CHALMERS
UNIVERSITY OF TECHNOLOGY

Improving a Production System to Increase Capacity

– An Analysis to Detect Productivity Potentials in Security and Defence Production

Master's Thesis in Production Engineering

EMELIE ROSLUND
NATALIE ZANGANEH

Department of Technology Management and Economics
Division of Supply and Operations Management
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016
Master's Thesis E2016:028

MASTER'S THESIS E2016:028

Improving a Production System to Increase Capacity

– An Analysis to Detect Productivity Potentials in Security and Defence Production

EMELIE ROSLUND
NATALIE ZANGANEH

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Technology Management and Economics
Division of Supply and Operations Management
Chalmers University of Technology
Gothenburg, Sweden 2016

Improving a Production System to Increase Capacity
– An Analysis to Detect Productivity Potentials in Security and Defence Production

EMELIE ROSLUND
NATALIE ZANGANEH

Supervisor: Peter Almström, Department of Technology Management and Economics
Examiner: Peter Almström, Department of Technology Management and Economics

Master's Thesis E2016:028
Department of Technology Management and Economics
Division of Supply and Operations Management
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Simulated manual assembly.

Photographers of cover photo: Emelie Roslund & Natalie Zanganeh

Improving a Production System to Increase Capacity
– An Analysis to Detect Productivity Potentials in Security and Defence Production

EMELIE ROSLUND
NATALIE ZANGANEH
Department of Technology Management and Economics
Chalmers University of Technology

Abstract

The purpose with the master's thesis was to increase the capacity within a production unit by analysing the operation time, productivity, production disturbances, production ergonomics and material handling system. The increase in capacity intends to handle possible future increase in demand.

The master's thesis was conducted within a production unit at a Swedish company, referred to as Global Manufacturing Company (GMC). The company provides high-tech products within security and defence industry. The study focused on the production for one specific product at GMC. An in-depth analysis was made by utilising a structured methodology. Specifically, the methodology followed an adapted model of methods engineering inspired by Freivalds and Niebel (2009).

The thesis has identified a discrepancy at one of the business areas between the operation time in the ERP system and the ideal operation time. The main reasons for production disturbances were machines and equipment, design of the product and support systems. The recommended solutions provided an operation time reduction of 7.4 hours per unit, a productivity increase of 34% and a capacity increase of 35.3%.

Keywords: Production Engineering, Productivity, Capacity, SAM, AviX, Production Ergonomics.

Acknowledgements

We would like to thank Lena Lindqvist for giving us the opportunity to conduct our master's thesis at Global Manufacturing Company (GMC). A special thanks to our supervisor at GMC, Karin Siby, for her engagement, support and feedback throughout our project. We would also like to thank all operators in the production unit for participating in our study by being filmed and providing us with valuable information.

Lastly, we wish to give a special thanks to our supervisor and examiner from Chalmers University of Technology, Peter Almström. We appreciate your guidance and support that have helped us during the entire project.

Emelie Roslund & Natalie Zanganeh

Gothenburg, May 2016

Abbreviations

BA1 – Business Area 1

ERP – Enterprise Resource Planning

GMC – Global Manufacturing Company

IFS – Industrial and Financial System

MPU – Method, Performance and Utilisation

MTM – Methods-Time Measurement

MTO – Make-To-Order

RULA – Rapid Upper Limb Assessment

REBA – Rapid Entire Body Assessment

SAM – Sequential Activity and Methods analysis

SWOT – Strengths, Weaknesses, Opportunities and Threats

TDM – Time Data Management

TTD – Total Travel Distance

Table of Contents

List of Figures

List of Tables

1 Introduction

The introduction of this master's thesis is described in following chapter, providing a short presentation of the company referred to as Global Manufacturing Company (GMC). Moreover, the project background, problem definition, and delimitations are presented.

1.1 Global Manufacturing Company

Global Manufacturing Company (GMC) is an international defence and security company that develops and manufactures military and civilian solutions. The main purpose of the company is to protect the citizens and borders of Sweden. Their vision is to keep people and societies safe by constantly pushing intellectual and technological boundaries. The company's defence portfolio is wide and can be used in different areas such as hospitals, airports, prisons, and major sports events.

As a defence and security company, GMC has a main goal to provide both cost efficient and high-tech products and solutions for their customers. This master's thesis is conducted at one of the five business areas of GMC.

1.1.1 Business Area 1

The business area in which the master's thesis is conducted is hereafter called BA1 and is located at Location A, Sweden. During 2014, the sales within BA1 reached roughly 4.6 billion SEK, which corresponds to 13% of the total sales of GMC. The headquarters of BA1, as well as one of the two production sites, is located at Location A, Sweden. In total, there are around 2500 employees at BA1.

This master's thesis is conducted at the division Sourcing and Production, in which all production of this business area is incorporated. The production unit at Location A consists of four parts; Project Office, Industrialisation, Supply Chain and Manufacturing.

The project is executed at Industrial Engineering, which is a part of Industrialisation at BA1, see Figure 1. However, the product and production system that is studied in this project belongs to Manufacturing. The studied product is hereafter called Alpha.

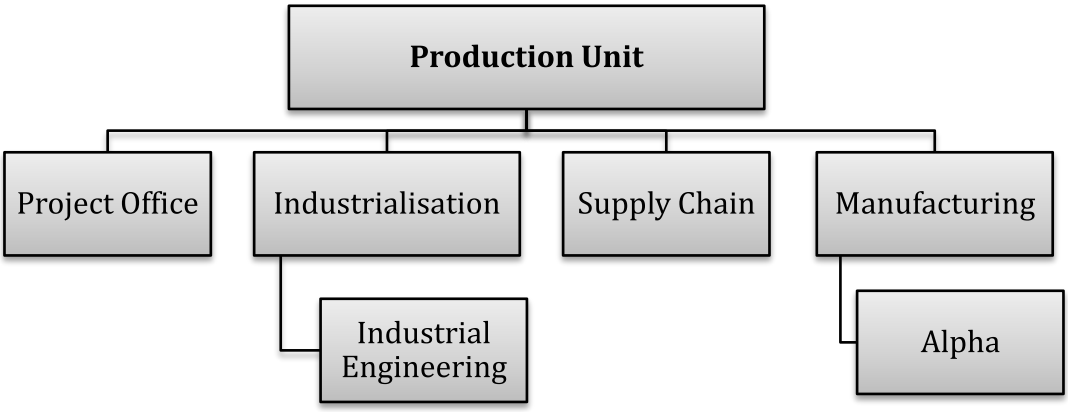


Figure 1: GMC production organisation

The production unit for Alpha is separated into two rooms; Cleanroom 7 and Cleanroom 8. The manual assembly is performed in Cleanroom 7, while the majority of the performance tests are made in Cleanroom 8.

1.2 Project Background

Jonsson and Mattsson (2009) state that the production capacity of a company is measured as output divided by input. More specifically, the capacity is determined as an amount of products produced per time unit. Being a global company that operates in different regions and countries requires flexible production systems in terms of ability to increase the capacity level when the demand changes. GMC is facing changes in the demand since the company is developing and offering new products and variants to their customers. In order to handle these changes in demand, GMC is in need of improving their production systems and increase the capacity to stay competitive in the market.

Productivity at a corporate level contributes to a high profitability and competitiveness (Almström, 2012), which are two significant factors for world leading companies in today's market. According to Zandin (2001), productivity is considered as an essential factor in order for industries to grow and become competitive in the market. It is therefore important that the industries keep the pace and deliver products and services of high quality that fulfil the customer requirements. GMC operates within the security and defence industry and provides long-lasting products to their customers. It becomes significant for the company to constantly improve the production systems in order to provide innovative products of good quality and high precision. One of the business areas of GMC, BA1, is growing and developing new product variants. Hence, there is a need to increase the productivity in order to strengthen their position in regards to their competitors in the market.

Capacity and productivity are both defined as output divided by input. However, capacity regards the ability to produce products with the available resources while productivity focuses on the efficiency during production.

There have been only a few improvement projects regarding the production system for the studied product Alpha and it is therefore considered to have a high productivity potential. The employees at BA1 are aware of the many problems that the production of Alpha entails. However, the personnel have not specified these problems in detail and there is currently no improvement projects associated with the production of Alpha. Furthermore, it is convenient that the company solves the current issues related to the production of Alpha before manufacturing new product variants in the production system.

1.3 Problem Definition

BA1 will soon introduce a new product to the production unit where Alpha is produced and they expect the demand for Alpha to increase in the future. To be able to handle these tightened requirements on the production, they wish to reduce the lead time and manufacturing costs associated with Alpha, as it is the product that is produced in the largest volume in this production unit.

Reducing the lead time and manufacturing costs can be done by increasing the capacity, which in this master's thesis has been done by investigating and analysing the productivity potentials. The purpose of finding the productivity potentials is to decrease the total operation time, which in turn contributes to increase the capacity. Areas in which these potentials may be found are ergonomics, material handling, communication and production layout.

Production disturbances is a large problem in the studied production unit today and they occur within different areas of the production. Both the operators and management are aware of their existence, but they are not defined or investigated. The disturbances contribute greatly to decreasing the capacity. There is therefore a need to find the causes behind the production disturbances in order to reduce and eliminate them and thereby increase the capacity.

The management believes the Enterprise Resource Planning (ERP) system to show the truth and uses it to plan the production. The operators on the other hand know the system does not reflect their work correctly. There seems to be a missing link between the operators and the management in regards to the descriptions of the production work. This misalignment between management and production was also noticed by Skinner (1969) who claims that the management generally perceives the production wrong. To bridge this gap and allow the operators and management to share the same understanding of the production, the data from the ERP system should be compared to data regarding an ideal production state.

1.3.1 Research Questions

The research questions that have been investigated and are answered in this study are:

RQ 1: How much does the operation time in the ERP system differ from the ideal operation time?

RQ 2: What are the reasons production disturbances occur in Cleanroom 7?

RQ 3: Can the capacity be increased by 50% for Alpha?

1.4 Delimitations

The main goal of this master's thesis is to aid GMC in reducing lead times and manufacturing costs, primarily by increasing capacity. The main delimitation is therefore to only include those aspects that can help achieve this goal. Other delimitations that have been made are:

- The focus is on one specific product, Alpha, in one specific production unit at the division of Sourcing and Production at Business Area 1 (BA1).
- The product- and production flow regards Cleanroom 7 and Cleanroom 8.
- The analyses cover only the specific production area and only the material flow within this specific production unit.
- The SAM analysis is based on the assembly and testing operations executed in Cleanroom 7, excluding the operations required for inspection and assembly of the sub-product resonator.
- The analyses are made without consideration to rework.
- The ergonomic evaluation is conducted for the operations in Cleanroom 7.

2 Method

The following chapter describes the method and tools used in this research study. This chapter is organised in a stepwise method procedure inspired by methods engineering. Discussions in regards to the research quality and ethical considerations are also presented.

2.1 Methods Engineering

Methods engineering comprises of a systematic procedure of manufacturing a product according to the most optimal methods, processes, tools, equipment, and skills that fulfil the requirement specification created by the product engineers (Freivalds and Niebel, 2009). The main focus in methods engineering is to design and develop work stations to manufacture a product and to continuously restudy the work environment in order to achieve improvements in terms of e.g. productivity and quality. The process of developing work centres, manufacture products or provide services is organised into eight steps described below (Freivalds and Niebel, 2009):

Step 1 – Select Project
State a problem definition for the project. The selected project is often characterised by a product that is facing economic, technical or human difficulties in production, e.g. high manufacturing costs, quality control issues and many repetitive tasks.

Step 2 – Get and Present Data
Gather and document data of high significance for the study.

Step 3 – Analyse Data
Analyse the data from previous step in detail. The main focus is to identify operations that are considered as waste in the system. Moreover, operations with improvement potentials are identified.

Step 4 – Develop Ideal Method
Develop an ideal method for the operations specified in previous steps. Productivity, ergonomics and safety are taken into consideration.

Step 5 – Present and Install Method
Present the developed method in detail to the managers and workers that are responsible for the operations.

Step 6 – Develop Job Analysis
Ensure that the staff are trained and prepared for the job.

Step 7 – Establish Time Standards
Standardise the developed method in a reasonable way.

Step 8 – Follow Up
Follow up the method in order to verify improvements. Repeat the methods procedure to make further improvements.

The methodology of this master's thesis was organised in four steps adapted from Freivalds and Niebel (2009):

- Step 1 – Research Approach
- Step 2 – Data Collection
- Step 3 – Analysis of Data
- Step 4 – Develop Recommendations

2.2 Step 1 – Research Approach

Borrego et al. (2009) point out that the choice of conducting a quantitative, qualitative or mixed research method should be driven by the research questions. A qualitative research approach is characterised by collecting and analysing textual data, i.e. surveys and interviews. The opposite strategy is to use a quantitative method that enables an objective procedure to answer the research questions. However, Borrego et al. (2009) state that there is a possibility to use a mixed method that combines quantitative and qualitative approaches. A study based on mixed methods includes gathering and analysing both quantitative and qualitative data simultaneously.

The focus of this master's thesis was to improve a production system in terms of increasing capacity. The research process was based on both numerical data and textual information in order to create an optimised production system. The master's thesis was therefore deployed through a mixed methods approach. Specifically, a triangulation design, visualised in Figure 2 , was used in order to answer the research questions. Thus, data was gathered through complementary methods and combined during the process to conduct the research.

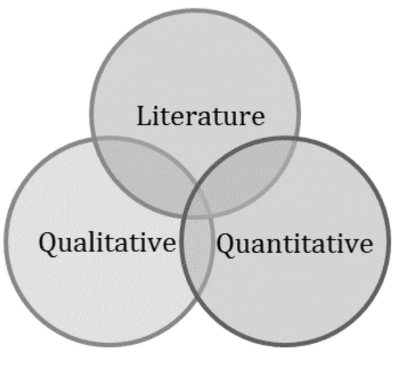


Figure 2: Triangulation

2.3 Step 2 – Data Collection

The data collection of this master's thesis concerns a literature review and a current state description, which are presented in sections 3 and 4.

2.3.1 Literature Review

The literature review was conducted with the purpose of creating an analytical framework that would act as a support throughout the master's thesis. The data collection of theory was made within technologies and methodologies associated with production engineering. In addition, the literature review would deepen the authors' knowledge within relevant fields required to execute the analysis. The literature was gathered from Google Scholar and Chalmers Library and the electronic data bases listed below:

- Access Engineering
- Chalmers Publication Library
- IEEE Xplore
- ProQuest
- Science Direct
- Springer Link

The completion of the literature review was systematically organised in the procedure described in Table 1 (Cronin et al., 2008).

Table 1: Literature review procedure. Adapted from Cronin et al. (2008)

Procedure	Description
Define knowledge areas	The literature review should include relevant knowledge areas for the research. Literature within Production System, Productivity, Time Data Management, Production Ergonomics and Visual Planning were considered appropriate for this master's thesis.
Search in data bases	The library service at Chalmers University of Technology, and Google Scholar were used to search for the literature. Different data bases were used in order to access published literature.
Read and analyse the literature	The gathered theory was analysed in order to decide what to include in the literature review. Information that would support the study was chosen since it provided useful knowledge for the completion of the analyses.
Document and create a literature review	The selected theory was documented and summarised in order to create a literature review.

2.3.2 IFS and Prosus

Two digital systems used by BA1, Industrial and Financial Systems (IFS) and Prosus, were two information sources for the data collection.

Data regarding operations and time as well as work instructions for the assembly of Alpha were gathered from IFS. Prosus is a reporting system used by the operators where the required operations for an order are displayed. Both estimated and reported operation times were gathered from the reporting system in order to detect differences between predicted time and real time to accomplish an operation.

2.3.3 Video Recordings

One specific operator in Cleanroom 7 was video recorded throughout the assembly process in order to gather information regarding the assembly tasks of Alpha. The video recordings were used to define the assembly tasks, and determine the real sequence that is used in production. The main purpose with the video recordings was to conduct a SAM analysis of the assembly in the software AviX, described in section 2.4.2.

2.3.4 Observations

Participant observation sessions were carried out on the shop floor in order to get an insight of the daily activities and operations managed by the operators. The documentation was made during the observation and summarised after each session. The observations enabled a possibility for the authors to be engaged in conversations with the operators, observe behaviours, and ask questions (Jonker and Pennink, 2010). Additionally, the operators contributed with their opinions regarding the activities that were considered as troublesome. The participant observations were significant for the study in terms of detecting differences between the reality and the data identified in the ERP system. In addition, the main storage in Location B was studied and the material handlers observed and talked to.

2.3.5 Meetings

Meetings were held with employees to gather valuable qualitative data for the project. The authors chose employees working at different hierarchical levels in order to gain a holistic perspective of the production system of Alpha. The main themes during the meetings were production planning, material handling, production flow, product design, and assembly operations. The meetings were therefore held with the following employees:

- Head of production
- Production manager
- Material planner
- Production planner
- Product design engineer
- Operators

Notes were taken during the meetings and further summarised into a document to provide useful information to conduct the analyses.

2.4 Step 3 –Analysis of Data

The gathered data was analysed through a spaghetti diagram, a SAM analysis, ergonomic evaluation methods, and a SWOT analysis.

2.4.1 Spaghetti Diagram

The spaghetti diagram is a visual lean tool used for understanding movement and transportation (Wilson, 2010) that focuses on the physical locations of flows through a system (Allen, 2010). It is a simple, yet powerful tool that aids in finding opportunities for reducing wastes (Wilson, 2010) by, for instance, eliminating unnecessary transportation of material (Allen, 2010).

To create the spaghetti diagram, the following eight steps were used (Allen, 2010):

- Step 1: Acquire a layout of the factory.
- Step 2: Acquire the routing through the factory.
- Step 3: Draw a continuous curve from the first location to the succeeding locations, according to the routing.
- Step 4: Calculate the Total Travel Distance (TTD) according to (eq.1):

$$TTD = \sum_i n_i d_i \qquad (1)$$

  where the sum is over all routes travelled, n_i is the number of times the route is traveled, d_i is the distance of the route.
- Step 5: Estimate travel time by multiplying the TTD with the speed of travelling. The speed for walking is normally set to 1.4 m/s.
- Step 6: Identify improvement potentials by studying the spaghetti diagram and looking for areas of the layout that are highly used and areas that are seldom used.
- Step 7: Rearrange the processes or other elements of the layout with the purpose of reducing TTD.
- Step 8: Repeat step 4-7 for the new layout(s).

2.4.2 SAM Analysis in AviX

A time study analysis was considered a suitable research method since the assembly of the product is manual. Therefore, a SAM analysis was conducted in the software AviX in order to generate standard times to accomplish the required tasks for the entire assembly procedure. The SAM analysis measures the manual operations in terms of basic motions used during the assembly process (Freivalds and Niebel, 2009). The operations that include complex motions were measured with stopwatch since SAM is not a suitable method to analyse such motions.

The analysis in SAM provided information regarding the operation time and distribution of value-adding and non-value-adding activities in the production system. This information was significant to detect improvement potentials in terms of increasing capacity.

2.4.3 Ergonomic Evaluation

A part of this thesis was to conduct an analysis of the method used by the operators during assembly. The operators are currently not satisfied with the ergonomic situation. In addition the ergonomic design of a workplace affects the output rate of the assemblers (Al-Zuheri, 2013). Therefore, an ergonomic evaluation was essential in order to analyse the current health factor and support for the operators. The physical ergonomic evaluation was conducted for the most severe working postures. The methods used were:

- RULA – Rapid Upper Limb Assessment
- REBA – Rapid Entire Body Assessment

A thorough description of these evaluation methods can be found in section 3.4.3. The cognitive ergonomic evaluation was used to detect improvement potentials in terms of the quality of the work instructions and visual aids.

2.4.4 SWOT Analysis

The main storage is currently located at Location B which is outside the walls BA1. A SWOT analysis of moving the main storage from Location B to BA1 and removing the kitting procedure was conducted. Strengths, Weaknesses, Opportunities and Threats were identified in order to determine challenges and rewards (Goodrich, 2015).

2.5 Step 4 – Develop Recommendations

The problems identified in the analyses were taken into consideration during the development of recommendations and improvements. The authors brainstormed and discussed potential improvements with the production personnel in order to involve them in possible future changes. Furthermore, the recommendations were visualised and described in detail in order to facilitate implementation at the company.

The literature review was used as an inspiration source when brainstorming the different improvement suggestions. The authors reconnected the developed improvements with the conducted literature review to increase the credibility of the generated recommendations.

2.6 Research Quality

The quality of quantitative and qualitative data should not, and sometimes cannot, be assessed in the same ways (Bryman and Bell, 2007). What has been taken into consideration for this study are the trustworthiness criterion for assessing qualitative data and the corresponding criteria for assessing quantitative data. Trustworthiness consists of four elements: credibility, transferability, dependability and confirmability. The criteria are paired, briefly explained and countermeasures are presented in the four following sections.

2.6.1 Credibility and Internal Validity

These criteria address to what degree the data is believable and whether or not the conclusions that are drawn match the observations that have been made (Bryman and Bell, 2007). To overcome this, the authors have discussed their observations internally to ensure objectivity and correctness. Where ambiguities lingered, the discussions were widened to include concerned parties.

2.6.2 Transferability and External Validity

Whether or not the findings are applicable to other situations, i.e. whether or not they can be generalised, is covered by these two criteria (Bryman and Bell, 2007). The recommendations presented in this study are focused on Alpha. However, in order to avoid sub-optimisation, the company should consider the provided recommendations for all production units at BA1 and adapt them accordingly.

2.6.3 Dependability and Reliability

The dependability and reliability criteria address to what degree the data is applicable at other points in time, i.e. if the data is consistent and whether or not the study can be replicated (Bryman and Bell, 2007). A way of handling this is by keeping all records and material to be reviewed in an external audit according to Bryman and Bell (2007). Most records and material from this research was kept but due to resource restrictions, no auditing was made.

2.6.4 Confirmability and Objectivity

The last pair of criteria covers to what extent the researcher has allowed his or her own values and opinions to affect the results (Bryman and Bell, 2007). Some previous knowledge and experiences along with personal opinions and values may have affected the analyses and results of the thesis. The authors coped with this by acting in good faith, being aware of the risk and trying not to influence by having an open mind and keeping objectivity close at hand.

2.7 Ethical Considerations

It is crucial to be aware of the ethical principles involved when conducting research (Bryman and Bell, 2007). One of these principles is "harm to participants", which includes assessing and minimising the possibility of harm to the participants. Harm consists of many aspects; physical harm, stress, harm to participants' self-esteem or future employment. In addition, this ethical principle includes honouring requests regarding anonymity and confidentiality as well as ensuring that individuals and organisations are identifiable only if permission is given. For the purpose of this thesis and the wish of the company, product- and production specific details are not published. There is one thesis report for the company, with all details enclosed, and one thesis report for publication, which contains little or no detailed information about the product and production. The assurance was made by employees at the company before publication. There is no information in neither of the reports regarding the individuals that participated in the study and no, features enabling identification of them. When filming the operators, extra care was given to inform them about the purpose of the movies. The harm done to the company and employees is therefore regarded as very low.

Another principle is that of informed consent (Bryman and Bell, 2007). It means that potential research participants should be given enough information to be able to make an informed decision regarding whether or not they want to participate in the study. Due to the authors' need to film the employees, much information was given by the authors and the production manager as to why the movies were important and what they would result in. Further questions that the employees had were answered immediately by the authors to ensure a high level of transparency regarding the purpose of the movies. Only those operators that wished to be filmed and answer questions were included in those elements of the study.

The third principle concerns invasion of privacy and what levels of it that are tolerable (Bryman and Bell, 2007). This principle is closely connected to the previous one; that of informed consent. This principle can be of particular importance when dealing with videos for example. As the main purpose of filming for this thesis was to analyse the methods used when assembling and testing, and not to judge or measure the speed of the workers, only the relevant body parts of the operators were filmed. The focus was on the hands and arms and no faces were included. The authors made a test movie of a short assembly sequence, where only the hands and arms were filmed, and showed it to the operators. In this way, the operators could see for themselves what would be visible in the movies and understand the degree of invasion of their privacy that the movies would do.

3 Literature Review

This chapter presents the literature review conducted in the master's thesis. The review is organised into different knowledge areas within the production engineering field.

3.1 Production System

A production system is considered as a transformation process of input to output (Bellgran and Säfsten, 2010). Machining and assembly are examples of transforming raw material into complete products. However, the output from a particular system can be input to another system.

It is important to have a system perspective in order to understand production systems with high complexity (Bellgran and Säfsten, 2010). A system is divided into sub-systems in order to generate an overview of a complex system. The organisation of a system consists of personnel, machines and a methodology to accomplish a set of activities. Furthermore, the combination of processes and resources such as material, work and capital creates products and/or services in a production system.

There are three different system perspectives (Bellgran and Säfsten, 2010):

- Functional perspective
- Structural perspective
- Hierarchical perspective

The functional perspective considers the system as the process of input to output. A structural perspective regards the different elements in the system and the relations between these elements. The hierarchical perspective describes the different system levels in relation to each other.

3.1.1 Production Flow Strategies

A production flow strategy regards the movement of a product through a particular system, for instance a facility (Zandin, 2001). According to Zandin (2001), three of the factors that affect the production flow are the product, production environment, and layout.

The type and size of the product will have a huge impact on the direction of the flow (Zandin, 2001). Make-to-stock, assemble-to-order and make-to-order are three different environments with different types of demand and lead time restrictions. Therefore, the production flow will vary depending on the environment. A product managed in a make-to-order (MTO) environment has several benefits in terms of saving money, for instance by reducing inventory.

However, since there is no finished goods stock in an MTO environment, the delivery precision might be jeopardised. The production flow can also be affected by the product customisation required from the customers. The customer has unique requirements on the product design in an MTO environment. Therefore, the products are normally more expensive in this environment and the customers are aware of the long lead times.

There are in total three main types of production environments (Zandin, 2001):

- Mass production
- Job shop
- Batch production

Quality and low price characterise mass production while variety is achieved through job shop or batch production. Customers usually request products with good quality and low price, but also the option to choose from different variants. In mass production, products are manufactured in high volumes and few variants (Zandin, 2001) with lower lead times due to the machine arrangement (Skoogh, 2014). The flexibility is low in this type of production environment since there is a high automation level.

Job shop production concerns production of low volume products in many different variants (Zandin, 2001). Therefore, customised products are often processed in job shop production since there is a high flexibility of production. Job shop production has a machine-oriented layout, i.e. machines are grouped together according to their functionality (Winroth, 2014). The layout consists of several machine stations and the product is moved between these different stations. Moreover, this type of layout enables sequence flexibility as the product can be moved to any available workstation.

Batch production enables manufacturing of medium volume and medium amount of variants (Zandin, 2001). Batch production has a product-oriented layout where the products are processed in groups, i.e. batches, and moved between different workstations (Winroth, 2014).

The production environment normally decides what type of layout is considered as suitable (Zandin, 2001). The different facility layouts are:

- Continuous flow layout
- Product-type layout
- Process-type layout
- Fixed layout
- Cellular-type layout

The continuous flow layout is arranged for processing products such as fluids and chemicals where the products are moved in a continuous flow line (Zandin, 2001). In a product-type layout, the lines are organised so that only one product can be processed on each line. There are large investments in such an environment and is appropriate when manufacturing large volumes. In a process-type layout is the equipment organised according to its function and the flow can go back and forth between different work centres. This layout is suitable in an environment with high diversity of product flows and is usually used for job shop production since it enables processing many small orders, each with its unique flow. Detailed planning is required in this layout due to high complexity and the diversity of product flows in the system. Fixed layout basically means that the resources such as equipment, tools and personnel are moved to the product. This layout is common for infrastructural systems in the construction industry, for example when building bridges. The cellular-type layout concerns product families that are processed in a similar way. Machines, tools and personnel are grouped in different cells in order to process products with similar usage of resources.

3.1.2 Production Disturbances

According to Bellgran and Säfsten (2010), production disturbances is not a concept that is defined equally by everyone. They also state that some of the different perspectives from which disturbances can be looked upon are maintenance, production and efficiency, quality, and security. Moreover, Bellgran and Säfsten (2010) also state different events that can cause disturbances such as equipment failure and machine breakdowns, mistakes in planning, time to change or replenish material, set-up, cleaning, breaks, and stops caused by waiting for material/products/resources.

3.1.3 Manual Assembly

In order for manufacturing companies, that also have assembly operations, to quickly and economically respond to the ever-changing customer needs, manual assembly systems are still highly relevant and important (Al-Zuheri, 2013). Humans are more flexible, creative and with a higher degree of intuition than the features machines and robots possess.

The most common challenge in production is the increased complexity due to several elements in the production system with complex interactions (Al-Zuheri, 2013). The complexity in manual assembly concerns the different variances in the system. For instance, variances in task completion provide dissimilar operating times. Moreover, variances in the workers' skill levels and knowledge contribute to the complexity in the manual assembly system.

The process of manual assembly consists of multiple parts that are put together i.e. assembled into either a main component or a final product (Al-Zuheri, 2013). A typical assembly line consists of several stations where a set of activities are completed at each station. The main characteristics of manual assembly are repetitive tasks, monotonous work, and mental and physical stress. Moreover, manual assembly work usually involves severe postures that negatively affect the human body.

3.1.4 Capacity

The capacity of a facility is defined as the amount of products manufactured per time unit (Jonsson and Mattsson, 2009). Olhager (2013) says that the capacity of a facility is affected by the available resources. Capacity is measured according to (eq.2):

$$Capacity = \frac{Maximum\ Product\ Output}{Given\ Time\ Period\ Input} \tag{2}$$

There are two strategies for capacity changes; lead strategy and lag strategy (Jonsson and Mattsson, 2009). These strategies are associated with different levels of risk taking. A lead strategy contributes to taking great risks since the capacity is changed before the demand is changed. The opposite approach, lag strategy, means that investments and changes in the capacity are only made when the change in demand is clarified.

3.2 Productivity

Changes in productivity are usually made when industries face challenges and need to survive, or when success factors are aimed for (Zandin, 2001). Measuring productivity is usually a way to determine the performance of a production system (Bellgran and Säfsten, 2010). Furthermore, measuring productivity might provide useful information to a firm regarding the usage of resources over time. The productivity of a production system concerns the relationship between all activities in the system and the generated output from these activities. The best scenario is to only have value-adding activities and zero waste in the production system.

Productivity is a measurement of performance that describes the relationship between output and input (Sundkvist, 2014) (eq.3):

$$Productivity = \frac{Output}{Input} \tag{3}$$

The input considers the amount of resources, e.g. labour, capital and energy, required to manufacture products and services (Zandin, 2001). Increased productivity is achieved through producing more products and services with the same amount of resources (Sundkvist, 2014). Lack of resources or an inappropriate usage of a firm's resources will negatively affect the productivity. Furthermore, reducing waste in a production system will improve the productivity and add value to the processes.

The manufacturing trend is shifting from mass production to MTO production, which requires production systems with high flexibility (Sundkvist, 2014). Furthermore, the concept of lean production has influenced the industrial engineers to rather focus on eliminating waste and create value-adding activities (Zandin, 2001). A suitable approach to improve productivity in an environment with e.g. MTO production is to analyse the different work processes at the shop floor (Sundkvist, 2014).

Productivity at the shop floor level is affected by three factors: method, performance and utilisation (Almström, 2012). The method (M) is the anticipated productivity rate (Almström, 2012), and the actual work method used by the operators (Sundkvist, 2014). The performance (P) is equal to the speed of the activity and work performance of the operators in relation to the ideal cycle time (Almström, 2012). The utilisation (U) regards the usage of resources in the production system (Sundkvist, 2014), i.e. the time spent on planned work in relation to the planned available time (Almström, 2012). Productivity can be calculated according to the following formula (eq.4):

$$Productivity = M \times P \times U \tag{4}$$

The factor M corresponds to the manual work method and has great improvement potentials to increase the productivity (Almström, 2012). Method improvements are made in order to support the worker to produce more, i.e. to increase the output (Zandin, 2001). Another positive aspect is that major improvements can be achieved through the factor M with small, or no, investments (Almström, 2012).

The P factor comprises of two sub-factors; personal performance rate (P_P) and skill-based performance rate (P_S), while the U factor can be broken down into three sub-factors; need-based utilisation rate (U_N), system design utilisation rate (U_S) and disturbance affected utilisation rate (U_D) (Almström, 2014). Equation (4) can therefore be formulated as (eq.5):

$$Productivity = M \times P_P \times P_S \times U_N \times U_S \times U_D \tag{5}$$

It is recommended to improve the factor M through involving the personnel before considering improvements of the factors P and U. For instance, the U factor might be complex and time-consuming to improve since aspects such as company culture and managerial issues might affect this factor.

3.3 Time Data Management

In manufacturing companies, time data management (TDM) is vital for gathering necessary information to manage strategic and operative planning (Kuhlang et al., 2014). The information provided by time data is considered as an essential factor both for decision-related activities and from a planning perspective. In production, time data is considered to be an important factor for monitoring and controlling different processes. Lead times, operation times and setup times are examples of relevant time data that can be used during analyses and design of production systems. Therefore, time data is significant to use when optimising a production system since it will determine time-related factors for the analysis.

3.3.1 Methods-Time Measurement

Methods-time measurement (MTM) is a technique used during analyses of manual operations that focuses on the movements and motions required to accomplish an operation (Maynard et al., 1948). The MTM procedure provides an opportunity to analyse both method and time simultaneously in order to detect improvement potentials. There are three different types of MTM called MTM-1, MTM-2 and MTM-3, where MTM-1 is the most detailed type (MTM-föreningen i Norden, 2016).

MTM generates a predetermined time standard for each movement and motion performed during the operation (Maynard et al., 1948). The predetermined time standards are established through taking the method used during the manual operation into consideration. Thus, MTM provides time data based on the used method during the observed manual operations.

3.3.2 Sequential Activity and Methods Analysis

Sequential activity and methods analysis (SAM) is a development of the MTM-2 system (MTM-föreningen i Norden, 2016). SAM is a predetermined time system that enables analysis of work activities (Sundkvist, 2014). The main objective with SAM is to establish work methods that enable high productivity (IMD, International MTM Directorate, 2004). The analysis generates norm times based on the determined work methods, i.e. the norm time depends on the method. The norm time regards the total time it takes to accomplish a manual task with the assumption that the work is performed according to a performance level set by SAM. The manual work required to accomplish a task consists of motions that are defined as different activities that are grouped into three categories (IMD, International MTM Directorate, 2004):

- Basic activities
    - Get
    - Put

- Supplementary activities
    - Apply force
    - Step
    - Bend
- Repetitive activities
    - Screw
    - Crank
    - To and from
    - Hammer
    - Read
    - Note
    - Press button

The basic activities consist of e.g. getting an object from the workbench (Sundkvist, 2014). The supplementary activities such as step and bend might be necessary in order to get the actual object. The repetitive activities include the use of tools when processing the object.

3.3.3 AviX

Solme AB developed AviX with the main objective to enable an analysis of manual work through combining video analysis and time studies (Solme, 2015). The activities mentioned in section 3.3.2 are documented in AviX. In particular, the SAM analysis is made in the module AviX Method that generates MTM standard times for the defined activities. AviX separates the non-value adding and value-adding activities in order to detect improvement potential. The non-value-adding activities can be further separated into losses, waiting and required.

3.4 Production Ergonomics

Production ergonomics can be defined as a study to design the workplace (Zandin, 2001) and entails a physical and a cognitive element (Berlin and Adams, 2014). There are several factors that affect the output rate of the assembler, and the ergonomic design of the workstation is one of them (Al-Zuheri, 2013). The interaction between the workers and their working environment is in focus in order to provide a safe environment and a possibility to improve the performance (Berlin and Adams, 2014). Production ergonomic analysis has a main focus on the human activity in order to prevent injuries, pain, discomfort, demotivation and confusion in their daily work.

Neglecting ergonomics in the planning stages usually creates problems such as worker pain and sick-leave (Berlin and Adams, 2014). Therefore, production ergonomics should be included in the early planning phases in order to generate long-term cost savings and decrease the risk of having an unhealthy workforce.

3.4.1 Physical Ergonomics

Posture, force and time are three factors that affect the physical loading (Berlin and Adams, 2014) and create ergonomic stress (Zandin, 2001). The body posture contributes to internal loading on the body's muscles when working and maintaining different postures (Berlin and Adams, 2014). A good posture includes a symmetric body where the feet, knees, hips, shoulders and ears are aligned and positioned directly above each other. If the back and legs are loaded, they should be so in the axial direction as they are best at withstanding loads in this way. In addition, a good posture includes handling loads close to the centre of the body.

A bad posture is a weak position and is not suitable for physically demanding work (Berlin and Adams, 2014). Indications of a bad posture are; asymmetry, body parts stretched or bent to the outer range of movement and imbalance between the legs. The source of bad postures may be ergonomic traps such as the need to stretch to reach, the need to keep arms above shoulder-height or lifting an object that is awkwardly shaped and difficult to lift.

