the bottom of the product seen in Figure 4.10 where assembly work is performed inside the dashed boxes. The tasks in these positions result in poor working postures, but since they are rather infrequent the risk of injury or wear is low. During the assembly of the lowest components the machine is lifted up using an overhead crane and placed on a steel fixture, which can be seen in Figure 4.10 below the lower of the two boxes. A work task that is less extreme when it comes to er-

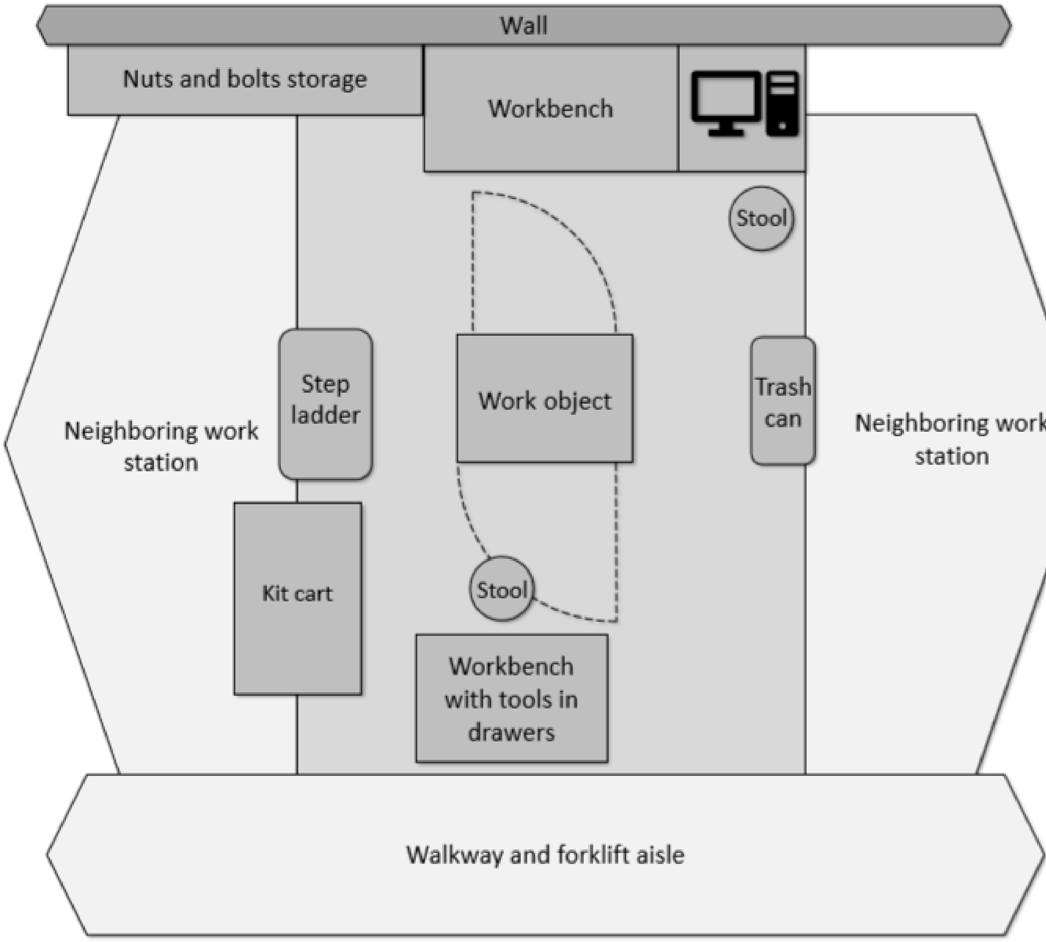

Figure 4.9: Current workplace layout. Work stations are manned by one person.

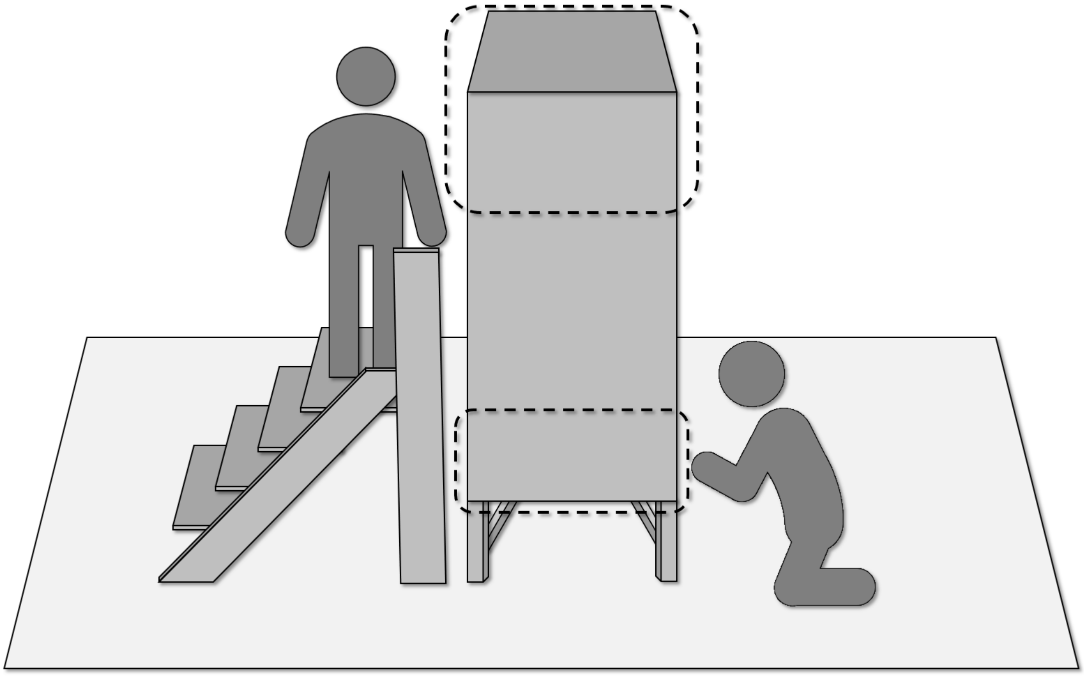

Figure 4.10: Extreme working positions. The most extreme work positions are performed at the top and the bottom of the product, indicated in the figure with dashed lines.

gonomical load, but all the more frequent, is the fastening of screws. Due to both the screws and the screw holes often being made of stainless steel, the fastening is done by hand. [Berlin, 2017]

4.1.5 Strategy analysis

Arcam provides a unique solution for additive manufacturing through their patented technology. The technology provides superior performance for some applications compared to competing technologies, and is coupled with a dedication for quality and functionality rather than providing cost benefits. The strategy is based around providing the best machines on the market for additive manufacturing, and this is apparent also internally. The focus on product development and service shows, and the company strives to constantly provide new and better functionality and services surrounding the product. There are many different product improvement projects being tested on machines in production, and there is an outspoken sentiment of taking your time with each machine to ensure quality isn't compromised.

Arcam has a model called the Arcam production model that among other aspects includes different priorities seen in Figure 4.11. It became apparent during interviews that this is not just a fancy model, and that it really affects the way executives take decisions. The priorities are safety, quality, delivery and economy with the first being most important and the last being the least important. This

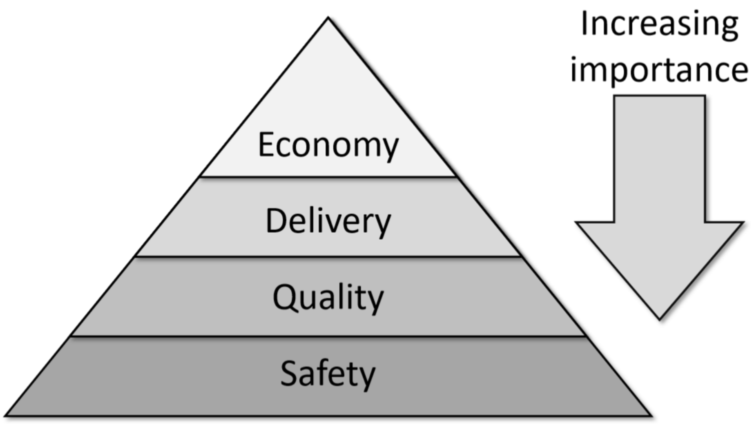

Figure 4.11: Prioritized company metrics. Safety is considered most important, followed by quality, delivery and economy.

model is closely tied to Arcam's competitive advantages and order winning factors. For Arcam's customers the most important thing is the quality of the parts produced by the machines, as in both the aviation and orthopedic industry the effects of quality deviations could lead to life or death situations. The quality of the product itself is also of utmost importance, since the user experience will affect future sales more than a competitive price tag.

Since there is a wide range of possible application areas for additive manufacturing, there are apparent benefits to having some degree of variety in product models to be able to satisfy different customer segments. It is a fairly high commitment from customers to do a technological switch and invest in additive manufacturing - partially due to the extensive validation processes, and partially due to the high cost of each machine. At the same time it can be a big deal to get a new customer, since it could potentially result in large orders. Thus, customer requirements and requests are valued very highly. This obviously affects product development activities, in the sense that new product models will have to be developed to meet emerging demand for performance and functionality. In addition to the introduction of new models, some degree of customization will also be necessary in the future. The implications of maintaining support and production capabilities for legacy products are significant. Production would be simpler and more efficient if there were fewer models and less customization, but providing what the market desires is considered a much greater priority. [Osterwalder, 2010]

4.1.6 Analysis of other companies

In addition to studying the current situation at Arcam, visits to two other companies were conducted. The companies that were visited were chosen because they were believed to be rather similar in some regards, and because they were considered to have relatively developed and mature production systems. The reasoning was that these study visits could then give valuable insight into what works well and what doesn't, and that these insights could be easily translatable into Arcams situation.

The companies exhibited some similarities to Arcam with regards to products and production systems, but there were still many contextual differences. The visited companies produced many more products per year for example, and were in general more efficiently industrialized. They also performed more processes than only assembly, such as machining, welding and painting of components or products. To some degree this results in having a higher degree of control over the ingoing parts into the assembly system. Finally, a higher degree of design for assembly was apparent at the other companies.

One of the visited companies had similar challenges with uneven demand, both in total and with regards to product mix. This was handled by having mixed assembly lines with several different assemblers doing assembly on the same product. By shifting around the number of people working on a certain product at any given time, the differences in assembly time between different product models could be mitigated. In addition the product models with a larger work content had more of the work externalized to pre-assembly, also resulting in less balancing losses. Another effort for minimizing issues with balancing was something called Fixes in the Courtyard. This meant that if there were issues or deviations with a product, they would not be solved in line but would instead be finished without fixing these issues. The product would then be sent to a specific department that could solve any remaining issues.

The different companies all had similarly large and heavy products and components to handle, with different material handling solutions. One of the companies had Automated Guided Vehicles (AGVs) for transporting and rotating the products during assembly. This enabled easy access to the product throughout all assembly operations, regardless of where on the product assembly was performed. The AGVs and products were specifically designed/adapted to enable this, resulting in it being a fairly costly solution. Other solutions for transporting heavy products were simple frames on wheels, where the products could be placed in the frame and then be easily transported around, locking the wheels when necessary for assembly.

One of the companies used rather well developed and automated material handling systems, where material was sorted, stored, picked, machined and kitted according to specific orders. While the system is resource efficient when it comes to personnel, the investment cost for such a highly automated system is likely to have a long payback-time, and would need fairly high production volumes to be justifiable.

Fixed position work stations were used for assembly at one of the companies for some of the larger products. These work stations were structured and space efficient, with tools and work benches taking up minimal space, and with specialized and very space efficient kit carts. These kit carts were built with modular components, and had been adapted over time by assemblers at the company to suit their specific needs.

4.2 Pre-study

This section includes findings and analysis related to the future production system, based on suggestions by Bellgran and Säfsten [Bellgran and Säfsten, 2010]. Data from different interviews related to requirements, desired objectives and performance measures together with observations and previous knowledge has been compiled and filtered to produce a requirements specification, thereby answering research question 1. The structure, intended use and content of the specification is further explained and discussed. The requirement specification can be seen in Appendix A.