Force is the second factor affecting the physical loading. There are five different types of forces (Berlin and Adams, 2014); dynamic, static, repetitive, external and internal forces. Several muscle groups are active when using dynamic forces in the work while a limited amount of muscle groups are used during static forces. Both static forces and repetitive forces have a tendency to not let the human body recover and rest. Repetitive forces arise when motions that are short in time are frequently repeated. External forces arise when handling weights such as lifting or pushing an object. Internal forces arise when, for example, striving to maintain an awkward posture at the outer ranges of movement.

Time is the third and last factor and regards how often and the amount of time that the human body is loaded, i.e. the repetitiveness and frequency of work (Berlin and Adams, 2014). The same muscle groups are used frequently during repetitive work, which most likely will lead to injuries and pain, since there is no time to rest the muscles. Time factors are tricky since a small and harmless load might lead to a long-term injury due to the amount of repetitive activities in the work.

The way the three factors are used is what determines the level of the ergonomic risk (Berlin and Adams, 2014). If all three are of a small-risk nature, the total risk will also be rather small. However, if one or more of the three factors are of great risk, the total risk will also be great. High-precision work requires extra attention and concentration of the operator. To avoid harmful effects of high-precision work there is a need for very good working conditions and working postures. In addition, the conditions and postures are important for the efficiency and quality of the work.

3.4.2 Cognitive Ergonomics

Cognitive ergonomics regards how the design of a workplace contributes to the worker's ability to understand and solve problems (Berlin and Adams, 2014). The aim with cognitive ergonomics is to avoid mental overload, errors and misinterpretations. Designing for cognitive ergonomics in production systems involves consideration of how information is handled and to create a cognitive support system for the workers. An example of how to present information in a good cognitive ergonomic way is to present the same information in different ways, e.g. with a picture and a text. This reduces the risk of misinterpreting the information.

Information should be easy to find and the effort and amount of time spent on finding the relevant information should be as small as possible (Berlin and Adams, 2014). The longer time that is needed, the less motivated will the workers be and the less efficient is the process.

Standardised work and work instructions are two commonly used approaches to support cognitive ergonomics (Berlin and Adams, 2014). Standardised work prevents the worker from ending up in different decision-making situations since it provides one optimised standard method. Work instructions act as a guideline for the operators on how to perform different tasks.

3.4.3 Physical Ergonomic Evaluation Methods

The work characteristics and the goal with the evaluation should act as a basis for which method to use (Berlin and Adams, 2014). The analysis of postures identifies deviations from a natural standing position. The higher the score, the more the body deviates from the reference position. According to Berlin and Adams (2014) the two most used methods analysing postures are:

- RULA – Rapid Upper Limb Assessment
- REBA – Rapid Entire Body Assessment

RULA is a suitable evaluation method for work that mainly consists of hand-arm movements (Berlin and Adams, 2014). The postures are assessed and given a total score between one and seven. The final result implies what actions need to be taken.

REBA includes the entire body in the posture analysis (Berlin and Adams, 2014). The assessed posture is given a score between one and eleven, which implies what actions need to be taken.

3.5 Visual Planning

Visual planning is a method used to create communication and improve knowledge transfer (Lindlöf and Söderberg, 2011). Meetings and physical boards are commonly used in visual planning where the activities and deliverables are illustrated (Jurado, 2012). The personnel have an opportunity to discuss the information that is visualised on the board during the daily meetings. The main objective with visual planning is to illustrate the different activities in order for the personnel to create a coherent view of the process (Lindlöf and Söderberg, 2011). A strength is that the visual planning method comprises of real time information, which is significant for enabling efficient communication among the personnel. Furthermore, visual planning creates a work environment where the personnel can give each other feedback since everyone knows *who* is doing *what*.

According to Lindlöf and Söderberg (2011), levelling of workload is affected by visual planning. It becomes easier to coordinate the work since the planning method visualises the current status of the work in progress. Moreover, daily meetings are of high significance in order to discuss how to solve current problems and how to avoid the occurrence of potential problems.

4 Current State

This chapter regards the status of the production system, production planning, production ergonomics, and material handling. A thorough description of the product, production layout, and product flow is also presented.

4.1 Production System

The production within BA1 is divided into seven production units where different products are manufactured. The focus of this master's thesis is within the production system concerning Alpha, which is located at the fourth floor at BA1. The studied production system concerns both products manufactured from scratch and units for repair.

The organisation concerning Alpha consists of production managers, project- and sub-project managers, design engineers, industrial engineers, testing operators, and assembly operators. Alpha is handled in two separate production units; Cleanroom 7 and Cleanroom 8. The assembly is conducted in Cleanroom 7, and the tests are executed in Cleanroom 8. Hence, the assembly operators work in Cleanroom 7 and the testing operators in Cleanroom 8. Moreover, Cleanroom 7 and Cleanroom 8 follow ISO 14644-1, which concerns air cleanliness, i.e. the number of allowed particles per cubic meter, and contamination control, which is a process of limiting the contamination below a tolerable amount (Welker et al., 2006). Cleanroom 7 and Cleanroom 8 follow regulations according to ISO class 7 and 8 respectively. Therefore, the operators assembling and testing the products must use protective clothing in order to keep the contamination at a tolerable level.

There are 10 operators working in Cleanroom 7. The production managers and industrial engineers support the operators throughout the production process. The operations executed in Cleanroom 7 consist of four main areas:

- Arrival control
- Assembly of resonator
- Assembly of unit
- Inspection

Each operator works within one of these areas and do not rotate between them. Alpha is assembled manually, with a high degree of precision and complexity handled by the operators.

4.1.1 Alpha

The studied production system handles different product types. The focus of this master's thesis is to analyse the production of Alpha, which constitutes 82% of the total production volume within the studied production unit, excluding units for repair. Alpha consists of several components that are manually assembled by the operators. The requirements on the product, including exceptional precision and high performance in extreme conditions, generate a high level of complexity.

The production of Alpha starts once the customer places an order, i.e. make-to-order is practiced. Some of the main components are bought while some need to be assembled by the assembly operators. All components must together go through numerous tests of tough character in order to get approved and also mounted in the product.

The routing of Alpha is divided into three parts; routings 500:A, 584 and 500. In 500:A is most of the assembly made and components are mounted into the housing. The units spend the majority of the time in this routing in Cleanroom 7. Routing 584 covers the assembly and testing of a component called resonator. Lastly, routing 500 mainly consists of testing in Cleanroom 8. However, some assembly and inspection is also included and is performed in Cleanroom 7.

The main focus of this master's thesis is on the assembly tasks connected to routings 500:A and 500 performed by the assembly operators in Cleanroom 7.

4.1.2 Production Layout

The production of Alpha is located on the fourth floor and is categorised as a job shop production with a process-type layout, described in section 3.1.1. A hierarchical perspective is the system perspective used to understand the production, with focus on the different system levels, as mentioned in section 3.1.

As mentioned previously, the production is divided into two separate rooms, Cleanrooms 7 and 8, which are situated right next to each other. The nature of the tasks in the two rooms differs quite much; all assembly is made in Cleanroom 7 and most of the tests are made in Cleanroom 8. An airlock interlinks the two rooms. All material that must be moved from one cleanroom to the other must go through this airlock. In addition, material cannot be brought into Cleanroom 7 through any other way than via this airlock.

The layout of Cleanroom 7 can be seen in Figure 3. The thick, black lines signify the area restricted to Cleanroom 7, where extra precautions to dust and dirt must be taken. Thereafter follows a description of the different rooms.

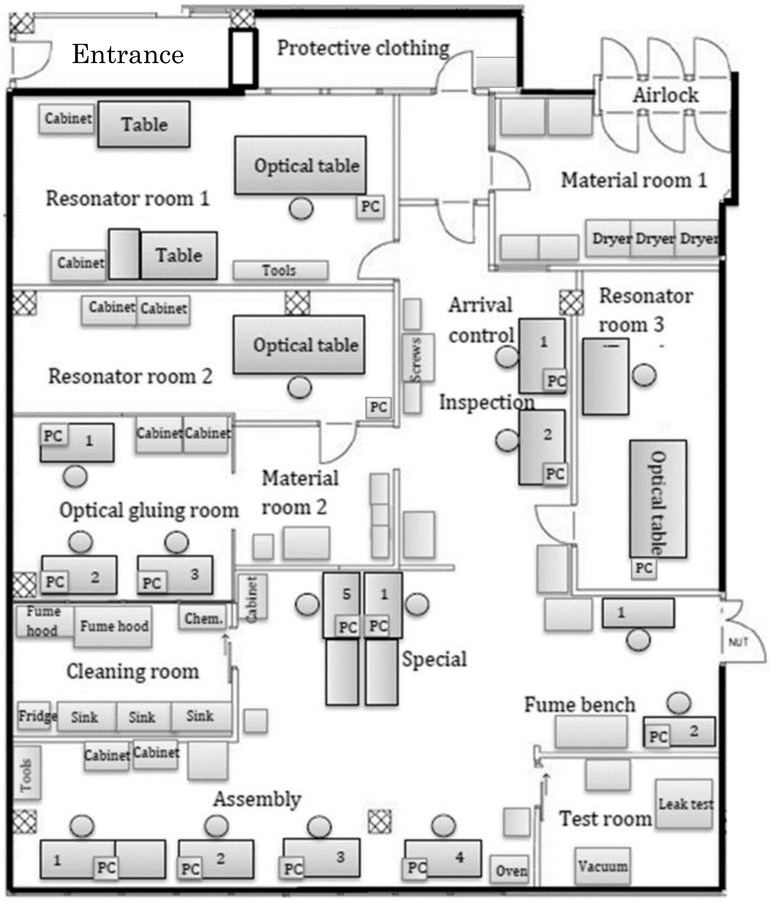


Figure 3: Layout of Cleanroom 7

- Protective clothing – where proper shoes, protective clothing and hairnet are put on before entering the cleanroom.
- Material room 1 – where finished and semi-finished products and consumable material are stored. There is also an airlock connecting the two cleanrooms, through which material is sent between the rooms.
- Resonator room 1 – one of the three rooms where the resonators are assembled and tested.
- Resonator room 2 – one of the three rooms where the resonators are assembled and tested.
- Arrival control – where the components and products are inspected upon arrival to the facility.
- Inspection – where the finished and semi-finished products are inspected.
- Resonator room 3 – one of the three rooms where the resonators are assembled and tested. It is assumed that all resonators for Alpha are made in this room.
- Optical gluing room – dedicated for gluing operations. Special air vents, microscopes and other equipment are located here.

- Material room 2 – where components and semi-finished products are stored.
- Cleaning room – where all components are cleaned and glue is prepared.
- Special – the workstation where most of the units for repair are handled.
- Fume bench – where most components and products are placed to harden the glue.
- Assembly – five workstations used for assembly of all parts of Alpha except the resonator. All parts are mounted into the housings at these stations as well.
- Test room – where the leak tests are made.

In addition to the above mentioned rooms, there is also another room that is used by the assembly operators to clean the housings. It is not located within Cleanroom 7 but in another part of the fourth floor. The sinks in the cleaning room in Cleanroom 7 are too small for the housing, which is why this other room is used.

In Cleanroom 8 there are not only rooms and equipment for testing Alpha but also other products in addition to office spaces for e.g. design engineering. The area of Cleanroom 8 is therefore much larger than 7. The layout of Cleanroom 8 can be seen in Figure 4, where only the relevant rooms for Alpha are mentioned by name. An explanation of each room follows the figure.

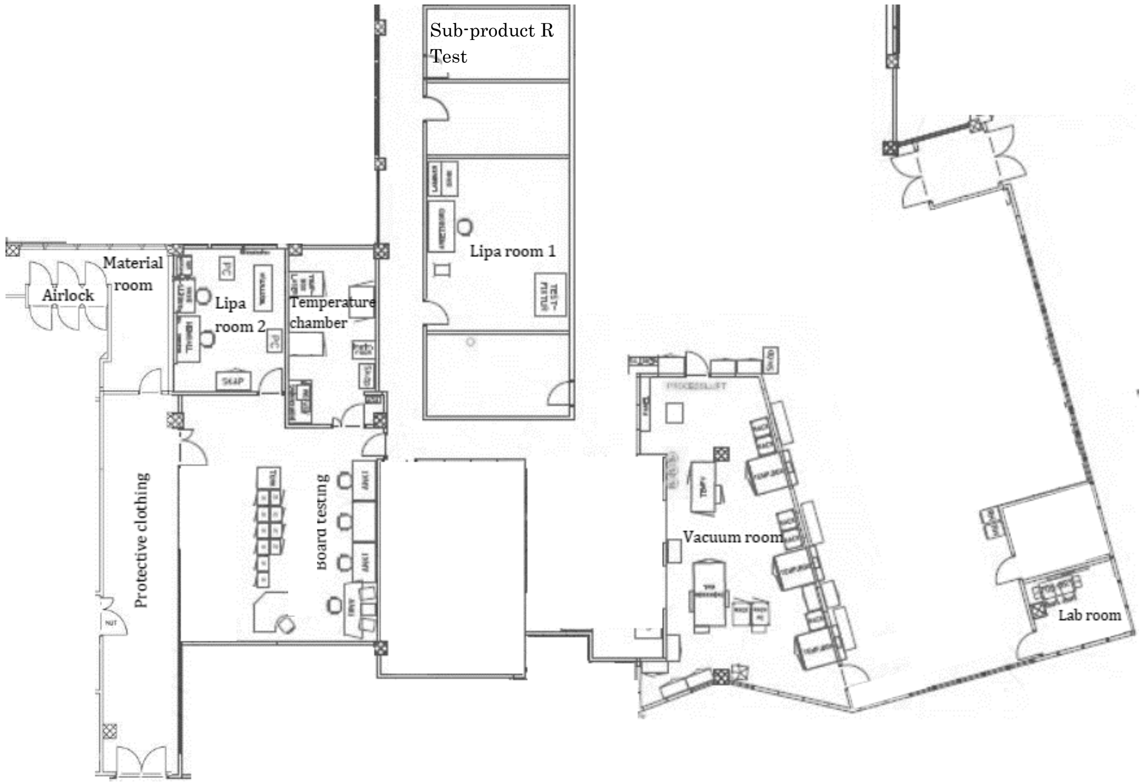


Figure 4: Layout of Cleanroom 8

- Material room – where finished and semi-finished products are stored. There is also an airlock connecting the two cleanrooms, through which material is sent between the rooms.
- Lipa room 2 – where tests on the almost-finished Alpha are made.
- Temperature chamber – where tests concerning temperature are made.
- Lipa room 1 – identical to Lipa room 2. Newly built.
- Sub-product R test – where sub-product R is tested.
- Protective clothing – where proper shoes and protective clothing are put on.
- Vacuum room – where the final vacuum tests are made.
- Lab room 1 – where the long term tests are made.

In addition, there are two tests made in other parts of the building; one on the ninth floor and one on the third floor. These tests are performed by the personnel from Cleanroom 8.

4.1.3 Product Flow

Due to the final product operating in tough conditions it must be tested many times during its manufacture to ensure quality, stability and endurance. The nature of the tests varies and the tests are made at various points in time to ensure the final product being able to handle real-life conditions. Testing is made in both cleanrooms and the product therefore travels many times through the airlock in the material rooms. Between the tests there is additional assembly and gluing.

The Alphas manufactured from scratch, the travel through the process starts with components being inspected upon arrival in Cleanroom 7, continues with cleaning, assembly, mounting and some testing, final testing and ends with a final inspection. Figure 5 shows the most simplified flow.

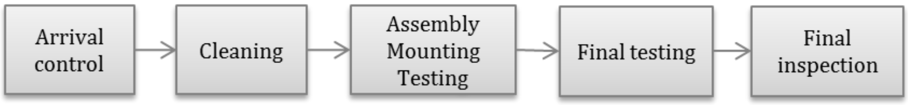


Figure 5: The highest-level flow of the product

Alpha consists of optical components that must be inspected in an ISO 14644-1 certified environment, i.e. Cleanroom 7. If the quality of these components is accepted after the arrival control, they are sent back to the main storage, which is located at Location B. There they wait until they are needed for an order, at which point they are sent back to Cleanroom 7. One of the assembly operators starts with cleaning all components, which is a time-consuming process that takes approximately one day for each unit. All components, both bulk material, such as screws and o-rings, and more specific components, are cleaned in the cleaning room in Cleanroom 7, except for the housing and cover top that are cleaned in the other room mentioned previously. According to the routing, the cleaning process should be done at the start of every order. Due to the amount of time required, however, the operators store cleaned bulk material in shared boxes and only clean when they have time to spare. In this way, the operators can always find cleaned components when they need and therefore save time.

After the cleaning, the flow divides into two major parallel flows; one for the assembly of the housing and almost all sub-products, and one flow for the assembly of the resonator. The two flows later converge when the resonator is mounted into the housing, completing the assembly of the product. Several tests are made on the final product and the final inspection is made before the product can be dispatched to the customer. This is visualised in Figure 6.

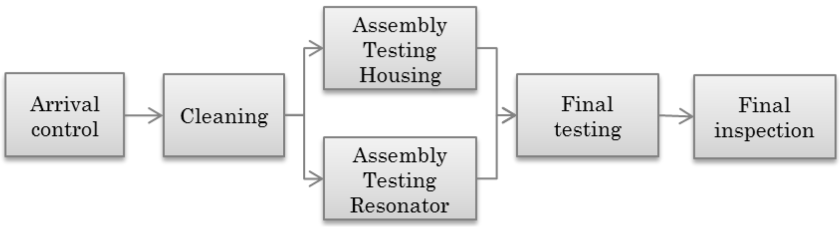


Figure 6: The main flow of Alpha

The assembly and testing of the housing, visualised by the upper-most flow in the figure, includes many steps and components. Some of the tests are made in Cleanroom 7 and some are made in Cleanroom 8. The purpose of the tests are to make sure the unit can handle extreme conditions, that it does not change its precision due to the extreme conditions and that the quality of the product is according to specifications. Before and after almost all tests, measurements are taken in order to assure the tests have not affected the precision of the product. During the mounting of the sub-products, the whole housing is tested several times in different ways to continually ensure quality. After a sub-product has passed a test, it is fastened in the housing with glue to ensure long-term quality. This means that the product must be in Cleanroom 7, as every gluing operation is made there, and the glue thereafter has to harden for 16 – 24 hours.

As mentioned before, the resonator is being assembled in one of the three resonator rooms in Cleanroom 7. Simultaneously to the resonator being assembled, it is also tested and adjusted. Before it is finished it needs to do additional testing in Cleanroom 8. If it passes, it can be mounted into the housing, making it the final component to be mounted into the housing.

The final testing can be broken down into a more detailed flow, shown in Figure 7.

Figure 7: The broken-down flow of the final testing

The numbers in brackets show in which cleanroom the operation is taking place. It becomes apparent that the units travel back and forth between the rooms repeatedly. What is not specifically shown in Figure 7 are the tests performed outside of the fourth floor. The first testing performed in Cleanroom 8, shown in Figure 7, include the tests on the third and ninth floor. As these tests are performed by the testing operators from Cleanroom 8, they were not separated from the other tests performed in Cleanroom 8. Almost all tests that are performed in Cleanroom 7 are leak tests, with the purpose of detecting leakage in the unit.

After all final tests are performed, the unit is sent to the final inspection in Cleanroom 7. This is the final visual quality assurance before the unit is delivered to the customer.

__Rework__

The complete flow that has been described above assumes a unit that has passed every test and rework has therefore not been taken into consideration. This is however seldom, or even never, true. Most units fail at least one test and some degree of rework is therefore necessary on most units. Rework is a large part of the operators' work and is difficult to plan.

Where in the flow a specific unit will fail is impossible to predict but when it fails, regardless of it being a unit for repair or a unit that is manufactured, the operators must analyse and find the reason for the failure. The amount of rework required corresponds to how far back in the flow it must travel, which in turn depends on the root cause. If components need to be demounted, the unit must go through all subsequent tests again. Some tests might need to be run several times, with adjustments in between, until the test is passed. The number of runs required is also an unpredictable factor. The task of finding and solving the root cause is disruptive and very difficult to predict as it differs from unit to unit. Oftentimes a trial-and-error approach is needed to find the root cause and solve the problem.

<u>Units for repair</u>

The units for repair, which were mentioned in the beginning of this chapter, do not necessarily follow the same flow as the units that are manufactured from scratch. The general flow for units for repair is shown in Figure 8.

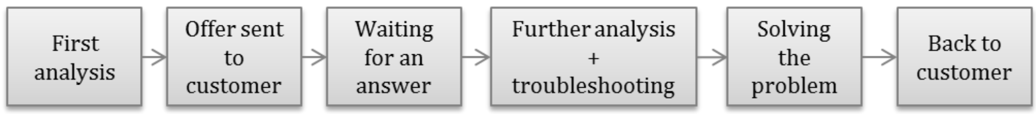


Figure 8: A general flow of the repair process

The first thing the operators must do is to analyse the unit to find the probable cause for the problem. This analysis consists of a visual inspection and several tests. The likely root cause, together with a cost estimate, is sent to the customer who considers whether or not the reparation should proceed. The time until an answer is received from the customer cannot be predicted; it can take anywhere from months to over a year. Until then, the unit is stored in Cleanroom 7. Once the operators are approved to proceed with the reparation, they must go deeper and make additional tests to make sure that their first conclusion was correct. They then solve the problem and the unit is sent back to the customer. This part of the flow differs radically from unit to unit. There is no standardised way of proceeding as the defects of different units may differ greatly and it is generally not equally easy or difficult to find the root cause for each unit. The amount of time spent on repairing a unit is therefore next to impossible to predict.

4.2 Production Planning

Firm plans are used for the production of Alpha and the frozen planning horizon is one week. This means that the planning is set one week ahead. Each week the product planner, production planner and production unit manager meet to set the firm plan for the upcoming week. The orders that should be opened are based on the ERP system IFS. The order releases generated by IFS are based on the deadlines for the products at the highest level. At the meeting it is decided what orders should be released and what to do with possible backlog from the previous week.

The released orders are sent to the operators. The intent is that each order is handled by one assembly operator in Cleanroom 7 who executes all assembly tasks for the unit. The operators themselves decide when the different tasks should be performed and in what order; the production planner or production manager do not meddle. The more experienced assembly operators generally have two open orders each and alternate between the two, while the less experienced operators have one open order each.

IFS plans when the assembly of the different sub-products should start in order for them to be ready at the same time for final assembly and mounting. These plans are based on information from the routing. However, a manager can overrule the ERP system and manually decide the prioritisation, e.g. based on customer preference.

The production plan is not visualised in Cleanrooms 7 and 8, i.e. there is no physical board available in production. The operators in Cleanroom 7 do not know what each operator in Cleanroom 8 is working with and vice versa. The operators in Cleanrooms 7 and 8 are currently communicating with each other through e-mail in order to inform each other when a unit is ready for assembly or test. Communication through e-mail also occurs when the operators inform the production management that e.g. material is needed for an order. This way of communicating indicates that the current production planning system is not visualised and integrated between the production management and operators, and between the operators in Cleanrooms 7 and 8.

As mentioned in section 4.1.3, most units fail at least one test and some sort of rework is therefore required in the product flow. The status of the production flow is reported in Prosus where the operators report that a specific assembly task is accomplished. However, there is no information regarding where in the flow the product must go back for rework.

4.3 Production Ergonomics

The assembly operations of Alpha are conducted manually in Cleanroom 7. The operators spend most of their available time at their assembly stations. Each workbench has a computer, tools, and some of the material that is needed during the assembly. The computer is generally positioned at the edge of the workbench, while the tools and material are located in front of the operators, above the workbench, or in drawers and cabinets a few meters away. The operators are mostly working in a sitting position at their workbenches during the assembly. The operators transport the product between different rooms in Cleanroom 7 on a regularly basis, but also between the assembly station and the airlock since the product is frequently transported between Cleanrooms 7 and 8.

The assembly operations in Cleanroom 7 include long-lasting activities which may put the human body at risk due to the used posture, and the time spent on the activity (Berlin and Adams, 2014). The operators have some repetitiveness in their work in terms of e.g. mounting screws. Repetitiveness leads to repeated usage of the same muscle groups which in turn might lead to injuries (Berlin and Adams, 2014).

Much of the utilisation of equipment in Cleanroom 7 is not optimal from an ergonomic perspective. Some of the equipment forces the operators to work in a bad posture, other equipment is positioned at a low height, e.g. on the floor, which forces the operators to bend in order to reach the equipment. Moreover, some of the machines are not optimally designed for neither physical nor cognitive ergonomics.

The operators in Cleanroom 7 have three different sources that act as a cognitive support during the assembly; work instructions, Prosus and 2D drawings. The main work instructions are available in a separate PDF file, and are further explained by the other two sources. These work instructions tell in which order things are to be performed, within a certain operation. However, the operation descriptions in the instructions are not organised according to the assembly sequence. The operators therefore have to spend time on finding the information required for the assembly. The reporting system Prosus used by the operators tells the correct sequence of the operations in most cases and also includes information about the material that should be assembled during a specific operation. Therefore, the operators can use Prosus to get information about the needed material for a specific assembly task, such as quantity and part number. The third support available is drawings in 2D. The drawings identify in which position a component should be mounted.

In other words, Prosus is used for information regarding the assembly sequence of the highest level. The main work instructions are thereafter used to understand the assembly sequence within a specific operation and in which positions components should be mounted. Prosus is then used to find the components that are to be mounted in the positions. Lastly, the 2D drawings are used to find the place on the unit in which the positions are located.

4.4 Material Handling

The material flows between the main storage at Location B and the production at BA1 at Location A is visualised in Figure 9.

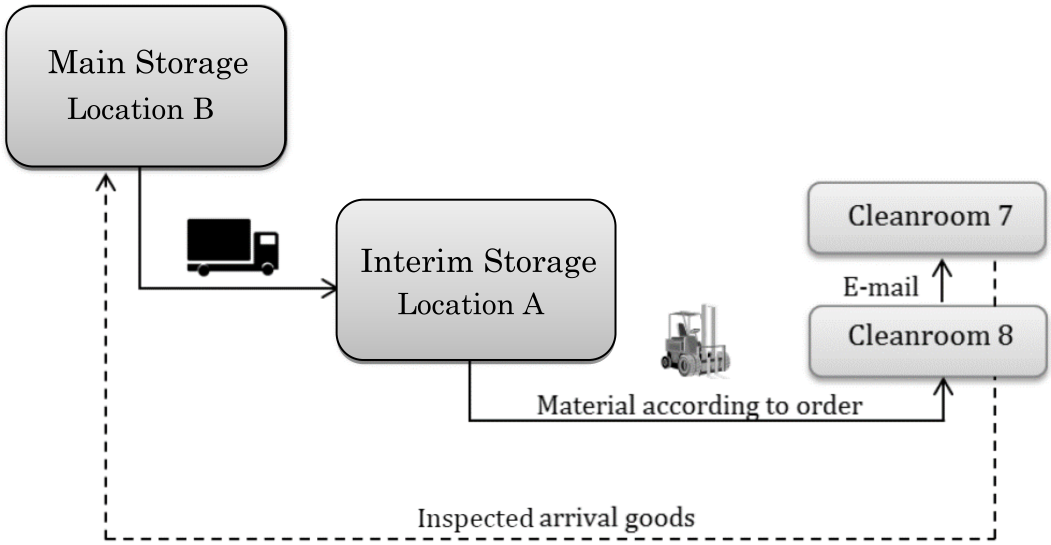


Figure 9: Material handling process

Material is ordered from the suppliers by the purchase department, based on quantity and timing from the ERP system, and transported to the main storage at Location B, where the majority of the material is stored. Goods arriving at the main storage must be inspected. This is done at Location B for all components except the optical components, which must be inspected in an ISO 14644-1 environment. They are therefore packed in hard plastic cases in the main storage, transported to Cleanroom 7 at BA1 and inspected by an operator responsible for arrival control. As mentioned previously, the material cannot be brought directly into Cleanroom 7 but must be placed in the airlock between the two cleanrooms and brought in via Cleanroom 8 due to cleanliness regulations. After inspection, the components are sent back to the main storage, unless the components are especially delicate in which case they are stored in Cleanroom 8.

Once an order is released according to the firm plan, a picking list based on the ERP system is sent to the main storage defining what components are needed and what needs to be kitted. The material handlers at Location B do the kitting by placing components in plastic bags and placing labels on the bags with information about part number, quantity and related order. Each part number is intended to have its own plastic bag, see Figure 10. However, if components of the same part number are to be mounted in different positions on the product, they are sometimes placed in different bags. The material is thereafter transported to an interim storage located in the goods reception area at BA1. It takes approximately 24 hours for the material to arrive at BA1 once it is ordered from the main storage.

Figure 10: Kitted material in plastic bag

There is no dedicated space for storing material in Cleanroom 7 and material is therefore not distributed to Cleanroom 7 until an order is released. The in-house distribution is made using forklifts. As mentioned previously, material cannot be brought directly into Cleanroom 7, which is why the material from the interim storage is brought to Cleanroom 8 by the forklifts. The material meant for Cleanroom 7 is placed in the airlock by an operator. The operators of the two cleanrooms inform each other via e-mail, once material is available in the airlock.

The assembly operators are responsible for reporting to the system when, for example, an incorrect part has been delivered. One of the first processing steps is to remove the material from the plastic bags used for kitting. Similar components are then cleaned together before assembly.

The testing operators in Cleanroom 8 transport Alpha in a trolley between the different testing rooms. However, trolleys are not used when moving Alpha between the different workstations in Cleanroom 7. Instead, the product is carried by the assembly operators.

There is a kanban system in Cleanroom 7 that controls consumable material such as gloves and cotton swabs. The assembly operators use kanban cards to dictate the need to refill consumable material in Cleanroom 7. They place the card of the material in question in a black box at the entrance to the cleanroom, which is collected and returned with the replenishment from the interim storage at BA1.

5 Analysis

The current state was analysed and the results of the analyses are presented in this chapter. The production system layout was analysed using a spaghetti diagram. A SAM analysis was conducted in order to analyse the assembly and detect productivity potentials. Furthermore, the production ergonomics was evaluated to analyse the work environment.

5.1 Production Layout

Spaghetti diagrams were made for the two cleanrooms according to the steps presented in section 2.4.1. No rework is included which means that the spaghetti diagrams show the minimum TTD. The diagram for Cleanroom 7 is presented in Figure 11.

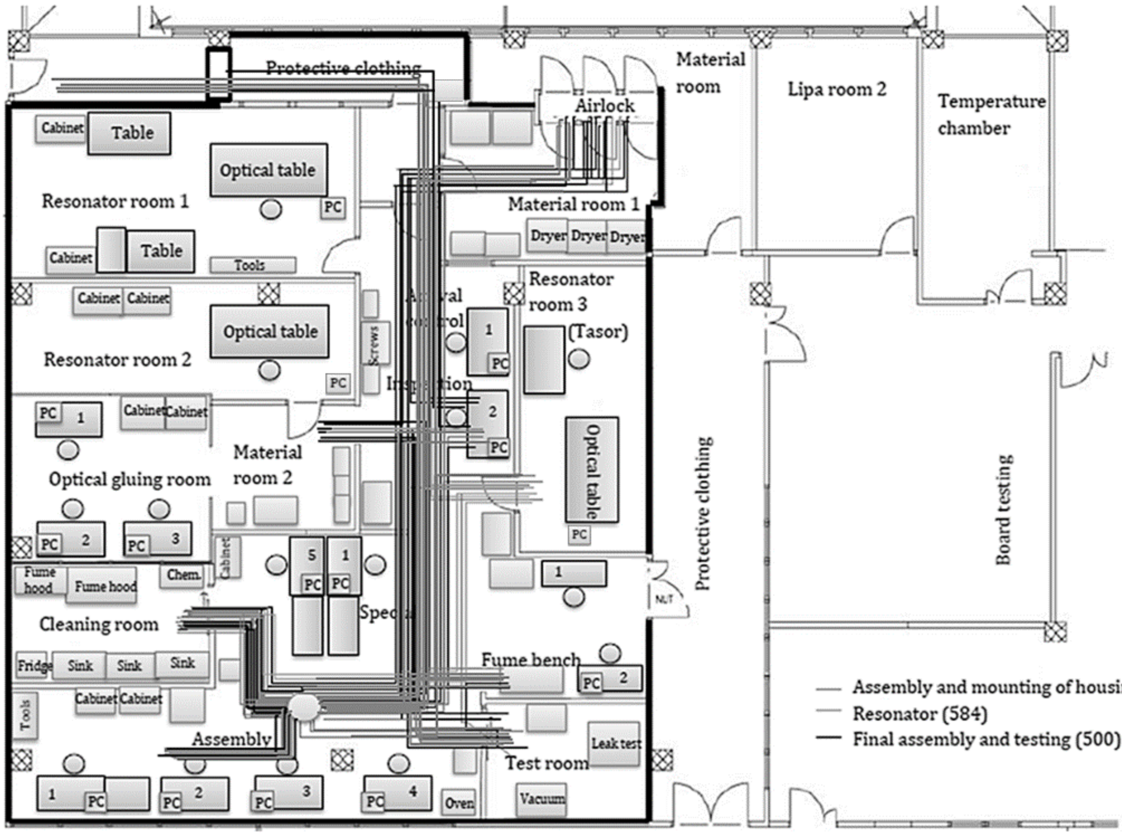


Figure 11: Spaghetti diagram of Cleanroom 7

As previously, Cleanroom 7 is distinguished by the bold black lines. What is seen to the right of Cleanroom 7 is a small part of Cleanroom 8. The diagram has been divided into three parts:

- The route the unit takes when the housing is assembled and mounted during routing 500:A.

- The route the resonator takes when being assembled and tested during routing 584.
- The route the unit takes for the final assembly and testing during routing 500.

Even though the resonator for Alpha can be assembled and tested in all three resonator rooms, it is assumed that all assembly and testing is made in Resonator room 3.

As there are five assembly stations and all stations are used for the same purpose, the distance between an assembly station and another function is calculated to and from the point located approximately in between all assembly stations. However, as the bulk material is kept next to one of the assembly stations, and the operators have to go there to retrieve the material, it will be distinguished from the assembly stations. The lines drawn from the assembly point to the empty space at the assembly stations signifies these movements to get bulk material.

The total travel distance (TTD) for one unit, regarding the tasks performed by the operators in Cleanroom 7, is 3190 meters and the corresponding travel time is calculated to 38 minutes, according to steps 4-5 in section 2.4.1.

The spaghetti diagram for Cleanroom 8 is presented in Figure 12.

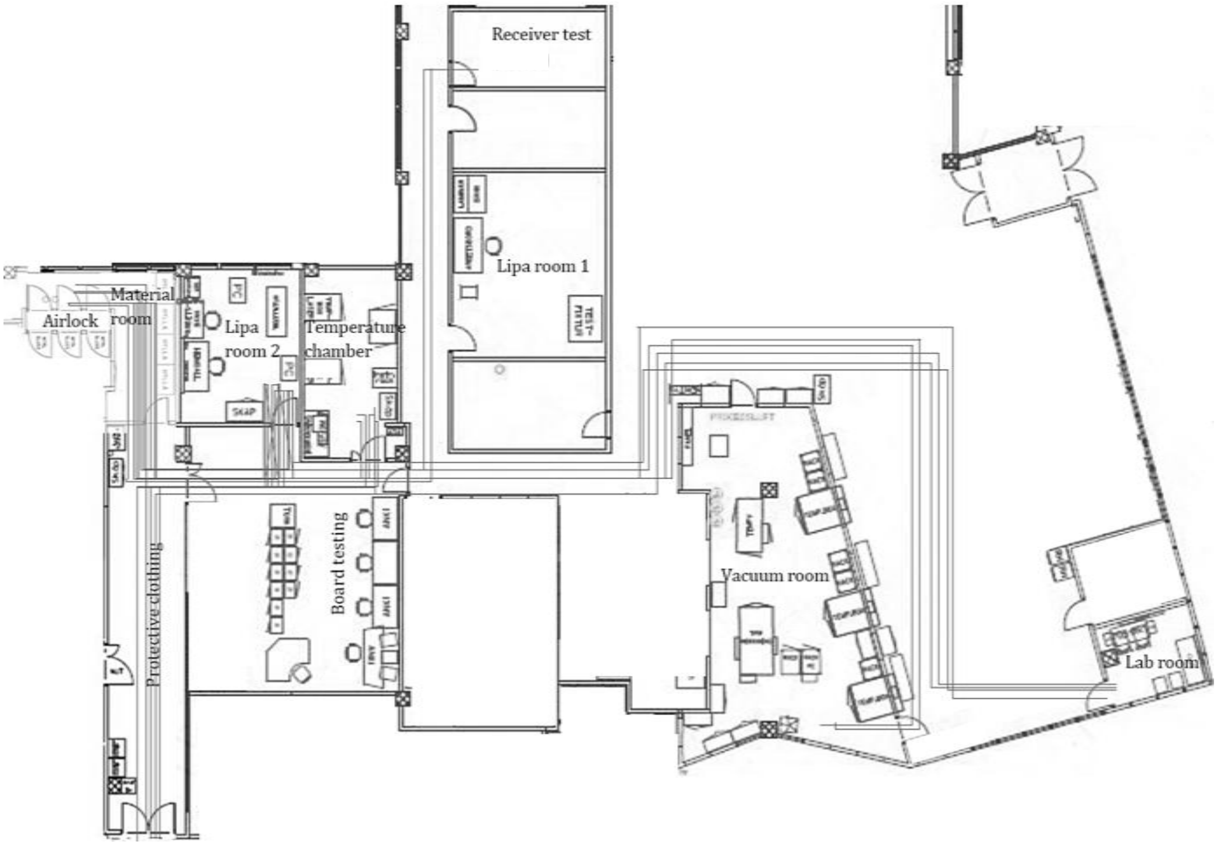


Figure 12: Spaghetti diagram of Cleanroom 8

In this diagram, there is no distinction between the different degrees of a finished unit that travels through the cleanroom; all routes a product takes through the cleanroom are marked in the diagram. Even though Lipa room 1 and 2 are identical, it is assumed that all units always go to Lipa room 2, as room 1 is not finished at the time of conducting this diagram.

The TTD for one unit in Cleanroom 8 is 713 meters and the corresponding travel time is calculated to 8.5 minutes, according to steps 4-5 in section 2.4.1.

The fact that the resources to complete a unit are located in different rooms constitutes a large part of the TTDs for each cleanroom. These distances have been separated from the TTDs and added together. The included elements are the following:

- The movements of the unit and operators to and from the airlock in both cleanrooms, to send the unit and components between the two cleanrooms.
- The movements to the other cleaning room to clean the housing.
- The movements of the assembly operators to and from Cleanroom 8 to retrieve and leave the unit or other components in the airlock.

The distance and time created due to the production flow being spread out over different rooms have been calculated to 2012 meters and 24 minutes respectively. In addition to these movements on the fourth floor there are movements of the testing operators to and from the third and ninth floor. These distances have not been included due to the limitations of this thesis.

5.2 Productivity

Production systems operating in an MTO environment require high flexibility (Sundkvist, 2014), which BA1 achieves through their operators, as humans are more flexible than machines and robots (Al-Zuheri, 2013). As mentioned by Sundkvist (2014), it is suitable to improve productivity in an MTO environment by analysing the production processes on the shop-floor. The assembly and testing in Cleanroom 7 have therefore been analysed and the result from the analyses are presented in this chapter.

Sections 5.2.1 and 5.2.2 cover the part of the productivity that is connected to the method used during assembly. Section 5.2.3 covers the total productivity, which includes the performance of the operators and the utilisation of the assembly operators' time. Lastly, section 5.2.5 covers the production disturbances that affect the productivity.

5.2.1 SAM Analysis

A SAM analysis was conducted for the operations in Cleanroom 7. The SAM analysis has not taken rework into consideration due to the delimitations of this master's thesis. The tests in Cleanroom 8 are handled with a high level of automation, and were therefore not evaluated in the same detailed manner as the tasks in Cleanroom 7. The operation times for the tests in Cleanroom 8 were gathered from the ERP system IFS. Data for the assembly of the resonator was also gathered from IFS. However, mounting the resonator into the unit was assessed in the SAM analysis. The data for the operations that have been thoroughly analysed was acquired from the movies made of one assembly operator working.

The SAM analysis includes all operations handled by the operators in Cleanroom 7. A norm time for these operations was generated in SAM by studying the method the assembly operators currently use. Figure 13 presents the assessed operations and the generated norm times provided by the SAM analysis. The operations included in the figure are from two different routings; 500:A and 500. The operations in routing 500 are marked by the rectangle with dashed borders. Moreover, the operations that include an additional operation time of 2h, 16h or 24h indicate that glue must harden. According to the operators is 24 hours of hardening time used before leak tests are performed, while 16 hours is used if additional assembly will be done. In the work instructions and routing, the time for hardening the glue is set to 24 hours. The exception is when mounting the cover bottom as that operation only requires 2 hours of glue hardening, because the unit is placed in an oven. Also, for operation 500 there is an additional time of 16.75 hours. 16 hours is for the glue hardening but the extra 0.75 hours is the time the paint needs to dry.

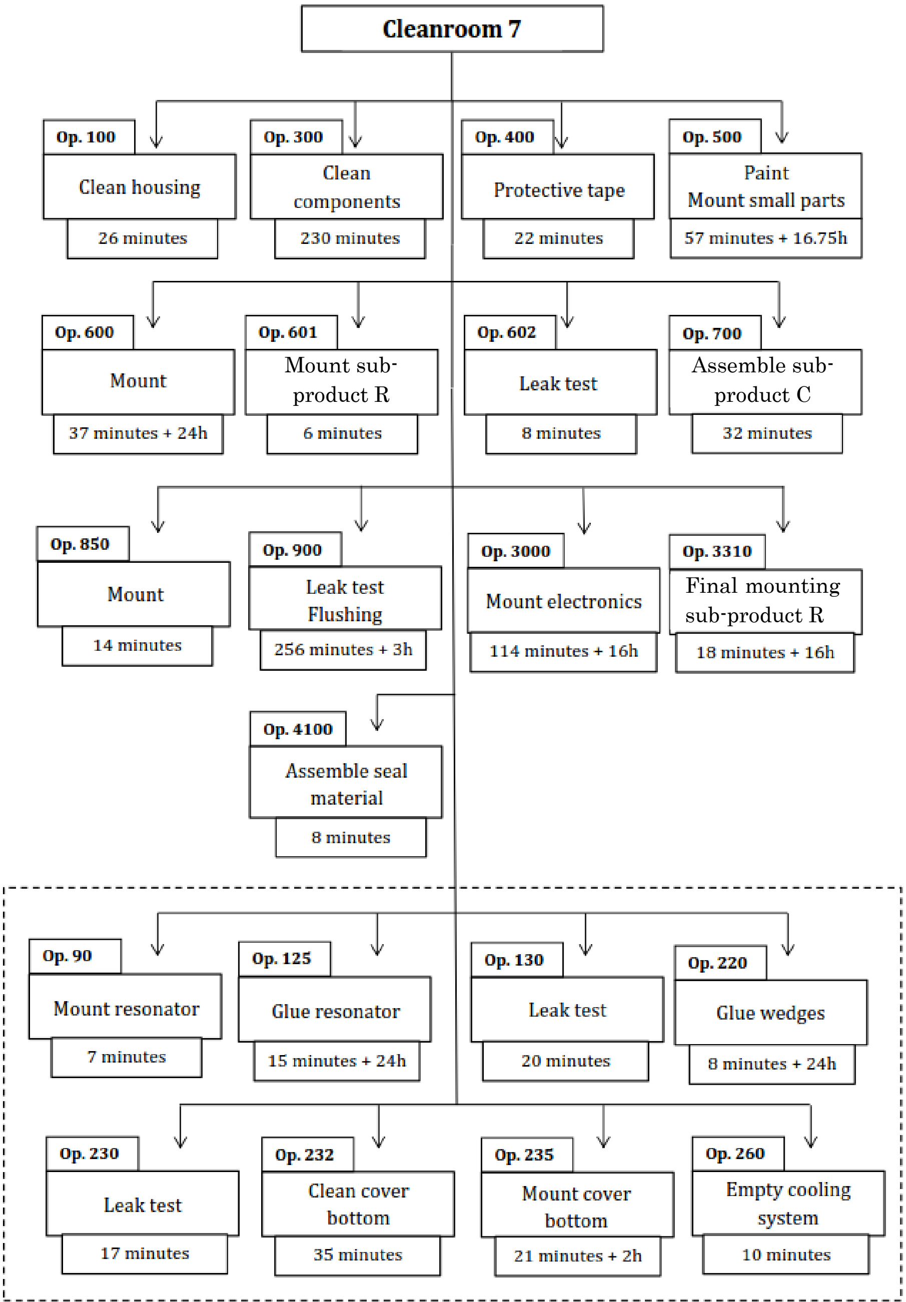


Figure 13: Operations evaluated in SAM

In addition to the operations included in Figure 13 there are three more operations. Operation 750, which the operators do not know what it entails, and operations 960 and 3200, which are gluing operations that the operators do not perform separately but include in other operations. These operations have not been included in the analyses because they are not used by the operators.

The total required hours for one unit is called the total operation time in this report. Some of the above-mentioned operations are possible to perform in parallel to each other and to other operations performed in Cleanroom 7 and Cleanroom 8, but that is not taken into consideration by the operation time.

As mentioned in section 3.3.3, the SAM analysis in AviX separates value-adding and non-value-adding activities. A value-adding activity adds direct value to the product, i.e. transforms input into output. The non-value-adding activities are separated into three categories: losses, wait, and required activities. The losses are considered as waste in the system and should be eliminated or reduced in order to increase productivity (Sundkvist, 2014). The required activities concern all activities that are needed to operate on the actual product, e.g. reading instructions and getting material.

Figure 14 illustrates the total operation time for one unit and concerns all operations in Cleanroom 7 and Cleanroom 8.

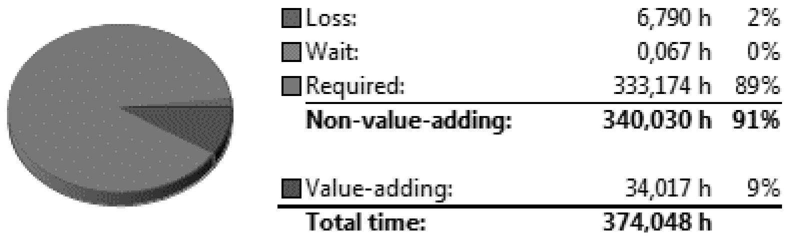


Figure 14: Work distribution Alpha

Figure 15 presents the distribution of value-adding and non-value-adding activities for all operations conducted by the assembly operators in Cleanroom 7. Therefore, the glue hardening, the time needed for the paint to dry, cool down time, assembly time for the resonator and time for inspection are excluded in the pie chart.

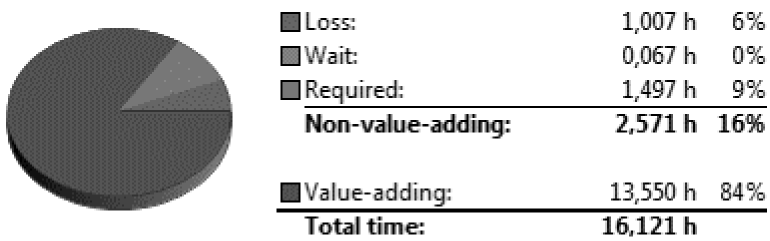


Figure 15: Work distribution, assembly tasks in Cleanroom 7.

The operations included in Figure 15 are performed by the assembly operators in Cleanroom 7 and are the main focus of this master’s thesis. They will be further explained below.

Operation 100: Clean housing

The following operation includes the cleaning of the housing and cover top, which is a procedure that is not conducted in Cleanroom 7, but another room on the same floor. The operators must make plastic bags to carry the housing and cover top in when returning to Cleanroom 7. The operators use protective clothing when cleaning the housing.

According to IFS, the time to conduct this task is estimated to 1 hour and 12 minutes. However, the SAM analysis indicates that this task should, according to norm time, take approximately 25.7 minutes.

Figure 16 visualises the distribution of value-adding and non-value-adding activities for Operation 100.

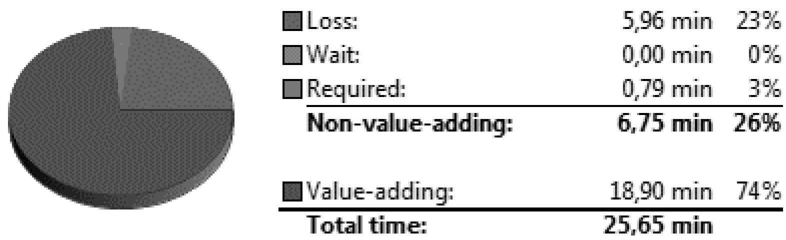


Figure 16: Work distribution, operation 100

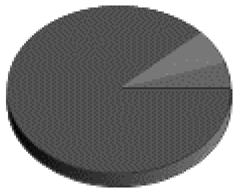
74% of the total time is spent on value-adding activities such as cleaning the actual housing and cover top. There is in total 26% non-value-adding activities, which mainly consists of the amount of steps required to transport the unit between the different rooms. In addition, the needed material and equipment for the cleaning procedure are not positioned close to the operators. Thus, the operators must walk, stretch, and bend to retrieve required material and equipment.

Operation 300: Clean components

The tasks in Operation 300 consist of cleaning both bulk material, such as screws and o-rings, and sub-components for the unit. The bulk material is kitted in the main storage at Location B and placed in plastic bags. Therefore, the operators must first take the material out from the bags and categorise them according to cleaning procedure. The material is sorted at the assembly station and the cleaning process is conducted in the cleaning room.

IFS determines that it should take 90 minutes to clean the components. According to the SAM analysis is the cleaning procedure estimated to 3 hours and 50 minutes. One reason for this time difference is that the ERP system does not take the implications of the kitting into consideration, i.e. the need to sort the components both before and after the cleaning procedure.

Figure 17 presents the amount of value-adding and non-value-adding activities in percentage for Operation 300.



Loss:	0,196 h	5%
Wait:	0,000 h	0%
Required:	0,260 h	7%
Non-value-adding:	**0,455 h**	**12%**
Value-adding:	3,383 h	88%
Total time:	**3,838 h**	

Figure 17: Work distribution, operation 300

88% of the total time is considered as value-adding activities, and 12% is defined as non-value-adding activities. Operation 300 includes tasks that are conducted at two places; assembly station and cleaning room. Therefore, the operators must walk repeatedly between the assembly station and the cleaning room, which creates waste in the system. Another factor that contributes to waste is that the material and equipment are placed at a low height. Thus the operators must bend to retrieve the needed material and equipment, which occurs several times.

Lastly, the effects the current material handling system has on this operation should be mentioned. The bulk material must first be removed from its plastic bag by the operators who have to cut open all the bags. The material is sorted according to part number, then according to how they can be cleaned and after the cleaning procedure it is sorted according to part number again. It requires a lot of the operators' time and patience. It is defined as value-adding activities in the SAM analysis but it would perhaps be more appropriate to categorise these activities as losses as they do not add value to the final product.

<u>Operation 400: Protective tape</u>

The unit is covered with protective tape and temporary signs are fastened on the unit in Operation 400. The tasks are conducted at the assembly station. However, the operators must get tape from a locker positioned a few meters from the assembly station and labels from the inspection workbench. There are 15 pieces of protective tape that have previously been cut to desired shapes, which the operators fasten on the corresponding shapes on the unit. However, the unit requires 16 pieces of protective tape and the operators must therefore cut the last piece of protective tape manually according to the desired shape. Temporary signs are attached on the unit once it is covered with protective tape.

IFS defines the operation time to 3 hours, while the SAM analysis estimates the time to almost 22 minutes. Figure 18 shows the distribution of value-adding and non-value-adding activities for Operation 400.

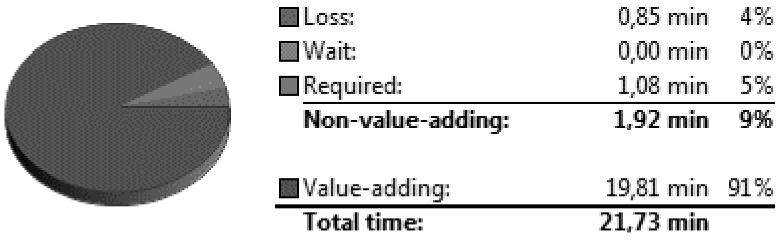


Figure 18: Work distribution, operation 400

91% of the total time for Operation 400 is spent on value-adding activities, and 9% is determined as non-value-adding activities according to the SAM analysis. In this case, the waste concerns the amount of steps required to get material from the locker. Also, waste is created due to the operators having to bend low to retrieve material.

<u>Operation 500: Paint + mount small parts</u>

The following operation includes painting a part of the unit, mounting components on the outside of the unit, and isolating the unit with seal material. A majority of the activities are performed at the assembly station. The part is painted with primer and paint that are retrieved from and mixed in the cleaning room. Components and seal material must be retrieved from a few meters from the assembly station.

According to the ERP system IFS, the time to accomplish Operation 500 is set to 1 hour and 12 minutes. The SAM analysis estimates the time to 57 minutes to conduct the task, with an additional 45 minutes for the paint to dry and 16 hours for glue hardening.

Figure 19 presents the value-adding and non-value-adding percentage of Operation 500. The time for the paint to dry and glue to harden is excluded in the pie chart.

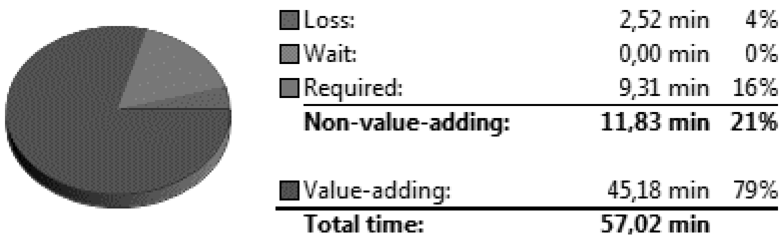


Figure 19: Work distribution, operation 500

The result indicates that 79% of the total time is considered value-adding, while 21% is defined as non-value-adding. The waste in the system relates to the operator getting material for the unit, and moving between the assembly station and the cleaning room. Also, both the paint and glue used in this operation must be mixed in the cleaning room. They are often mixed at two separate occasions, forcing the operators to walk back and forth to the cleaning room twice. When the cover top is assembled it must be left in the fume bench to harden, and to walk to the fume bench to leave the unit is yet another loss in this operation.

Operation 600: Mount

Operation 600 includes mounting several sub-products in the housing. The operation time is set to 7 hours in IFS. The result from the SAM analysis determines the time to 37 minutes. This difference in time might depend on the SAM analysis not taking rework into consideration. In addition, the operation requires troublesome assembly, which the SAM analysis does not take into account. The required hardening time for the glue of 24 hours is not included in the stated operation times from neither IFS nor SAM.

The percentages of value-adding and non-value-adding activities are visualised in Figure 20 below. The glue hardening is excluded in the pie chart.

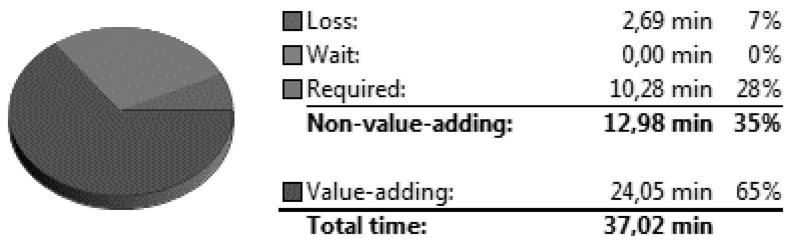


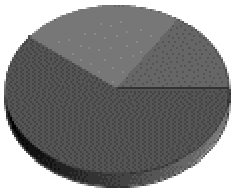
Figure 20: Work distribution, operation 600

The value-adding activities are estimated to 65% of the total time, and 35% of the time is considered to be non-value-adding. The waste is identified as the activities where the operators are forced to move in order to retrieve components, but also to get and leave the unit in the fume bench. In addition, the operators must move between different stations in order to get protective paint and to the cleaning room to mix glue. The time for required activities mainly stems from the operators looking at instructions. Lastly, a specific tool must be used, which is only available in the test room, forcing the operators to go there and retrieve it.

Operation 601: Mount sub-product R

The operation includes retrieving sub-product R from the bag it was delivered in, attaching a fixture, which allows sub-product R to be easily handled, placing sub-product R in the housing and fastening it with screws. The whole operation is performed at the assembly station.

In IFS is the time for this operation set to 1 hour, while it should take approximately 6.5 minutes according to the norm time. The amount of value-adding and non-value-adding work is shown in Figure 21.



Loss:	1,01 min	16%
Wait:	0,00 min	0%
Required:	1,54 min	24%
Non-value-adding:	**2,54 min**	**39%**
Value-adding:	3,92 min	61%
Total time:	**6,46 min**	

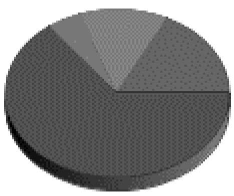
Figure 21: Work distribution, operation 601

The non-value-adding work amounts to 39% of the total time, while the value-adding work amounts to the remaining 61%. Most of the waste of the non-value-adding activities is due to the operators having to walk to different places. The operators have to walk to the fume bench to retrieve the housing, to a cabinet to get a required fixture, to another workbench to get bulk material and to the airlock to leave the unit. The rest of the non-value-adding activities are mainly due to reading instructions and getting and returning material around the workbench.

<u>Operation 602: Leak test</u>

This leak test is made once the housing is sealed and all open holes are closed. It tests whether or not the unit is completely airproof. If it does not let through any air, the unit can move forward to the next operation. If the unit lets through air it has to be further examined and rework has to be made. The unit is placed in the leak test machine, which is located in the test room, and attached to tubes. The test takes two minutes, assuming no leakages.

The leak test operation is given a time of 1 hour in IFS and according to the SAM analysis should it take almost 8 minutes to perform. The norm time assumes no leakages or any other problems, which the IFS time most likely takes into account. The distribution of value-adding and non-value-adding activities is shown in Figure 22.



Loss:	1,36 min	17%
Wait:	1,00 min	13%
Required:	0,39 min	5%
Non-value-adding:	**2,75 min**	**35%**
Value-adding:	5,02 min	65%
Total time:	**7,77 min**	

Figure 22: Work distribution, operation 602

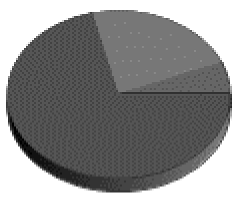
65% of the work is value-adding, while 35% is not. Most of the waste is due to the operators having to walk back and forth to the test room. Some of the non-value-adding activities also stem from fetching and returning tools and equipment. The waiting time of one minute is due to the time it takes before the machine is ready to start the test.

Operation 700: Assemble sub-product C

The operation includes, as the name suggests, the assembly of sub-product C. It consists of components that are sensitive to dust, scratches and air. The assembly is performed at the assembly station and must be made carefully and delicately in order to not damage any of the components. Two components in sub-product C cannot be exposed to air for more than two hours before they oxidise and can no longer be used. This time frame may put pressure on the operators. These components must be polished and cleaned in the cleaning room before being mounted in sub-product C.

The time is set to 3 hours in IFS and according to the norm time from the SAM analysis should the operation take approximately 32 minutes. Any rework or problems when assembling is not included in the norm time which may account for the difference in time. Some components must be cleaned and inspected before being mounted in sub-product C. Sometimes the components may be clean enough after only cleaning them once, while at other times they might be required to be cleaned many times before being approved. The inspection of cleanliness is made in a microscope, which is not located at the assembly bench.

The amount of value-adding and non-value-adding work can be seen in Figure 23.



Loss:	1,97 min	6%
Wait:	0,00 min	0%
Required:	7,34 min	23%
Non-value-adding:	**9,31 min**	**29%**
Value-adding:	23,03 min	71%
Total time:	**32,35 min**	

Figure 23: Work distribution, operation 700

There are 71% value-adding activities and 29% non-value-adding activities. The non-value-adding activities include the operators having to read instructions as well as walking to and from the cleaning room and fume bench. The air sensitive components are cleaned in the cleaning room and sub-product C is placed in the fume bench until tests are to be performed on it. In addition, the fact that the operators must walk, bend and stretch to retrieve and return material and tools also adds to the non-value-adding activities.

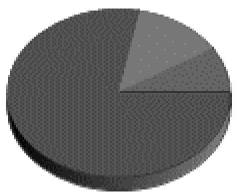
Shrink tubes are used during the assembly of sub-product C. However, they are too long when delivered and must be adjusted by the operators. This indicates a loss in the form of lack of quality.

Operation 850: Mount

This operation includes mounting several sub-products in the housing, including sub-product C. Once the sub-products are mounted into the housing they are attached to each other and some sub-products that have been mounted in previous operations. It is a very complicated task to perform since every sub-product must be in the correct position and aligned to each other. The task requires experience and knowledge. There is also a time pressure put on the task because of the two components in sub-product C that cannot be exposed to air for more than two hours. It is therefore important that the mounting goes quickly in order to not damage the sub-products.

The time is set to 2 hours in IFS and according to the norm time it should take 14 minutes. The difference is most likely due to the fact that in IFS there has been time added to allow for problems and difficulties when mounting sub-product C. The time from SAM assumes all sub-products are mounted without any issues and on the first try. This is however highly unlikely to happen, even for one of the more experienced operators.

How the work is distributed between value-adding and non-value-adding work is shown in Figure 24.



Loss:	1,24 min	9%
Wait:	0,00 min	0%
Required:	1,85 min	13%
Non-value-adding:	**3,09 min**	**22%**
Value-adding:	11,03 min	78%
Total time:	**14,12 min**	

Figure 24: Work distribution, operation 850

According to the SAM analysis is 78% of the total time used for value-adding work while 22% consists of non-value-adding tasks. Most of the waste is due to the operators having to walk to retrieve and leave the unit and getting material for the mounting. The required non-value-adding tasks mainly consist of reading instructions and getting equipment to the workbench.

Operation 900: Leak test and flushing

A leak test, identical to the leak test in Operation 602, is made to test unit and make sure there are no leakages. Directly after the leak test, the unit is filled with a coolant, assuming the unit passed the leak test. The filling is called flushing and is made in the cleaning room. The unit is connected to a machine which pumps fluid into the unit during at least four hours. Once every half hour an operator has to turn the unit upside-down a couple of times to make sure there are no air bubbles in the system. The unit must cool down to room temperature once the flushing is completed, which takes approximately three hours.

The task itself has been assigned 4 hours in IFS and additional 3 hours for the cooling down. The task, excluding the cool down time, should according to the SAM analysis take 4 hours and 14 minutes. The amount of value-adding and non-value-adding work, excluding the cool down time, is shown in Figure 25. The distribution, including the cool down time, is shown in Figure 26.

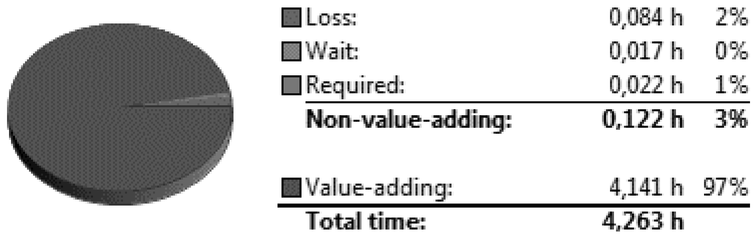


Figure 25: Work distribution, operation 900 (cool down time excluded)

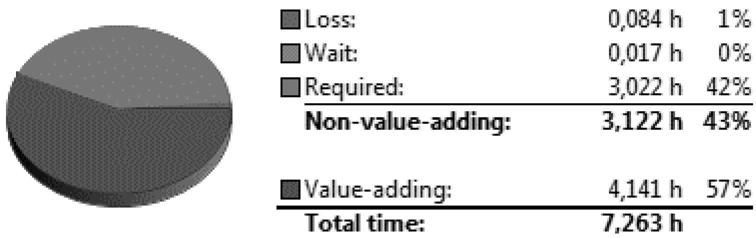


Figure 26: Work distribution, operation 900 (cool down time included)

Figure 25 shows that, excluding the cool down time, 97% of the time is spent on value-adding work, while only 3% of the time is not. When the cool down time is included, as Figure 26 shows, only 57% of the time is spent on value-adding activities and 34% on the non-value-adding. The large difference between the two pie charts is due to the cool down time, which is categorised as required. There are only 2% losses and they are mainly due to having to walk between the assembly station, the test room and the cleaning room.

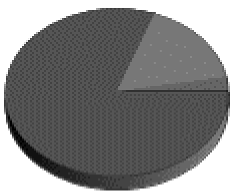
During the four hour flushing, the operators must go into the cleaning room at least 10 times to turn the unit upside-down and make sure the air bubbles leave the system. However, there is no way of knowing whether or not there are any bubbles left. To have to walk back and forth to the cleaning room to turn the unit creates losses due to the walking.

Once the flushing is completed, a small amount of extra coolant must be manually added. The fact that the machine cannot add the last coolant creates waste, even though the SAM analysis generally categorise it as value-adding. In addition, the amount of extra coolant is vital for the unit. It is, however, impossible to know exactly when that amount has been added. Also, the lighting in the cleaning room is too bad and height of the sink is too low, which is why the operators normally bring the unit to their workbench when adding the last amount of coolant. Waste is created because the operators cannot stay in the cleaning room.

<u>Operation 3000: Mount electronics</u>

This is a large operation that includes assembling, in some cases, and mounting nine electronic sub-products in the housing. In addition, binding the cables is included as well as fastening screws with glue. The glue must harden and is usually done for approximately 16 hours. The first tests must be made in Cleanroom 8 once Operation 3000 is completed and the unit is therefore placed in the airlock after this operation.

The time set in the ERP system is 6 hours for mounting and 1 hour for gluing. The same activities should according to the norm time take 1 hour and 55 minutes. The probable reason for this difference is that the time from the SAM analysis does not include any rework or trouble with the mounting and assembly, while the time in IFS most likely includes events like that. The distribution of value-adding and non-value-adding activities in Operation 3000 can be seen in Figure 27.



Loss:	0,053 h	3%
Wait:	0,000 h	0%
Required:	0,317 h	17%
Non-value-adding:	**0,371 h**	**19%**
Value-adding:	1,537 h	81%
Total time:	**1,908 h**	

Figure 27: Work distribution, operation 3000

The total time consists of 81% value-adding activities and 19% non-value-adding. Some of the non-value-adding activities are waste that occur because the operators must walk to the airlock to leave the unit and to the cleaning room to mix glue. Other reasons for the non-value-adding activities are retrieving and returning tools and material. The bulk material, such as screws and o-rings, are shared between the operators and kept in one place. The operators therefore have to walk there when material is needed.

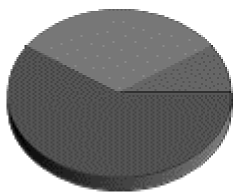
Shrink tubes are used in this operation as well as in operation 700 and the same problem of tube length exists. They have to be adjusted by the operators. One of the sub-products is delivered in the wrong dimension, forcing the operators to make necessary adjustments.

In addition, the operators must read the instructions and look at the drawings to know what is to be mounted where in the housing, which constitutes a large part of the required activities. Lastly, the operators must send an e-mail to the operators in Cleanroom 8 telling the unit is placed in the airlock and ready for testing.

Operation 3310: Final mounting sub-product R

After sub-product R has been checked and approved in Cleanroom 8 is it possible to fasten it with glue in the housing at the assembly station. First, sub-product R has to be pulled out of the housing and the o-rings on sub-product R must be replaced. Glue must be mixed and screws on sub-product R are glued before sub-product R is placed in the housing and fastened with screws. These screws are also fastened with glue. The glue on the screws must harden for 16 hours in the fume bench. The unit is thereafter left in the airlock as a final inspection and testing of sub-product R must be made in Cleanroom 8.

In IFS is the time for the task determined to 1 hour while the SAM analysis says approximately 18.5 minutes. The amount of value-adding and non-value-adding work is shown in Figure 28. The hardening time of 16 hours is not included.



Loss:	1,74 min	9%
Wait:	0,00 min	0%
Required:	5,72 min	31%
Non-value-adding:	**7,46 min**	**41%**
Value-adding:	10,94 min	59%
Total time:	**18,40 min**	

Figure 28: Work distribution, operation 3310

The non-value-adding work constitutes 41% of the total time while the value-adding time corresponds to 59%. A large part of the waste is due to the operators having to walk; to the cleaning room to mix glue and to the airlock to retrieve and leave the unit. To get and return tools also generates waste. One reason behind the required activities is the fact that the operators have to send an e-mail to the operators in Cleanroom 8 telling the unit is placed in the airlock and ready for testing.

Operation 4100: Assemble seal material

Once all components except the resonator are mounted in the housing, and several tests are made, is it time for Operation 4100. The seal material in question is for the outer cover of an already mounted sub-product. The cover has not been fastened to the housing of the unit until this operation. The cover and sub-product are however connected and to place and fasten the sealing is therefore not an easy task. In addition, the seal material cannot be glued to the cover but must be kept in place by small pieces of tape until the cover is fastened on the housing. Small pieces of tape must therefore be cut and the sealing placed in the cover. The tape pieces are thereafter strategically placed on the cover. Once this is done is the cover fastened to the housing with screws. The tape pieces must thereafter be removed before the screws are tightened completely. It must be done carefully to ensure all tape pieces are removed and nothing is left behind.

The time set for Operation 4100 in the ERP system is 6 minutes. According to the norm time is 8 minutes required for this task. The amount of value-adding and non-value-adding work is shown in Figure 29.

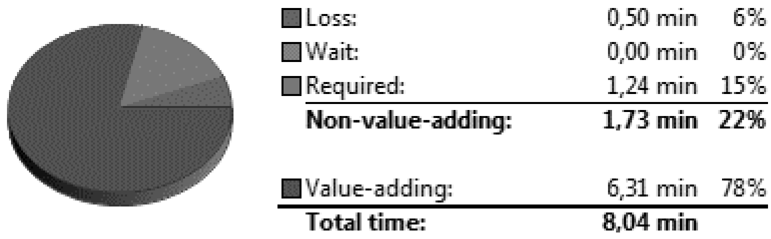


Figure 29: Work distribution, operation 4100

78% of the task is value-adding, while 22% is not. The amount of non-value-adding stems from the operators fetching and returning tools, retrieving the unit from the airlock and reading instructions.

<u>Operation 90: Mount resonator</u>

The final sub-product that is mounted in the housing is the resonator. It has been assembled and tested parallel to all other activities. Once the housing is inspected for dust, the resonator is mounted and fastened with screws.

The operation has 1 hour assigned to it in IFS, while it according to the SAM analysis should take approximately 7.5 minutes. The reason for this is probably, as for many of the other operations, due to the SAM analysis assuming a perfect mounting, without any problems arising. This is most likely not the case in reality however. The distribution of value-adding and non-value-adding work is shown in Figure 30.

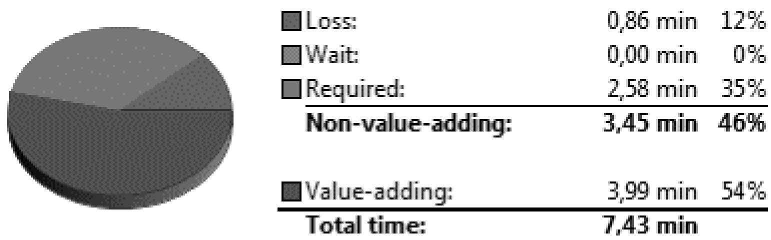


Figure 30: Work distribution, operation 90

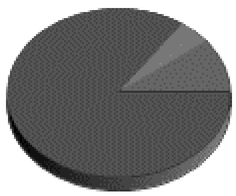
54% of the time is spent on value-adding work and 46% on non-value-adding work. The required activities are due to the operators reading instructions. The losses stem from retrieving the resonator from a cabinet and leaving the unit in the airlock. In addition, the operators must walk some distance to get components.

Operation 125: Glue resonator

The resonator is tested in Cleanroom 8 after it has been mounted and the tests require the outer cooling system of the unit to be filled with water. However, the cooling system must be emptied before the assembly operators can continue the assembly. The water is manually emptied from the unit and alcohol must be poured into the unit to ensure cleanliness. The unit is filled with alcohol and the operators must rotate the unit to assure alcohol fills the entire unit. The alcohol is thereafter emptied from the unit by lifting the unit quite high and shaking it a little. The procedure is repeated approximately five times.

Once the unit has been cleaned with alcohol, the resonator is fastened in the housing by gluing. To reach all screws on the resonator it must first be demounted from the housing. Thereafter is it remounted and more screws are glued. In total there are approximately 75 screws that are glued. To be able to see all screws that will be glued, the operator must use a magnifying glass and a flashlight. The unit is thereafter left to harden for 24 hours.

In IFS is the time for this operation set to 2 hours, while the SAM analysis states it should take just over 24 minutes. Neither of these times includes the time for hardening the glue, nor does Figure 31, which shows the amount of value-adding and non-value-adding work for the task.