4.2.1 Requirements Specification

The requirements specification includes strict requirements, desired objectives as well as important performance measures. It is intended as a filter for the production system design process, where a design can be checked against the specification at any time throughout the project. The design can thus be gradually refined and rechecked against the requirements specification in an iterative process, ensuring only the best possible solutions are chosen. [Bellgran and Säfsten, 2010]

The specification was created using data from interviews with key project stakeholders. The different statements in the interviews were structured into strict requirements, desired objectives and important performance measures, as well as into different chapters based on which dimensions the requirements pertain to. The results were verified through member checking in the form of workshops and presentations [Buchbinder, 2011], and any statements that in this way were found to be contradictory or erroneous were edited or omitted from the final requirements specification.

4.2.2 Analysis of requirements, desired objectives and performance measures

Additive manufacturing in general and Arcam's patented technology in particular is in its relative infancy. Products are mostly sold for use in orthopedic and aerospace applications, both of which have extremely high requirements on quality and reliability resulting in the same aspects being of utmost importance for Arcam as well. As applications of additive manufacturing is rather unexplored in most industries, entry into new markets might also be possible. Demand for

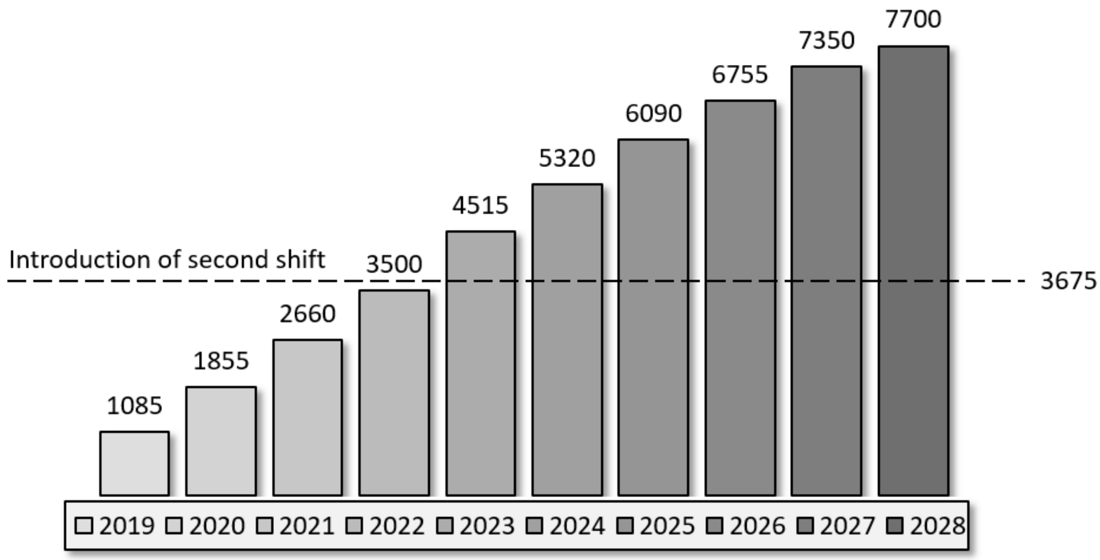

Figure 4.12: Forecasted total demand. The diagram shows a forecast of total demand for the coming 10 years. A second shift is planned to be introduced when demand exceeds 525 units.

many different application areas means many different customer requirements, possibly resulting in a need for more product models and a higher degree of customization. Since Arcam is so dependant on it's few customers the production has to be flexible enough to comply with their current and future demands. [Osterwalder, 2010]

The total demand of all different product models combined has been forecasted by Arcam to increase by roughly 700 products annually during the coming years, for more exact numbers see Figure 4.12. This is a dramatic increase for a production currently outputting 375 products in a year. While efforts are needed to increase the capacity of Area 1 dramatically, quality also needs to not only be maintained but be improved. This is coupled with the introduction of a new product model, increasing the number of models produced from 3 to 4. Since the demand is uncertain for the individual models as well as overall, assembly in Area 1 will be hard pressed to improve not only flexibility with regards to product mix, but also with regards to overall volume.

There are two major reasons for why the company has decided to move to new facilities. The first is the obvious issue with space limitations, restricting the company and their production from growing. The other is the product flow through the production which has grown organically, resulting in the product coming in through one door and then flowing though the facility, to finally leave though the same door it came in, as seen in 4.2. This flow is an issue since the different departments often disturb each other, and logistics release particles and dirt which causes problems during the assembly of some of the more sensitive parts. To reduce these issues the layout of the new Area 1 should be designed to minimize the movement of other personnel through the assembly area.

The possibility for assemblers to perform all different steps in the production of a machine is considered by management at Arcam to be rather positive, as this allows for a greater understanding of the product as a whole. Understanding the product to a greater degree could potentially enhance quality, however the issue of complexity must also be addressed. Relevant stakeholders acknowledge that it might not be possible or even desirable to continue with this kind of generalized work force. Since having a broad work content results in a high degree of complexity, the effect on quality could actually be negative. Specialization could make it easier to standardize work, support continuous improvements, reduce variation and improve efficiency. While the current work content is vast, work variety must still be considered as to avoid making the work monotonous and unfulfilling.

With increasing demands on the production system it becomes exceedingly important to improve system performance. Visual management has been expressed as an explicit requirement for the future system, not only to convey a clear sense of pace for production, but also to act as a follow-up on system performance. There are however issues with performance data in the current system in the first place. The activity of logging the time spent on assembly operations is often omitted by assemblers, and the same is true for reporting deviations or quality issues. Improving data collection processes could ensure more complete and accurate data, which is a fundamental part of a good visual management system. This could be achieved through digital solutions, which could be enabled by the presence of relevant hardware and software. [Ortiz, 2011]

One of the biggest issues with the current system is variation. Assemblers have several times stated that no two machines are alike, and that there are apparent differences depending on who assembled the machine. While there are work instructions and standards to some degree, they are somewhat flawed and incomplete, and are also not fully conformed to by assemblers. This partial lack of standardized work is a large reason for the variations in the system. In addition, it obstructs efforts for continuous improvements, consequently hindering development of system performance. As a way to handle the variation Arcam has focused on improving the competence of the assemblers, thereby achieving a flexible workforce that can handle variation well. In this way, the focus has been put on developing the staff rather than the processes, making it harder yet to standardize work.

5

Design Generation & Evaluation

This chapter contains a description of how the conceptual design proposal was developed as well as the content of the conceptual design. The result of the conceptual design generation and evaluation is also presented along with motivations for the choices that were made and explanations of the thoughts and ideas that lead to the decisions.

5.1 Scope of Conceptual Design

According to Bellgran & Säfsten [Bellgran and Säfsten, 2010] a conceptual production system design should include solutions to issues such as flow principle, tools and equipment, material supply, work organization, and work environmental considerations. The method was however developed for a broader context than what it is being used for in this thesis, namely production system development rather than assembly system development. Some parts of work organization and work environment span over more than just the assembly system and are therefore considered to lie outside the scope of this thesis. The remaining parts of work organization and work environment are not considered to be crucial aspects that affect other decisions related to the conceptual design, and are therefore postponed to the following phase where the detailed design will be produced. The aspect covered during the conceptual design phase were consequently flow principles, material handling as well as tools and equipment.

5.2 Evaluation process

In addition to developmental work, solutions were continuously and iteratively evaluated throughout the design generation process. This served to eliminate solutions that didn't fulfill requirements and to choose solutions that were better than others with regards to company priorities.

The requirements specification was used to narrow the possible solutions regarding the different areas of the conceptual design. Design choices that were

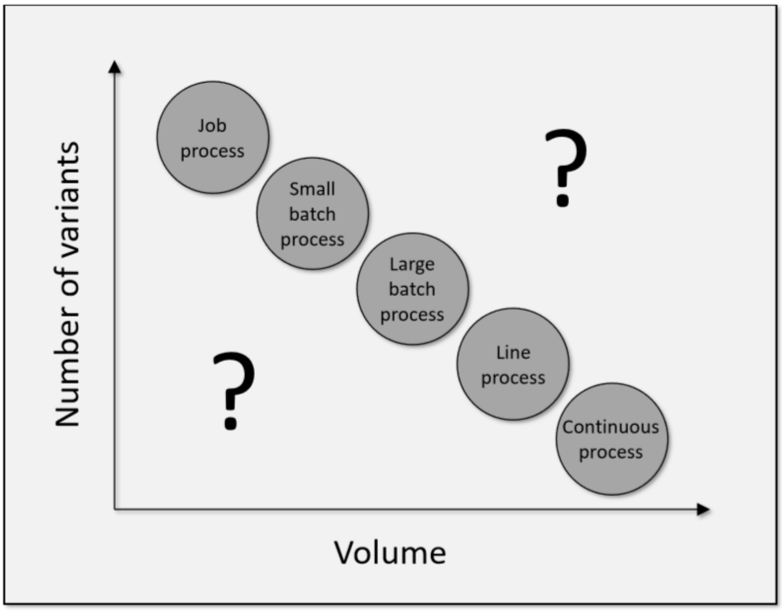

Figure 5.1: The Product Process Matrix. The figure illustrates common production process choices, based on the number of variants as well as the volumes to be produced. Figure based on [Hayes and Wheelwright, 1984]

incompatible with strict requirements were discarded early, while priorities and wishes were used as support for evaluation throughout the design process. Reconfigurability aspects [Rösiö, 2012] were also used as support when evaluating different alternatives.

The initial conceptual design was also presented to employees at the company for evaluation. The design concept was discussed with the production engineer responsible for coordinating the move to the new facilities during several occasions. Later the design was handled at a larger workshop with personnel from production, management and support functions. The results of these iterative evaluation activities were used to produce the final conceptual design proposal.

5.3 Conceptual Design Specification

This section specifies how and why different concepts were chosen for the conceptual design. The proposal is also summarized into a table.

5.3.1 Flow

The choice of process flow is affected by many parameters, making the choice complex [Wiendahl and Scholtissek, 1994]. According to the Product Process Matrix seen in Figure 5.1, a correlation between the product type and the choice of process flow is common in industry. Low production volumes with high num-

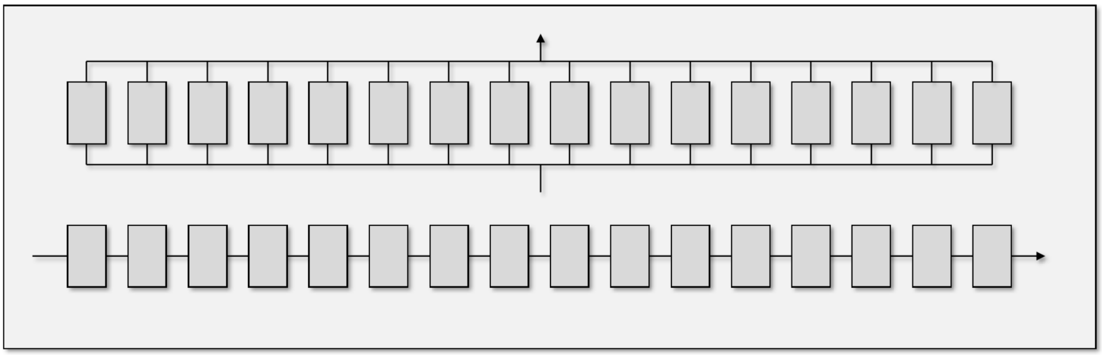

Figure 5.2: Extreme flow principles. The figure illustrates a fully parallel flow as well as a fully serial flow.

bers of variants is commonly done through parallel flows (job process), while high volume and low number of variants are often combined with serial flows (line process) [Hayes and Wheelwright, 1984].