Loss:	2,53 min	10%
Wait:	0,00 min	0%
Required:	1,16 min	5%
Non-value-adding:	**3,69 min**	**15%**
Value-adding:	20,49 min	85%
Total time:	**24,19 min**	

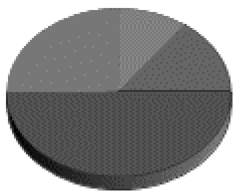
Figure 31: Work distribution, operation 125

The value-adding work constitutes 85% while the non-value-adding work adds up to the remaining 15%. The losses are mainly due to walking; to the cleaning room to mix glue, and to leave the unit when hardening. The rest of the non-value-adding work stems from the operators reading instructions.

Operation 130: Leak test

Another leak test is made, which consists of the same steps as the previous tests. The unit is prepared at the assembly station, the test machine in the test room is turned on and the unit is placed in the machine. The test is run and if it is passed, the unit is brought back to the assembly station for some additional work. The time is set to 1 hour in IFS, while the result of the SAM analysis says it should take just over 10 minutes. In case of leakage, additional testing is needed, which is not taken into consideration in the norm time from SAM. This is the likely reason for the time difference between IFS and SAM.

The work distribution is shown is Figure 32.



Loss:	1,50 min	15%
Wait:	1,00 min	10%
Required:	2,58 min	26%
Non-value-adding:	**5,09 min**	**50%**
Value-adding:	5,04 min	50%
Total time:	**10,13 min**	

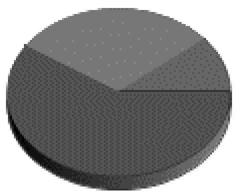
Figure 32: Work distribution, operation 130

50% of the time is spent on value-adding activities and 50% on non-value-adding. The latter constitutes of walking back and forth to the test room, in addition to retrieve the unit from the hardening and leaving it in the airlock afterwards. Also, the non-value-adding work includes the operators sending an e-mail to the operators in Cleanroom 8 telling that the unit is placed in the airlock.

Operation 220: Glue wedges

The unit is transported to Cleanroom 8 for testing after the leak test in Operation 130 is performed. The unit is retrieved from the airlock once the tests are passed. Four screws in the housing must be fastened with glue that is mixed in the cleaning room. The unit is thereafter left to harden for 24 hours.

According to the SAM analysis, the time for this operation should be almost 8 minutes, excluding the hardening time, while the time is set to 1.5 hours in IFS. A pie chart showing the amount of value-adding and non-value-adding work can be seen in Figure 33. The time for glue hardening is not included in the pie chart.



Loss:	0,85 min	11%
Wait:	0,00 min	0%
Required:	2,32 min	30%
Non-value-adding:	**3,17 min**	**41%**
Value-adding:	4,61 min	59%
Total time:	**7,78 min**	

Figure 33: Work distribution, operation 220

The operator is doing value-adding work 59% of the time and 41% of the time is spent on non-value-adding work. The non-value-adding work is due to the operators having to walk to mix glue, to retrieve and return the unit, and to send an e-mail to the operators in Cleanroom 8 telling them that the unit is placed in the airlock.

<u>Operation 230: Leak test</u>

Some tests are made in Cleanroom 8 after Operation 220 and the outer cooling system must once again be emptied. The procedure is identical to the one performed in operation 125. A final leak test is thereafter made using the same procedure as before. The unit is retrieved from the airlock but left at the assembly station after the test.

The time set in IFS is 2 hours, while the time according to the SAM analysis is just over 17 minutes. The distribution of value-adding and non-value-adding work is shown in Figure 34.

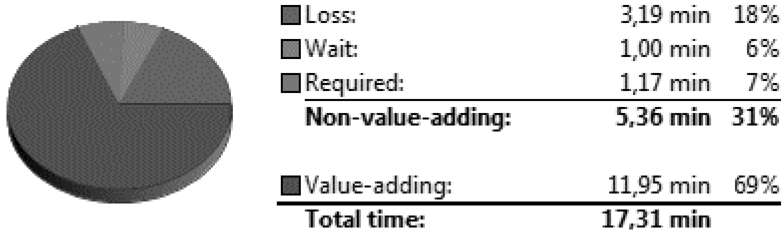


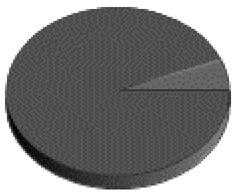
Figure 34: Work distribution, operation 230

The value-adding time constitutes 69% of the time and the non-value-adding work, corresponding to 31% of the total time, is mainly due to walking back and forth between the assembly station and test room.

<u>Operation 232: Clean cover bottom</u>

Up until this operation has one of the two covers of the unit only been a production cover. Once the unit has passed all tests hitherto made, the final cover, which the unit will be delivered with, will be mounted on the housing. First, however, the cover must be cleaned in the cleaning room. The cover is cleaned using two different types of chemicals that are located at a low height in a locker in the cleaning room.

The time it takes to perform this operation is set to 30 minutes in IFS and according to the SAM analysis it takes roughly 35 minutes. Figure 35 shows the distribution of the work.



Loss:	1,94 min	6%
Wait:	0,00 min	0%
Required:	0,29 min	1%
Non-value-adding:	**2,23 min**	**6%**
Value-adding:	32,51 min	94%
Total time:	**34,74 min**	

Figure 35: Work distribution, operation 232

94% of the time is value-adding, while 6% is non-value-adding. Most of the non-value-adding time is due to the walking to and from the cleaning room but also because walking within the cleaning room, to retrieve and return the chemicals, is necessary.

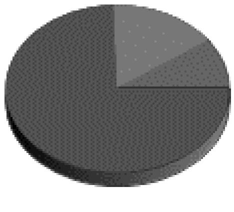
<u>Operation 235: Mount cover bottom</u>

Once the cover is cleaned, components are mounted on the cover with glue. The components are located in a cabinet in the same material room as the airlock. Glue is then mixed and the components are fastened on the cover. This needs to harden in an oven, also located in the same material room as the airlock, for 2 hours. The cover is stored until it is mounted onto the housing, which must be done within three weeks to avoid damaging the components.

The production cover must be removed and an o-ring in the housing must be replaced before mounting the cover on the unit. The cover is then fastened with ten screws and protective tape is placed on the cover. The unit is thereafter left in the airlock as the unit must go through the final tests before delivery to customer.

According to the SAM analysis is the time to perform the operation almost 21 minutes, excluding the hardening time of 2 hours. The time defined in IFS for this operation is 1.5 hours, but no extra time for hardening exists.

The distribution of the value-adding and non-value-adding work of the operation is shown in Figure 36. The glue hardening time is excluded.



Loss:	2,02 min	10%
Wait:	0,00 min	0%
Required:	3,28 min	16%
Non-value-adding:	**5,30 min**	**26%**
Value-adding:	15,45 min	74%
Total time:	**20,76 min**	

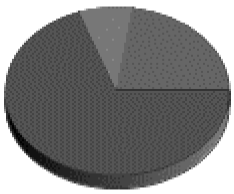
Figure 36: Work distribution, operation 235

74% of the time is spent on value-adding activities, while the non-value-adding activities constitute 26% of the total time. The majority of the losses stems from the operators having to walk a lot; to and from the cleaning room, a cabinet and the airlock. The majority of the required activities are due to reading instructions and sending e-mails to the operators in Cleanroom 8.

<u>Operation 260: Empty outer cooling system</u>

After the unit has been submitted to the final tests in Cleanroom 8, the outer cooling system must be emptied one last time. This procedure is identical to the two previously mentioned procedures, performed in operations 125 and 220. The time set in IFS for this operation is 1 hour, while the time it takes to perform the task according to the SAM analysis is almost 10 minutes.

Figure 37 shows the distribution between value-adding and non-value-adding work.



Loss:	2,26 min	23%
Wait:	0,00 min	0%
Required:	0,78 min	8%
Non-value-adding:	**3,04 min**	**30%**
Value-adding:	6,94 min	70%
Total time:	**9,98 min**	

Figure 37: Work distribution, operation 260

70% of the time is spent on value-adding work, while 30% is spent on non-value-adding work. A lot of the non-value-adding work is due to retrieving the unit from the airlock and to get alcohol and other necessary equipment.

5.2.2 Operation Time

Currently, the operation time for one unit, according to the SAM analysis, is 374 hours, assuming that there is no rework. When calculating the operation time it is assumed that no operations are performed in parallel, i.e. all operations are performed successively. This is comparable to only one operator doing all activities alone.

286.3 hours, corresponding to 76.5% of the total lead time, are composed of process time, which is time for automated tests in Cleanroom 8, time for glue to harden in Cleanroom 7 and time for the unit to cool down after flushing it. Therefore, the operators are only working on the unit or preparing tests during 23.5% of the total operation time. Table 2 shows the distribution of the manual work and Table 3 shows the distribution of the process time.

Table 2: Total manual work time for one unit

	Hours	Percentage of total operation time
Manual assembly, Cleanroom 7	16.1	4.3
Inspection, Cleanroom 7	12.1	3.2
Resonator assembly, Cleanroom 7	22.6	6
Manual time, Cleanroom 8	36.9	9.9
Total manual time	87.7	23.4

Table 3: Total process time for one unit

	Hours	Percentage of total lead time
Process time, Cleanroom 7	125.8	33.6
Process time, Cleanroom 8	160.5	43
Total process time	286.3	76.6

In Table 4 is the calculation of the total operation time shown. It corresponds to the time it takes to complete one unit, assuming no rework is necessary and only one operator performs the operations.

Table 4: Total operation time for one unit

	Hours
Total manual time	87.8
Total process time	286.3
Total operation time	374

The manual work that is conducted in Cleanroom 8, which comprises 9.9% of the total operation time, has not been studied in this project. Additionally, the assembly of the resonator and the inspection of the unit has not been studied either, as mentioned in section 1.4. What is left is the work performed by the assembly operators in Cleanroom 7 and this time constitutes 4.3% of the total operation time. It is these 4.3% of the total operation time that this master's thesis focuses on.

The total operation time for the manual assembly in Cleanroom 7 is 46.5 hours according to the ERP system IFS. This can be compared to the ideal manual assembly time generated by the SAM analysis which corresponds to 16.1 hours. There is a large discrepancy between the ideal operation time and the time used for production planning.

5.2.3 Method, Performance and Utilisation

The productivity for the production of Alpha is estimated according to Equation 4 in section 3.2. The method (M), performance (P) and utilisation (U) must be determined in order to calculate the productivity.

The work conducted by the operators concerns manual work only. The calculations regarding MPU does not take processing times into consideration, since they are not dependent on the presence of operators.

The M factor, which is a theoretical number of Alphas that the production unit should be able to produce each year in the current state, has been calculated based on the norm times generated in the SAM analysis. The total amount of available production time per year, regarding the operators connected to the production of Alpha, has also been included in this calculation. The M factor has been calculated according to the following equation (eq. 6):

$$M_{SAM(CS)} = \frac{Available\ production\ time\ per\ year}{Production\ time\ per\ unit} \tag{6}$$

The result of the equation above is, as mentioned, only theoretical and the actual number of Alphas that the company produce is considerably lower. The reason for the difference in the theoretical and actual numbers is the performance (P) and utilisation (U) factors. The P and U factors have been calculated using the following formula (eq. 7):

$$PU_{CS} = \frac{M_{BA1}}{M_{SAM(CS)}} = 37\ \% \tag{7}$$

where M_{BA1} is the actual amount of produced Alphas per year, which was given from production statistics. The exact number for neither the theoretical nor the actual production volume of Alpha can be disclosed in this report because it is company sensitive information. The value of PU_{CS} indicates that 63% of the operators' time is spent on activities that do not add value to the product.

As mentioned in Equation 4 in section 3.2, the performance and utilisation factors are divided into sub-factors. The factor PU is comprised of the following:

- $P_P = Personal\ performance\ rate$
- $P_S = Skill\ based\ performance\ rate$
- $U_N = Need\ based\ utilisation\ rate$
- $U_S = System\ design\ utilisation\ rate$
- $U_D = Disturbance\ affected\ utilisation\ rate$

P_P depends on the individual's physical ability (Almström, Hansson and Samuelsson, 2014). The operators have different physical attributes that affects this rate, e.g. height and strength. Some of the operators appear to use supporting tools more than others when force is included in the work. This leads the value of P_P varying among the operators.

The amount of work experience among the operators differ which decreases the total value of P_S. The more experienced operators have a higher work pace than the less experienced operators. In addition, the less experienced operators are in need of cognitive support and must have drawings and instructions available during assembly. The cognitive support has shown a lack of quality in the current state. The operators spend time on searching for needed information to conduct the assembly. The rate of P_S varies among the operators since some are more skilled than others due to experience.

U_N depends on personal time that is often determined according to agreements (Almström, Hansson and Samuelsson, 2014). The operators spend their personal time according to set regulations. The personal time include paid breaks for the operators.

The assembly of Alpha is conducted 100% manually by the operators. This leads to U_S being excluded from the MPU formula. There is no assembly line, and therefore there are no balance losses to detect.

U_D includes losses that occur due to disturbances (Almström, Hansson and Samuelsson, 2014). This sub-factor has the greatest impact on the total utilisation rate (U). Most units fail at least one test and require some sort of rework. Hence, rework is currently a large part of the total work. Another aspect of the U_D factor is the amount of disturbances in production. Searching for tools and maintenance are some of the production disturbances mentioned in the next section.

5.2.4 Capacity

The capacity for production of Alpha is calculated according to Equation 2 in section 3.1.4:

$$Capacity = \frac{Maximum\ Product\ Output}{Given\ Time\ Period\ Input}$$

The maximum product output corresponds to the actual amount of produced Alphas per year. This value was given from production statistics and will not be presented due to company sensitive information.

The given time period input is the available production time per year associated with the resources connected to the production of Alpha.

The capacity for the current state is calculated to 0.17 products per week.

5.2.5 Production Disturbances

The disturbances that exist in the system and prevent the operators from doing value-adding work will be presented in this section, for the operations where disturbances exist. Disturbances can be looked upon from different perspectives, as mentioned by Bellgran and Säfsten (2010) in section 3.1.2, and the disturbances mainly affect the productivity, quality and safety in the studied production system. What is presented below is based on the video recordings made of the assembly and the conversations with the operators in Cleanroom 7.

There are some disturbances and losses that occur several times throughout the assembly and these are presented below.

- The operators must oftentimes search in the cognitive support when needing work instructions, as they are not optimally designed or organised.
- Material is sometimes not delivered to the production personnel in time. It may be due to miscommunication between operators and production planner but it could also have other reasons such as mistakes in the main or interim storages. Either way, it causes disturbances for the operators as they must wait for the material to arrive.
- Before the o-rings are mounted in the housing or in a sub-product, they must be cleaned with alcohol and lens paper at the assembly stations to ensure they are free of dust. This takes a lot of time, as there are many o-rings in one unit.
- The fact that the o-rings are dry, without a cover that makes the o-rings more sustainable and facilitates the compression, forces the operators to pour large amounts of alcohol on them. This is done to facilitate the mounting and avoid damaging the o-rings. It is, however, disruptive and requires a lot of time from the operators.
- Sometimes after a unit has been in Cleanroom 8 for tests, some o-rings have unfastened. This forces the operators to search for it inside the unit and try to retrieve it. It creates disturbances in the assembly.
- There is no standardised work which leads to differences in assembly sequence between the operators. This is a disturbance and may turn into a loss when different assembly operators are working on the same unit, at different points in time. If an operator assumes that the previous work has been done according to his or her own usual sequence, something may be forgotten.

<u>Operation 300 – Clean components</u>

The components are cleaned in different types of alcohol and chemicals, which are stored in a cabinet in the cleaning room. Oftentimes, the alcohol containers are emptied during the cleaning procedure which forces the operators to put the container down and go over to the cabinet to retrieve a new one. It is disruptive and wasteful. The empty containers must be placed outside Cleanroom 7 for the material handler to replenish.

Not all components fit in the cleaning device at the same time which leads to waiting times. This is especially true if more than one operator is cleaning components simultaneously.

When pouring alcohol into the disposal tanks, it is impossible to know when the tanks are full. The operators must pour the alcohol out slowly and assume there is room left. Sometimes, however, the tanks get filled up and alcohol brims over and spills onto the floor. This requires more of the operators' time and effort. In addition, the fumes from the alcohol can be dizzying, especially when the alcohol has spilled onto the floor.

<u>Operation 600 – Mount</u>

There is a v-ring on one of the sub-products and to avoid folding the v-ring when mounting the sub-product, a thin plastic film must be used. The operators normally have one of these plastic films each, but sometimes one has accidentally been thrown away and the operators must search for a new one or borrow from someone else.

Sub-product H is very difficult to mount and the operators do not know a good way of mounting it. The main reason for the difficulties that arise is the fact that sub-product H must be aligned with other sub-products in the housing that are not fastened tightly. In addition, it might be difficult for one operator to do this alone as it facilitates to pour alcohol onto the housing and sub-product H during mounting.

<u>Operation 601 – Mount the sub-product R</u>

There is a pipe on sub-product R that must usually be adjusted to fit properly in the housing, causing disturbance in the work.

<u>Operation 602 – Leak test</u>

To place the unit in the leak test machine and attach the tubes is not easy; the operators must bend into the machine and press hard on the tubes. The fact that it is quite tricky creates disturbances and prolongs the operation time.

Only one unit at a time can be tested, which may cause waiting times if there are more units that need to be tested.

There is a display connected to the leak test machine that for a very short time, approximately 0.5 seconds, shows a number that the operators must note. The operators must therefore be very attentive to not miss the displayed number.

Operation 700 – Assemble sub-product C

Sub-product C consists of a large amount of components and it is easy for the operators to forget a component. The operators must demount the sub-product and start over in case of that happening.

Operation 850 – Mount

It is quite difficult to place sub-product C in the housing as it must match other sub-products in the housing. If something goes wrong, it could damage sub-product C beyond repair, forcing the operators to start over with a new sub-product C.

Operation 900 – Leak test and flushing

Every fifth time a flushing is made, the flushing machine requires maintenance. It takes approximately two hours and creates great disturbances in the system as that may hinder the operators from flushing a unit the same day as maintenance due to time limitations.

Operation 3000 – Mount electronics

Only one tool for pressing e.g. cable lugs exist in Cleanroom 7. As the operators share the tool it can be located at any workbench in the production. The operators are therefore interrupted in their work to search for the tool.

During the mounting, the housing must be tilted using a plastic cup in order to see and reach everything. The fact that the housing must be tilted creates a disturbance in the assembly.

Operations 130 and 230 – Leak test

The same disturbances that were mentioned in Operation 602 occur in this operation as well.

5.3 Physical Ergonomics

Because the current work tasks carried out by the operators are mainly manual, as mentioned in section 4.3, and both long-lasting and repetitive, there is a need to assess the physical ergonomics during assembly of Alpha. In addition, the physical ergonomics affects the output rate of the operators (Al-Zuheri, 2013).

Worthy of note is that the ergonomic evaluations are conducted only for the work procedures in Cleanroom 7 due to the limitations of this master's thesis. The analyses are based on information gathered from video recordings of one specific operator assembling Alpha. However, the operators in Cleanroom 7 have different physical character and capabilities, and any conclusions made based on this analysis should take that into consideration.

The authors have chosen to assess the ten postures that were interpreted as the most critical during the video recordings i.e. where the human body is put at risk from an ergonomic perspective. A posture for each of these situations were analysed with the ergonomic evaluation methods RULA and REBA, described in section 3.4.3.

Table 5 presents the chosen work tasks and the ergonomic evaluation methods used to determine the current production ergonomics in Cleanroom 7. An explanation of each situation follows the table.

Table 5: Ergonomic evaluation in Cleanroom 7

Work Task	Ergonomic Evaluation Methods
Usage of computer	RULA
Material handling 1	REBA
Material handling 2	REBA
Place funnel in tank	REBA
Empty alcohol	REBA
Leak test	REBA
Flushing	REBA
Fastening screws	RULA
Mount sub-product H	RULA
Manual assembly	RULA

<u>Usage of computer – RULA</u>

The computer screen is suspended in the air at the left-most side of the workbench with the keyboard suspended in front of the computer screen. To reach the keyboard, the operators must twist their back and neck, and to type the operators must keep their arms suspended, without support.

This posture does not enable the shoulders to be situated directly over the hips or alignment between the ears and the shoulders. It is therefore considered to be a bad posture, in accordance to Berlin and Adams (2014). In addition, working with the arms in the air without support puts a load on the shoulders. The computer is a valuable aid in understanding the assembly, primarily for an inexperienced operator, and this posture might therefore be frequently used. Frequency in a posture can cause ergonomic stress and might be harmful (Zandin, 2001).

The posture was analysed with the RULA method and was given the score 4, with 7 being the highest. A score of 4 indicates that further investigation is needed and that a change might be required. The posture and RULA analysis can be found in Appendix A – Usage of Computer.

Material handling 1 – REBA

When cleaning components for sub-product C, cloths and silver foam are needed. They are both found in the cupboard under the sink in the cleaning room. The cloths are found in a plastic bag at the bottom of the cupboard. In order for the operators to reach this bag, they must bend very low towards the floor and at the same time fully extend the arms. In addition, one must generally bend the knees when bending ones back this low.

The arms and back are working in the outer range of movement in this posture and is therefore a very bad posture according to Berlin and Adams (2014). It is also a bad posture based on the REBA analysis, in which the posture got a score of 12 out of 11+. This score means that the posture is a very high risk for the operator and should be changed immediately. The picture of the posture and the assessment sheet can be found in Appendix B – Material Handling 1.

Material handling 2 – REBA

When the operators are cleaning the components in the cleaning room, alcohol is needed frequently. The alcohol is kept in containers which are located at the bottom of a cabinet. This cabinet must be closed at all times due to fire hazard, and the alcohol must be put away immediately once used. This implies that the operators must fetch and return the alcohol containers several times during the cleaning procedures. Each time, the operators must bend low to get the container and bring it to the counter by the sink. To lift a full container from the ground is not ergonomically optimal; the back and legs should be loaded axially (Berlin and Adams, 2014), which is not the case in this situation. In addition, the external load of the alcohol container is not handled close to the centre of the body, which it should (Berlin and Adams, 2014).

The posture was analysed with the REBA method and got a score of 13 out of 11+, which can be seen in Appendix C – Material Handling 2. The score indicates a posture that is a very high risk for the operators and a need for immediate changes.

Place funnel in tank– REBA

Used alcohol must be disposed of in tanks placed on the floor. To be able to pour alcohol into a tank, a funnel must be placed in the opening of the tank. To open the tank, a handle must be pulled backwards with force and, while holding the handle steady with one hand, the funnel is picked up from the floor with the other and placed in the opening of the tank. This is all done while bending low to reach the tank and funnel.

This is also a posture that is not good from an ergonomic perspective; the back and knees are bent to reach and the neck is bent to see. In Appendix D – Place Funnel in Tank, the picture of the posture and the assessment sheet of the REBA method can be found. The REBA analysis resulted in a score of 11 out of 11+, which indicates a significant risk for the operators and immediate change.

Empty alcohol – REBA

Once the funnel is placed in the tank can the used alcohol be disposed of and poured into the tank. The alcohol is generally poured from a metallic or glass container which contains the alcohol and components that have been cleaned. To empty the container, the operators must hold the container while at the same time holding the components to make sure they do not fall into the tank. As the tank is located on the floor, the operators must bend down to ensure that the alcohol is poured into the funnel. The container must then be tilted to enable the alcohol to pour down into the tank. To ensure all alcohol has been disposed of, the container must be fully tilted, resulting in a bad ergonomic posture. The bad posture leads to internal forces being present due to the awkward position that the operator must strive to maintain (Berlin and Adams, 2014).

REBA was used to analyse the posture and it got a score of 11 out of 11+, which can be seen in Appendix E – Empty Alcohol. Immediate changes are required and the posture puts the operator at a very high risk.

Leak test – REBA

Leak tests are performed on every unit at least four times during the production. Tubes connect the leak test machine to the unit, which must be attached to the housing. When doing so, the housing is located inside the machine, with the connections to the tubes facing inwards. To be able to connect the tubes on the housing, the operators must stand on one side of the machine and bend inwards, over the housing, to reach. The tubes are connected to the housing with a combination of force and technique, while bending over the housing.

The need for bending in addition to having to reach out one arm is what makes the posture a bad one. Stretching to reach is, according to Berlin and Adams

(2014), one factor that can increase the risk of injury. It was assessed using REBA, which can be seen in Appendix F – Leak Test. The posture got a score of 7 out of 11+, which implies that the operators are exposed to a medium risk and that further investigation and a change is needed.

<u>Flushing – REBA</u>

Tubes are connecting the housing to a small machine for four hours during the flushing. Fluid is pumped into the housing and every 30 minutes an operator must lift the housing and turn it upside-down to ensure no air bubbles are left in the system. This is done while the tubes are still connected to the housing. To lift an object that does not have designated handles is an action that may lead to injuries in the future and is something that should be avoided (Berlin and Adams, 2014). In this case, the lack of proper handles leads to asymmetry in the body of the operators as they must bend their back sideways and keep one arm abducted to be able to turn the unit upside-down. The posture puts a strain on the shoulders and back as well as adding mental stress stemming from the worry of accidentally losing the grip of the housing and dropping it.

This posture got a score of 11 out of 11+ in the REBA assessment, which can be seen in Appendix G – Flushing. It means that the operators are at a very high risk and the changes must be made immediately.

<u>Fastening screws with screwdriver – RULA</u>

The operators have many different tools and many different kinds of screwdrivers that are used in different situations. There are special screwdrivers for fastening screws with a fixed torque. One of these screwdrivers is very long, to enable the operators to reach all screws. However, it is not only used for inaccessible or remote screws, but also for clearly visible screws, e.g. on the outside of the housing. This forces the operators to hold their hand and arm very high up in the air while fastening the screw. The arm may even be held above shoulder height, which is an ergonomic trap that should be avoided according to Berlin and Adams (2014).

A picture of the posture, together with the result of the RULA assessment can be seen in Appendix H – Fastening Screws. The posture got a score of 6 out of 11, which indicates that further investigations are necessary and changes should be implemented soon. The posture puts a strain on the shoulders as well as the neck. In addition, it may be difficult for the operators to make the fastening motion with the hand located a considerable distance from the screw being fastened.

Mount sub-product H – RULA

Sub-product H is mounted onto two connections, which is what makes this sequence an ergonomic risk for the operators. To be able to mount it properly, the operators are forced to keep the housing in their lap, supporting the unit with the legs and shoulders. At the same time, each hand holds a screwdriver that is used to steer sub-product H onto the connections properly. Both force and technique are required. The difficulty of the task means that quite many minutes may be necessary in order to properly mount sub-product H in the housing. To use force in an awkward position for a longer period of time is a high risk for the operators and may increase the risk of injuries (Berlin and Adams, 2014). Force may, in addition, cause ergonomic stress as mentioned by Zandin (2001).

A RULA assessment was made in which the posture got a score of 7 out of 7. The high score means that the posture must be further investigated and changes must be implemented as soon as possible. The assessment sheet and a picture of the posture can be found in Appendix I – Mount Sub-product H.

Manual assembly – RULA

A lot of the work that the operators perform concerns small details and requires concentration. Berlin and Adams (2014) say that high-precision work, such as this, requires working conditions and working postures of high quality. However, to be able to see properly, the operators must often bend over the workbench to come close to the unit. This entails a bent back and a very bent and twisted neck. A bent and twisted neck during assembly work is something that should be avoided according to Al-Zuheri (2013). In addition, the wrists must often be bent in order to reach.

The posture got a RULA score of 6 out of 7, which indicates that the posture is bad and that investigations and changes are required. The assessment sheet and a picture of the posture are attached in Appendix J – Manual Assembly. The posture puts a strain on the neck and back, as well as the mental load of having to concentrate on small details for a longer period of time.

5.4 Cognitive Ergonomics

The product studied in this master's thesis is of a high level of complexity and includes many different components and tasks. To aid in the production of this product there are three different types of assembly aids, as mentioned in section 4.3. There are work instructions, 2D drawings, and the reporting system Prosus, which contains the production routing and descriptions of bulk material, such as screws and o-rings.

The fact that the instructions are in three separate places implies that the time to find the correct information is substantial. In addition, the work instructions are not ordered according to the assembly sequence, but quite random, which makes it difficult to find the right information and further increases the time needed to search for information. The fact that the operators spend a lot of time on searching through the assembly support indicates a lack of quality in the cognitive ergonomics. According to Berlin and Adams (2014) should the time spent on finding information be minimised in order to maintain efficiency and motivation.

Furthermore, there are quite many steps in the work instructions that do not coincide with how the operators are actually performing their work. An example of this is when the operators use glue. The work instructions state that glue should be applied whenever a component has been fastened at its right place. According to the operators, however, this is a waste of time. It is better, according to them, to not apply glue until tests have been passed, ensuring that everything is as it should, and to apply glue to as many components at the same time as possible. The first reason stems from the fact that it is easier to rectify problems shown in the tests if glue has not already been applied. The second reason is due to the fact that the operators do not wish to mix glue more often than necessary but rather mix glue once and use for several components. There are other instances where the work instructions and the reality do not converge and sometimes the sequences, or instructions, in the work instructions are direct faulty and not possible to follow.

In addition, the instructions themselves are sometimes inadequate in explaining exactly what is to be done. This means that the operators with less experience must ask the operators with more experience, which could have been avoided with richer work instructions. Also, there are pictures in the work instructions but they are not adapted to being printed in black and white. In some places where there is no picture there should be one to clarify and further explain the assembly process. To explain or present something in more than one way decreases the risk of misinterpretations (Berlin and Adams, 2014).

The order of operations in Prosus is correct for the most part, but some operations do not match the sequence as performed in reality. For each operation it is possible to open a dialogue box with further information about the operation. For some cases there are references to the corresponding chapter in the work instructions file to facilitate the information search, but it does not exist for all operations. In addition, there are operations that even the most experienced operators do not know what they entail. Lastly, the operations in Prosus each has a designated time, which is the amount of time the operation should take. These times are used for planning the production. However, these times rarely match the real amount of time the operators spend on the operations, which gives a false picture of the assembly work.

Throughout the three sources of instructions there is a lack of concurrence regarding what names are used for the different components. For the larger components, there is usually one name in English and one in Swedish, in addition to at least one or two more in either English or Swedish or both. The names in the work instructions differ internally but also with how they are mentioned in Prosus. In addition, the operators call some components entirely different names than mentioned in the work instructions and Prosus. This complicates the understanding of the product and the assembly as well as increases confusion.

The 2D drawings that are used are in a separate PDF file and are cluttered with position numbers and arrows. The product consists of many components and all are shown, together with their position, in these drawings. It is quite difficult to find the correct position number and its position in the housing, even when using the zooming tool in the PDF reader. Furthermore, not all operators have sufficient knowledge to read the drawings, making a third of the cognitive support inaccessible to some operators. Even for an operator trained in reading drawings are these drawings sometimes difficult to read because of the large amount of components.

The insufficient quality and lack of coherence in the three parts of the assembly support may lead to defects in the assembly because of e.g. difficulty in finding information, misinterpretation of the information or incorrect instructions. The lack of quality of the instructions is probably a reason for why there is currently no standardised way of working. All operators assemble in the way that they see fit and think is the best way. No one therefore knows which way is the best or how the work is performed in the simplest and most efficient way.

Perhaps most importantly, the lack of coherence and quality makes it very difficult for operators with little or no experience of assembling this product to work. It forces a much higher degree of presence from the more experienced operators and allows little independence for the non-experienced operators. The time before a new operator can work independently is most likely prolonged due to the complexity of the cognitive support.

5.4.1 Work Instructions

The work instructions are in a separate PDF file of 62 pages and are not, as mentioned previously, optimal for the operators, and especially not for new operators. The elements that need attention will be presented in this section.

The three main categories of problems are sequence of chapters, assembly descriptions and names of components, which are described in Table 6.

Table 6: Main categories of problems in the work instructions

Element	Problem/error
Sequence of chapters	The chapter sequence does not correspond to the assembly sequence. For example: the two first operations (Op. 100 and 300) correspond to chapter 4.3 in the work instructions while the next operation (Op. 400) corresponds to chapter 7.
Assembly descriptions	There are parts of the work instructions, within a chapter, that do not correspond to what or in what order it is performed by the assembly operators. In some cases are the instructions faulty and cannot be followed.
Names of components	Most components and sub-products are called an English name, even things such as screws. In addition, most of the names of the sub-products differ between the work instructions, the routing explanations and what name the operators use.

These categories are more thoroughly explained in the appendices. Appendix K and Appendix L show which chapters in the work instructions that each operation in routings 500 and 500:A corresponds to. From this, it is visible that the sequence of the chapters is not in accordance with the order they are used. This is especially true for routing 500:A.

Within operation 3000, in routing 500:A, it is possible, to some degree, to change the sequence according to one's preference. The order visualised in the appendices is the order performed by the studied operator.

The next main category is the assembly descriptions. A table is available in Appendix M – Assembly descriptions, which states issues with many of the chapters. The majority of issues are due to insufficient descriptions; they lack information and steps of procedures as well as pictures that thoroughly explain how the unit should be assembled. Some parts of the instruction sequence are in an order that cannot be followed according to the operators or an order that the operators deem faulty and results in errors and defects on the unit.

The issues with the work instructions may not matter much to the experienced operators that generally do not use the instructions much, but are of vital importance to new operators. Due to the lack of quality of the instructions the new operators may learn doing things the wrong way and the learning period increases. It requires, in addition, the experienced operators to take a more active part, for a longer time, in the new operators training, which may affect the productivity as well as the new operator's self-esteem.

The last category is the names of the components. The issues in this category create confusion for the operators, particularly for less experienced operators. As mentioned in Table 6, there can as many as three or more names for the same component or sub-product. There are usually at least two names used. Sometimes one name is used in the headline and another name is used in the instructions themselves, usually is the English name used in the headline and the Swedish name in the instructions. The fact that the English name, which is usually not the name the operators use when referring to the component, is used in the headlines makes it more difficult to find the correct chapter.

In addition to the quality issues in the instructions mentioned above there is also information that the operators use that is not part of the instructions. These are:

- A description of all tools, their names and part numbers.
- A description of all material needed and the positions in which they will be mounted. This information is currently only available in IFS.

5.5 Material Handling

The material handling at BA1 is evaluated through a cost calculation and a table listing the advantages and disadvantages regarding the current state. A SWOT analysis is conducted for a future scenario where the kitting procedure and the location of the main storage are changed.

As stated in section 4.4, the kitted material is placed in plastic bags by the material handlers at Location B, and delivered in larger bins to the operators in BA1. Worthy of note is that each bin regards the material for one production order.

The current procedure of material handling is not an optimal solution according to the operators in Cleanroom 7. The operators state that it is a time-consuming task to get all the material out from the plastic bags, since there are a lot of components to handle. Furthermore, the delivered material is sorted according to part number at Location B, while the operators must organise the material according to cleaning procedure, which they consider to be another waste.

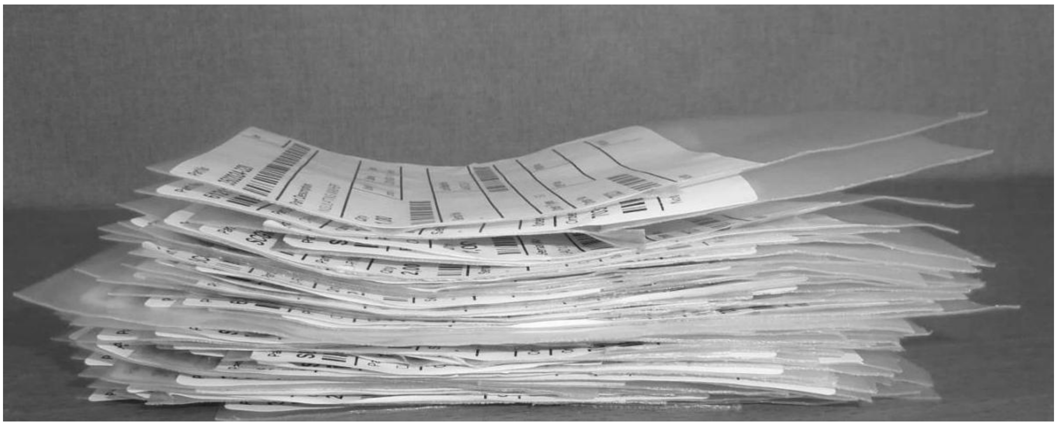


Figure 38: Kitting of bulk material

One product requires 63 plastic bags with bulk material such as screws, o-rings, and washers. Figure 38 visualises a pile of plastic bags that an operator has cut open and removed components from.

The advantages and disadvantages of the main storage at Location B and the kitting are summarised in Table 7 and Table 8.

Table 7: Advantages and disadvantages of main storage at Location B

Elements	Description
Available space	Advantages: Having the main storage at Location B contributes to more available space in BA1. Disadvantages: Material in the main storage creates tied-up capital. Since there is a lot of available space at Location B, there is a risk that the amount of material is not kept at an optimal level.
Location	Advantages: One advantage is that all material is transported to Location B and not BA1. This is considered as an advantage due to the fact that BA1 is in the security and defence industry, and therefore careful about whom is allowed to enter the facility. Disadvantages: If the incorrect part number has been delivered to BA1 it must be transported back to the main storage at Location B. The process of sending an incorrect part number back to the main storage, and receiving the correct one is estimated to 1 day. Moreover, the main storage at Location B is not considered to be flexible in the situation where article numbers are needed in urgent matters.

Competence	Advantages: All material handlers at Location B are specialised within the concerned knowledge area, and considered suitable for the work. Disadvantages: Since there are no operators present at Location B, there is no exchange of knowledge and ideas regarding material handling. In the current situation, the operators and material handlers cannot inspire each other.
Delivery precision	Disadvantages: There is a lack of integration between BA1 and Location B. Last-minute changes are made in the orders which negatively affect the planning procedure of shop orders. In addition, last-minute changes might hinder the material to be delivered on time.
Environmental factors	Advantages: The trucks are stocked with material intended to be transported to more than one facility. Disadvantages: There is no available cleanroom at Location B. Therefore, some components must be transported for inspection to BA1, and sent back to Location B for storage. Furthermore, obvious drawbacks are emissions, pollutions and costs related to transports by truck.

Table 8: Advantages and disadvantages of kitting

Elements	Description
Resources	Disadvantages: High costs for kitting and for the plastic bags and labels needed for the kitting. Additional work for the operators to remove the components from the plastic bags. Same part number for the same order in different plastic bags is cost inefficient. There are many components to kit; the kitting takes a long time to perform. All components must be placed in the machines by someone upon arrival.
Competence	Advantages: Operators can focus on assembly and testing. Material handlers can focus on kitting. Disadvantages: The knowledge and opinions of the operators have not been taken into consideration when deciding how the material is handled and packed.
Technology	Advantages: Machines and computer systems support the material handlers and reduce the risks of errors. Disadvantages: Computer systems are slow and inefficient. The high level of automation makes it very difficult to kit if system or machine is down, which may lead to delivery delays.
Environmental factors	Disadvantages: Many plastic bags and labels are used, none are reused. Same part number for the same order can be split into several plastics bags. Many transports to and from the storage with small quantities of the same part number.

5.5.1 Cost Calculations

The calculations regard the costs that arise due to the current material handling procedure of bulk material at BA1. Labour costs and material costs are included in the calculations in order to provide a brief overview of the material handling system. The costs include the material handling for one product only. Therefore, the calculations do not include any transportation costs since several orders for different customers are delivered in the same truck. Any conclusions made based on this analysis should therefore take that into consideration.

The salaries for operators and material handlers in the Västra Götaland region, Sweden are presented in Table 9 (Lönestatistik, 2016).

Table 9: Salaries for operators and material handlers

Profession	Salary [SEK/month]
Operator	23 921
Material handler	23 927

An addition employer fee of 31.42% is added to the salaries for the operators and material handlers (Skatteverket, 2016). Additional costs such as pension are excluded in the calculations. The amount of working hours per month is estimated to 169 hours (Arbetstimmar per månad, 2016). This leads to an hourly cost of approximately 186 SEK/hour for both operators and material handlers.

The SAM analysis in section 5.2.1 provided norm times for the following tasks in Cleanroom 7:

- Material handling before cleaning procedure – The work tasks include cutting and opening the plastic bags to get the components. Organising the components and sorting them according to cleaning process are also taken into account.
- Cleaning procedure – The work tasks concern both preparations and waiting during machine times for cleaning the material.
- Material handling after cleaning procedure – The work tasks concern sorting and placing cleaned components by the assembly stations.

The norm times generated by the SAM analysis regards one production order, see Table 10.

Table 10: Norm times according to the SAM analysis

Work Task	Time [h]
Material handling before cleaning procedure	0.27
Cleaning procedure	3.86
Material handling after cleaning procedure	0.18

The total time for material handling and cleaning components is estimated to (eq.8):

$$Total\ time = 0.27 + 3.86 + 0.18 = 4.31\ h \tag{8}$$

There is a rather high level of automation for the material handling in the main storage. The material handler uses a digital device to get a desired part number. However, the automation system is not efficient and the material handler must often wait until he/she gets access to the material. Once the system provides the correct part number, the material handler gets the desired quantity and places the material in the plastic bag. Lastly, the plastic bags are labelled and placed in a larger bin. The time to kit one part number according to this process is estimated to 5 minutes, which is based on the information received from the authors' visit at the main storage. Therefore, the total time to kit for one production order is (eq.9):

$$Total\ time\ kitting = \frac{5\ min \times 63\ plastic\ bags}{60\ min\ per\ hour} = 5.25\ h \tag{9}$$

The labour costs are calculated according to following formulas (eq.10-11):

$$Labour\ cost\ Operator = 186 \times 4.31 = 802\ SEK \tag{10}$$

$$Labour\ cost\ Material\ handler = 186 \times 5.25 = 977\ SEK \tag{11}$$

Table 11 presents the material cost per piece of plastic bags and labels.

Table 11: Material costs per piece

Material	Cost [SEK/pcs]
Plastic bag	0.50
Label	0.50

As already mentioned, one production order comprises of 63 plastic bags. The total material cost for one production order is estimated in accordance with Equation 12:

$$Material\ cost = 63 \times (0.5 + 0.5) = 63\ SEK \tag{12}$$

The total cost for material handling of one production order regards the total labour costs and material costs (eq.13):

$$Total\ cost = 802 + 977 + 63 = 1\ 842\ SEK \tag{13}$$

Worthy of note is that the cost for material handling per order excluding the actual cleaning procedure is estimated to (eq.14):

$$Kitting\ cost = 186 \times (0.27 + 0.18) + 977 + 63 = 1\ 124\ SEK \qquad (14)$$

Thus, 1 124 SEK concerns the costs due to the current kitting procedure, including the material costs for plastic bags and labels.

5.5.2 SWOT Analysis

A scenario of moving the main storage from Location B to the BA1 building at Location A was evaluated in a SWOT analysis. It also includes removing the material kitting that is the current way of handling material and replacing it with larger bins of the different part numbers. Smaller bins should also be distributed to the production and stored there but most of the material is stored in the warehouse in the BA1 building. The analysis mainly concerns the bulk material such as screws and washers.

The analysis is presented in Figure 39 and the contents of the four categories will be further presented in the following sections.

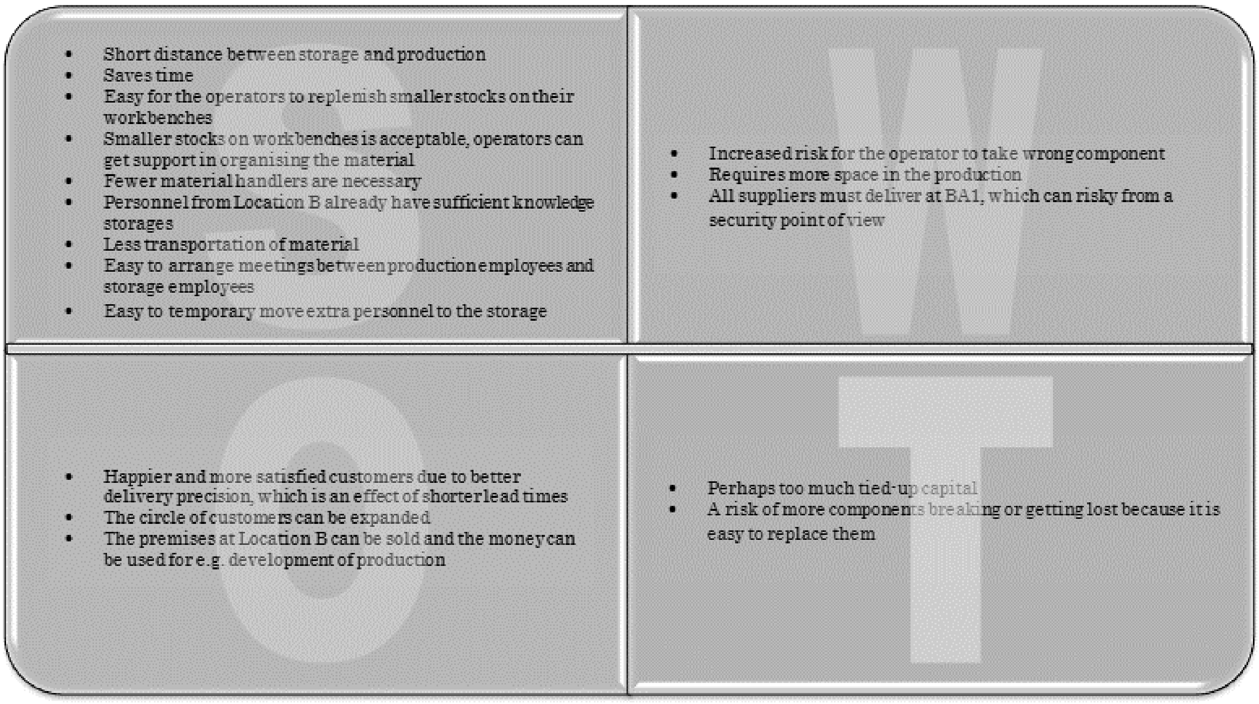


Figure 39: SWOT analysis of new material handling system

<u>Strengths</u>

There are many factors of strength of moving the main storage. The short distance between the storage and the production makes it easy for the material to be sent to production and also to rectify any problems or wrongly sent components. In addition, the closeness facilitates knowledge sharing between the operators and material handlers as well as shortens the distance that the optical components must be transported for inspection and later storage. Meetings between the warehouse personnel and production-related personnel are easier to arrange as well due to the closeness. These meetings can lead to increased understanding for the firm plan and the consequences of not following it.

The elimination of the kitting process also saves time and resources for the company. There is no need to have personnel working with kitting all day and there is no need for the assembly operators to remove the components from the plastic bags, one bag at a time. In addition, the operators can clean many components of the same part number at once and store them in a separate bin in the production. Lastly, there is no need to have the warehouse personnel place all components in the right box in the right shelf in an automated machine.

Bulk material would always be available in the production, which facilitates the replenishment of material at the workbenches. In addition, should something be wrong with a component or should it go missing, it is easy for the operators to pick a new component. Furthermore, to have bulk material close at hand would be legitimate and the operators can get support in terms of storing and organising this material.

Without the kitting, the material requires less transportation; it is delivered to BA1 by the supplier, moved to the warehouse and transported in-house with forklifts. There is no need for the material to be transported with trucks other than from supplier and to customer.

The competence of running a warehouse is already available in the personnel from the storage at Location B and no external competence is needed. Lastly, it is quite easy to temporarily move personnel to the storage in case something is needed urgently that the regular warehouse personnel do not have time for. This enables the warehouse to be flexible.

<u>Weaknesses</u>

Eliminating the kitting procedure contributes to a few weaknesses in the system. For instance, the material is not kitted and delivered in plastic bags to the operators, which might lead to a situation where the operators by mistake picks incorrect material from the bin. Another aspect that needs to be taken into consideration is that the bins require more available space in production.

The process of relocating the main storage might be complex due to the fact that the storage at Location B concerns other companies than BA1. Thus, several stakeholders are involved which adds complexity in the procedure to find an optimal solution of relocating the storage.

Since BA1 manufactures products within the security and defence industry it might be inconvenient to have the main storage in-house due to daily visits from e.g. truck drivers and suppliers.

Opportunities

The case of having the main storage in-house leads to an opportunity to increase the quality of delivery to the different production units at BA1. Moreover, the facility at Location B can be announced for sale in order to gain investment capital for e.g. research and development at BA1.

Another important factor is the ability to shorten the total operation time due to the removal of the kitting process. It facilitates the cleaning process in Cleanroom 7 as a large quantity of the same part number can be cleaned simultaneously because the material is delivered in bins. Moreover, the exclusion of kitting leads to a complete elimination of the troublesome process of opening plastic bags. Thus, a shorter total operation time can be achieved which gives an opportunity to increase the capacity for the production unit.

Threats

Relocating the main storage to BA1 might be considered as a threat in terms of increased tied-up capital. In addition, implementing storages in the production unit will generally increase the tied-up capital in the organisation.

Another aspect that needs to be taken into consideration is the storage of material in bins. There is a risk that the operators take for granted that material is available, since the bins might not indicate a restricted amount of parts available, and use more bulk material because it is easier to access than preciously.

6 Recommendations

The recommendations are presented and thoroughly described in the following chapter. The proposed improvements are divided into sub-sections that concern different knowledge areas; visual management, production ergonomics, material handling, production layout and productivity. The motivation behind the recommendations and expected outcomes are presented in each sub-section.

6.1 Visual Management

The production of Alpha concerns assembly tasks for new products, units for repair and rework. As mentioned in 4.1.3 the product flow is not predictable due to the fact that the products usually require rework of some sort. Most units fail at least one test and it is impossible to predict where in the flow the unit will fail. Since the product is moved back in the production flow due to test failures, it becomes significant to visualise the planning procedure to increase the communication among the operators.

The visual planning recommendation only regards Alpha due to the limitations of this master's thesis. However, there is a great potential to apply this suggestion to other products at BA1.

The traditional way of visualising the planning procedure on a white board together with post-its is not an option in this case. The production system in Cleanroom 7 is ISO 14644-1 certified with class 7 which does not allow the usage of material made from natural fibres found in e.g. paper and certain pencils. Therefore, a software-based visual planning suggestion is proposed for Cleanrooms 7 and 8 due to the restrictions defined in ISO 14644-1.

The planning procedure for the production of Alpha should be visualised on one big touch screen in each cleanroom. The assembly and testing operators can directly on the screen move a card corresponding to a particular product between different assembly or test operations, in order to update the real time information. The cards include information regarding the production of the specific unit, which is described in more detail in 6.1.2. As the product is transported back and forth between Cleanrooms 7 and 8, the production flow and visual planning for Alpha includes both cleanrooms with the airlock as the main link. Having the same planning procedure in the two cleanrooms will help the assembly and testing operators to create a good production flow by better synchronising the activities conducted in Cleanrooms 7 and 8. Therefore, the assembly operators and testing operators have access to the same software and can make changes on the screens simultaneously.

6.1.1 Visual Planning Solution

It is crucial that the interface of the visual planning is easy to understand and control to ensure utilisation of it and therefore production gains. The suggested planning board is divided into eight main parts, see Figure 40.

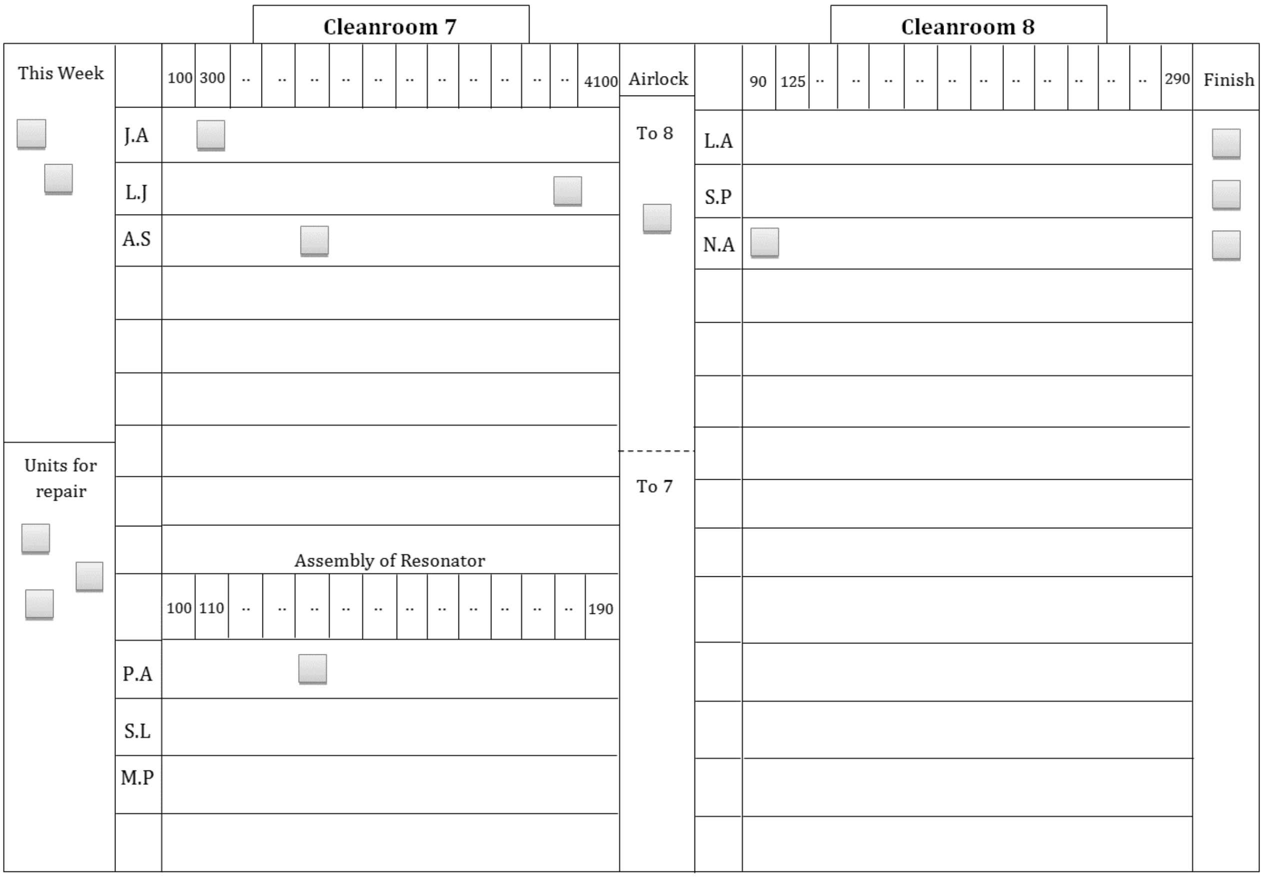


Figure 40: Visual planning solution

The first part from the left is “This week” and concerns the units that should be assembled during the week. The planning of which units, and how many, that should be handled during the week is set by the production management team during their firm plan meetings. Cards corresponding to these units are put on the board under “This week”. It clearly shows the operators what is expected of them during the week.

The next part is “Units for repair”. Cards put under this headline correspond to units for repair that have been received from customer but that the operators have not yet started repairing. This means both units for repair that awaits a decision from customer and units for repair that waits to be included in a firm plan.

The part called “Cleanroom 7” is a matrix where the actual planning and real time information is shown and updated. The columns in the matrix correspond to the operations performed on Alpha in Cleanroom 7 and the rows in the matrix correspond to the operators, visualising what units are handled by which operators. When the operators wish to start with a new unit, or a unit for repair that has not yet been handled, they simply drag a card from "This week" and drop it in the intersection between the operator's name and the first operation. Once that operation is finished, the operators drag the card to the next operation. In this way, the flow of the units is visualised quite clearly; everyone knows where each unit is in the production flow and who is responsible for performing that operation.

In addition, there is also a sub-headline to "Cleanroom 7" that is called "Assembly of Resonator". These operations are also performed in Cleanroom 7, but there are three operators specifically designated for the resonators, which is why this assembly is separated from the rest of the assembly. Furthermore, several of the operations concerned with the resonator can be handled in parallel with other assembly and test activities.

To the right of "Cleanroom 7" is "The Airlock", which signifies units waiting to be transferred from one cleanroom to the other. "The Airlock" is divided into two parts; "To 8" and "To 7", referring to the two cleanrooms. A card is put under one of these headlines when the corresponding unit physically has been placed in the airlock. The operators of both cleanrooms can easily see what units are waiting to be handled, what type of operation is next and what operations the units have already been through. This part of the visual planning is used as a communication tool between the operators in the two cleanrooms.

The part called "Cleanroom 8" works in the same way as the previously mentioned "Cleanroom 7". In the first column are the names of all operators in Cleanroom 8 put and in the first row of "Cleanroom 8" are all operations in Cleanroom 8 put. It is a way of tracking the units' progress through the production in Cleanroom 8.

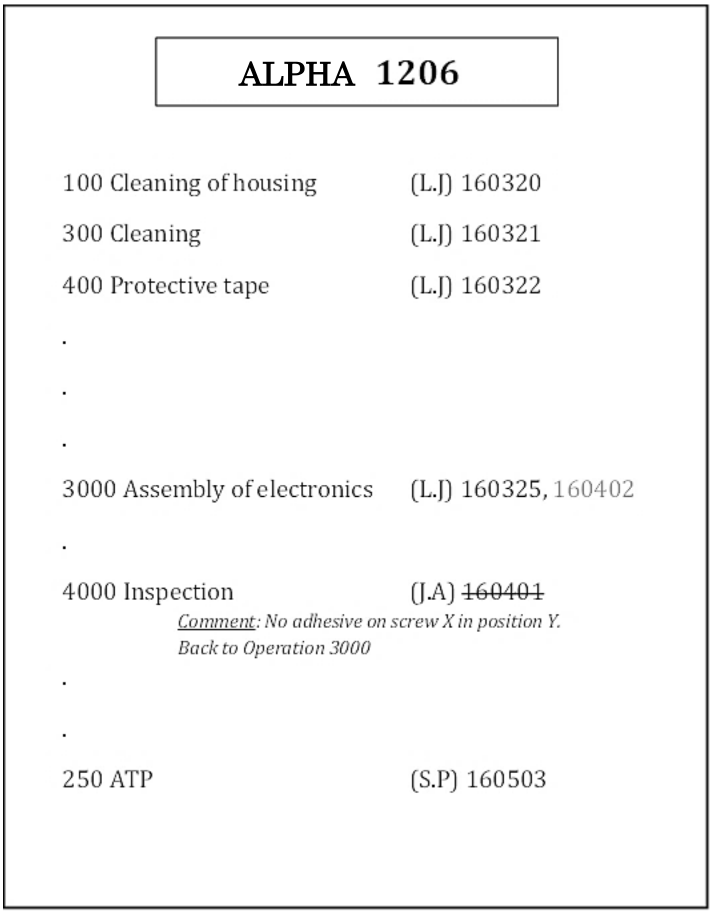
Lastly, once a product is finished for delivery to the customer, the corresponding card is put in the part named "Finish". This is a way to inform operators in both cleanrooms and the production management team that a product has passed all tests and is ready for delivery.

6.1.2 Product Card

The main objective with the product card is to provide significant information regarding the product to the operators and production management team. The product has a complex production flow where several assembly and test operations are conducted multiple times. The information provided in each card intends to visualise the production flow and clarify where in the process the product must go back due to e.g. test failures.

The product cards that are moved by the operators include information regarding the conducted assembly and test operations, see Figure 41. The product card is named with the product name and order number, e.g. Alpha 1206. Once an operation has been accomplished the operators report the completion date which indicates that the product is ready to be moved to the next operation. The operators complement the documentation with their initials. This is crucial for enabling a good communication among the operators in Cleanrooms 7 and 8.

In the case where a product has failed a test, the date is struck out by the operator. In addition, the operator specifies where in the flow the product must go back and why in order to update real time information. Operations with more than one date indicate that the operation has been accomplished more than once.


ALPHA 1206

100 Cleaning of housing (L.J) 160320

300 Cleaning (L.J) 160321

400 Protective tape (L.J) 160322

.

.

.

3000 Assembly of electronics (L.J) 160325, 160402

.

4000 Inspection (J.A) ~~160401~~

Comment: No adhesive on screw X in position Y.
Back to Operation 3000

.

.

250 ATP (S.P) 160503

Figure 41: Product card

6.1.3 Purposes with Visual Planning in Cleanrooms 7 and 8

One main objective with this recommendation is to give the operators the responsibility to plan their own work with some guidance from the production management team that set the firm plan. The operators receive information from the firm plan regarding the products that should be assembled during the week. However, it is the operators that have the responsibility to plan the start and sequence of the required assembly operations for the products specified in the firm plan. This way of working is based on the fact that the operators have both exceptional knowledge and experience of the time required to conduct the different operations. Moreover, to enhance a good communication among the employees it is recommended to discuss the visualised planning procedure during the morning meetings. This, in turn, creates an opportunity for the employees to give feedback to each other, and create strategies to avoid potential issues in the different production flows.

The two main purposes with implementing visual planning are to increase the *communication* and enable a *levelling of the workload* (Lindlöf and Söderberg, 2011):

- Communication: Visual planning enables an increased communication both among the operators and between the production management team and operators. The visual planning solution illustrates the entire production flow procedure, including different assembly and test operations required before delivery to the customer. Therefore, both the assembly operators and testing operators know *who* is doing *what*. This will in general create a holistic view for the operators regarding the product and its production flow. Using the same visual planning method in both cleanrooms will enhance the communication between the assembly and testing operators. Sending e-mails, as stated in section 4.2, to inform each other when a unit is ready to be moved between the two cleanrooms is eliminated. The visual planning solution illustrates when a unit is in need of either assembly operations in Cleanroom 7, or tests in Cleanroom 8. Furthermore, the production management team will get an insight of the work conducted in the production, which is essential in order to support, not control, the operators throughout the process. An example of supporting the operators is to supply the operators with material at the right time. Therefore, the visualisation intends to prevent waiting time in production.

- Levelling the workload: Visual planning creates a basis for levelling the workload among the operators. The visual planning method provides a clear picture of the amount of work each operator has. This information should be used to achieve an even workload among the operators which can be further discussed during the morning meetings. Therefore, visual planning enhances the opportunity to delegate the work evenly among the operators since the current status of the work in progress is visualised.

6.2 Physical Ergonomics

The recommendations regarding physical ergonomics intend to prevent the operators from working in the bad postures identified in section 5.3. The following situations identified in the analysis force the operators to work in bad postures that are harmful for the body:

- The keyboard is positioned in front of the computer and the operators must twist their back and keep their arms suspended, without support, when typing.
- Material and equipment used frequently are kept at a low height.
- Attachment of tubes to the housing before the leak tests requires a combination of force and technique, while the operators are bending.
- The flushing device requires the operators to manually rotate the unit repeatedly when fluid is pumped into the housing.
- A long screwdriver is used to fasten screws with a fixed torque.
- The operators keep the unit in their lap while mounting sub-product H.
- Manual assembly with high-precision work forces the operators to come close to the unit.

As mentioned, the current position of the keyboard creates a posture where the operators must twist their back and neck, and keep their arms suspended without support. In order to avoid this bad posture, the authors recommend the company to invest in workbenches that have a withdrawable desk. The intention is to place the keyboard on the withdrawable desk in order to decrease the load on shoulders. There are mainly two factors that are important with this recommendation; the arms are supported while typing and the shoulders are situated directly over the hips (Berlin and Adams, 2014). The new position of the keyboard on the withdrawable desk decreases the amount of load on the shoulders. Moreover, the computer is considered as a valuable aid for the cognitive support in terms of work instructions and drawings. This implies that the operators frequently use the computer during the assembly work. Berlin and Adams (2014) claim that frequency in a posture might cause ergonomic stress. The improved posture will therefore decrease the ergonomic stress for the operators (Berlin and Adams, 2014).

The analysis indicates that the operators must bend and stretch to retrieve material and equipment during different cleaning procedures. The components are cleaned with alcohol which is located at the bottom of a cabinet. A recommendation is to relocate the containers with alcohol to a shelf that is higher located the cabinet. The relocation of containers will decrease the load on back and knees since the operators are not forced to bend (Berlin and Adams, 2014).

Moreover, the containers should be positioned at the front row of the shelves to prevent the operators from extending their arms to reach the container. In addition, the containers should be handled close to the centre of the body which is recommended when managing external loads (Berlin and Adams, 2014). The company should apply this recommendation for all material and equipment that are currently positioned at a low height in order to improve the physical ergonomics.

As mentioned in the analysis there is a tank located on the floor into which the used alcohol is emptied. Firstly, a funnel must be attached to the tank which is also positioned on the floor. The authors recommend the company to place the tank and funnel on a trolley, positioning the tank at waist height. The trolley will prevent the operators from having to bend low, where the back and knees are foremost put at risk due to physical loading (Berlin and Adams, 2014). Currently the operators must bend the neck to ensure that the funnel is attached into the tank. Therefore, the physical load on the neck is also eliminated with the proposed relocation of the tank.

The operators must use a combination of force and technique in an awkward position while attaching the tubes to the unit before the leak test. It is the design of the leak test machine that forces the operators to work in a bad posture. The authors therefore recommend the company to investigate other leak test machines that do not require the same amount of physical load as the current device. In addition, the same suggestion is recommended for the flushing device. In the current state, the operators must manually rotate the unit which creates both physical load, because of the need to bend the back, and mental stress, since there is a risk to lose grip and drop the unit (Berlin and Adams, 2014). It would therefore be suitable to invest in a new, automatic flushing machine that does not demand the operators to manually rotate the unit in order to completely eliminate both physical load and mental stress.

As stated in the analysis, the screwdriver that is used to fasten screws with a fixed torque is not suitable for all parts of the assembly of the unit. The screwdriver is for instance longer than the unit which makes it difficult for the operators to mount screws inside the housing. The screwdriver is too long which forces the operators to position their hand and arm at an inconvenient height. The operators should use a screwdriver with a shorter lever in order to keep the arm below shoulder height while mounting screws on the unit. A shorter screwdriver will improve the physical loading through decreasing the load on shoulders (Berlin and Adams, 2014). Furthermore, the operators will more easily access surfaces inside the unit with the shorter screwdriver. However, the longer screwdrivers should still be available as they are sometimes essential in reaching certain screws that are impossible to access with a shorter screwdriver.

The mounting of sub-product H into the housing is considered as a severe task from an ergonomic perspective. The operators are forced to keep the unit in the lap in order to accomplish the assembly task. The operators must use both hands simultaneously when mounting sub-product H into the unit. It is therefore convenient to provide the operators with a fixture. The intention with the fixture is to hold the unit in a desired position instead of placing the unit in the lap. The fixture would eliminate the awkward posture of keeping the unit in a steady position with static force from legs and shoulder (Berlin and Adams, 2014). In addition, the fixture can keep the unit in a desired position during a long period of time without causing any risk of injuries for the operators. Furthermore, the fixture will eliminate the usage of force from legs and shoulders which prevents the operators from feeling ergonomic stress during the mounting.

The operators must come close to the housing since the different assembly tasks require high-precision work. In the current state the unit is placed on the workbench and the back and neck are negatively affected during the assembly due to bad posture. The authors recommend supplying the operators with fixtures that can keep the unit in a desired position. The main objective with the fixtures is to shorten the distance between operator and unit in order to reduce the strain put on the back and neck (Berlin and Adams, 2014).

6.3 Cognitive Ergonomics

The recommendations to increase the cognitive support for the operators are based on the problems identified in the analysis in section 5.4. The root causes for a lack of quality in cognitive support during the assembly are summarised below:

- The 2D drawings are confusing rather than supporting since they entail too much information due to the product's high complexity.
- No standardised work.
- Assembly instructions are in three separate databases; Work instructions in PDF format, 2D drawings in PDF format, and reporting system Prosus.
- The work instructions in the PDF file are not organised according to the assembly sequence.
- The work instructions differ from how the work is done in reality.
- Different terms are used for the same component or sub-product.
- The work instructions are not sufficiently descriptive.
- The set operation times in Prosus do not correspond to real production time.

The 2D drawings are considered to be confusing rather than supporting due to the high complexity of the product. The drawings include too much information since the product consists of a lot of components. Another issue is that not all operators are familiar with handling 2D drawings. The authors therefore recommend the production management to offer the operators education regarding engineering drawing techniques. The education would positively affect the cognitive ergonomics since the operators would feel more comfortable and secure with gathering information from the drawings. Another approach, which also is a larger investment, would be to convert the 2D drawings into 3D model. This suggestion enables the operators to navigate around the 3D model to get information where a specific component should be assembled, e.g. Screw M2x10 in position 8Y. This solution intends to reduce the time spent on reading the 2D drawings, and increase the visualising aids during assembly. Instructions such as these are already used in other production units at BA1 and appear to be working very well.

Standardised work supports cognitive ergonomics since it provides one optimal method to conduct the assembly (Berlin and Adams, 2014). It enables all operators to perform the tasks in the way that is best at the moment, and the confusion currently existing regarding how the assembly should be done can be reduced. Moreover, standardised work is a cornerstone when working towards continuous improvements as it is easier to improve the work methods when everyone has the same foundation to work from. To implement standardised work will require a lot of time and effort from both the operators and the production management to ensure the standardised methods capture the best currently used methods of every task. When discussing the actual task times, as mentioned previously, the different ways of performing the tasks could also be discussed and the best ways of performing the tasks can be agreed upon.

6.3.1 Work Instructions

As mentioned in section 5.4.1, there are many problems with the work instructions and the lack of quality creates confusion among the operators. Another negative effect is that the instructions are not organised according to the assembly sequence and therefore forces the operators to spend time on searching for a specific work instruction. It is difficult to find the desired information in these instructions due to the vastness of the document.

The authors recommend the production management to assign the operators with a project to update the current work instructions. The work instructions should support the operators by providing guidelines of how to conduct different assembly tasks (Berlin and Adams, 2014). The operators have both experience and essential knowledge regarding the assembly procedure of the unit. It is therefore more suitable to assign this project to the operators than to the production management.

A suggestion is to include two operators, one with more experience than the other, in order to create instructions that support both new employees and employees that have worked in the production for a long period of time. This will lead to an opportunity for the operators to work more independently, and reduce the amount of time spent on searching for information. The main objective with such a project is to create work instructions that are based on how the assembly is conducted in reality. Another factor is that the updated work instructions will provide the operators with cognitive support in terms of instructions that are designed according to an optimal assembly sequence. This, in turn, will lead to an opportunity for the operators to assemble the unit equally.

One solution to facilitate for the operators is to make one separate file for the assembly operators in Cleanroom 7, one for the inspections made in Cleanroom 7 and one for the testing operators in Cleanroom 8. Thus, the operators do not need to search through instructions that do not concern them. A similar solution is already used as the instructions for the assembly and testing of the resonator is located in a separate PDF file. However, it is important to keep in mind that all instructions should be available to all operators, regardless of which cleanroom they are working in.

The three main problem areas; sequence of chapters, assembly descriptions, and names of components, which were mentioned in section 5.4.1, should be solved in order to facilitate the work for the operators, especially less experienced operators. A solution for all three categories could be revised work instructions. The order of the chapters should be changed to correspond to the actual assembly order, which facilitates the information search for the operators. The most suitable sequence should be investigated and discussed with the operators, e.g. in a project as mentioned above. Also, all names and words used in the work instructions, routing and elsewhere should correspond to what the operators use.

6.3.2 Routing

From talking to the operators, studying their work and the work instructions it becomes apparent that there are discrepancies in the routing, concerning both the operations themselves and the description in IFS, the system in which the routing is found. Appendix N – Routing 500:A and Appendix O – Routing 500 show a complete list of all things that should be updated for each operation in routings 500:A and 500 respectively. How the discrepancies should be solved is also enclosed in the table.

As mentioned previously, routing 500:A entails most of the assembly operations in Cleanroom 7, while routing 500 entails most of the testing operations in Cleanroom 8. There are some exceptions to both routings however. In addition to these two routings there is one third, for the resonator. This routing has not been studied and is therefore not included in this chapter.

There are three general recommendations for all routings that will be described. The first concerns the fact that the numbering of the operations in the routing does not follow a logical path. Currently, the numbering is quite arbitrary and does not follow a pattern. It would be beneficial for the operators and others to change it. Every new operation could start at a new ten, i.e. Operation 10, Operation 20, Operation 30 etc. When an operation requires what is currently called process time it could be added in the same tens as the operation, i.e. Operation 10, Operation 20, Process time 21, Operation 30 etc.

The second general recommendation concerns the referencing in the operation descriptions. In some descriptions there are references to the work instructions. To facilitate for the operators should all operations have these references.

The last general recommendation is to update the operation times for many of assembly tasks in the reporting system Prosus and the ERP system IFS. It is mentioned for the concerned operations in the appendices. As mentioned in section 5.4, most of the designated operation times do not match the real amount of time spent on different assembly tasks. This misalignment affects the production planning in a negative way since a lot of re-planning might be necessary due to incorrect time data. Another important issue is that due to incorrect data, the operators might find it difficult to plan their own work since they are not aware of the actual time required for the different assembly tasks. This especially applies to operators with less experience of assembling this product.

The recommendation is that the production management involves the operators when defining the operation times in order to together match the times in Prosus with the actual time spent in production. The norm times generated by the SAM analysis in section 5.2.1 could act as a basis for the discussions between the production management and operators. However, the SAM analysis does not take rework into consideration and adjustments of the norm times are therefore likely to be necessary. The main objective with this recommendation is to provide the operators with the actual operation time which is essential in order to achieve standardised work.

The three above-mentioned recommendations and the recommendations mentioned in the appendices will contribute to reduce the time the operators spend on searching for information, make it easier for the operators to plan their time and reflect reality.