The proposed process flow through Area 1 was chosen by first considering the extremes of a fully parallel or a fully serial flow. A fully parallel flow would signify a fixed position concept and is the flow type that Arcam currently uses, where products are assembled in cells independent of each other. It is very resistant to disturbances, and can easily handle Arcam's large variation in product mix, introduction of new models and the forecasted ramp up resulting in a gradual increase in the number of work stations. It generally also has a higher productivity potential than serial flows, as there are no system or balance losses [Bellgran and Säfsten, 2010]. However, this potential is not always realized as it is often compromised by other elements such as the work organization and control systems [Neumann, 2006]. While a parallel flow provides great flexibility which is an important factor when the variation in product mix and lead time is as large as it is at Arcam, the lack of specialization and dependency on other work stations also results in problems not being revealed, but instead being obscured and hidden by the flexibility in the system. A fully parallel flow would result in a work content of 6,1 hours of assembly work at each work station, and would require a large number of tools and consumables such as screws and washers to be kept at each station. To keep such a work space clean and in order requires more effort than one with fewer tools and consumables. A larger work content results in greater possibilities to perform tasks in a different sequence than what is intended, based on varying preferences among assemblers. While a larger work content is likely to lead to larger variations in quality and lead time, the work content would be fairly large even with a high degree of serialization. Standardization of work is therefore an important aspect regardless of whether a parallel or serial flow is chosen. [Liker, 2004]

A fully serial flow would correspond to a classical line layout, where products are moved through a sequence of work stations. This type of flow would be sensitive to the frequent disturbances caused by material shortages at Arcam, as well as the variation in product mix. Introduction of new models is also quite common at Arcam. Since the processes initially aren't as developed when assembling new models, they are likely to cause the whole line to slow down and significantly increase lead time. During the ramp up of production needed to reach the forecasted demand the length of the line would have to be increased. Consequently, the work content of each station would need to be re-balanced with each extra station, which requires large industrial engineering efforts. As a fully serial flow is very sensitive to variation, issues would be revealed that could be solved if they are likely to occur again. This would provide a lot of input to the continuous improvement process. With more input and issues to choose from it is hopefully easier to find the issues that are easy to solve and that result in great improvements. [Lambrecht, 2012]

As serialization divides the work content over several work stations, it is possible for assemblers to perform a smaller part of the work content by working at only one work station. This can be useful to reduce the competence requirements on assemblers, or to allow for new assemblers to learn smaller parts of the full assembly at a time. A reduction in work content per assembler is not a necessity however, as the assemblers could move with the product through multiple or all work stations. A smaller work content per work station than today could also reduce the number of tools and consumables needed at each station, resulting in a workplace that is easier and less time consuming to keep tidy and organized.

The most expensive equipment used in Area 1 is the overhead crane, which is used roughly during the first 25% of the assembly process. A serial line would make it possible to only install an overhead crane over the first fourth of the stations in each line, thereby saving money and reducing the number of fixed installations in the facility. However, as serialization implies lower cycle times, the overhead crane will be used more frequently. To avoid issues where several lines require the overhead crane simultaneously, several telphers could be installed if necessary.

As opposed to fully parallel flows, a fully serial flow always has some losses due to the work stations' dependency on each other. These losses can be due to differences in process times between assembly stations, due to differing work content between different models or due to differing skill levels between different assemblers. There can also be losses from intra-station variations, such as variations in the individual assembler's performance. As intra-station variations affects the efficiency of the whole assembly line it is essential that such variations are minimized. [Lambrecht, 2012]

It is possible to reduce the time that a station is either blocked or starved by for example better balancing work stations or allowing cross-over functionality between several lines. It is also possible to reduce the impact of blocked or starved stations. This could be done by allowing flexibility in what assembly operations are done at which assembly station and by making it possible for assemblers to collaborate on one machine when needed. It's also possible to have a list of tasks that can be performed at any time during the day, week or month, such as when a station is blocked for more than a few minutes.

The requirements specification that was created as a result of the background study and pre-study includes requirements on standardized work and continuous improvements. This is easier to uphold if there is a number of serial work stations, as changes to individual work stations containing a smaller work content are easier to implement than if the work content is vast. At the same time there are requirements that the system must be able to handle all sorts of product mixes, introduction of new models and variations between models. As there are large differences in assembly times between different product models, some level of parallelization in the flow is necessary. The process flows of an assembly system can consist of a compromise between the two extremes. Having multiple lines, each containing a number of work stations, can exhibit some of the advantages and disadvantages of both depending on context [Neumann, 2006]. In this case there are conditions making any of the extremes unsuitable, and so different middle of the road solutions should be explored.

The most complex product model was found to be the one that has the most accurate data regarding process time. Since there is little to no data on the simpler models, and because the more complex model will probably slow down production in the case of any serialization, the assumption is made that all models require the same process time as the complex model. The median process time of that model is 6,1 hours, as seen earlier in Figure 4.3. The processes could very well be improved through engineering change in a way that significantly lowers process times over the coming years. Figure 4.4 suggests that a large part of the process times is spent on activities such as rework, reading instructions and fetching materials. Improvements to the processes could greatly reduce the time spent on such activities, which could relatively easily lead to reductions in total process times of between $25 - 50\%$. The time span of such a reduction is uncertain however, since reducing process time is not high on Arcam's priority list and engineering resources are generally focused elsewhere. This uncertainty makes it difficult to design the system to have the correct capacity, and depending on the assumed process times there is a risk of overcapacity or undercapacity. It is worth noting however that the system in this sense does not include staffing. System capacity refers to the number of work stations, and as such overcapacity does not imply an idle workforce.

Designing the system based on the assumption that process times will not change runs the risk of having more capacity than necessary, while assumptions of a high degree of reduction in process times might result in undercapacity. Undercapacity is very important for Arcam to avoid, not only because it can be costly, but because delivery is a top priority, second only to safety and quality, as seen earlier in Figure 4.11. In addition, any overcapacity is only temporary, as a second shift will be introduced when the demand exceeds the capacity of Area

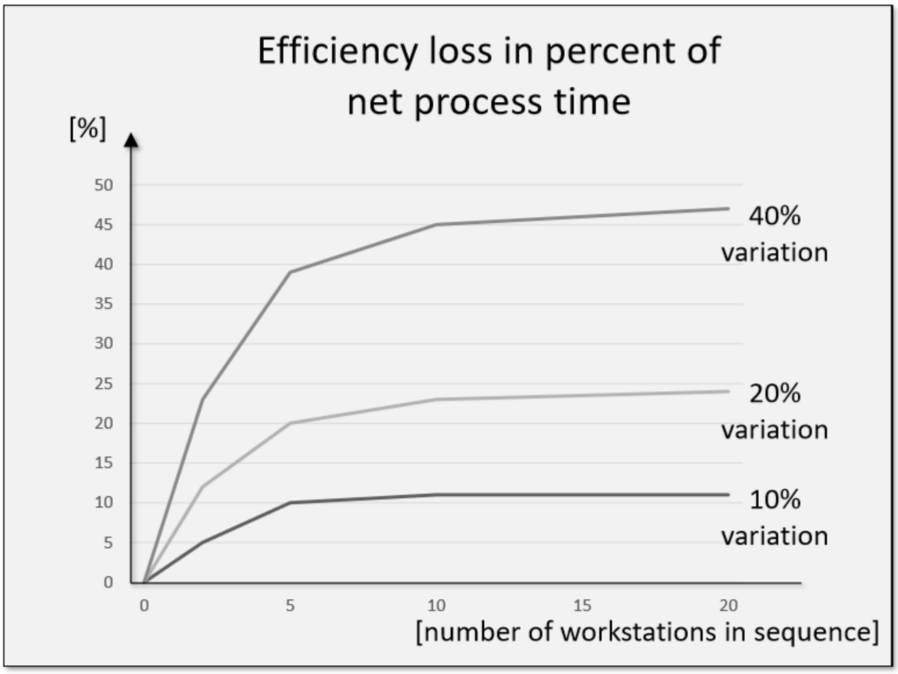

Figure 5.3: Efficiency loss due to intra-station variation based on [Engström et al., 1996]. The figure illustrates how efficiency losses depend on the intra-station variation as well as on the number of work stations.

2, which is where the products are sent after Area 1. Area 2 is designed for a maximum capacity of 3675 products per year. Therefore that is also the maximum capacity that Area 1 is designed to produce per year while running on one shift. Overcapacity means the introduction of work shifts can be postponed, which reduces costs as shift work is expensive. It is considered unlikely that there will be any significant increases in engineering or leadership focus on improving assembly processes, and it is therefore reasonable to assume process times will remain the same when designing the assembly system.

The output when using a certain number of work stations will likely differ depending on the chosen flow principles. Serial flows have balance and system losses, which increases waiting times through either blocked or starved work stations [Lambrecht, 2012]. Figure 5.3 shows the efficiency loss due to intra-station variation as a function of the number of workstations in sequence and the coefficient of variation [Engström et al., 1996]. System losses can be reduced through the use of standardized work, but there will always be some level of system losses in a serial flow. At the same time, a combination of reduced cycle times and level of complexity of serialization, improved potential for collaboration and teamwork as well as facilitation of continuous improvements has been shown to affect the product flow in a positive way [Neumann, 2006]. Reduced work content in serial flows potentially also reduces the number of components and tools handled at the work station, which also makes it easier to become skilled at performing tasks quickly. Adler and Cole (1993) argue that the more traditional serial layout used at the New United Motor Manufacturing, Inc. (NUMMI) plant in California is superior to the parallel cell system which was used at the Volvo Uddevalla plant. They claim that the lower performance of the Uddevalla plant is due to the fact that the system does not ensure or encourage organizational learning which is crucial to increase productivity [Adler and Cole, 1993]. However, Neumann *et al* notes that hybrid system designs, using elements of teamwork and strategically implemented parallel flows, may yield improvements to both ergonomics and productivity [Neumann, 2006].

It is difficult to estimate system losses as well as estimating time differences based on reductions in complexity and the effects of easier improvement work. The literature on the subject does little to alleviate this uncertainty, since results point in different directions in different studies. They also predominantly compare cycles that are measured in seconds or minutes, while in this case it is a matter of hours or days. It is therefore uncertain to which degree the literature is relevant. The advantages for different flow principles with regards to productivity are near impossible to quantify. In addition, calculating the system losses of different solutions would require data which is not available, such as coefficient of variation, accurate assembly times etc. However, some calculations are necessary to determine how many work stations, and consequently how much floor space at the new facilities is needed. Simplified calculations are therefore used, where losses as well as changes in process times are omitted.

The equations below show calculations for the minimum number of stations needed to meet forecasted demand. Current process times are used together with expected capacity requirements for the first 4 years after the move, as well as the volume at which a second shift will be introduced.

$$Output\ per\ station\ per\ year = \frac{220\ days/year\ \cdot\ 6,5\ hours/day}{6,1\ hours/product} \approx\ 235,5 \tag{5.1}$$

$$Minimum\ number\ of\ stations\ year\ 1\ = \frac{1085\ products}{235,5\ products/year} \approx\ 4,6 \tag{5.2}$$

$$Minimum\ number\ of\ stations\ year\ 2\ = \frac{1855\ products}{235,5\ products/year} \approx\ 7,9 \tag{5.3}$$

$$Minimum\ number\ of\ stations\ year\ 3\ = \frac{2660\ products}{235,5\ products/year} \approx\ 11,3 \tag{5.4}$$

$$Minimum\ number\ of\ stations\ year\ 4\ = \frac{3500\ products}{235,5\ products/year} \approx\ 14,9 \tag{5.5}$$

$$\begin{matrix} Number\ of\ stations\ before \\ introduction\ of\ a\ second\ shift \end{matrix} = \frac{525\ products}{33,6\ products/year} \approx\ 15,6 \tag{5.6}$$

As can be seen above, the minimum number of stations needed before an introduction of a second shift is 15,6. One set of solutions is simply several identical,

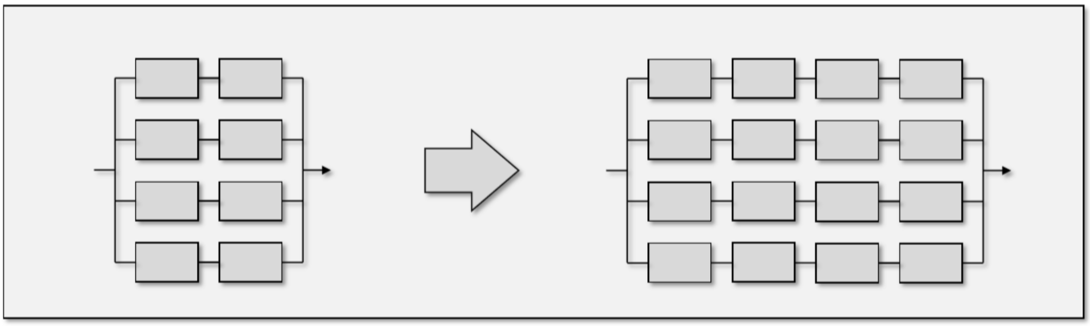

Figure 5.4: Proposed flow principles. 4 parallel lines that each contain 2 serial work stations is suggested for the initial design. This is then suggested to be increased towards a flow of 4 parallel lines with 4 serial work stations each.

general lines with the same number of work stations. As 16 work stations in total is the goal, any combination of X lines and Y work stations that result in $X \cdot Y = 16$ are possible. As such, $2 \cdot 8$, $4 \cdot 4$ and $8 \cdot 2$ are all alternatives. It is also possible to have differently sized lines, that can be used for different products. In this way a combination of lines with A, B, C and D number of work stations resulting in $A + B + C + D = 16$ are also possible. Examples could be $3 + 3 + 5 + 5$ or $2 + 2 + 4 + 8$.