6.4 Material Handling

The main storage is currently located at Location B, the components are transported in kitted packages to BA1 at Location A and distributed to Cleanroom 7. The current way of handling and distributing material to and from the production is not optimal. Therefore, another material handling system will be presented in this section.

The authors recommend the company to consider implementing the scenario in the SWOT analysis in section 5.5.2, since the benefits overweighs the drawbacks. The suggested change is to keep the main storage within the walls of BA1 and to distribute components to the production in larger quantities, allowing storage in the production. This suggestion regards the bulk material such as screws and o-rings. Concerning the more expensive components, such as housings and completed sub-products, the distribution should be maintained as it is today; these components and sub-products should be delivered to the production once the need for them is confirmed, i.e. once an order is released.

The underlying factors for eliminating the kitting procedure are based on the results from the analysis in section 5.5.1:

- The total cost for the kitting procedure is estimated to **1 124 SEK** per production order. This cost regards the total material handling before and after the cleaning process, and the material costs.
- The total time spent in production on non-value-adding activities due to the kitting procedure is estimated to approximately **30 minutes** per order, based on norm times generated in the SAM analysis.

The new material handling system intends to reduce the costs and amount of time spent by the operators on other activities than assembly. The suggested change is thoroughly described in following sub-section.

6.4.1 New Material Handling System

The bulk material can be stored in cabinets and shelves in the optical gluing room, which is currently not being used. Figure 42 illustrates, in dashed border, the area of cabinets and shelves for this recommendation. One workbench in the optical gluing room is removed and replaced by cabinets and shelves for the bulk material.

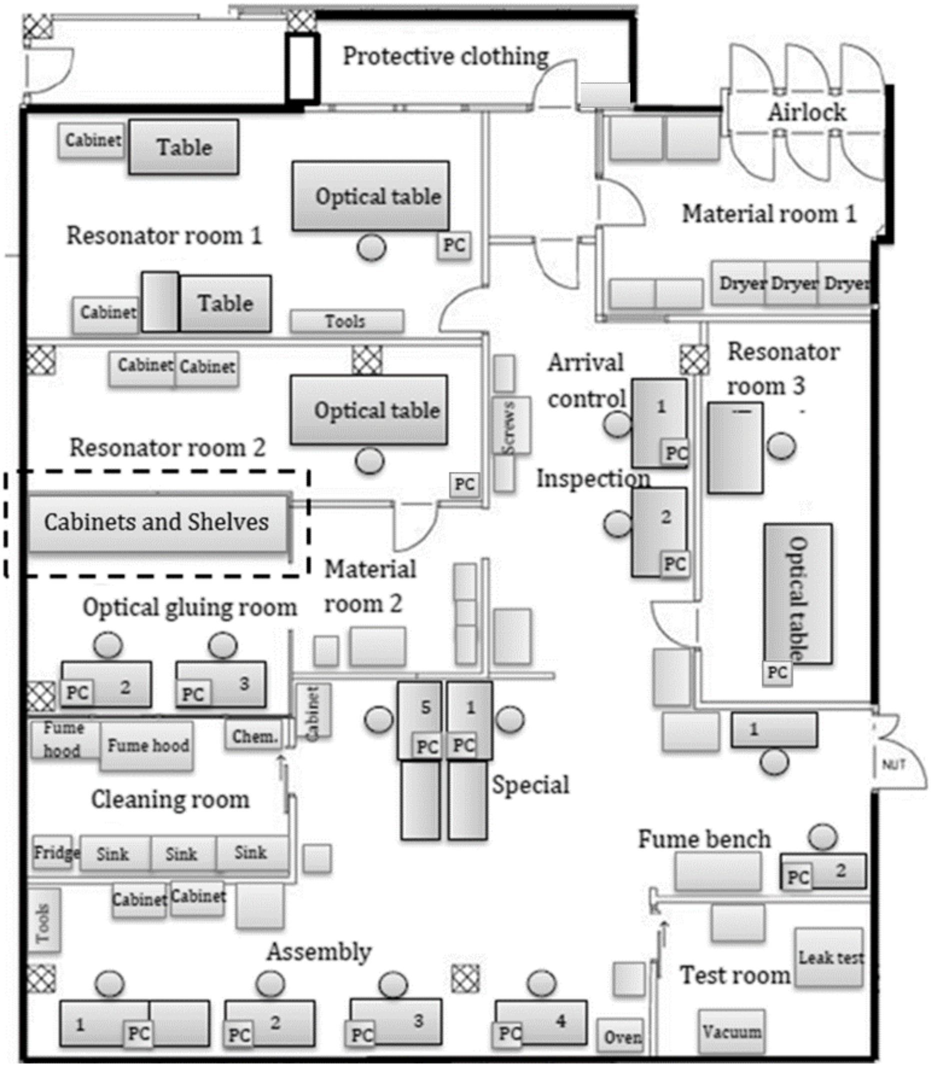


Figure 42: Location of bulk material

The cabinets must have doors to avoid dust exposure of the components and each shelf in the cabinets should be assigned to a specific type of component, see Figure 43. The rows of shelves should be organised in a way that facilitates the searching for a specific component, for instance in alphabetical order or ordered by size. Another way of arranging the shelves is to keep the most frequently used components in waist-to-shoulder-height and the less frequently used components above and below that height. The latter way of organising intends to support the operators from not bending in order to retrieve material. This is favourable from an ergonomic point of view due to less physical load on back and knees (Berlin and Adams, 2014).

Figure 43: Cabinet of bulk material

In each shelf, there should be smaller bins or boxes separating the different components from each other. This is illustrated in Figure 44.

Screws

Screws

O-rings

Figure 44: Bulk material in bins

Each bin should in turn be featured with a lid to minimise the amount of time the components are exposed to air and dust, see Figure 45.

Figure 45: Bin with lid to minimise dust

As the components are delivered in larger quantities, the operators can clean larger quantities of each part number simultaneously. This also requires a system for separating the cleaned components from the non-cleaned. One way of doing this is to use different colours for cleaned and non-cleaned respectively. In addition, labels should be used to ensure that everyone understands, and to avoid misinterpretations due to colour blindness for instance. Both the colours and the labels are tools to improve the cognitive ergonomics by supporting the operators with visualising aids (Berlin and Adams, 2014). Furthermore, the colour-coded system would help the operators finding what they are looking for and minimise the number of picking errors.

To further facilitate the picking of components and reduce picking errors, each operator should have their own tray to put the components on. The tray should have different compartments to separate the components, see Figure 46. In addition, the compartments should be labelled with the type of component and the quantity to ensure that the correct components are picked and the correct quantity of each. Each compartment should have a lid, protecting the components from dust, which are opened once that specific component is needed. When the operators start the assembly, they already have all bulk material cleaned and close at hand. It should be possible to pick all components for a whole unit on one tray. In this way, the operators do not need to go back and forth to the cabinets. Another important factor is that the tray will act as a built-in-quality during the assembly. Hence, if there is any remaining material after completion of assembly the operators must go back in the process to detect and repair the mistake.

Figure 46: Tray with components

The consumable material, such as cotton swabs, is today replenished through the use of a Kanban system. This is suggested to be used for the bulk material as well. A two-bin system should be used, which means that each component is assigned two bins or boxes in the cabinet. Once one bin is empty, it is placed outside the cleanroom with a Kanban card, picked up by the material distributer and replenished. As nothing can be brought straight into Cleanroom 7, the replenished bins must be left in Cleanroom 8 and brought into Cleanroom 7 through the airlock. Figure 47 illustrates the two-bin system for bulk material according to following procedure:

1) There are two bins for each component. The figure illustrates two bins for material M3x20.
2) The bin to the right is empty and is in need for replenishment.
3) The operator places a kanban card telling which component the bin belongs to and the re-order quantity.

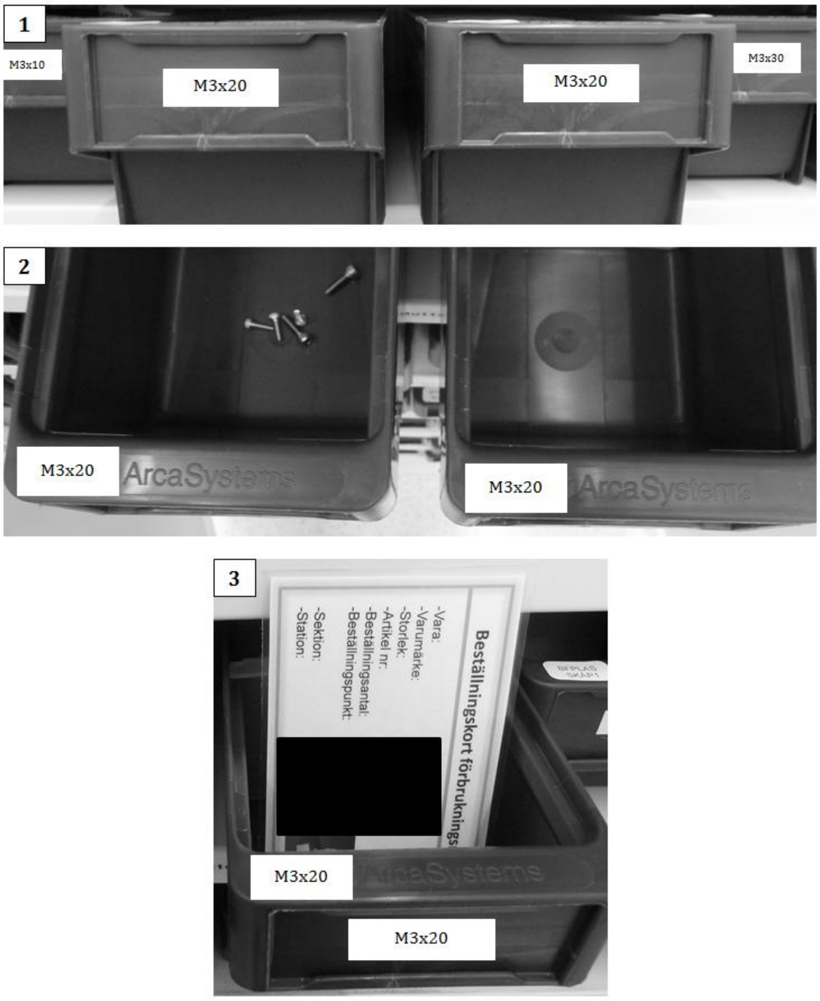


Figure 47: Two-bin system

In the room where protective clothing is put on before entering Cleanroom 7 there is a bench, marking where the cleaner area begins i.e. regulations from ISO 14644-1. Shelves could be placed above this bench and in these shelves could the empty bins be placed, see Figure 48. To place the empty bins here facilitates the leaving of the bins, by the operators, and the collecting of bins, by the material handler. The operators can place the bins in the shelves on their way out from the cleanroom and the material handler does not need to put on any specific clothes to get the empty bins. The only requirement is specific shoes, which the material handler already constantly uses.

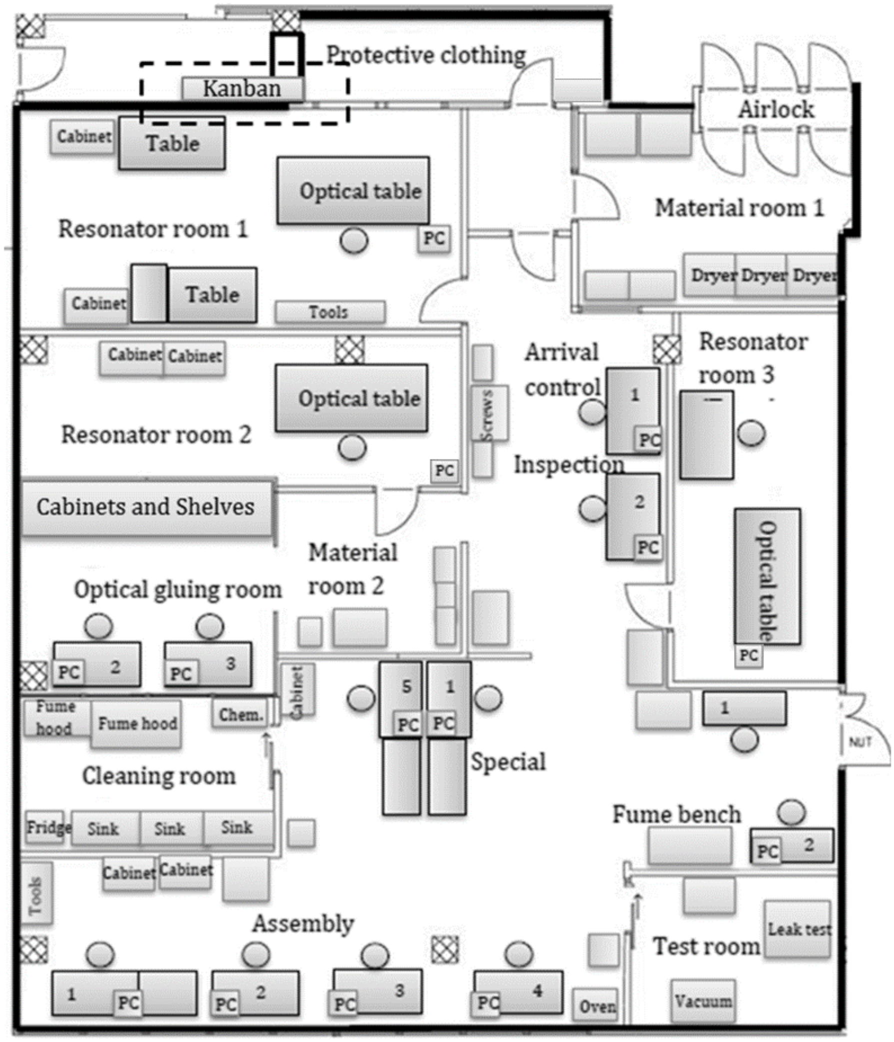


Figure 48: Kanban system in Cleanroom 7

Similar shelves should be placed just outside Cleanroom 8, also in the room where the protective clothes are put on. The operators can bring the replenished bins to the airlock when they are entering the cleanroom and place empty bins from Cleanroom 8 in the shelves on their way out.

6.4.2 Solved Problems with New Material Handling System

The new material handling system has the main objective to eliminate and reduce the identified problems in section 4.4. Table 12 presents the previously mentioned problems, and how a relocation of the main storage, and elimination of the kitting procedure aim to improve the current situation in Cleanroom 7.

Table 12: Solved problems with new material handling system

Element	Problem	Solution
Location	The delivery time to receive urgent material is estimated to 1 day. Thus, an incorrect or missing part number sent from the main storage in Location B causes waiting times for the operators in BA1.	The relocation of the main storage reduces the risk of production disturbances in terms of waiting times. An incorrect part number must not be transported back to another building as it is in the current state. Thus, the operators can expect to receive the correct or missing part number the same day as it is detected.
Resources	The labour cost for the kitting procedure in Location B is estimated to approximately 977 SEK per order. The material cost, i.e. plastic bags and labels, is determined to 63 SEK per order.	The recommendation does not include a kitting process and eliminates the associated labour cost of 977 SEK. In addition the total material cost of 63 SEK per order is excluded.
Productivity	The operators spend, according to norm times in the SAM analysis, approximately 30 minutes per order on material handling before and after the cleaning process.	The material is delivered in larger bins and not in kitted plastic bags. The process of opening plastic bags before the cleaning process is eliminated. Moreover, the delivery of material in larger bins enables the operators to clean components for several orders simultaneously. The operators can therefore clean components for more than one order.

Delivery precision	The current material handling system is not flexible to last-minute changes in the orders. Therefore, late changes in the material orders might cause late deliveries to BA1. In general, BA1 must take a delivery lead time of 1 day into consideration.	The new material handling system, with the main storage in-house, is considered more flexible to late changes in the process. The delivery from the main storage to the production unit does not include a lead time of 1 day. Therefore, the recommended material handling system has good conditions to achieve an improved delivery precision.
Environmental factors	The current distribution of material from the main storage in Location B to BA1 requires transports by truck.	The total amount of transports from suppliers to BA1 is reduced due to eliminating the transportation between Location B and BA1. This is favourable from an environmental point of view since emissions and pollutions are reduced.

6.5 Production Layout

This section presents a new layout for Cleanroom 7 that is recommended for the company to implement. The design of the new layout is based on following factors:

- Move material and equipment closer to the operators in order to reduce the total amount of steps detected in the production layout analysis in section 5.1.
- According to the SAM analysis in section 5.2.1, Operation 100 is conducted outside Cleanroom 7. The new layout intends to implement necessary equipment in order for the operators to conduct all tasks in Cleanroom 7.
- Eliminate cabinets, shelves, and equipment that are not utilised by the operators.
- Include dedicated space in the layout for the visual planning recommendation in section 6.1.
- Implement supporting tools such as fixtures based on the recommendations for improved physical ergonomics in section 6.2.
- Integrate the new material handling system, described in section 6.4, in Cleanroom 7.

Figure 49 illustrates the new layout for Cleanroom 7 with the main stations Arrival control, Inspection, Material room 1, Test room, Resonator rooms 1-3, Cleaning room, Optical gluing room, Material room 2, Assembly and Planning.

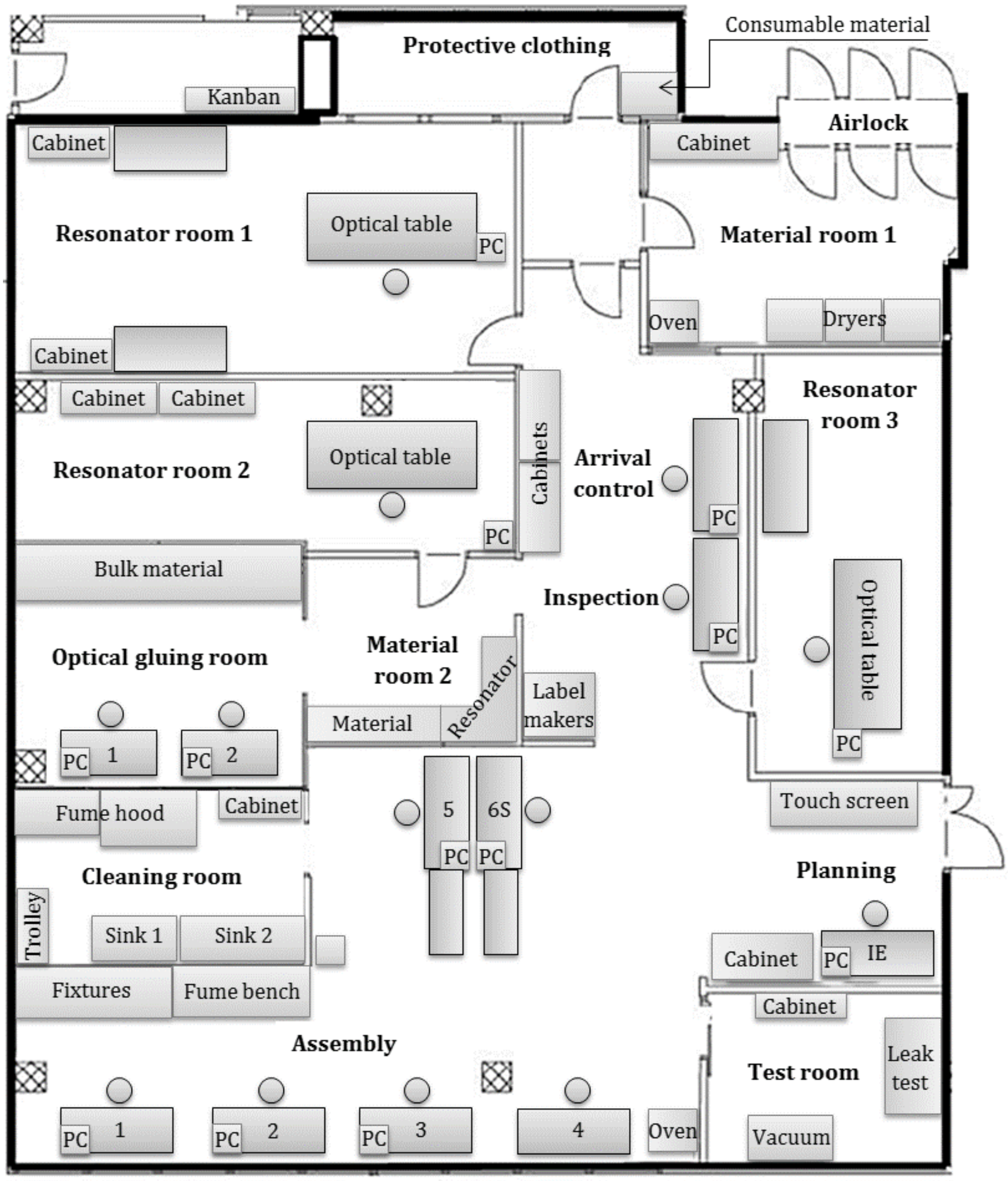


Figure 49: New layout for Cleanroom 7

The *Arrival control* and *Inspection* have two separate cabinets dedicated for material and equipment used for the tasks at these stations. There are also two label makers located on a bench nearby the two stations since these operators frequently print labels.

The minor changes in *Material room 1* concerns eliminating equipment, such as one of the ovens, which are not utilised by the operators. No changes in the layout are made for the *Test room* and *Resonator rooms 1-3*. The machines in the *Test room* are considered to have a well enough position. *The Resonator rooms* should not be changed since the design of the room is adjusted to required tests during the assembly.

Two changes are made in the *Cleaning room*; two sinks are replaced with one larger sink, and a trolley is placed in the room. Sink 1 is assigned to the flushing of the unit. The purpose with Sink 2 in Figure 49 is to enable the operators to conduct the cleaning of housing, i.e. Operation 100, in Cleanroom 7. Moving Operation 100 into Cleanroom 7 will decrease the amount of steps associated with the task from 230 steps to 11 steps. These steps concern the distances from the *Assembly station* to the two cleaning rooms; the *Cleaning room* in Cleanroom 7, and the cleaning room outside the production. Thus, the new layout indicates that the operators are no longer forced to transport the housing to another cleaning room outside the production unit. Another change is the implementation of a trolley, as mentioned in the recommendations for improved physical ergonomics in section 6.2. The tanks where the alcohol, after the cleaning process, is emptied into should be placed on the trolley visualised in Figure 49. Moreover, the liquids used for the cleaning process, such as alcohol and distilled water, remain stored in the cabinet. As mentioned in section 6.2, the most used liquids should be kept in waist-to-shoulder-height, and the less frequently used liquids above and below that height.

The number of work stations in the *Optical gluing room* is reduced from three to two. The operators do not use the *Optical gluing room* during the assembly according to the spaghetti diagram in Figure 11 in section 5.1. Therefore it is considered more convenient to utilise the space for other resources. The new material handling system described in section 6.4 includes storage of bulk material within the walls of Cleanroom 7. The bulk material delivered in larger bins from the main storage is kept in cabinets in the *Optical gluing room*, see Figure 49. Other material and kitted sub-components for the resonator is located in the next room i.e. *Material room 2*. The current situation is that the operators walk back and forth within the assembly area to gather bulk material. One of the main objectives with the new layout is to reduce the amount of steps associated with collecting material. A suggestion is that the operators start in the *Optical gluing room* and walk successively towards *Material room 2* to gather needed material for a complete production order. This is visualised in Figure 50 where the operators pick material starting from the point in the *Optical gluing room*, and returns to the point at the *Assembly station*. Thus, the operators only need to gather material one time during the assembly of the unit, with the aid of the recommended tray visualised in Figure 46 in section 6.4.

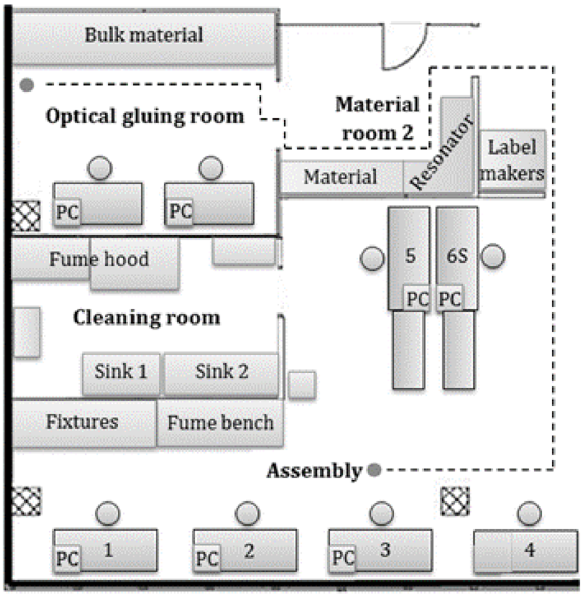


Figure 50: Material handling in Cleanroom 7

There are in total six available work benches at the *Assembly station* visualised in Figure 49. Work station 6S still concerns assembly of special units, while a microscope has been positioned at work station 4. Thus, it is not intended to conduct any assembly operations at station 4. The microscope is currently positioned in the area named *Planning*, and the operators must often inspect the cleanliness of different components in the microscope. The new layout aims to shorten the distance between the different assembly stations and the microscope. Moreover, a table is currently attached to the bench at work station 1 where the operators store bulk material. The recommendation is to remove this table since the new layout has dedicated space for storage of bulk material in *Optical gluing room.* Existing fixtures and recommended fixtures mentioned in section 6.2 should be organised and stored in a separate cabinet behind work station 1. Furthermore, the fume bench is moved from the planning area to be positioned next to the cabinet of fixtures. The unit is placed on the fume bench to harden the glue during several occasions. The new position of the fume bench aims to shorten the distance to transport units from the work stations to the fume bench.

A difference between the current layout in Figure 3 in section 4.1.2 and the proposed layout is the implementation of a new station; *Planning*. The intention is to enable an opportunity for the operators and production management to arrange daily meetings in this area. The benefit of having meetings in the production is the great accessibility to products, material and equipment. The operators can for instance easily demonstrate an issue to the production management by using the product, material or equipment. The touch screen in Figure 49 illustrates the recommended visual planning system described in section 6.1. Thus, the operators and production management can discuss the information illustrated on the screen during the meetings. The industrial engineer, illustrated by IE in Figure 49, should be available during production hours in Cleanroom 7 in order to act as support for the operators. Furthermore, the cabinet next to the IE should be utilised to store both units for repair that are waiting for a decision, and semi-finished products.

6.5.1 Spaghetti Diagram

The following subchapter presents the savings that the company could gain with the new layout, in terms of decreasing the total travel distance (TTD) and the total travel time in Cleanroom 7.

A spaghetti diagram for the new layout is illustrated in Figure 51. The black lines correspond to the route that a unit takes during the assembly.

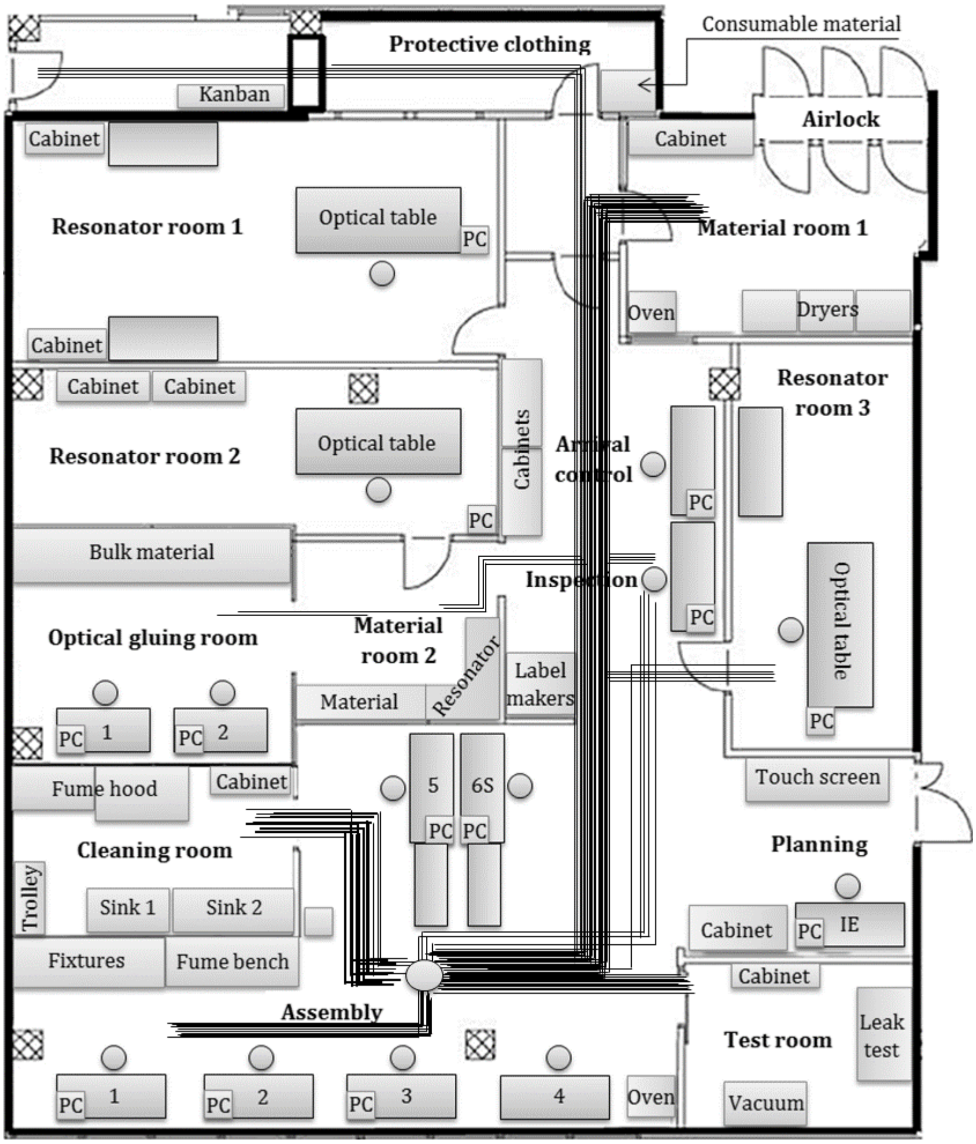


Figure 51: Spaghetti diagram for the new layout

The spaghetti diagrams for the current layout in Figure 11 and the new layout in Figure 51 indicates following changes:

- The operators do not walk back and forth within the assembly station to gather bulk material. Instead, the operators gather all bulk material for one order in the Optical gluing room and Material room 2.
- The distance to transport the unit to the fume bench is shortened due to relocating the bench close to the Assembly stations.
- Figure 51 shows that the operators are in general working within the assembly area. This is achieved through moving equipment and material closer to the operator.
- Conducting all assembly tasks in Cleanroom 7 eliminates the travel distances outside the production unit.

The TTD for a unit regarding the tasks performed by the operators in Cleanroom 7 is estimated to 1538 meters, and the travel time is calculated to 18 minutes. Table 13 presents a comparison between the TTD for the current and new layout.

Table 13: Total travel distance

Total Travel Distance (TTD), Cleanroom 7		
	Current state	New layout
Distance [meters]	3 190	1 538
Time [minutes]	38	18

The numbers presented in Table 13 result in following improvements:

- The total distance is decreased with **1652 meters**.
- The total travel time is decreased with **20 minutes**.

These improvements are mainly achieved through the new material handling system, conducting all assembly tasks within Cleanroom 7, and relocating equipment and material closer to the operators.

6.6 Productivity

The effects that the recommendations are estimated to have on productivity will be addressed in this chapter.

6.6.1 Methods Improvement

Table 14 presents how the recommended improvements affect both the distribution of non-value-adding and value-adding work, as well as the total operation time. The assembly operations in Figure 13 are included in this section together with a thorough description of proposed changes. The intention with the changes is to reduce the total operation time for each unit.

Table 14 presents the operations in the current state as well as in a future state where the suggested recommendations have been implemented. The operation times are from the SAM analysis. Glue hardening is excluded in the total operation time.

Table 14: Assembly tasks, before and after implementing recommendations

Operation		Non-value-adding [%]	Value-adding [%]	Total time [min]
100	Current	26	74	25.65
	Future	11	89	19.61
300	Current	12	88	230.29
	Future	9	91	66.8
400	Current	9	91	21.73
	Future	5	95	20.29
500	Current	79	21	57.02
	Future	84	16	48.43
600	Current	35	65	37.02
	Future	26	74	31.23
601	Current	39	61	6.46
	Future	32	68	5.73
602	Current	35	65	7.77
	Future	19	81	6.25
700	Current	29	71	32.35
	Future	19	81	27.76
850	Current	22	78	14.12
	Future	18	82	13.43
900	Current	3	97	253.08
	Future	3	97	73.05
3000	Current	19	81	114.50
	Future	14	86	92.18
3310	Current	41	59	18.40
	After	27	73	15.03
4100	Current	22	78	8.04
	Future	17	83	7.61
90	Current	46	54	7.43
	Future	26	74	5.39
125	Current	15	85	24.19
	Future	14	86	23.74

130	Current	50	50	10.13
	Future	23	77	6.50
220	Current	41	59	7.78
	Future	19	81	5.66
230	Current	31	69	17.31
	Future	22	78	15.37
232	Current	6	94	34.74
	Future	5	95	34.25
235	Current	26	74	20.76
	Future	15	85	17.91
260	Current	30	70	9.98
	Future	28	72	9.56

Figure 52 presents the new distribution of non-value-adding and value-adding work for all manual assembly tasks conducted in Cleanroom 7. A comparison between the data in Figure 15 and Figure 52 indicates the following achievement for the production of one unit in Cleanroom 7:

- The total time in Cleanroom 7 is reduced with 7 hours, from 16.1 hours to 9.1 hours.

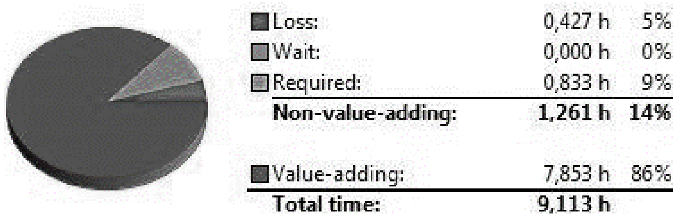


Figure 52: New work distribution in Cleanroom 7

The total operation time for one unit regards all operations in Cleanrooms 7 and 8. Due to the limitations of this master's thesis, changes have not been suggested for the tasks conducted in Cleanroom 8. However, the time for some of the operations in Cleanroom 8 is reduced by the visual planning tool.

Figure 54 illustrates the new work distribution and total time, based on norm times from SAM, for one unit.

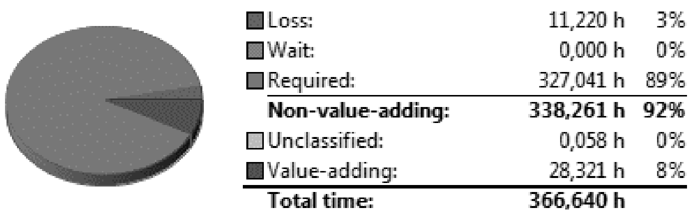


Figure 53: New work distribution for one unit

Thus, the total operation time for one unit is reduced with **7.4 hours**, from 374 to 366.6 hours. How the operations are affected by the suggested changes and what contributes to the reduction of the operation time is presented below.

The amount of time spent on searching for and reading instructions is assumed to be greatly reduced due to the improved instructions. Also, because of the visual planning board, it is no longer necessary for the operators to e-mail each other but they can instead move the product card from their computer or on the touch screen. The time for this type of communication is therefore also shortened.

<u>Operation 100: Clean housing</u>

The main difference for Operation 100 is that the cleaning procedure is conducted in Cleanroom 7, and not in another room outside the production unit. The larger sink, i.e. Sink 2 in Figure 49, enables the operators to clean larger components such as the housing and cover top in Cleanroom 7. The operators do not have to transport the unit to another cleaning room located in the building. The relocation of Operation 100 decreases the TTD for the operators. Another change is that material and equipment, such as soap, gloves and protective clothing, are positioned in waist-to-shoulder height. Thus, the operators do not need to bend or reach for the required material and equipment.

<u>Operation 300: Clean components</u>

The main reason for the time for this operation being reduced from 230 minutes to 66.8 minutes is due to the new material handling system, in which the kitting is removed. Because of this, it is possible for the operators to clean components for multiple units simultaneously. It has been assumed that components for three units can be cleaned together with the current equipment that exists. The time for cleaning that has been assigned to one unit is the total cleaning time for three units divided by three. This is the time required for one unit, even though the cleaning procedure is not performed once for every unit.

The material and equipment for the cleaning procedure, e.g. alcohol, distilled water, and the disposal tanks, are positioned at waist-to-shoulder height. The disposal tank that is used to empty the alcohol after the cleaning process is located on a trolley instead of the floor. The relocation of the disposal tanks prevents the operators from bending when emptying used alcohol in the tanks. Thus, unnecessary movements are eliminated.

Another change is the implementation of a new material handling system in Cleanroom 7. The new material handling system eliminates all activities related to getting bulk material from plastic bags, and sorting components before and after the cleaning process.