While it can be beneficial to have specialized lines for different product models as to avoid issues with uneven process times, the product mix and volumes of different models are uncertain. It is therefore preferred to have more generalized and evenly sized lines that can handle different models at different times. Pairs of generalized lines that run in parallel could also potentially enable cross-over functionality, where products could be moved to the next work station in any one of two lines that are paired.

There are currently 3 different product models in production simultaneously, with a fourth about to be introduced into production. According to a detailed forecast including figures for each of the current models as well as figures for future models, the number of different models in production is unlikely to be higher in the foreseeable future. Production planning is done with customer demands as the top priority. This means production can not be batched, as it must correspond to varying customer needs. To reduce the negative effects of variation between models, which is assumed to remain, it would be beneficial to have roughly the same amount of lines as the number of product models. All lines should, however be able to produce all models since the product mix is uncertain. 4 lines enable efficient sequencing that can minimize losses due to variation in lead times between models and also reduces the effects of variation since any imbalances only affect one of the lines [Kucukkoc, 2014].

At the time of the planned move date, only parts of the new facilities are available for use. More specifically the building will be expanded by building an extra warehouse. During the time of the construction, parts and components will instead be stored in different areas of the facility, for example in Area 1. The footprint for Area 1 that has been allocated in new facilities measures $24,7m \cdot 27,2m \approx 670m^2$. However, approximately half of the area will be used for storage and preassembly during the first 2 years after the move. Therefore, all of the 16 stations needed to meet the demand of 3675 products per year can not be built from the start, and instead the layout needs to be adjusted to fit in the available area. As can be seen in Equation 5.3 the forecasted demand is also lower at that time, and the production flow is estimated to only require 7,9 work stations during year 2. 4 lines with 2 stations in each would provide the flexibility needed to significantly reduce effects of process time variation and manage the capacity requirements.

The proposal is therefore to design Area 1 according to a $4 \cdot 2$ flow initially, which over time can be scaled up towards a $4 \cdot 4$ flow, see Figure 5.4. As no significant changes in total throughput time is expected, this would result in cycle times of 3,1 hours and 1,5 hours respectively.

5.3.2 Material handling

Decisions related to material handling were made by first considering different material handling concepts, such as line stocking and kitting.

In general line stocking is considered suitable when the work content at a certain work station is low, or when there are few different products or product models [Caputo and Pelagagge, 2011]. Kitting or sequencing on the other hand is considered suitable when the work content is large, when there are large differences between models or when material would take too much space if stored by the line side [Bozer and McGinnis, 1992].

Line stocking minimizes total time spent on material handling activities, as there is no structuring to be done and small to medium sized components can be transported in relatively large numbers. While line stocking often reduce capacity by approximately 20% due to assemblers spending more time fetching materials, less time in total is spent on material handling compared to kitting as there is no double handling of materials [Finnsgård et al., 2011]. In addition, the availability of extra parts reduces the effects of faulty components. Instead of having to order a new component, another component can just be taken from the line stock. One major downside is that line stocking often takes much space by the line side, the work space becomes cluttered and it is easy to make mistakes if there are many similar components stored near each other [Hua and Johnson, 2010].

Kitting on the other hand enables smaller work stations and a high level of order and cleanliness, as less material must be stored by the assembly stations. Kits can act as cognitive support for assembly personnel, reducing or eliminating the risk of mistakes [Engstrom and Medbo, 2009]. Faulty components can also be identified earlier, during the kitting process instead of during assembly. Introduction of new product models as well as engineering changes are relatively easy to handle, as updates to or introduction of new kits are easier and faster to implement than changes in line stocks. Operators can also spend more of their time doing value adding work, resulting in potential reductions of lead time and work in progress. One downside however is the extra space and resources required for producing the kits. [Hanson and Brolin, 2013]

When supplying material to work stations, it is not necessary to handle all material in the same way. It is fully possible to provide some components in kits while some are line stocked. In fact this can often be more suitable than only kitting or only line stocking, as some components might be either too large to efficiently line stock or too small and used in too high quantities to efficiently kit. The products in this case have components ranging from very large and singular, such as steel sheets or cooling systems, to very small and in high numbers, such as screws and washers. Some sort of hybrid solution is therefore desirable.

The proposal is to provide most components through 4 separate kits, instead of the current setup which is 1 large kit for the entire assembly. The amount of components will remain roughly the same as today. An illustration of the current kit cart can be seen in Figure 4.6. The contents of the three overcrowded shelves would be more suitable to split over several kits. Dividing it over 4 kits would enable having most components accessible at a suitable height, while also achieving less cluttered kits. In this way ergonomics and cognitive support is improved. The kits will be prepared in custom made kit carts made with modular components. In this way the kit carts can easily be changed or improved based on the needs and ideas of the assembly personnel. This promotes continuous improvements, which over time can have positive effects on efficiency of assembly operations.

The more common components such as screws, clamps and washers are instead proposed to be stored by line stocking. Such components are resource inefficient to kit, and it is beneficial to have easy access to additional components if for example a screw has damaged threads. If the number of line stocked components are kept low, the work space remains uncluttered and does not require much extra space for components. As opposed to the current situation where there is shared line stock from which assembly personnel from all stations fetch components, the proposal is to have line stocking by each individual work station only containing components needed there.

Some components are very large and bulky, and are therefore not ideal to provide through line stocking nor through kitting. These components are proposed to instead be kept at intermediate storage near the assembly line. While this means assembly personnel must fetch the components, it does not clutter up the assembly line work stations. In the long run, the kit carts might be possible to adapt so that these large and heavy parts can be provided through kits. This is however omitted in the initial proposal, and is instead suggested to be a part of the continuous development of the kits.

Kitting and re-supplying line stock is currently handled by logistics personnel, and this is planned to continue at the new facilities. Since the over-arching work organization falls outside of the scope of this thesis, no alternative solutions have been considered.

5.3.3 Tools and equipment

The requirement specification together with the decision to propose a flow principle where the product is moved between stations resulted in four different areas where there is a need for heavy equipment. The first of these is the need to lift the machine about 50 - 70 cm from the ground to enable assembly of components under the vacuum chamber. This is currently done by using an overhead crane to place the machine on a steel stand. Other possible solutions to this problem that have been considered are installations of hydraulic lift tables or combining a hydraulic lift table with a trolley. However, the proposal is to continue with the current method of using an overhead crane to place the machine upon a steel stand. Since several parallel lines has also been proposed earlier, and the lifting of the machine is only done during the first fourth of the assembly process, there is only need for an overhead crane above the first station in each line. As the overhead crane is only used very briefly for a few different lifting operations, it can be shared between the different lines without any significant disturbances. More specifically the proposal is to install one overhead crane that spans over the first station of each line, and to provide steel stands for each of the 4 product models that can be shared between the lines.

During the interviews it became apparent that the method of using the overhead crane worked well and was quite effective, where the only issue was that the one available crane was sometimes occupied by the personnel in the pre-assembly area which shares the same overhead crane. The overhead crane is a multi-functional tool, which in addition to lifting the machine is also used for assembly of a heavy pre-assembled module placed on top of the machine. Replacing the overhead crane would require additional equipment for the assembly of that module which is a factor that has been taken into consideration. The overhead crane is also relatively cheap, easy to install, a verified method, and it is easy to move if changes are needed in the future.

The second and very obvious problem that needs to be solved is how to move the machines between stations. This is a problem that spans over more than just Area 1, and introduces the need for collaboration with other project groups. However, as it is uncertain how both demand and the layout of Area 1 will evolve over time, it's clear that any permanent installations are not viable options. This leaves only wheel based options, such as moving the machines with pallet jacks, AGVs or special trolleys pulled with electric tugs.

Currently the machines are moved by either pulling them on pallet jacks with an extra wide fork for more stability, or the machines are moved with a forklift if it's not occupied. The operators state that this method is not ideal because of the high force needed to get the machine moving. However, they also state that they have never had any issues or pains related to this task. The proposed flow results in the machine being moved four times within Area 1 and this is during a period of 6,1 working hours. With the machine being moved as seldom as once every 1,5 hours it is hard to motivate investing large amounts of money in AGVs. The proposal is to continue using the pallet jacks to move the machines between stations. The reason is that it is an easy method that uses common and cheap equipment. The other project group responsible for the Area 2 is currently investigating whether special trolleys is the best solution for that Area. If that is the case, implementing the same trolleys in Area 1 is possible and would enable the machine to stay on the same trolley throughout production.

The third issue is the lifting of heavy and cumbersome components. This is an issue that is currently not addressed, and the operators often lift components that are too heavy to lift ergonomically, or ask each other for help and lift the components together. This issue needs to be solved since safety is Arcam's top priority, and the operators also stated during the interviews that these tasks were problematic. Most of the heavy components are large steel sheets with or without additional components mounted on them. The proposal is to invest in one portable industrial manipulator for each line which can be shared between the two last stations where the heavy components are assembled. Lifting these components will only make up a very small part of cycle time, meaning there won't be any significant disturbances from sharing industrial manipulators between two stations.

The final equipment that needs to be addressed is something to enable the operators to assemble components near the top of the machine. This can be done either by lowering the machine or by enabling the operator to work from an appropriate height. The method proposed is the same that is currently being used, namely to provide each station that requires it with a robust yet movable stepladder. This is the method used today, and the interviews revealed that the method works well. The equipment is cheap and does not require any fixed installations. In addition, more specialized equipment such as walkways or installations for lowering the machine into the floor would be inflexible. As the assembly system will be expanded over time, this makes such solutions unsuitable.

5.3.4 Conceptual Design Summary

The proposal can be summarized as a desired state after relocating to the new facilities, followed by further goals over the next 3 years, see Table 5.1. In addition to the concrete suggestions that are listed, it is important to work with continuous improvements of the assembly system.

Table 5.1: Conceptual Design Summary

Initial state after relocation

- 4 lines with 2 work stations each
- Introduce 4 smaller kits with components instead of 1 large kit
- Build custom carts adapted to the kit contents
- Install small shelves for line stocking at each work station
- Install an overhead crane above the first station of each line
- Re-use steel frames from current facilities to place machine on top of
- Re-use step ladders from current facilities
- Re-use pallet jacks from current facilities
- Industrial manipulator for heavy lifting

Goal state by 3675 products per year

- 4 lines with 4 work stations each
- Improved kit content and design

6

Final Design Specification

This chapter details the final design specification. Based on the conceptual design from Chapter 5, the current assembly tasks are divided into four blocks. Material handling structure and technicalities are then specified for the different blocks. Necessary equipment and materials corresponding to each block are then used as a basis for designing work stations, which is followed by a detailed layout of the complete assembly system. Finally, a work organization for the system is suggested.

6.1 Division of work content

Dividing the work content of Area 1 requires several considerations to be made. The work content should be divided based on a flow that is initially 2 work stations in sequence, and that is later expanded to 4 sequential work stations. The process times for the different work blocks should ideally be evenly balanced for all different product models, as to minimize balance losses. The division should also take into consideration different functional requirements, such as costly equipment or materials and subassemblies that require additional space. The only such functional requirement that also requires permanent installations, and therefore needs extra consideration, is the need for an overhead crane in the first steps of the assembly process.

The work is divided into 4 blocks directly, as the initial 2 work stations can then correspond to blocks $1 + 2$ and $3 + 4$, see Figure 6.1.

The data on process times is only available for one of the models. This data is only estimates which means the balancing when dividing the work content is uncertain and will need further work in the future. The different models have the same functional structure, which leads to the assumption that both the time distribution between activities and the functional requirements are roughly the same for all models. The overhead crane that is used in the initial steps is only used in the first block for all different models. Other functional requirements, such as the need for stepladders to access the top of the product, are not considered when dividing the processes into blocks as the equipment is cheap and balancing for

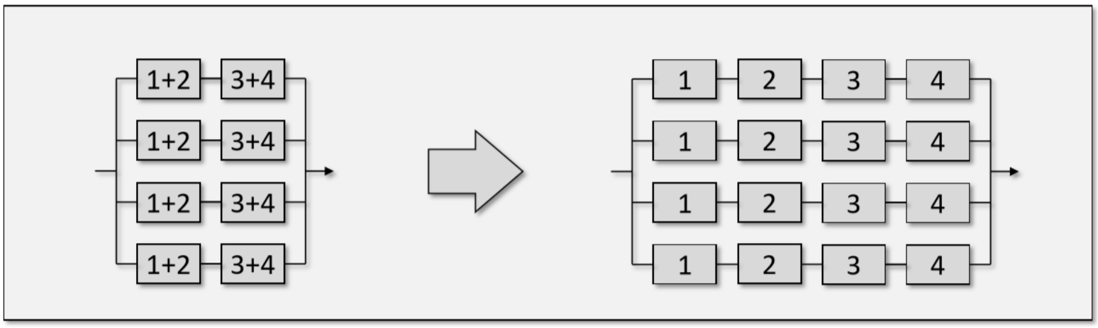

Figure 6.1: Division of work blocks between stations. In the initial design, each work station will include 2 work blocks. In the final design each station only contain 1 work block.

time is prioritized. The resulting blocks of assembly work can be seen in Table 6.1.

6.2 Material Supply

The material is divided into three different material handling categories; line stocking, intermediate storage, and kitting. Small components such as screws and washers are line stocked, large and heavy components or subassemblies are stored in an intermediate storage near the assembly system, and remaining components are supplied through kits. As there are multiple models, each divided into 4 work blocks, there are a wide variety of components and subassemblies that need to be supplied to the different work stations.

Line stocked components will be provided through bin racks with small bins suitable for screws and washers, which for each work station contains the components necessary for the corresponding work block or blocks. All line stocked components will be stored in standardized bins, which means the size of the bin rack is proportional to the number of unique components needed at each work station, see Table 6.2. The most extreme work station uses 84 unique components, which can be stored in standard bin racks that are already in use at Arcam today. Such racks fit 8 bins in width, meaning different work stations would need between 6 and 11 rows of bins, see Figure 6.2. These bin racks should be structured according to how components are used. For example, some components are more commonly used throughout the assembly steps of all models, while others are used just in one model at one point. Components could also be structured from left to right according to the order in which they are used.

Large components and subassemblies will be kept in intermediate storage, from which assemblers can fetch them when needed. Some of these are transported on specialized carts or trolleys, while others are moved with pallet jacks. To minimize the time assemblers spend fetching these components and subassemblies, it would be ideal to keep them as close as possible to the work stations at

Table 6.1: Division of assembly tasks into work blocks. Assembly tasks are divided into 4 work blocks with even time consumption. Needs for specific equipment and components have been taken into consideration.

OpNr	Name	Process time [min]	Acc. Time [min]	Overhead crane	Ladder	Industrial manipulator	Large components	
10	Framework and vacuum chamber in framework	21	21	X			Vacuum chamber, framwork	**Block 1** Process time: 90 min
20	Z-actuator assembly	51	73	X			Z-actuator	
30	Vacuum parts assembly 1	9	81	X				
40	EB-unit assembly	9	90	X	X		Electron beam unit	
50	Rake actuator assembly	21	111				Rake actuator	**Block 2** Process time: 90 min
60	Vacuum parts assembly 2	34	146		X			
70	Light and shutter assembly	26	171		X			
80	Cable ladder assembly	9	180					
90	Cooling liquid assembly	34	214		X	X	Cooling system, metal sheets	**Block 3** Process time: 92 min
100	Helium system assembly	17	231					
110	Pneumatic valves assembly	26	257					
120a	Main stand assembly	15	272		X	X	Metal sheets	
120b	Main stand assembly	19	291		X	X	Metal sheets	**Block 4** Process time: 92 min
130	Exterior design assembly	26	317		X	X	Metal sheets, heat exchanger	
140	Protection shield assemby	21	339			X	Metal sheets	
150	Build unit assembly 1	26	364					

Table 6.2: Line stocked components per work block. The table shows the number of unique components needed at different work stations, based on work blocks. Line stocked components are things like screws and washers, and the numbers include all different product models.

Work block	1	2	3	4	1+2	3+4
Number of unique components	55	56	46	47	84	69

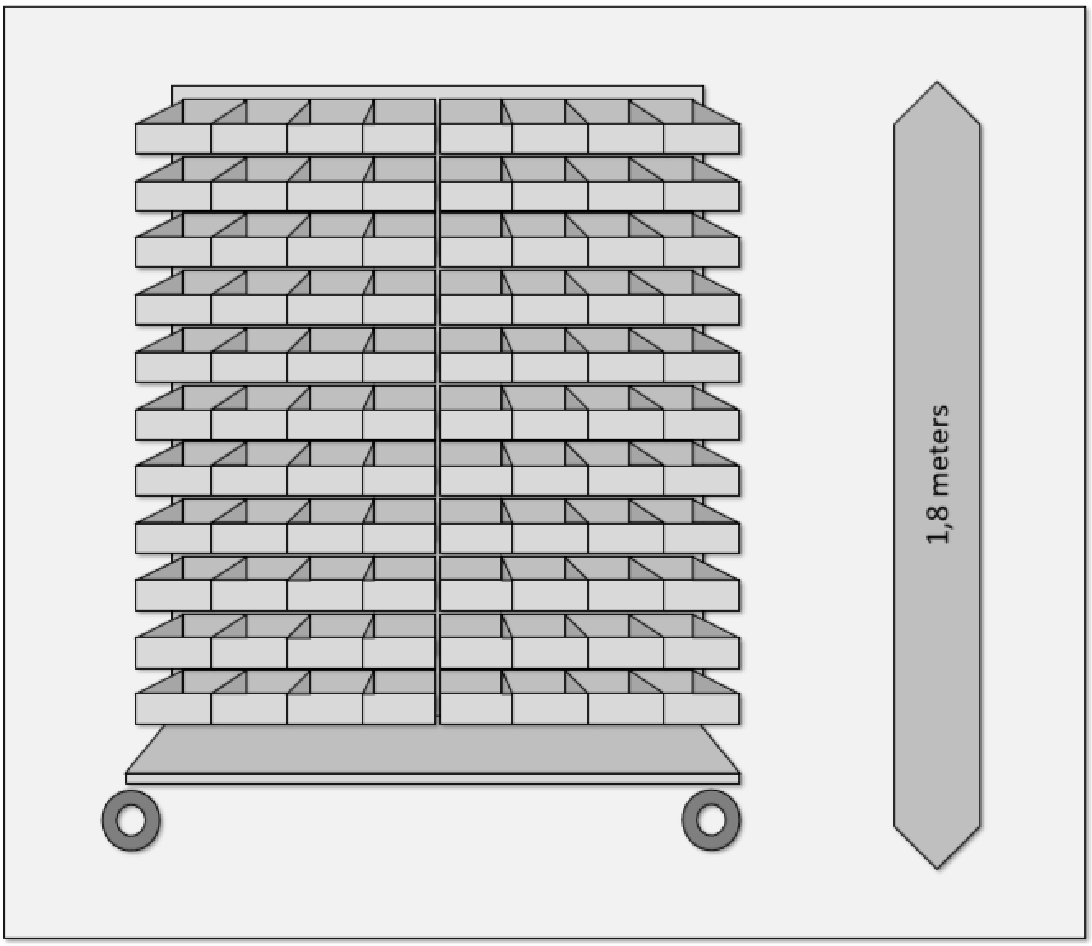

Figure 6.2: Bin racks for line stocked components. The racks fit many small bins for components such as screws and washers.

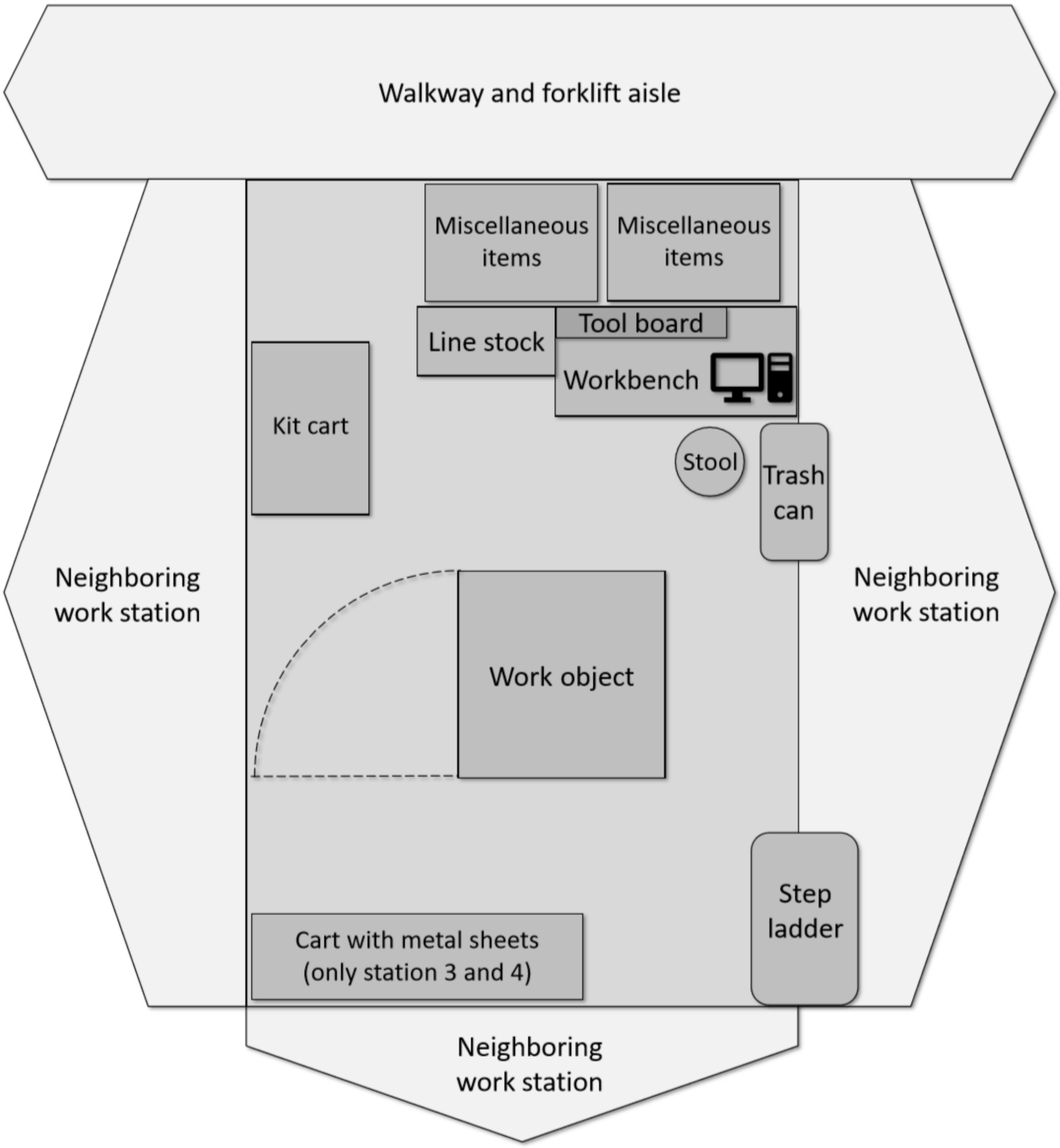

Figure 6.3: Proposed workplace design. Each work station includes some extra space for miscellaneous items. This can be used either for specific components necessary at a certain work station, or for general objects needed in Area 1.