Operation 400: Protective tape

The operators have direct access to the protective tape and temporary signs since they are now placed at the workbench. Thus, the operators do not need to move from the assembly station in order to get required material for the operation. Another change is the delivery of protective tape. Currently, the operators get 15 pieces of protective tape that fits the unit. However, the unit must be covered with 16 pieces of protective tape. Therefore, the operators should get 16 pieces of protective tape and not spend time on creating the last piece for the unit.

Operation 500: Paint + mount small parts

The travel distance is changed since the fume bench is moved to the assembly stations, and some of the material, such as larger o-rings, is located in Material room 2. Operation 500 includes the usage of paint brush and a temporary cover top, and should therefore be placed at the workbench. The operators do not need to move from the assembly station to gather material for the painting in the proposed solution. Furthermore, all bulk material required for Operation 500 is stored in a tray positioned in front of the operators. These changes intend to reduce the TTD for the operators.

Operation 600: Mount

A lot of bulk material is required for Operation 600 which is proposed to be located by the workbench. Thus, the operators do not need to move back and forth to gather material for the assembly. Another change is that the tools, e.g. screwdrivers, are placed on the workbench. Another recommendation is to locate the red- and protective paint in the same cabinet in the cleaning room. The operators should gather these jars of paint simultaneously instead of moving between different cabinets in Cleanroom 7.

Worthy of note is that the operators should use fixtures during the mounting of sub-product H in order to improve the physical ergonomics. The operators must therefore get the fixture from a cabinet located at the assembly stations. One tool that is used is currently found in the test room. A recommendation is to place this tool together with the microscope on station 4 in the layout, in order to reduce the amount of steps. Moreover, the operators move between the assembly station and fume bench during several occasions. Thus, the relocation of the fume bench contributes to decreasing the total operation time through elimination of steps.

Operation 601: Mount sub-product R

Consumable material, such as nitrile gloves, is placed by the workbench and the operators are not forced to move away from the assembly station. Operation 601 includes bulk material that is now placed in front of the operators by the workbench. Thus, the travel distance to gather material is reduced. Another aspect that decreases the total operation time is the shortened distance between the assembly station and fume bench.

Operation 602: Leak test

The material needed to clean the unit before the leak test should be positioned by the workbench. Today the material is placed in a cabinet a few meters away from the station which forces the operators to move from the workbench. Also, a new leak test machine, which was mentioned in section 6.2, is assumed to shorten the time by reducing the need for bending, stretching and waiting as is the situation today.

Operation 700: Assemble sub-product C

Consumable material such as silver foam, nitrile gloves, paper towels and lens papers are positioned in waist-to-shoulder height. Thus, the operators are not forced to reach and bend in order to retrieve needed material. The assembly of sub-product C entails several components and the operators must move back and forth to gather bulk material. The recommended solution of having a tray positioned at the workbench intends to avoid unnecessary movements. Furthermore, the fume bench is now located closer to the assembly stations which shortens the distance from the workbenches to the fume bench.

Operation 850: Mount

The new material handling system with bulk material positioned on the workbench eliminates all movements from the assembly station to another location in Cleanroom 7. The operators work within the assembly station without interruptions in terms of collecting material. The design of the workplaces enables the operators to have direct access to both tools and consumable material. Thus, the operators do not need to reach, bend, or take any steps since the tools and material are positioned at arm's length from the operators. Furthermore, the relocation of fume bench is significant in terms of decreasing the amount of non-value-adding work.

Operation 900: Leak test and flushing

The same changes described in Operation 602 apply for the leak test in Operation 900 as well.

As mentioned in section 6.2 the company should invest in a new flushing device that handles the rotation of the unit in order to remove air bubbles. Furthermore, an upgraded flushing device decreases the processing time from 4 hours to 1 hour. Today the operators must regularly rotate the unit 10 times during the flushing procedure. The new flushing device enables the operators to focus on other assembly tasks during the flushing process time. Furthermore, the total amount of steps associated with manually rotating the unit is eliminated. Worthy of note is that the total time for Operation 900 presented in Table 14 excludes the required cool down time of 3 hours after the flushing process.

Operation 3000: Mount electronics

Operation 3000 concerns mounting several sub-products in the unit. The sub-products each include a lot of bulk material. The new material handling system eliminates all movements related to gathering bulk material. The operators have all material needed for this operation placed on the workbench.

The operators must on multiple occasions transport the unit to the fume bench that is now located closer to the assembly stations. The travel distance during this operation is therefore reduced. Furthermore, consumable material, tools and sub-products are positioned within arm's reach with the intention to reduce unnecessary movements from the assembly station.

As mentioned in section 5.2.1 there is a lack of quality related to delivered material. Shrink tubes that are used for several electronic components are manually cut to desired length by the operators. It is therefore recommended to deliver these tubes in correct length in order to reduce the amount of non-value-adding work. The same should be applied to the sub-products that are delivered with the wrong dimensions to prevent the operators from having to adjust them before mounting.

In addition, all assembly stations should be equipped with the pressing tool, since the operators currently share only one, which forces them to search for the tool when it is needed. This recommendation therefore intends to prevent the operators from searching for the tool during the assembly.

Operation 3310: Final mounting sub-product R

The distance between the assembly station and fume bench is reduced in accordance to the new layout. Another change is that tools, bulk material and sub-products are positioned closer to the operators which eliminates unnecessary movements.

Operation 4100: Assemble seal material

One minor change is made for this operation concerning the distance between material and operators. Material such as tape, ruler and knife are moved within arm's reach of the operators.

Operation 90: Mount resonator

The amount of non-value-adding work is decreased by positioning the bulk material on the workbench. Another aspect that decreases the non-value-adding work is moving tools, such as screwdrivers, closer to the operators.

Operation 125: Final mounting resonator

When emptying the outer cooling system, the operators no longer need to bend to retrieve and return the alcohol can. The operators must transport the unit to the fume bench in order for the glue to harden. The distance between the workbench and fume bench is shortened in the new layout, which reduces the amount of steps required. Another factor that reduces the amount of non-value-adding work is that tools and equipment are positioned closer to the operators. Thus, the operators must not take any supporting steps to reach for tools.

Operation 130: Leak test

The same changes described in Operation 602 apply for the leak test in Operation 130 as well.

Operation 220: Glue wedges

When emptying the outer cooling system, the operators no longer need to bend to retrieve and return the alcohol can. Required tools are positioned at arm's length and the operators are not forced to take any supporting steps to reach the tools.

Operation 230: Leak test

The same changes described in Operation 602 apply for the leak test in Operation 230 as well.

Operation 232: Clean cover bottom

The alcohol that is used for cleaning the cover bottom should be placed in waist-to-shoulder height in the cabinet. This eliminates strains on back and neck since the operator must not bend and reach for material. The same effect is given by positioning the disposal tank, used to empty the alcohol, on a trolley instead of the floor. Moreover, the operators must currently walk from the cleaning room to the assembly station to get a tray to place the cover bottom on. A recommendation is to have available trays in the cleaning room in order to eliminate unnecessary movements between different stations.

Operation 235: Mount cover bottom

The reduction of non-value-adding work for Operation 235 is achieved through locating required material at the workbench. The operators are today moving between different stations in Cleanroom 7, in order to gather material, such as bulk material and protective tape. Furthermore, tools and equipment are positioned at arm's length in order to avoid any supporting steps to reach the tools.

Operation 260 – Empty cooling system

When emptying the outer cooling system, the operators no longer need to bend to retrieve and return the alcohol can.

6.6.2 Operation Time Improvement

Table 15 shows the total operation time and how it changes with the implementation of the suggested changes.

Table 15: Total operation time, before and after improvements

	Hours		Percentage of total operation time	
	Before	After	Before	After
Total manual time	87.8	80.3	23.5	21.9
Total process time	286.3	286.3	76.5	78
Total operation time	374	366.6	100	100

The total operation time for Alpha is reduced by 7.4 hours; from 374 hours to 366.6 hours. It corresponds to a reduction of 2%. As can be seen in the table, there are no changes in the process times. The reduction of the total operation time therefore solely stems from changes in the manual work time.

Table 16 shows the process times in both cleanrooms. As already mentioned, no changes have been made for these elements. The only difference before and after improvements have been implemented is the percentage of the total operation time that the process times constitute. The process times constitutes 76.5% in the current state and 78% after the changes have been implemented. The reason for this is that the total manual time has decreased, thus increasing the share of the process times.

Table 16: Total process time, before and after improvements

	Hours	Percentage of total operation time	
	Same before and after	Before	After
Process time, Cleanroom 7	125.8	33.6	34.3
Process time, Cleanroom 8	160.5	43	43.7
Total process time	286.3	76.6	78

Table 17 shows the difference in time for the components of the manual work before and after the suggested improvements have been implemented.

Table 17: Total manual time, before and after improvements

	Hours		Percentage of total operation time	
	Before	After	Before	After
Manual assembly, Cleanroom 7	16.1	9.1	4.3	2.5
Inspection, Cleanroom 7	12.1	12	3.2	3.3
Resonator assembly, Cleanroom 7	22.6	22.5	6	6.1
Manual time Cleanroom 8	36.9	36.7	9.9	10
Total manual time	87.7	80.3	23.4	21.9

As the table shows, the reduction of the manual time is the same as the reductions for the total operation time; 7.4 hours. It means a reduction of the total operation time of 2% but for the total manual time it means a reduction of 8.4%.

Except the manual assembly in Cleanroom 7, there are smaller changes in all elements of the manual work that range from 0.1 to 0.2 hours. These changes are caused by the change in method of communication. Currently the operators send e-mails to one another when a unit is placed in the airlock. One of the recommendations is to implement visual planning, making e-mails of this type redundant as the planning board shows the operators what they need to know. The operators must still move a product card every time a unit is placed in the airlock, but that is more time efficient than e-mailing, thus saving time for all manual operations where communication is necessary.

However, the focus of this master's thesis has been within the first-mentioned element in Table 17; the manual assembly in Cleanroom 7 and that is where the largest difference in time is located. The time has been decreased from 16.1 hours to 9.1 hours. It corresponds to a reduction of 43.5%.

The fact that the total operation time is only reduced by 2% is due to the fact that the process times constitute more than 75% of the total operation time and that they are difficult to influence. To change the process times require deep and detailed knowledge of the processes and product, which the authors do not possess. Nonetheless, there is great potential in further reducing the total operation time by focusing on the majority of the operation time, i.e. the process times.

6.6.3 Method, Performance and Utilisation

The following section evaluates the potential of an increased productivity by implementing the already mentioned recommendations.

Assuming all previously mentioned recommendations are implemented, a new theoretical number of produced Alphas per year can be calculated. The method (M) for the future state has been calculated using the same formula as in section 5.2.3, which is shown in Equation 15 below:

$$M_{SAM(FS)} = \frac{Available\ production\ time\ per\ year}{Production\ time\ per\ unit} \tag{15}$$

As previously, the exact numbers cannot be disclosed because it is sensitive information. However, what can be shown is by how much the amount of products per year has increased due to methods improvements; 8.5%.

The performance and utilisation factors are also positively affected by the suggested recommendations. The changes for the future state regards the disturbance affected utilisation rate U_D and the skill based performance rate P_S.

The U_D factor is increased through reduction of production disturbances. Some of the production disturbances mentioned in section 5.2.5 are eliminated in the future state. The eliminated disturbances are summarised below:

- The amount of time spent on maintenance is reduced due to updated machines and devices.
- The operators are not struggling during assembly due to lack of fixtures. In addition, the usage of fixtures reduces operation times.
- The operators do not search for tools since each workbench is provided with all the required tools and equipment.

These mentioned changes increase the total utilisation rate (U) due to improvements of U_D.

The change in the performance factor regards improvements of the sub-factor P_S. The main changes that positively affect the skill based performance rate P_S are:

- The operators do not spend time on finding information regarding assembly procedure. The work instructions are organised according to the assembly sequence.
- The changes in the work instructions may also have a positive effect on P_S due to facilitating the learning for the operators, i.e. less experienced operators can faster learn the work, thus increasing P_S.
- The updated work instructions define an optimal sequence to conduct the assembly. Thus, the operators do not assemble the unit differently.

The intention is that the level of skill based performance rate should not be dependent on work experience. An increased quality in cognitive support aims to decrease the relation between skill level and work experience. However, the increased value of P_S has a minor impact on the total performance rate.

An assumption is that the elimination of some production disturbances and an increased quality of cognitive support contributes to following value on P and U:

$$PU_{FS} = 47\ \%$$

Hence, the combined PU factor is increased by 10% compared to the current state.

The estimated values of M, P and U can be used to calculate the productivity after implementation of recommendations according to the following formula (eq.16):

$$Productivity_{FS} = M_{BA1(FS)} = M_{SAM\,(FS)} \times PU_{FS} \qquad (16)$$

Thus, by how much the amount of produced products per year can be increased between the current and future state can be calculated, which has been done according to Equation 17 below:

$$Increased\,productivity = \frac{M_{BA1(FS)} - M_{BA1(CS)}}{M_{BA1(CS)}} = 34\ \% \qquad (17)$$

This indicates that the productivity is increased by 34% due to the implementation of the suggested recommendations.

6.6.4 Capacity

The capacity for production of Alpha is calculated according to Equation 2 in section 3.1.4:

$$Capacity = \frac{Maximum\ Product\ Output}{Given\ Time\ Period\ Input}$$

The maximum product output corresponds to the actual amount of produced Alphas per year after provided recommendations.

The given time period input is the available production time per year associated with the resources connected to the production of Alpha.

The capacity for Alpha after implementing the recommendations is calculated to 0.23 products per week.

The increased capacity is calculated according to Equation 18 below:

$$Increased\ capacity = \frac{C_{(FS)} - C_{(CS)}}{C_{(CS)}} = \frac{0.23 - 0.17}{0.17} = 35.3\ \% \tag{18}$$

Hence, the capacity for Alpha is increased by 35.3%.

7 Discussion

The following chapter presents a discussion about the methodology, analysis, and recommendations of this master's thesis. The authors also discuss directions for future research.

7.1 Method

The methodology used in this master's thesis follows a triangulation design comprising of a literature study, qualitative data, and quantitative data. The usage of a mixed methods approach intended to gather data from different sources that would provide equal conclusions. The main purpose with the triangulation method is to increase the credibility of the study.

The literature study was conducted to gain knowledge within areas concerning production engineering. The literature study was essential in order to create a theoretical framework that entails necessary information to answer the research questions. Different data bases were used for the study to avoid bias literature.

The qualitative data, including meetings and observations of the operators, was used in order to understand and describe the current state. Another approach that might have increased the quality of gathered data would have been to conduct semi-structured interviews with the operators. Semi-structured interviews are considered to be an organised methodology to gather qualitative data.

The collection of quantitative data was based on a methods engineering model proposed by Freivalds and Niebel (2009). However, the master's thesis was based on an adapted model that entailed differences from the model described by Freivalds and Niebel (2009). Hence, a different approach would be to conduct this master's thesis according to the model proposed by Freivalds and Niebel (2009) to increase the reliability of this study.

The SAM analysis was conducted in order to evaluate the possibility to reduce the operation time. However, the study focused only on the manual assembly and tests conducted in Cleanroom 7. The analysis therefore covered only a small part of the entire production time. The foremost part of the total operation time is currently spent on tests and glue hardening. A SAM analysis provides the largest benefits when analysing manual work. Thus, it may not be convenient to use SAM in order to evaluate the entire production of Alpha. This indicates the restrictions of using SAM, and another tool should be considered when analysing the complete production of Alpha.

The norm times provided by the SAM analysis are not related to the operators' real time spent in production. Hence, the SAM analysis does not include the operators' work pace which is favourable from an ethical perspective. Another strength with the SAM analysis is that the classification of value-adding and non-value-adding work is made objectively.

7.2 Productivity

As mentioned in section 6.6.1, the total operation time for Alpha is reduced by 7.4 hours. The operation time reduction aims to increase the capacity for the production unit of Alpha. The increased capacity is achieved since the time to complete a unit has been reduced.

Implementation of the suggested recommendations corresponds to an increased productivity of 34%. This master's thesis has evaluated the manual assembly of Alpha, which corresponds to 16.1 hours according to norm times in SAM. However, the total operation time for Alpha is estimated to 374 hours in SAM. Hence, the increased productivity of 34% only regards 4.3% of the total operation time for Alpha. This means that 95.7% of the work has not been evaluated. This indicates that there is a great potential to achieve further improvements in terms of an increased productivity.

Worthy to note is the fact that the norm times generated in the SAM analysis are ideal times that do not include any type of rework or problems during production, i.e. it assumes the product being robust. Also, the norm times assumes an operator that is working at a speed corresponding to a value of 100% of the performance (P) factor. The times generated by SAM cannot therefore, in most cases, be directly applied to reality. However, they give an indication of whether or not current assigned operation times are relevant. The fact that the manual assembly should take 16.1 hours according to SAM, while the same operations have been assigned 46.5 hours in total in IFS tells that the times in IFS may be misleading and that they do not reflect reality. The reasons behind this difference may be that rework and production disturbances are not included in the set times, and that they are not based on facts since no time studies have been conducted previously.

The recommended solutions are mainly focused on improving the method (M). Therefore is the increased productivity mostly achieved through method improvements. The suggested improvements do not include radical changes such as implementing a flow-oriented layout. There is therefore potential to achieve further improvements regarding the M factor. A flow-oriented layout that separates the new products from units of repair might be a solution that is likely to affect the M factor positively. However, separating the different product flows will most likely not be appreciated by the operators. The operators are currently working in close proximity where they can easily communicate with each other. A relocation of the assembly stations, with the aim to decrease the complexity in the production flow, might therefore not be appreciated by the operators. Most of the operators have worked in Cleanroom 7 for a long period of time, and radical changes might not get a positive response.

Another large method potential lies in the product itself. To redesign the product and reducing the amount of components, especially screws, would greatly improve the productivity, and thereby the capacity, as many tasks would be reduced or even eliminated.

To reduce the time spent on cleaning the components and bulk material should be investigated. Currently, the operators spend a lot of time on cleaning all components before assembly, which decreases the productivity. To find a way of eliminating this procedure would have a great positive effect on the productivity. The ideal situation would be to deliver cleaned components and bulk material to the operators. The company should therefore consider purchasing cleaned components from a supplier in order to eliminate non-value-adding work, further reduce the operation time and increase the capacity.

There is potential to achieve further increased productivity and capacity by improving the performance (P) and utilisation (U) rate. The multiplicative factor PU is in the future state estimated to 47% according to the calculations in section 6.6.3. This means that the operators spend 53% of their time on activities that do not add value to the product, instead of 63% as they currently do. The PU factor can be further improved by evaluating the amount of rework required. A fact is that every unit requires at least some sort of rework due to test failures and if the operators did not spend as much time on rework as they do today, they could produce many more new units instead. Also, there is no logical explanation behind the statistical values of the type and amount of rework required. A suggestion for future research would therefore be to evaluate the robustness of the product. The current lack of robustness might explain the variations in type of rework required. To change and improve the product by redesigning it to increase the robustness and decrease the amount of rework has the potential to greatly increase the utilisation rate (U), thus increasing the total productivity and capacity further.

The performance factor might be more difficult to improve than the other two factors. The personal performance rate P_P is most difficult to affect since it is highly dependent on the individual. However, the company can increase the productivity through improving the skill based performance rate P_S. An example of how to improve P_S is to give the operators a possibility to participate in training and educational activities. Trained operators might be significant for achieving further productivity improvements.

7.3 Capacity

The capacity strategy used by BA1 is called lag. This is shown by the fact that they wished to increase their capacity only after they had already started planning the introduction of new product variants. With the suggested method improvements, a capacity increase of 35.3% can be achieved. One of the reasons for this rather low value is due to the product design greatly affecting the production. The suggested method improvements affect production surroundings and not the product itself. The largest capacity increase can therefore be achieved by redesigning the product to reduce the amount of rework required.

7.4 Work Environment

The recommendations in section 6 intend to improve the current work environment for the operators in Cleanrooms 7 and 8. The recommended improvements have a positive effect on two of the research questions i.e. reduction of operation time and increase in productivity. In addition, the suggested recommendations aim to reduce and eliminate the detected production disturbances in Cleanroom 7, which relates to the second research question.

The areas of recommendations that affect the current work environment are visual management, physical and cognitive ergonomics, material handling, and production layout. The following sections present a discussion about how the findings affect the work environment.

7.4.1 Visual Management

The implementation of visual management aims at reducing the amount of production disturbances during assembly. Currently, there is no visual planning and the operators must communicate through e-mail. The operators in Cleanroom 7 must for instance inform the operators in Cleanroom 8 when a unit is ready for tests. A visual management system enables sharing of real time information, which might be significant in order to create a good work environment.

The visual management recommendation intends to prevent production disturbances associated with lack of material. The production management can through real time information support the operators in terms of delivering material when needed. Thus, production interruptions due to lack of material are reduced. The reduction of production disturbances, as a result of visual management, might be significant in order to further reduce the operation time and increase the productivity.

As mentioned by Lindlöf and Söderberg (2011), visual planning has a positive effect on communication. Thus, the employees within the production unit have a great potential to create a good communication. In addition, the visual management recommendation aims to increase the level of information sharing both among operators, and between operators and production management. A good information transfer might positively affect the daily production meetings since all employees are fully aware of the current situation in production.

7.4.2 Physical and Cognitive Ergonomics

The production ergonomics analyses in sections 5.3 and 5.4 focus on the most critical situations that were detected during observation of the assembly work. Some of the recommendations in sections 6.2 and 6.3 require more effort and resources than others during the implementation phase. However, all recommended solutions regarding physical and cognitive ergonomics should be equally prioritised by the company.

The physical and cognitive ergonomics have been improved in Cleanroom 7 according to the recommendations provided in sections 6.2 and 6.3. Improved production ergonomics intends to positively affect the productivity. Thus, the company should consider these recommendations carefully in order to optimise the operation time and productivity. Furthermore, improved production ergonomics creates a safe environment where the operators have a possibility to improve their work performance (Berlin and Adams, 2014).

The suggestions for improved physical ergonomics regard implementation of e.g. fixtures and new machines. Improved physical ergonomics is significant to create a good atmosphere and work environment for the operators. The recommended changes intend to support the operators during the assembly in order to create a good work environment, and achieve an optimised operation time and increased productivity. The current situation regarding sick leave was not evaluated in this master's thesis. However, the company has a great potential to reduce the sick leave by improving the physical ergonomics.

The operators in Cleanroom 7 have different amount of work experience and the need of cognitive support differs. The lack of information in the current cognitive support shows that less experienced operators will struggle to complete the assembly. The less experienced operators must ask the more experienced operators for advice. Thus, the more experienced operators are often interrupted during their work. The recommendations regarding the cognitive ergonomics aim to eliminate these interruptions, and create an environment where the operators can assemble Alpha independently. Another important aspect is that the company is currently reliant on the more experienced operators. The company must take into consideration that these operators might leave. It is therefore highly recommended that the company improves the cognitive support to decrease the dependability on the more experienced operators to be able to handle a situation where these operators are no longer working in the production. The main goal should be to create cognitive support of good quality that enables the operators to work independently, regardless of previous work experience.

7.4.3 Material Handling

The new material handling system intends to increase the efficiency by eliminating unnecessary operations. Another purpose is to reduce the amount of time spent on material handling. The current work of emptying plastic bags to retrieve material is both time-consuming and monotonous. Moreover, the storage of bulk material in Cleanroom 7 will increase the flexibility in the production system. For instance, the operators have a possibility to clean bulk material for more than one order due to the new system. Unnecessary material handling before and after the cleaning process of bulk material is eliminated. The operators can therefore spend their time on value-adding work such as assembly.

There are improvement potentials with the suggested recommendations that positively affects the operation time. To purchase already cleaned components from the suppliers, as mentioned in section 7.2, would eliminate all cleaning procedures, which are considered both troublesome and time-consuming. The implementation of the new material handling system requires resources such as time and effort. The current material handling system involves several actors, and an agreement must be settled between BA1 and the warehouse at Location B. The new material handling system increases the tied-up capital due to the implementation of storage in Cleanroom 7. Despite this drawback, it is still suitable to have storage in Cleanroom 7 to support the operators in their work. The operators are not pleased with the kitting, and the production management have received a lot of complaints. Thus, the new material handling system has a great potential to get a positive response from the operators.

7.4.4 Production Layout

The new production layout does not take the production flow into consideration. The main purpose with the changes in the layout is to eliminate waste in order to reduce the operation time and increase productivity. Material and equipment are located closer to the operator to avoid unnecessary movements that are classified as losses and production disturbances. The new layout therefore intends to reduce production disturbances noticed during the assembly. Thus, all three topics in the research questions are positively affected by the proposed layout; *reduction of operation time, increase in productivity* and *reduction of production disturbances.*

Changes within an organisation are rarely taken with ease. The changes in the layout might be considered as troublesome for the operators due to old habits. The operators might feel uncomfortable since material and equipment are relocated and they are not used to the new situation. However, from a long-term perspective, the operators might find these changes as appreciative since unnecessary movements are reduced.

No radical changes are made in the new layout. There is potential to achieve further improvements in terms of separating the production flows of new products and units for repair. However, organising the work stations according to product flow might affect the atmosphere within the group and will probably not be appreciated by the operators, as mentioned in section 7.2.

7.5 Future Research

Several issues were identified during the master's thesis that were outside the scope of this study. The following section presents possible suggestions for future research:

- The operators are currently spending a lot of time on transporting the unit between Cleanrooms 7 and 8. The possibility to integrate the two cleanrooms could be evaluated in order to minimise the amount of waste spent on transports.
- The conducted analyses focused on the manual work in Cleanroom 7. It would be beneficial to study the work methods in Cleanroom 8, since the majority of the production time is spent outside Cleanroom 7. There is therefore potential to achieve further improvements in terms of reducing the operation time.
- The process times in Cleanrooms 7 and 8 are mainly due to glue that needs to harden and tests. The sum of these times makes up a large part of the total operation time, making it beneficial to investigate whether it can be decreased.
- The study focused on one product within one production unit at BA1. A possible research study would be to look at the opportunities to apply the recommendations to other products within BA1 to avoid sub-optimisations.

8 Conclusion

The study has focused on the manual assembly and testing of Alpha in Cleanroom 7 at Business Area 1 (BA1). This part constitutes 4.3% of the total operation time required to produce one unit. The research questions will be answered below.

The thesis covers sustainability by taking social, ethical and environmental aspects into consideration. The social and ethical elements are included in the methodology, while environmental aspects are covered by the recommendations regarding material handling.

RQ 1: How much does the operation time in the ERP system differ from the ideal operation time?

The difference corresponds to 30.4 hours. The operation time according to IFS is three times as long as the operation time generated by the SAM analysis. This shows discrepancy between the documentation of the work and how the operators actually perform the work.

RQ 2: What are the reasons production disturbances occur in Cleanroom 7?

The reasons behind the production disturbances have been divided into the following categories:

- Machines and equipment
- Design of the product
- Support systems

The disturbances within the category Machines and equipment regard maintenance of machines, searching for tools and lack of fixtures. The category Design of the product includes disturbances due to lack of robustness and difficulties when assembling the product. This category is the main contributor to the amount of rework required. The final category, Support systems, entails the cognitive support that is not optimally designed, the lack of quality in the communication system and lack of standardised assembly sequences. The above-mentioned disturbances have been reduced during this project and contribute to the reduced operation time and increased productivity.

RQ 3: Can the capacity be increased by 50% for Alpha?

The capacity can be increased by 35.3% with the recommendations suggested in this thesis. However, there is great potential in achieving further increase in capacity by considering areas outside the scope of this thesis. The design of the product has a great impact on the production disturbances and to redesign the product will therefore greatly benefit the capacity.

The total operation time can be reduced by 7.4 hours and the productivity can be increased by 34%. The operation time reduction was achieved through improvements concerning the method, performance and utilisation rate. The increase in productivity is calculated with respect to the manual assembly and tests performed by the operators in Cleanroom 7.

A reduced operation time and an increased productivity means that the capacity is also improved, enabling the operators to produce more units per year. Only 4.3% of the total work was analysed and there is great potential to further improve both the operation time and productivity for Alpha.

Bibliography

AL-ZUHERI, A. (2013) Structural and Operational Complexity of Manual Assembly Systems. *Journal of Computer Science.* 9 (12). p.1822-1829.

ALLEN, T. T. (2010) *Introduction to Engineering Statistics and Lean Sigma: Statistical Quality Control and Design of Experiments and Systems.* Second Edition. London: SpringerVerlag.

ALMSTRÖM, P. (2012) Productivity measurement and improvements: A theoretical model and applications from the manufacturing industry. *Proceedings of the International Conference on Advances in Production Management Systems* APMS 2012, 24-26 September, Rhodes, Greece.

ALMSTRÖM, P., HANSSON, E. and SAMUELSSON, J. (2014) How to improve productivity by 160%. *The sixth Swedish Production Symposium.*

ARBETSTIMMAR PER MÅNAD (2016) http://www.arbetstimmarpermanad.se/ (2016-03-24).

BELLGRAN, M. and SÄFSTEN, K. (2010) *Production Development – Design and Operations of Production Systems.* London: SpringerVerlag.

BERLIN, C. and ADAMS, C. (2014) *Production Ergonomics – Designing work systems to support optimal human performance.* Course compendium. Chalmers Dept. of Product- and Production Development. Gothenburg, Sweden.

BORREGO, M. et al. (2009) *Quantitative, Qualitative and Mixed Research Methods in Engineering Education.* Journal of Engineering Education, p. 53-66.

BRYMAN, A. and BELL, E. (2007) *Business Research Methods.* Second edition. New York: Oxford University Press, Inc.

CRONIN, P. et al. (2008) Undertaking a literature review: a step-by-step approach. *British Journal of Nursing.* Issue 17, p. 38-43

FREIVALDS, A. and NIEBEL, B. (2009) *Niebel's Methods, Standards, and Work Design*, 12th Edition. McGraw Hill International Edition.

GOODRICH, R. (2015) SWOT Analysis: Examples, Templates & Definition. *Business News Daily*, 1st January.

IMD, International MTM Directorate. (2004) SAM: Sequential Activity-and Methods Analysis, System description. *IMD, International MTM Directorate.*

JONKER, J., and PENNINK, B. (2010) *The Essence of Research Methodology – A Concise Guide for Master and PhD Students in Management Science.* Springer Heidelberg Dordrecht London New York.

JONNSON, P. and MATTSSON, S-A. (2009) *Manufacturing Planning and Control.* McGraw-Hill Education.

JURADO, M. (2012) *Visual Planning in Lean Product Development.* Stockholm: Royal Institute of Technology. (Degree project in Industrial Information and Cont.).

KUHLANG, P. et al. (2014) *Morphology of time data management systematic design of time data management processes as fundamental challenge in industrial engineering.* Int. J. Industrial and Systems Engineering, pp. 415-432.

LINDLÖF, L. and SÖDERBERG, B. (2011) Pros and cons of lean visual planning: experiences from four product development organisations. *Int. J. Technology Intelligence and Planning, Vol 7, No 3, p. 269-279.*

LÖNESTATISTIK (2016)
http://www.lonestatistik.se/loner.asp/yrke/Operator-1534 [Accessed: 2016-03-24].

LÖNESTATISTIK (2016)
http://www.lonestatistik.se/loner.asp/yrke/Materialhanterare-7384/lan/Vastra-Gotaland-28 [Accessed: 2016-03-24].

MAYNARD, H., STEGEMERTEN, G.J. and SCHWAB, J.L. (1948) *Methods-time measurement.* New York: McGraw-Hill, Industrial organization and management series.

MTM-föreningen i Norden. (2016) Nordisk produktivitet SAM. [Online] Available from: http://www.nordiskproduktivitet.com/?id=71 [Accessed: 2016-01-28].

OLHAGER, J. (2013) *Produktionsekonomi: Principer och metoder för utformning, styrning och utveckling av industriell produktion.* Studentlitteratur, Lund.

SKATTEVERKET (2016)
http://www.skatteverket.se/foretagorganisationer/arbetsgivare/socialavgifter/arbetsgivaravgifter.4.233f91f71260075abe8800020817.html [Accessed: 2016-05-25].

SKOOGH, A. (2014) *Lecture – Production Flows*. Gothenburg. Chalmers University of Technology. Product and Production Development.
SOLME AB. (2015) AviX Method. [Online] Available from: http://www.avix.eu/ [Accessed: 2016-01-28]

SKINNER, W. (1969) Manufacturing – Missing Link in Corporate Strategy. *Harvard Business Review*, May-June.

SUNDKVIST, R. (2014) *Financial benefits of shop floor productivity improvements*. Chalmers University of Technology. Dept. of materials and manufacturing technology.

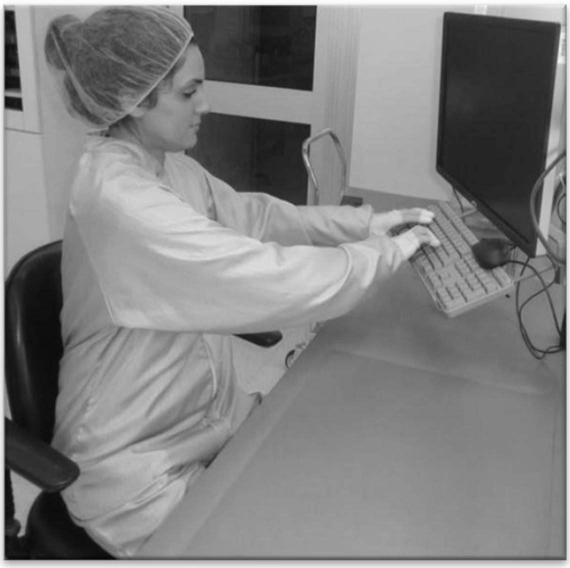
WELKER, R. W., NAGARAJAN, R. and NEWBERG, C. E. (2006) *Contamination and ESD Control in High-technology Manufacturing*. Hoboken: John Wiley & Sons, Inc.

WILSON, L. (2010) *How to Implement Lean Manufacturing*. New York: The McGraw-Hill Companies, Inc.

WINROTH, M. (2014) *Lecture – Manufacturing Strategies.* Gothenburg. Chalmers University of Technology. Operations Management.

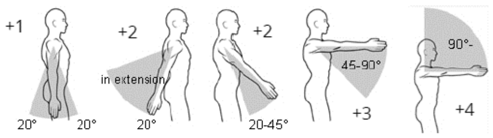
ZANDIN, K. B. (ed.). (2001) *Maynard's Industrial Engineering Handbook.* 5th Ed. New York: McGraw-Hill, cop.

Appendix A – Usage of Computer



A. Arm and Wrist Analysis

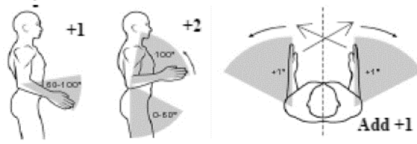
Step 1: Locate Upper Arm Position:



Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

4
Upper Arm Score

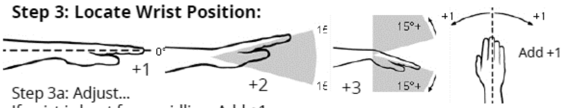
Step 2: Locate Lower Arm Position:



3
Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:



Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

1
Wrist Twist Score

4
Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

6
Posture Score A
+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

0
Muscle Use Score
+

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

0
Force / Load Score
=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain
Wrist and Arm Score. Find row in **Table C**.