Table 6.3: List of components kept in intermediate storage. Components are structured according to the work blocks in which they are used.

Work block	1	2	3	4
Large components	Vacuum chamber Framework Z-actuator Electron beam unit	Rake actuator	Cooling system Metal sheets	Heat exchanger Metal sheets

Work block	1+2	3+4
Large components	Vacuum chamber Framework Z-actuator Electron beam unit Rake actuator	Cooling system Heat exchanger Metal sheets

which they are used, see Table 6.3. Initially, the allotted area for the assembly system has plenty of additional space that can be used for intermediate storage. Once the volumes ramp up and more work stations are introduced these components will most likely be stored in the area named ”Micellaneous items” in Figure 6.3, However keeping all intermediate storage in the immediate proximity would possibly make for a rather crowded assembly system. The assembly system would likely benefit from either incorporating some of these components in the kits or introducing a system for delivering these components from the warehouse Just-in-time. This is however only a suggestion for future improvement and not part of the proposal.

Kits are based on the 4 work blocks specified in Table 6.1, meaning there will be 4 unique kits for each product model. The kits will be prepared in customizable kit carts that are of a suitable size for components to be accessible at roughly the same height, see Figure 6.4. Additionally, kit carts will be designed so that the material in the kit can be presented in a structured manner, thereby enabling cognitive support. For example, structuring components from left to right according to the order in which they are used would make it easy to see what component to assemble next, as well as giving a clear indication of current progress.

Kitting is done by logistics personnel, and kits are placed in a kit storage area until fetched by assemblers. This means there will be one kit at each work station. Since the initial design has work stations handling 2 work blocks each, a kit for the second work block needs to be fetched half way through the assembly. The actual kitting activities are outside of the scope of this thesis.

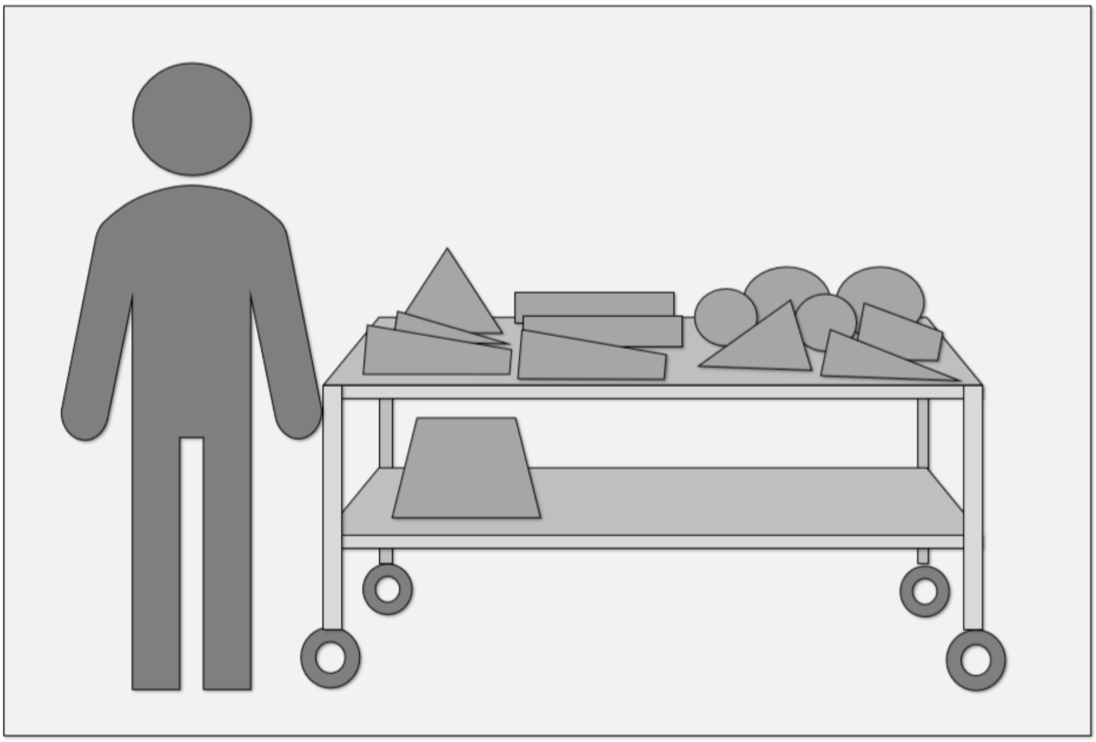

Figure 6.4: Future kit example. The figure illustrates a simple kit based on the division of work into 4 work blocks. All or most components are accessible at a ergonomically suitable height.

6.3 Work station design

The work station design can be considered to follow a basic template, with additional equipment at the different work stations based on work content. The basic template includes things like a work table with a computer, a tool board, line stocking of nuts and bolts, kit carts and a stool. All work stations measure $4m \cdot 6m = 24m^2$, which includes enough space for any additional equipment needed at specific work stations, see Figure 6.3.

In addition to the basics, the division of work over the initial 2 and later 4 work stations implies 6 set of requirements on work stations. These additional requirements can be derived from Table 6.1 and are summarized in Table 6.4. Some of the required components or equipment are kept directly at the work stations, while others are merely kept in the vicinity, for example in the "Miscellaneous items" area seen in Figure 6.3.

6.4 Detailed Layout

The detailed layout must accommodate work stations, equipment and intermediate storage within the alloted $670m^2$, for both the initial and final design. The way in which Area 1 interfaces with the rest of production must also be taken

Table 6.4: List of equipment and components required for different work stations.

Work block	1	2	3	4
Required equipment	Overhead crane Stepladder	Stepladder	Industrial manipulator Stepladder	Industrial manipulator Stepladder
Required components and subassemblies	Vacuum chamber Framework Z-actuator Electron beam unit	Rake actuator	Cooling system Metal sheets	Heat exchanger Metal sheets

Work block	1+2	3+4
Required equipment	Overhead crane Stepladder	Industrial manipulator Stepladder
Required components and subassemblies	Vacuum chamber Framework Z-actuator Electron beam unit Rake actuator	Cooling system Heat exchanger Metal sheets

into consideration, not least with regards to the direction of the production flows, see Figure 6.5. Another major consideration revolves around the overhead crane, as it is a rather permanent installation. It is desirable to design the initial layout in a way that does not require the overhead crane system to be moved. This means the first stations of the initial design, which include work blocks 1 and 2, should ideally be in the same position as the first station of the final design.

A list of objects that need a place in Area 1 has been compiled based on the current assembly system, see Table 6.5. Structuring these objects so that they are close to their point of use would be beneficial, as it minimizes walking distances for assemblers when using them. Intermediate storage for the objects is easy to accommodate in the initial design, as there is a lot of extra space available, see Figure 6.6. However, as the number of stations is increased these items will need to be moved elsewhere, for example in the "Miscellaneous items" area seen in Figure 6.3 or to the warehouse seen in Figure 6.5.

Everything but the overhead crane is relatively easy to move whenever the number of work stations are increased. While the final layout does have enough space for keeping all intermediate storage in area 1 (see Figure 6.7), it would become rather crowded. It is uncertain whether this would be practical, and thus it might be beneficial to store some things elsewhere.

6.5 Work Organization

The organization of work is an important aspect of the assembly system. Since a line flow is suggested, assemblers are largely dependent of each other in their

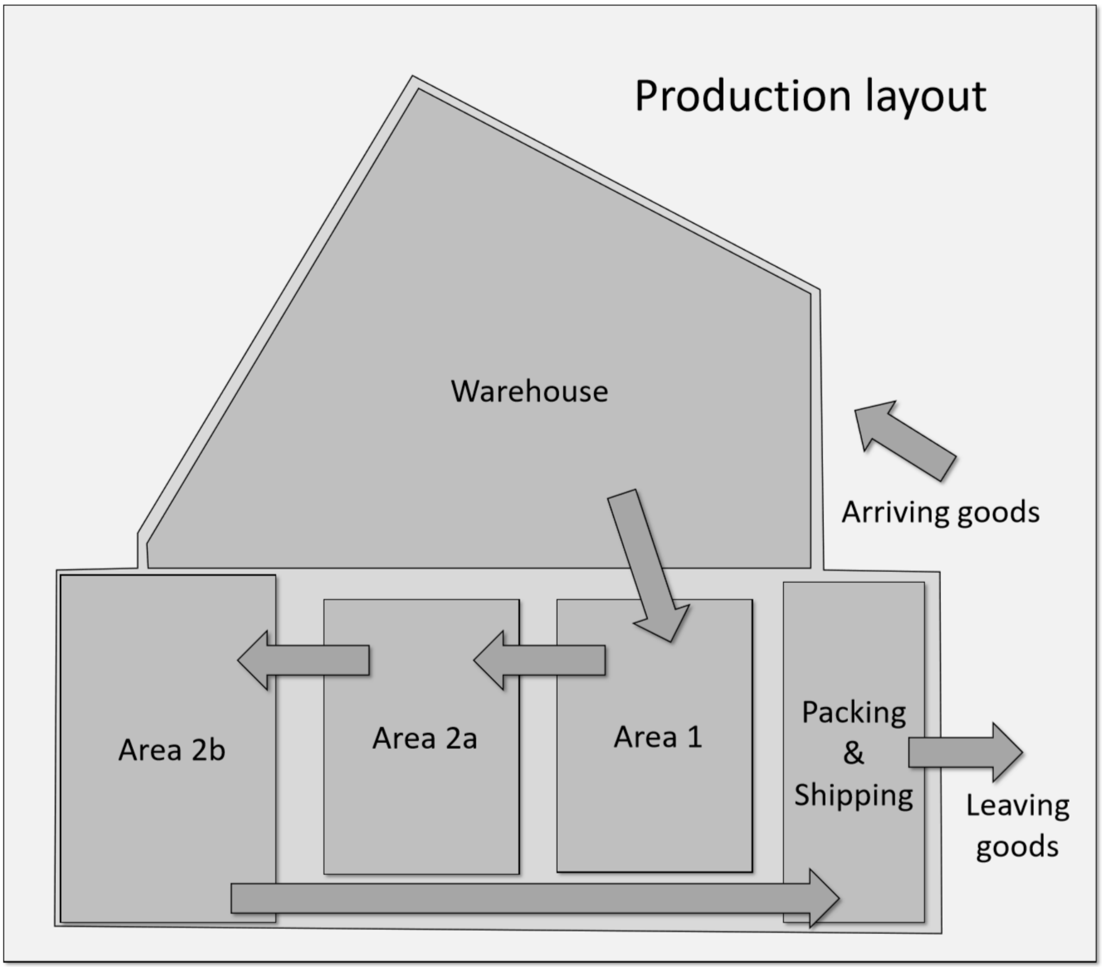

Figure 6.5: Layout of the new facilities. The arrows indicate the flow of materials and products through the production system.

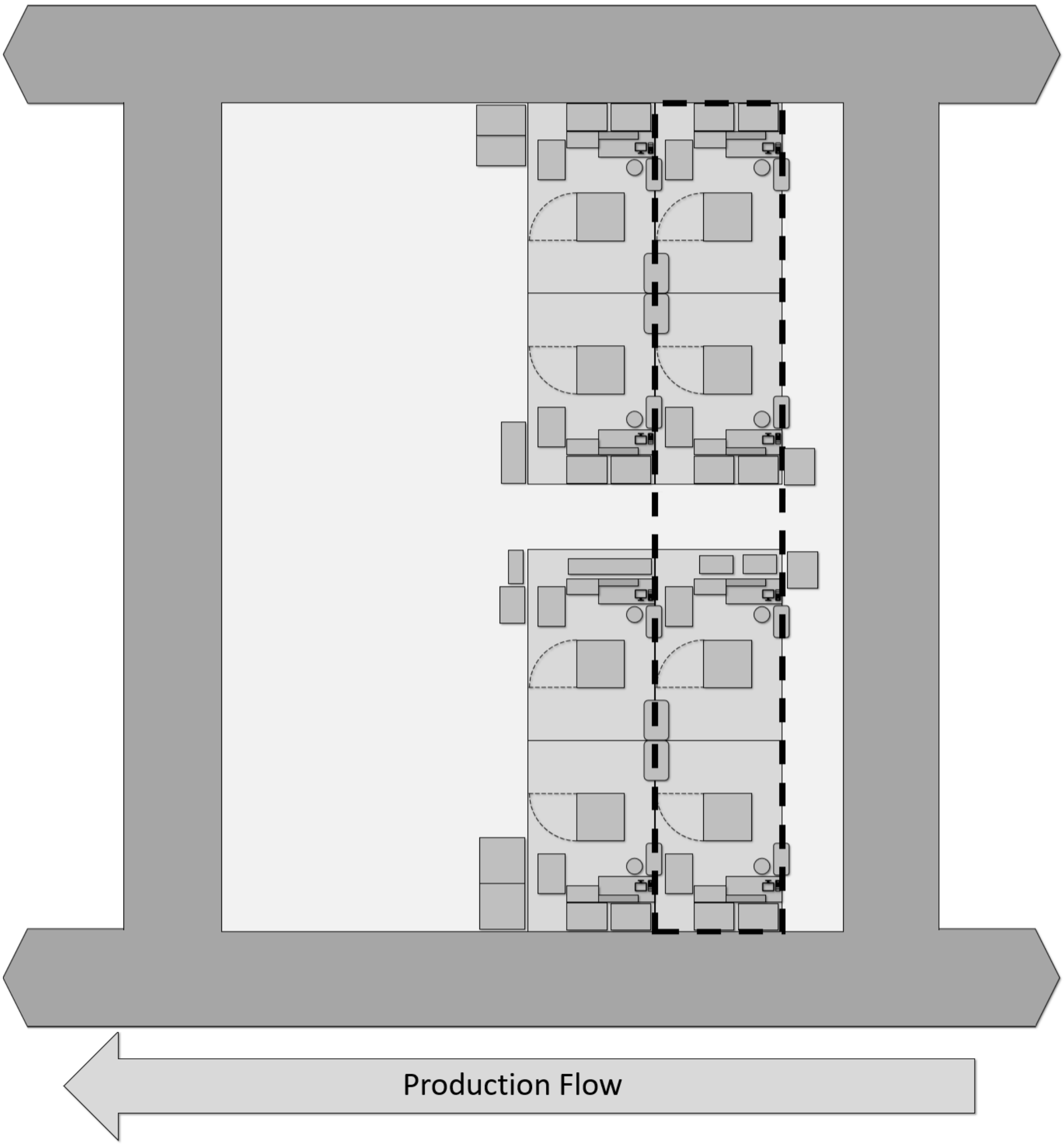

Figure 6.6: Detailed proposal for the initial layout. The dashed box illustrates the area covered by the overhead crane.

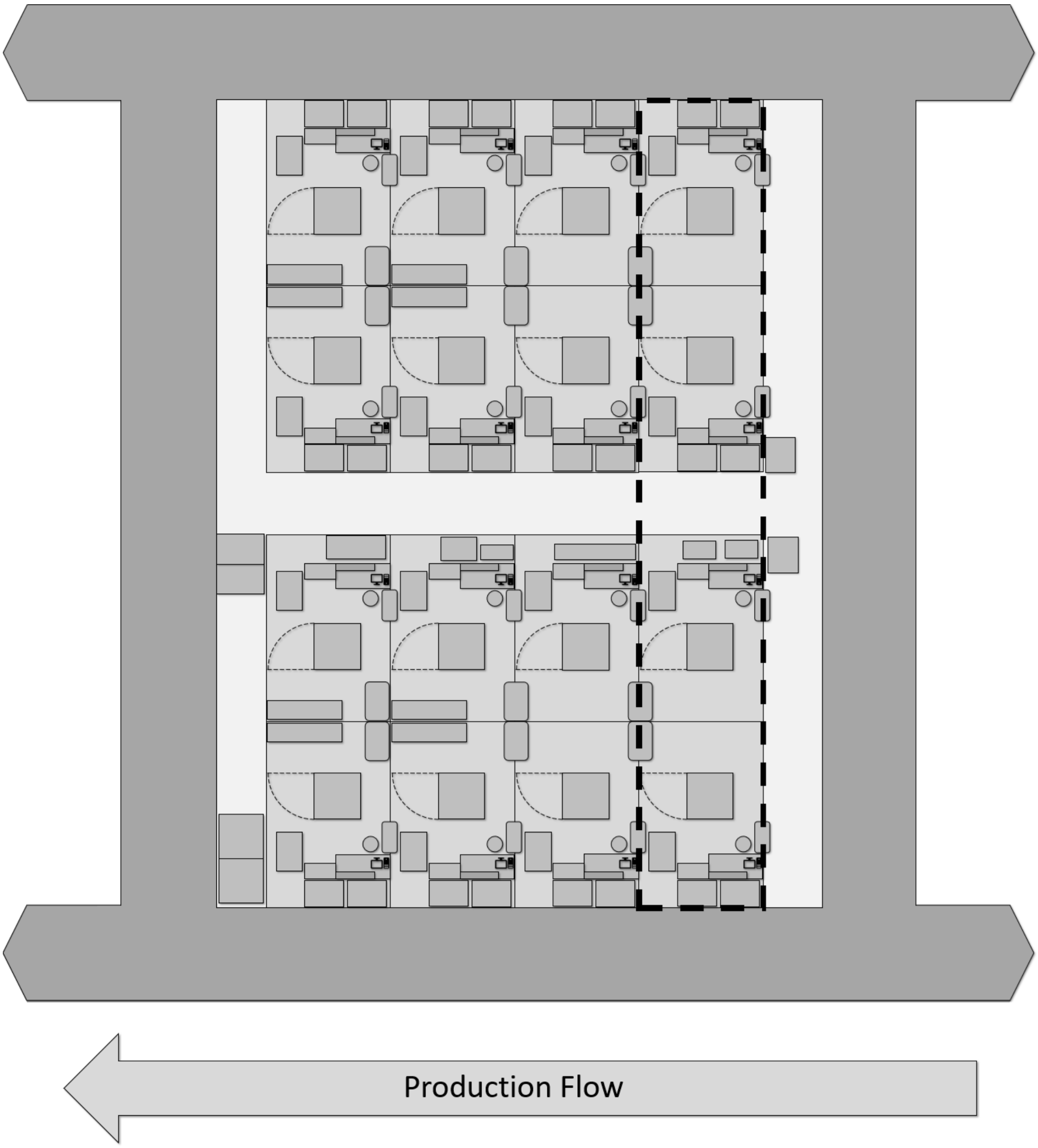

Figure 6.7: Detailed proposal for the final layout. The dashed box illustrates the area covered by the overhead crane.

Table 6.5: List of objects required within Area 1. The list is based on objects currently used in Area 1, and is structured by their point of use.

Object	Amount	Width [m]	Depth [m]	Point of use [work block]
Subassembly stand	5	1,3	1,1	1
Z-actuator lift trolley	2	1,2	1	1
Chamber (boxed)	2	1,3	1,5	1
Framework pallet	2	1,2	2,4	1
Machine stand	4	0,75	1,3	1
Cooling system stack	1	0,8	2	3
Heat exchange system pallet	1	0,8	1,2	4
Cart with metal sheets	4	0,9	2,5	3-4
Kit cart	16	0,85	1,25	1-4
Buffer to Area 2	2	1,5	1,5	4
Kanban shelf	1	1,1	0,5	-
Tool cabinet	1	1,1	0,6	-
Cleaning cabinet	1	1,1	0,6	-
Visual management board	1	1	3	-
Combustible waste container	1	1	1,6	-
Non-combustible waste container	1	1	1,6	-

work. The same goes for the interaction between Area 1 and other production related departments, such as pre-assembly, logistics and Area 2. Consequently, the need for collaboration and coordination is high.

Structuring work and allocating responsibilities is an important part of factory planning. Wiendahl *et al* list four basic approaches to work structuring; job enlargement, job rotation, job enrichment and partially autonomous teamwork. These approaches in relation to attainable goals can be seen in Figure 6.8. The figure does not include job rotation since its effects can not generally be assessed [Wiendahl, H., Reichardt, J., Nyhuis, P., 2015]. Job enlargement refers to the tasks performed by a specific employee gradually being expanded with similar activities, by for example increasing cycle time and work content. Job enrichment is when an employee is gradually given more tasks related to one activity. An example of this could be a machine operator gradually taking more responsibility of maintenance, quality testing and order control but is still only responsible for the same machine. Partially autonomous teamwork is when a small group of employees plan, prepare and control their own work activities within a well defined range [Wiendahl, H., Reichardt, J., Nyhuis, P., 2015]. When possible, structuring the work according to partially autonomous teams carries with it many easily attainable benefits, as seen in Figure 6.8. The size and complexity of the work content within Area 1 makes it suitable to structure according to one or several partially autonomous teams.

To achieve effective teamwork it is necessary to have teams with clear membership, and that are of the appropriate size [West, M. A., 2012]. The ideal size

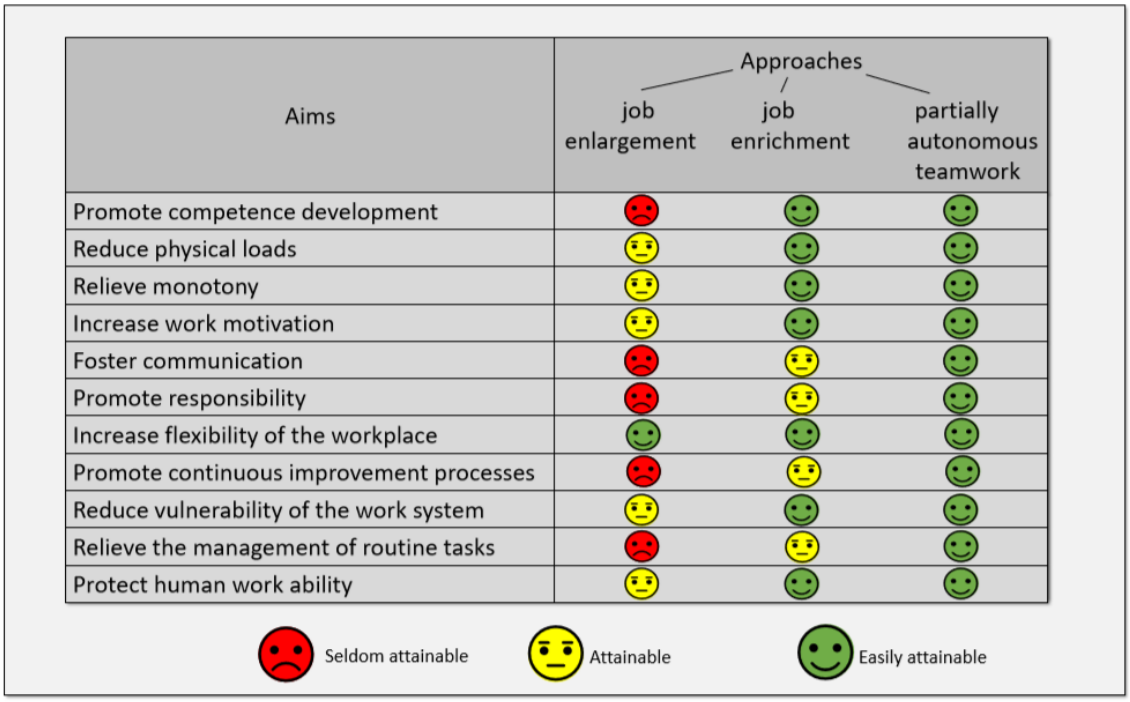

Figure 6.8: Approaches and aims of work structuring based on [Wiendahl, H., Reichardt, J., Nyhuis, P., 2015]. The figure illustrates how effective different approaches are for attaining different aims.

of teams depends on contextual aspects such as the complexity of the tasks to be performed, since both more complex tasks and larger team sizes make teamwork more difficult. In general teams should be as small as possible to complete the tasks of the team, while being no larger than 5 to 7 members (ibid).