6
Wrist & Arm Score

Scores

Table A		Wrist Score 1		2		3		4	
		Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
Upper Arm	Lower Arm	1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

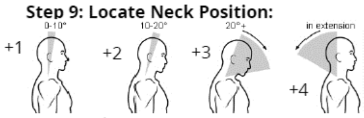
Table C		Neck, Trunk, Leg Score 1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

4
RULA Score

B. Neck, Trunk and Leg Analysis

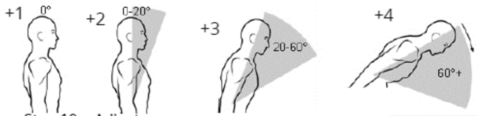
Step 9: Locate Neck Position:



2
Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:



Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

2
Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

1
Leg Score

Neck Posture Score	Table B: Trunk Posture Score 1		2		3		4		5		6	
	Legs		Legs		Legs		Legs		Legs		Legs	
	1	2	1	2	1	2	1	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above,
locate score in Table B

2
Posture B Score
+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

0
Muscle Use Score
+

Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

0
Force / Load Score
=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain
Neck, Trunk and Leg Score. Find Column in **Table C.**

2
Neck, Trunk, Leg Score

Appendix B – Material Handling 1

Scores

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

3 — Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

5 — Trunk Score

Step 3: Legs

Adjust: 30-60°: Add +1; >60: Add +2

3 — Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

9 — Posture Score A

+

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

0 — Force / Load Score

=

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

9 — Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Table A	Neck	1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B	Lower Arm	1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C	Score B											
Score A	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

11 (Table C Score) + 1 (Activity Score) = 12 (REBA Score)

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

5 — Upper Arm Score

Step 8: Locate Lower Arm Position:

1 — Lower Arm Score

Step 9: Locate Wrist Position:

2 — Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

7 — Posture Score B

+

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

1 — Coupling Score

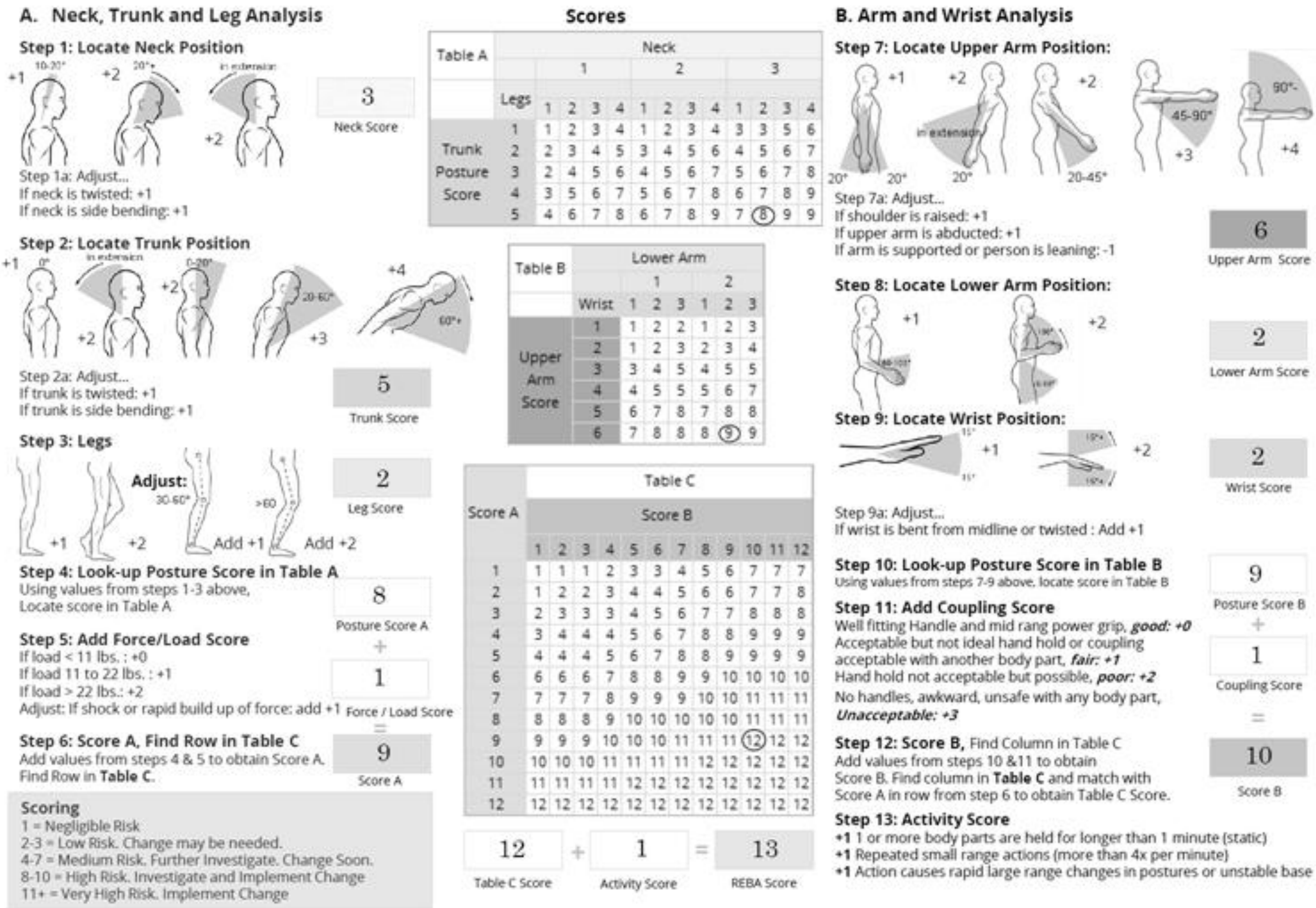
=

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

8 — Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix C – Material Handling 2



A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 10-20° | +2 20°+ | +2 in extension

Neck Score: 3

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 0° | +2 in extension | +2 0-20° | +3 20-60° | +4 60°+

Trunk Score: 5

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 3: Legs

+1 | +2 | Adjust: 30-60° Add +1 | >60 Add +2

Leg Score: 2

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A: 8

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score: 1

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

Score A: 9

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A	Neck	1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B	Lower Arm	1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C	Score B											
Score A	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score: 12 + Activity Score: 1 = REBA Score: 13

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 20° 20° | +2 in extension 20° | +2 20-45° | +3 45-90° | +4 90°+

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score: 6

Step 8: Locate Lower Arm Position:

+1 60-100° | +2 100°+ 0-60°

Lower Arm Score: 2

Step 9: Locate Wrist Position:

+1 15° 15° | +2 15°+ 15°+

Wrist Score: 2

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B: 9

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

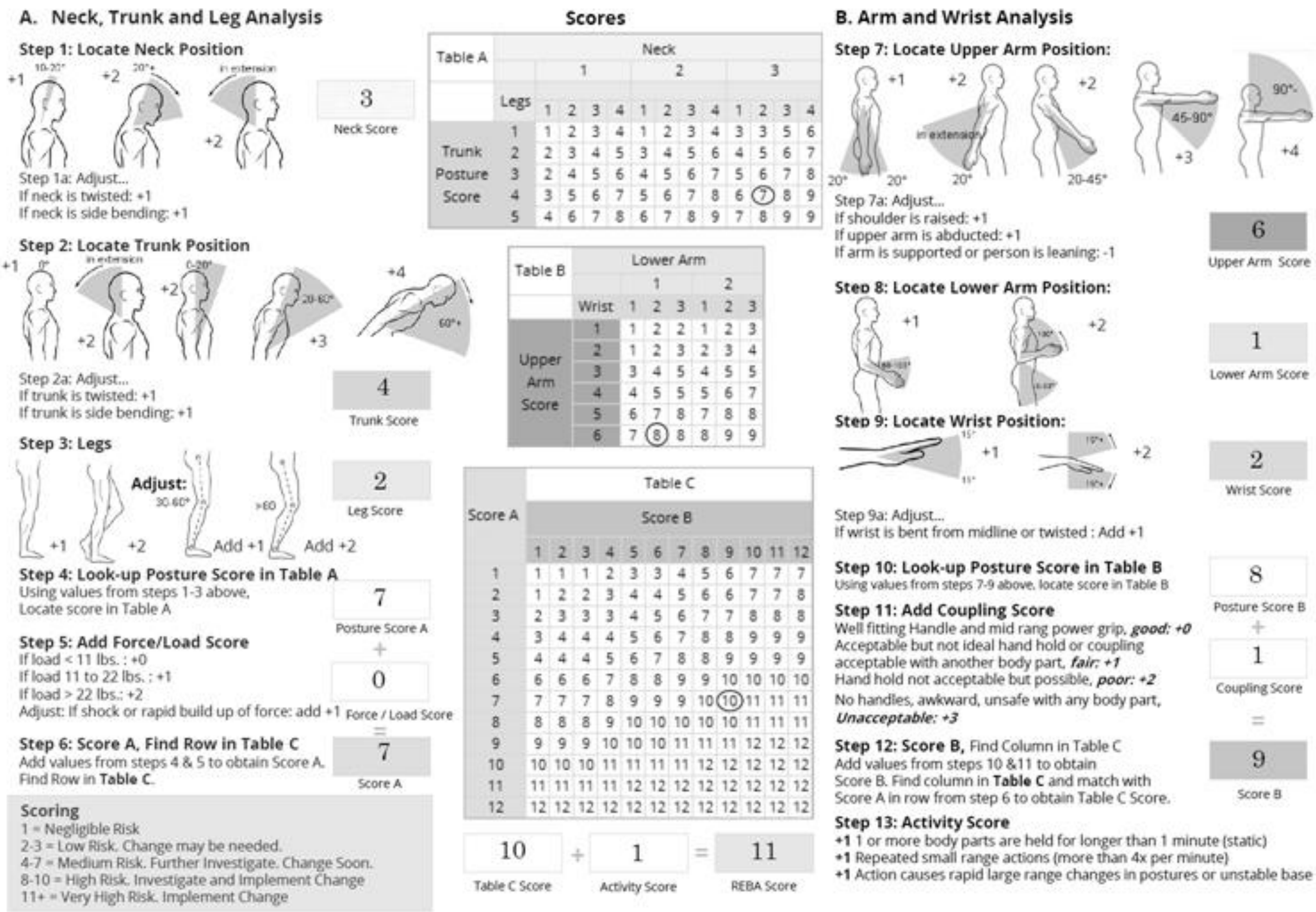
Coupling Score: 1

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B: 10

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix D – Place Funnel in Tank



A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

3
Neck Score

Step 2: Locate Trunk Position

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

4
Trunk Score

Step 3: Legs

Adjust: Add +1 Add +2

2
Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

7
Posture Score A

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

0
Force / Load Score

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

7
Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck 1				Neck 2				Neck 3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B		Lower Arm 1			Lower Arm 2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Score A	Table C / Score B 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

10 + 1 = 11
Table C Score, Activity Score, REBA Score

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

6
Upper Arm Score

Step 8: Locate Lower Arm Position:

1
Lower Arm Score

Step 9: Locate Wrist Position:

2
Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

8
Posture Score B

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

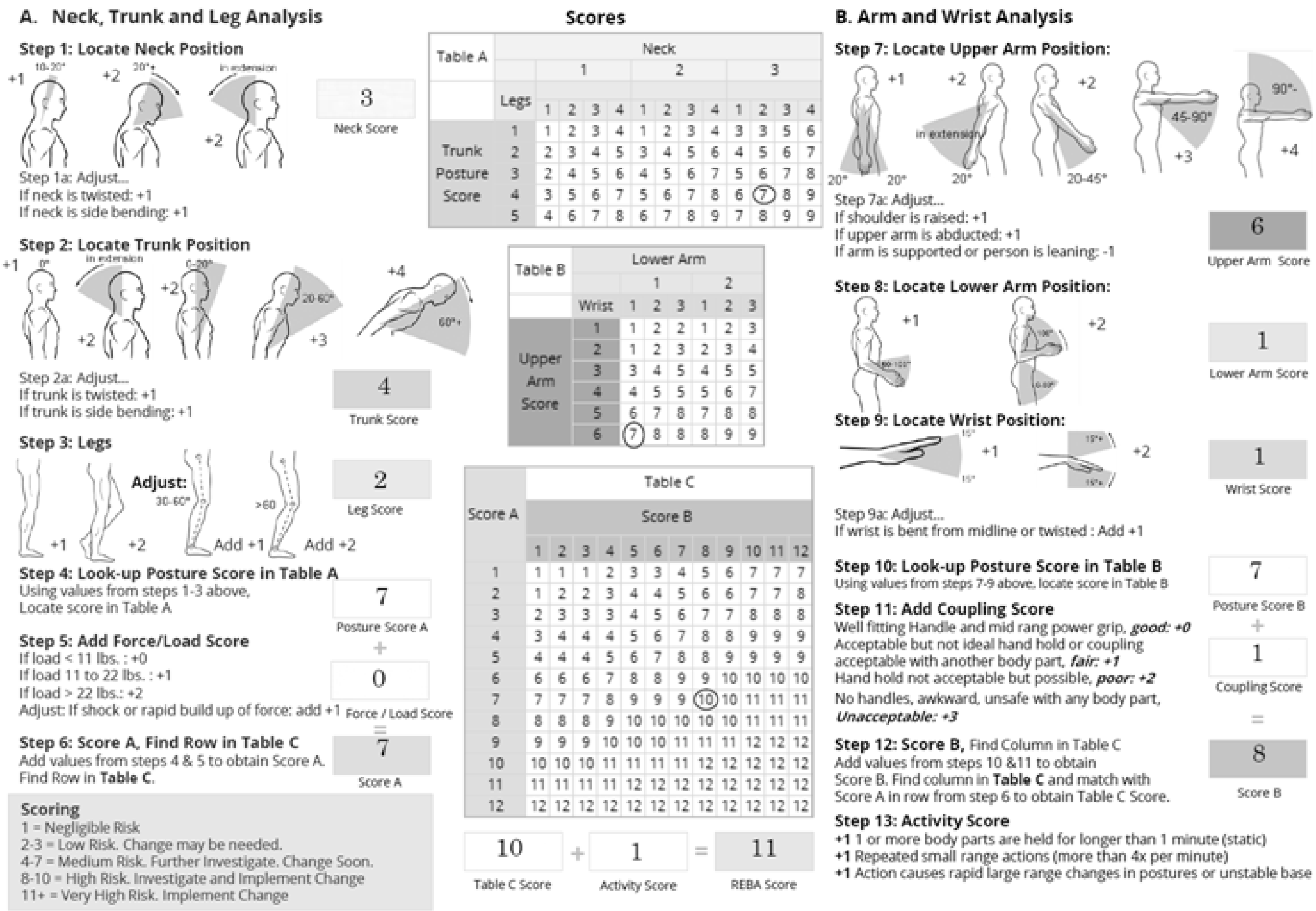
1
Coupling Score

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

9
Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix E – Empty Alcohol



A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 10-20° | +2 20°+ | +2 in extension

Neck Score: 3

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 0° | +2 in extension | +2 0-20° | +3 20-60° | +4 60°+

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score: 4

Step 3: Legs

+1 | +2 | Adjust: 30-60° Add +1 | >60 Add +2

Leg Score: 2

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A: 7

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score: 0

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

Score A: 7

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A

Trunk Posture Score	Neck 1				Neck 2				Neck 3			
Legs	1	2	3	4	1	2	3	4	1	2	3	4
1	1	2	3	4	1	2	3	4	3	3	5	6
2	2	3	4	5	3	4	5	6	4	5	6	7
3	2	4	5	6	4	5	6	7	5	6	7	8
4	3	5	6	7	5	6	7	8	6	7	8	9
5	4	6	7	8	6	7	8	9	7	8	9	9

Table B

Upper Arm Score	Lower Arm 1			Lower Arm 2		
Wrist	1	2	3	1	2	3
1	1	2	2	1	2	3
2	1	2	3	2	3	4
3	3	4	5	4	5	5
4	4	5	5	5	6	7
5	6	7	8	7	8	8
6	7	8	8	8	9	9

Table C

Score A \ Score B	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score: 10 + Activity Score: 1 = REBA Score: 11

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 20° 20° | +2 in extension 20° | +2 20-45° | +3 45-90° | +4 90°+

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score: 6

Step 8: Locate Lower Arm Position:

+1 60-100° | +2 100°+ 0-60°

Lower Arm Score: 1

Step 9: Locate Wrist Position:

+1 15° 15° | +2 15°+ 15°+

Wrist Score: 1

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B: 7

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score: 1

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

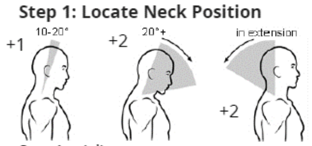
Score B: 8

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix F – Leak Test

A. Neck, Trunk and Leg Analysis

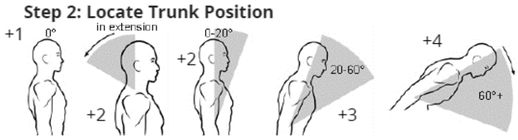
Step 1: Locate Neck Position



2
Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

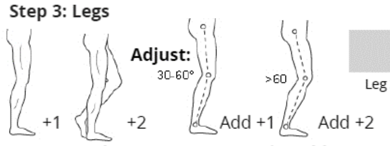
Step 2: Locate Trunk Position



Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

3
Trunk Score

Step 3: Legs



1
Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

4
Posture Score A

+

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

0
Force / Load Score

=

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

4
Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck											
		1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

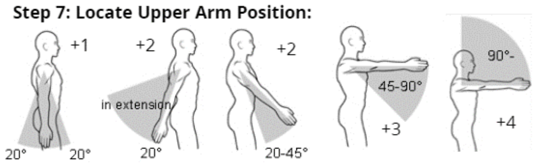
Table B		Lower Arm					
		1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Score A	Table C											
	Score B											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

6 + 1 = 7
Table C Score, Activity Score, REBA Score

B. Arm and Wrist Analysis

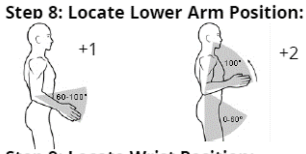
Step 7: Locate Upper Arm Position:



Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

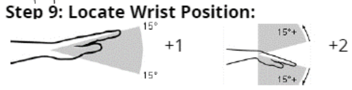
4
Upper Arm Score

Step 8: Locate Lower Arm Position:



1
Lower Arm Score

Step 9: Locate Wrist Position:



2
Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

5
Posture Score B

+

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

1
Coupling Score

=

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

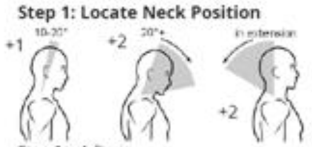
6
Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix G – Flushing

A. Neck, Trunk and Leg Analysis

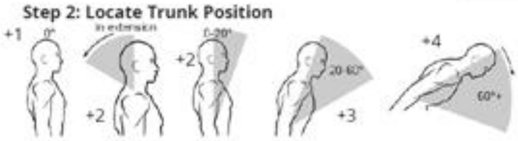
Step 1: Locate Neck Position



3
Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

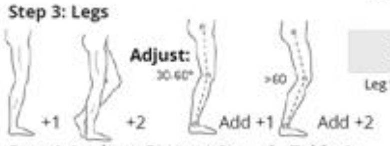
Step 2: Locate Trunk Position



Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

2
Trunk Score

Step 3: Legs



2
Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

5
Posture Score A
+

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

1
Force / Load Score
=

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C**.

6
Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck											
		1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

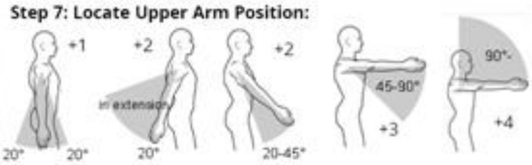
Table B		Lower Arm					
		1			2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Score A	Table C											
	Score B											
	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

10	+	1	=	11
Table C Score		Activity Score		REBA Score

B. Arm and Wrist Analysis

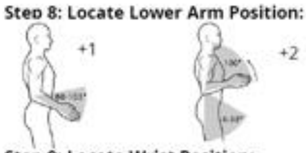
Step 7: Locate Upper Arm Position:



Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

5
Upper Arm Score

Step 8: Locate Lower Arm Position:



2
Lower Arm Score

Step 9: Locate Wrist Position:

2
Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above. locate score in Table B

8
Posture Score B
+

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling
acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part,
Unacceptable: +3

3
Coupling Score
=

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain
Score B. Find column in **Table C** and match with
Score A in row from step 6 to obtain Table C Score.

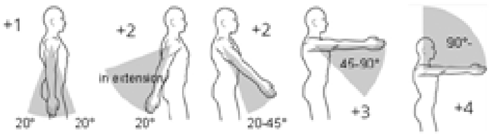
11
Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Appendix H – Fastening Screws

A. Arm and Wrist Analysis

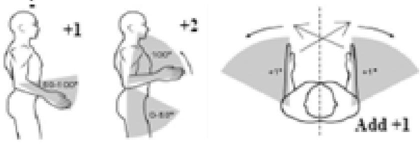
Step 1: Locate Upper Arm Position:



Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

4
Upper Arm Score

Step 2: Locate Lower Arm Position:



3
Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:

Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

1
Wrist Twist Score

3
Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

5
Posture Score A

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

1
Muscle Use Score

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

0
Force / Load Score

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain Wrist and Arm Score. Find row in **Table C**.

6
Wrist & Arm Score

Scores

Table A		Wrist Score 1		Wrist Score 2		Wrist Score 3		Wrist Score 4	
Upper Arm	Lower Arm	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

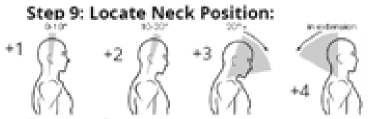
Table C		Neck, Trunk, Leg Score 1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

6
RULA Score

B. Neck, Trunk and Leg Analysis

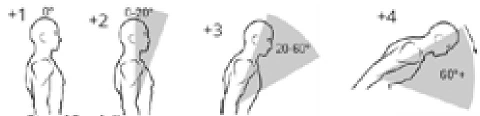
Step 9: Locate Neck Position:



3
Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:



Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

2
Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

1
Leg Score

Neck Posture Score	Table B: Trunk Posture Score 1, Legs 1	Legs 2	2, Legs 1	Legs 2	3, Legs 1	Legs 2	4, Legs 1	Legs 2	5, Legs 1	Legs 2	6, Legs 1	Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above, locate score in Table B

3
Posture B Score

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

1
Muscle Use Score

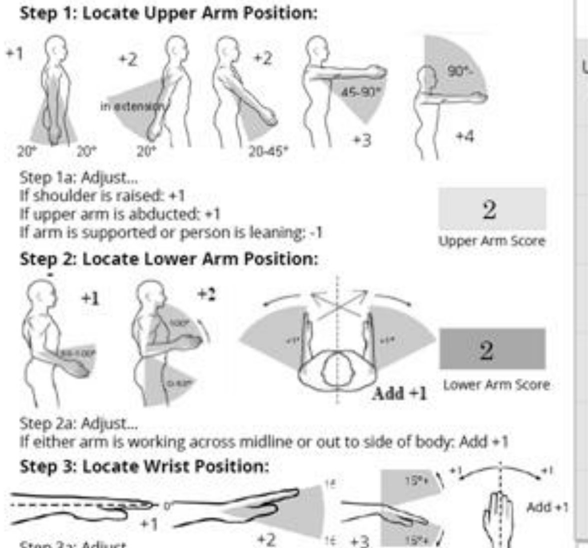
Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

0
Force / Load Score

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain Neck, Trunk and Leg Score. Find Column in **Table C**.

4
Neck, Trunk, Leg Score

Appendix I – Mount Sub-product H



Scores

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position:

+1 +2 +2 +3 +4

Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

2
Upper Arm Score

Step 2: Locate Lower Arm Position:

+1 +2 Add +1

2
Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:

+1 +2 +3 Add +1

Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

1
Wrist Twist Score

4
Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

4
Posture Score A

+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

0
Muscle Use Score

+

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

2
Force / Load Score

=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain
Wrist and Arm Score. Find row in **Table C**.

6
Wrist & Arm Score

Table A		Wrist Score							
		1		2		3		4	
		Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
Upper Arm	Lower Arm	1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C		Neck, Trunk, Leg Score						
		1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

7
RULA Score

B. Neck, Trunk and Leg Analysis

Step 9: Locate Neck Position:

+1 +2 +3 +4

3
Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:

+1 +2 +3 +4

Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

3
Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

1
Leg Score

Neck Posture Score	Table B: Trunk Posture Score											
	1		2		3		4		5		6	
	Legs		Legs		Legs		Legs		Legs		Legs	
	1	2	1	2	1	2	1	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above,
locate score in Table B

4
Posture B Score

+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

0
Muscle Use Score

+

Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

2
Force / Load Score

=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain
Neck, Trunk and Leg Score. Find Column in **Table C**.

6
Neck, Trunk, Leg Score

Appendix J – Manual Assembly

Scores

Table A		Wrist Score							
		1		2		3		4	
Upper Arm	Lower Arm	Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
		1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

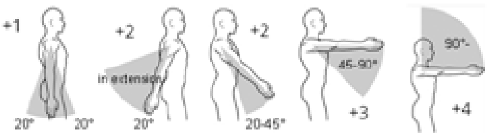
Table C		Neck, Trunk, Leg Score						
		1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

6
RULA Score

A. Arm and Wrist Analysis

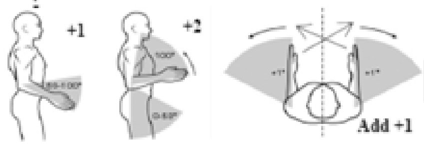
Step 1: Locate Upper Arm Position:



Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

1
Upper Arm Score

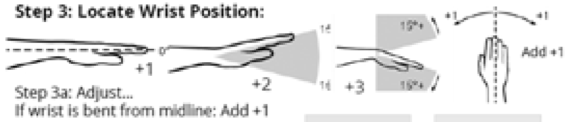
Step 2: Locate Lower Arm Position:



1
Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:



Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

1
Wrist Twist Score

3
Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

2
Posture Score A

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

\+
1
Muscle Use Score

Step 7: Add Force/Load Score
If load < 4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

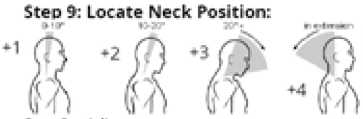
\+
0
Force / Load Score

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain
Wrist and Arm Score. Find row in **Table C**.

=
3
Wrist & Arm Score

B. Neck, Trunk and Leg Analysis

Step 9: Locate Neck Position:



5
Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:

Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

3
Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

1
Leg Score

Neck Posture Score	Table B: Trunk Posture Score											
	1		2		3		4		5		6	
	Legs		Legs		Legs		Legs		Legs		Legs	
	1	2	1	2	1	2	1	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above,
locate score in Table B

7
Posture B Score

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

\+
1
Muscle Use Score

Step 14: Add Force/Load Score
If load < 4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

\+
0
Force / Load Score

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain
Neck, Trunk and Leg Score. Find Column in **Table C**.

=
8
Neck, Trunk, Leg Score

Appendix K – Sequence of chapters, 500:A

Operation (routing 500:A)	Chapter (work instructions)
100 – Clean housing	4.3 + reference (separate file)
300 – Clean components	4.3 + reference (separate file)
400 – Protective tape	7, 8
500 – Paint + mount small parts	10, 11, 9, 19
600 – Mount	14.1 (paragraphs 1-10), 14.2 (paragraphs 1-2), 18 (paragraphs 1-7), 6 (paragraphs 1-2)
601 – Mount sub-product R	17.1
602 – Leak test	4.18 + reference (separate file)
700 – Assemble sub-product C	12 (except paragraph 24)
800 – Test sub-product C	13 (paragraphs 1, 3-4) + reference (separate file)
850 – Mounting sub-product C	14.1 (paragraphs 1-13), 14.2 (paragraph 3)
900 – Leak test + flushing	15 (refers to 4.15) + reference (separate file), 16
3000 – Mount electronics	20, 25 (paragraphs 1-5), 24, 27, 22, 21, 19, 12 (paragraph 24), 26.1 (paragraphs 1-7), 26.2 (paragraphs 1-6), 25 (paragraphs 6-18), 26.1 (paragraph 8), 26.2 (paragraphs 7-11)
3300 (8) – Test sub-product R	17.2
3310 – Final mounting sub-product R	17.3
3330 (8) – Inspection sub-product R	17.4
3500 – Assembly	Missing
4000 – Inspection	28 + reference (separate file)
4100 – Assemble seal material	18 (paragraphs 8-12)

Appendix L – Sequence of chapters, 500

Operation (routing 500)	Chapter (work instructions)
90 – Mount resonator	29
95-115 Tests in Cleanroom 8	31, 32, 33 (refers to chapter 4), 34 (refers to 4.14 and 4.15.), 35
125 – Glue resonator	36
130 – Leak test	37 (refers to 4.18 and 4.4), 4.1
140-198 Tests Cleanroom 8	38 (refers to chapter 4), 39 (refers to chapter 4), 40 (refers to chapter 4), 41 (refers to chapter 4), 42 (refers to chapter 4)
200 – Inspection	43 + references (separate files)
210 (8) – Adjustments	44 (refers to chapter 4)
220 – Glue resonator	45
225 – Test in Cleanroom 8	46 (refers to chapter 4)
230 – Leak test	47 (refers to 4.4 and 4.18)
232 – Clean cover bottom	4.3 + reference (separate file), 48.1 (paragraph 1)
235 – Mount cover bottom	48 (except paragraph 1 in 48.1)
240-250 Tests in Cleanroom 8	49(refers to chapter 4), 50 (refers to chapter 4), 51, 52.1 (refers to chapter 4)
260 – Empty cooling system	52.1 (refers to 4.1)
290 – Final inspection	52.3 + references (separate files), 53 + reference (separate file)

Appendix M – Assembly descriptions

Chapter (work instructions)	Issue
4.3 – Cleaning components *Rengöring av detaljer*	It does not say anything about the need to sort the components, how it should be done or which components can be cleaned together. Also, it could be good to explain what needs to be done directly before and after the cleaning. The housing and cover top are cleaned in another room and not the cleaning room. Before walking to this room, the operator must bring new plastic bags for transportation of the clean components. The cover bottom must be cleaned directly before it is to be assembled. Perhaps there should be sections in the chapter dedicated to each large component and type of component with descriptions of the procedure where it differs between the different components.
4.18 – Leak test *Läcktest*	The required preparations are not well described. No pictures are included either.
6 – Labelling and painting *Märkning och lackning*	There is no picture for paragraphs 1 and 2, which makes it a bit difficult to understand the procedure.
7 – Protective tape *Skyddstejpning av enhet*	Explanation is not very thorough. Information missing regards whether or not the tape is already cut into fitting pieces, how many pieces should be taped to the housing and where they should be placed.
8 – Temporary signs *Tillfällig märkning*	The existing pictures do not tell the whole story; at least one picture giving an overview of the unit should be present.
11 – Mounting small parts *Montering smådelar*	There should be more pictures of the locations of the components. There is a reference to a figure in paragraph 4, but the number of the figure is not included.
12 – Assembly of sub-product C *Montering* underprodukt C	Should specify that the mentioned housing refers to the housing of sub-product C and not the housing of the whole unit. The fact that the components must be inspected in a microscope is not included in paragraph 10, only in the reference. In paragraph 11 it could be suitable with a picture of how the o-rings are attached to as it is not a straightforward task. Paragraphs 12 and 13 would benefit from having a picture showing the end result. Paragraph 24 is not done at the same stage as the other paragraphs because it is a difficult and tricky task and if there are any problems and sub-product C has to be demounted would this difficult task have been done in vain the first time.
13 – Testing sub-product C *Provning av underprodukt C*	Only the first paragraph is done at this stage.
14.1 – Mounting	The first line of paragraph 13 must be made before

Montering	paragraph 12.
15 – Leak test *Läcktest*	Refers to section 4.15, but it should be section 4.17.
16 – Filling unit *Fyllning av enhet*	The description of the filling (or flushing as mentioned previously) is not very thorough, more details and pictures are necessary. In paragraph 12 it is mentioned that extra coolant might be necessary to pour into the system. How this is done is not explained however. The task is quite tricky and needs more explanation as well as one or two pictures. No estimation of the time until the unit has cooled down is given, which could be useful considering it takes several hours.
17 – Mounting sub-product R *Montering och provning av underprodukt R*	The fixture used by the operators when placing sub-product R in and removing sub-product R from the housing is not mentioned. All glue hardening is done simultaneously in section 17.3.
18 – Mounting *Inmontering*	Paragraphs 1 to 7 are performed in operation 600, while paragraphs 8 to 12 are performed in operation 4100. It would be beneficial to split the chapter into two parts accordingly.
19 – Mounting *Inmontering*	A figure is referenced to in paragraph 1, but no figure number is included. The picture currently included could be better in showing how the mounting. Improve the picture or add more pictures.
20 – Mounting *Montering*	A picture of how it should be mounted would be beneficial. In addition, there is nothing explaining the possible need to adjust the component.
21 – Mounting *Inmontering*	A picture showing the mounted component is missing.
22 – Mounting *Inmontering*	The description is scarce and no picture is included. To facilitate for the operators should the description be elaborated upon and pictures added.
24 – Mounting *Inmontering*	There is no picture visualising where and how the component should be mounted.
25 – Mounting *Inmontering*	Could be useful to divide the chapter into two parts; one for the assembly of the components into a sub-product and one part for the mounting of the sub-product into the housing.
26 – Cable from sub-product C *Ledare från underprodukt C*	The first halves of the two sections in this chapter are done before chapter 25, while the second halves of the section are done after chapter 25. Would be beneficial top split this chapter into two parts.
27 – Mounting *Inmontering*	The picture is not very illuminating; there should be an arrow or similar that can help the operators to understand where their focus should be in the picture.
29 – Mounting resonator *Inmontering av Resonator*	The handle (or fixture) used for holding the resonator, which facilitates both the assembly and mounting of it, is not mentioned. It needs to be removed by the assembly operator at the end of this

	chapter.
45 – Glue wedges of resonator *Limsäkring av resonatorns kilar*	Would be beneficial with a picture visualising where the wedges are located.
48 – Mounting cover bottom *Montering av Cover Bottom*	Paragraph 1 in 48.1 is done in operation 232, while the rest of the chapter is done in operation 235.

Appendix N – Routing 500:A

Operation	Issue	Solution
100 – Cleaning housing	Does not mention the cover top that is also cleaned in the operation.	Change the name of operation to include the cover top.
300 – Cleaning	Only 1 hour, takes approx. 4 hours in reality. No consideration has been taken to the amount of work the kitting produces.	Adjust the time to suit the reality. According to the current situation should the time be 4 hours.
500 – Paint + mount small parts	One of the terms used in the operation description is not used by the operators. No time is allowed for the glue to harden nor time for the paint to dry.	Change the term used in the description to what the operators use. Add 16 hours (minimum) for the glue hardening process and 45 minutes (minimum) for the paint to dry.
600 – Mounting	The name of the operation is unspecific and does not say anything about what is being mounted. In addition, not all components are mentioned in the description and it could be easy to forget one.	Change the operation name to a more clarifying one that includes at least some of the components. Also, add all components in the operation description.
601 – Mounting sub-product R	The name for sub-product R that is used in the operation name, is not used by the operators.	Change all names for sub-product R to what the operators use.
750 – Process time	This operation is not used according to the operators.	Remove this operation from the routing.
850 – Mounting sub-product C	The name is misleading as it does not include it one of the sub-products that mounted in this operation.	Change the name of the operation to include both sub-products
900 – Leak test + flushing	The time is set to 4 hours, but according to the work instructions should the flushing take 5 hours and according to the operators should it be 4 hours. In any case is there no time for the leak test. In addition, the description of the operation in IFS states “Leak test, Flushing 4 hours, Filling inner cooling system”, making is sound like flushing and filling are two different things when really, they are the same. Every fifth time the flushing machine is used it has to undergo maintenance, which takes	Adjust the time to suit the reality. According to the current situation should the time be 4 hours for the flushing and approximately 30 minutes for the leak test. The time for the maintenance should be added to this time, i.e. 24 minutes extra for the operation (which is 120 minutes divided by 5). The description should also be changed to entail

	approximately two hours. This extra task is not included in the time or description specified in the routing.	the maintenance to alert the operators. Also, the description should state leak test and flushing, only.
950 – Process time	The time is set to 3 hours and the description in IFS reads “Stabilisation”. What this means is not clear and the operators are not sure. They are assuming that it is the time it takes for the unit to cool down after the flushing.	Change the name of the operation to “Cool down time” (“Avsvalningstid”) to ensure that is made clear.
960 – Glue	Gluing is made simultaneously as previous operations.	Remove operation 960 and add the time to operation 850.
3000 – Mounting electronics	Some components are mentioned, but not all. Could be easy to forget a component.	Ensure all components are mentioned in the operation description.
3200 – Glue	Gluing is made simultaneously as operation 3000, not saved until 3000 is finished.	Remove operation 3200 and add the time to operation 3000.
3300 (8) – Test sub-product R	This is generally done straight after sub-product R has been mounted, i.e. after operation 601.	This operation should succeed operation 601.
3310 – Glue sub-product R	This is done after sub-product R has been tested.	This operation should succeed the above-mentioned operation.
3330 (8) – Inspection sub-product R	This is done after sub-product R has been glued.	This operation should succeed the above-mentioned operation.
3500 – Assembly	Not clear description of what this operation entails. It is some kind of extra inspection according to the operators.	The description should be richer in details about what should be done.

Appendix O – Routing 500

Operation	Issue	Solution
125 – Glue resonator	The outer cooling system must be emptied before the resonator is glued. It is not included in the description.	Add the emptying in the description of the operation or divide the operation into two; one for the emptying and one for the gluing.
130 – Leak test	In IFS it says that this operation also includes emptying the outer cooling system. However, the emptying must be done before Operation 125.	Remove the description saying that the cooling system should be emptied.
220 – Glue	There is no time designated for the hardening of the glue.	Add a succeeding process time of 24 hours.
232 – Cleaning	What is cleaned in this operation is not specified in the operation name.	Change the name to “Clean cover bottom”.
233 – Picking miscellaneous (“Plock övrigt”)	There is no description of this operation and the operators do not know what it entails.	Remove the operation or add a description of it.
235 – Mount cover bottom	There is no time designated for the hardening of the glue on the cover bottom.	Add a process time of 2 hours.