One good example of a team-based organization is Toyota. In *"Toyota Culture"*, Liker and Hoseus state that Toyota strives for a flat organization. At the same they see the benefits of having small teams of 5 to 7 members guided by one team leader, which implies a certain degree of hierarchy. It is considered wasteful if the communication is slowed down or hindered because of unnecessary hierarchical levels, but this can be counteracted by establishing contextually suitable communication structures and leadership styles. According to *"The Toyota Way"*, the people doing the actual value-adding work should be in the center of attention, and the term *"Servant Leadership"* is used as a way to describe leadership that focuses on enabling and empowering value-adding work. Furthermore, the team leader should be an employee from within the team who has learned all the tasks and thereafter taken the role of team leader, instead of someone taken from the outside to lead the team. This improves understanding and trust between team leaders and team members, thus reducing potentially negative effects of hierarchical structures. [Liker, J. K., Hoseus, M., 2008]

Another important aspect is having clear responsibilities and tasks for teams. Clear distinctions of what lies within a teams responsibilities and what doesn't

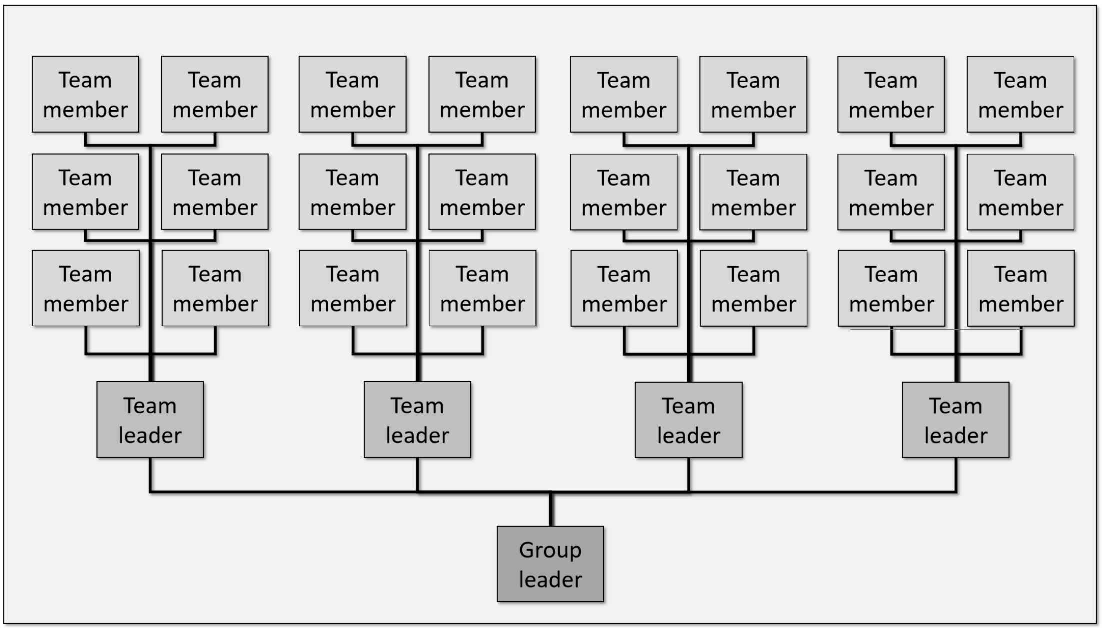

Figure 6.9: Example of a team-based organizational structure.

facilitates autonomy and positively impacts the social relationships within the group, thereby improving motivation and effectiveness of the team. Autonomy is also a prerequisite for the team to have if they are to take care of their responsibilities in a satisfying manner [Wiendahl, H., Reichardt, J., Nyhuis, P., 2015, West, M. A., 2012].

In this case, the task interdependence within the assembly system and the production system as a whole is considered to be at least moderate. The expected company growth also increases the legitimacy of hierarchical structures, as growing production related departments become increasingly difficult to coordinate without clear sub-groups. Dividing Area 1 into teams according to some combinations of the different lines and shifts is considered suitable. These teams should consist of 5 to 7 members guided by one team leader. They should also have a high degree of autonomy as well as a corresponding amount of responsibilities. An example of how the organization of Area 1 could be structured at a time when 28 assemblers is needed can be seen in Figure 6.9.

7

Conclusion

The purpose of the master thesis was to produce a design proposal for a new assembly system. An adaptation of a systematic method for production system design was used, with extra focus being put on reconfigurability of the system to ensure long term performance. The design proposals are hard to summarize without losing important nuance, and are presented throughout Chapters 5 and 6. This chapter includes discussion and answers to the three research questions of the thesis however.

RQ1: What are the production system requirements and which are the most important performance measures?

The purpose of this research question was to produce a requirements specification that could be used as support in system design activities. Interviews were held with different project stakeholders to collect data, which was then used to formulate a draft for the requirements specification. Since the data from the interviews required some interpretation, the requirements specification was also validated through member checking. A ranked list of the 4 most important performance measures as well as a wide range of requirements were included in the resulting specification, which can be found in Appendix A.

RQ2: What system design concept best suits the context and system characteristics?

Existing theory on system design methodology showed a high degree of complexity in system design activities. This research question served the purpose of reducing that complexity by first narrowing down the design process to a few central parameters. The most important conceptual parameters were found to be process flows, material handling as well as tools and equipment. The current assembly processes consist of a very large work content. The results showed that a division of the work content into partially serial flows would be suitable. A corresponding division of kits, tools and equipment over the sequential work stations was also found to suit the current context.

RQ3: How should the future production system be designed in detail to handle increasing requirements on capacity and other production metrics?

This research question served to increase the detail at which the system was specified, with a focus on requirements changing over time. Analysis of current assembly operation steps, process times, material consumption and equipment usage was used to divide the work content into 4 suitable work blocks. System capacity calculations showed that a gradual increase from 8 to 16 work stations over the coming 4 years would satisfy capacity requirements. Analysis of workplace requirements as well as space needed for equipment and materials was consolidated into a detailed layout of the assembly system. Finally, the results showed that a team-based organizational structure would be suitable for the assembly system.

8

Discussion

When designing an assembly system there are a huge number of details to consider. Since many design parameters affect each other, the design process becomes immensely complex. This thesis focused on designing a system for the impending move to new facilities, and consequently the level of detail and depth in different areas was moderate. We recommend that Arcam implements the design proposals detailed in Chapters 5 and 6 in conjunction with the move to new facilities. The proposed design also provides a good foundation for future improvement work. Throughout the thesis there are discussions and suggestions to how the system could be developed and improved in the future.

Throughout the thesis, some areas with particularly large improvement potentials were found. One of these areas is that there is a disconnect between design and assembly. One problem with this is that the products are rather difficult to assemble, both from a cognitive and ergonomic perspective as well as from an efficiency perspective. This means many assembly steps take unnecessarily long time, and also results in a variety of poor working postures. Another problem is that the number of different components used is much larger than it needs to be. The different products all use a wide range of components, which most of the time are nearly identical. This is prevalent throughout the bills of material, but is particularly obvious when it comes to screws. There are nearly a hundred different types of screws used, of which most are extremely similar. In fact, approximately half of the screw types are used in quantities of 4 or less for all different product models combined. If the products could be adjusted to use a much more narrow set of components, material storage and handling activities could be drastically reduced. Both of these issues are related to the lack of focus on design for assembly and manufacturability (DFA/DFM).

Another area of great potential improvement is within the collection and use of process data. There is no accurate data on for example process times, and thus production planning and goals are only based on rough estimates. These estimates lack detail, as they for all models but one are just estimates of the total time consumption for a machine. Since there is a lack of insight into how long time the processes actually take, it is difficult to plan capacity changes in production. It is also nearly impossible to judge what kind of goals would be reasonable to set, both on a individual and group level. This is not to say there are no efforts to follow up on metrics. There are regular follow up meetings on how production as a whole is performing, but the follow up on each individual area within production is insufficient. The lack of accuracy in the data, as well as the lack of data that feels relevant to the individual, results in a poor performance feedback loop.

The research questions of the thesis followed the different development phases and activities of the adapted systematic method for assembly system design. Answering these research questions helped provide a good solution for the company studied in this particular case. It would be of interest to study the general applicability of the adaptation of the method. Thus, future research could focus on investigating the method itself and its adaptation for different contexts.

Due to the high degree of complexity of the thesis, using a systematic method for assembly system design was very helpful. Planning of what different project phases to do and how much time they would take became much easier. The composition of activities was also more carefully balanced when using a standardized approach, which helped ensure a certain level of quality in the results. Much of the data collection was done in close collaboration with assemblers and others in the workplace. This helped provide valuable context and understanding of how things really are.

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A

Appendix 1

Requirement Specification Area 1

March 2018

1. Introduction

This document is a list of requirements, desired objectives and performance measures which the new design of Area 1 should comply with and be designed after. The content of this document has mainly been collected from interviews with people with insight into area 1 and production as a whole. However, observations of the current system and its advantages and disadvantages have also been taken into account.

This requirement specification uses the following verbs:

- "must" indicates requirements
- "should" indicates recommendation or wishes
- "may" indicates consent
- "can" indicates opportunity or ability

2. Requirements, desired objectives and performance measure

The requirements, desired objectives and performance measure have been divided into five different categories, namely, general, work content, workplace, organisation, and performance monitoring.

2.1. General

2.1.1. During selection of production concepts, the following dimensions must be prioritized in the given order:

1. Safety
2. Quality
3. Delivery
4. Economy

2.1.2. The production system must be able to produce at least:

a) 1085 machines during 2019
b) 1855 machines during 2020
c) 2660 machines during 2021
d) 3500 machines during 2022
e) 4515 machines during 2023
f) 5320 machines during 2024
g) 6090 machines during 2025
h) 6755 machines during 2026
i) 7350 machines during 2027
j) 7700 machines during 2028

2.1.3. The system must manage the capacity requirements regardless of the proportional distribution between product variants.

2.1.4. The system must be able to produce product variants that have been phased out without significantly affecting production performance.

2.1.5. The system should be able to handle customer specific product customization without significantly affecting production performance.

2.1.6. The system should be able to quickly start production of new products.

2.1.7. The system should enable quick identification of the source of quality and reliability problems.

2.1.8. The system should minimize the effects of variation in the number of persons working in Area 1.

2.2. Work content

2.2.1. The work content in Area 1 today is estimated to be 6,1 hours, but the system should be easy to modify to allow for increases in the work content. An example of a reason to increase the work content is more rigorous quality assurance procedures.

2.2.2. The system should facilitate continuous improvement work regarding quality and throughput.

2.2.3. The system should minimize the effects of variation in lead-time between product variants.

2.2.4. The system should minimize variation between individual products of the same variant.

2.3. Workplace

2.3.1. The system must be compatible with the company's ISO-9001 certification.

2.3.2. Each workstation must contain a computer, as to enable the implementation of digital solutions to problems.

2.3.3. The system should be designed to facilitate a high level of order and cleanliness.

2.3.4. The workplace should contain all frequently used tools and equipment.

2.3.5. The system should minimize traffic of personnel from other departments through Area 1.

2.3.6. The furniture, tools and equipment in the system should be easy to move around.

2.4. Organisation

2.4.1. The system must be based on and support the maintenance of standardized work.

2.4.2. It must be possible to introduce shift work as a tool for meeting the capacity requirements.

2.4.3. The system must allow for personel to be able to either work only in Area 1 or in Area 1 and other areas intermittently.

2.4.4. The system should encourage and simplify continuous improvements to processes and standards.

2.4.5. The amount of work tasks requiring more than one person should be minimized, for example heavy lifting.

2.4.6. The system should offer a large variety of work tasks.

2.5. Performance Monitoring

2.5.1. The system should clearly and continuously communicate the takt time to the personnel.

2.5.2. The system should enable clear visualization of status and goals.

2.5.3. Logging of time spent on different activities should be easy.

2.5.4. Quality data should be saved and be traceable.