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The influence of production ergonomics on product quality

A research project conducted at a paced assembly line

Master of Science Thesis in the master degree program Production Engineering

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Gothenburg, Sweden, 2012

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Glossary

ABC – Activity Based Cost, a common financial method of calculation

Adjusting department – The department were time-consuming errors are corrected.

Andon – Personnel that are responsible for correcting errors at the assembly line

Assembly element – One or several assembly tasks that have been added together for administrative reasons

Assembly task – A series of movements that have been ergonomically classified

Direct cost – A cost that is dependent upon how many units are produced

EMD – Ergonomic Mapping Device, Volvo's tool for gathering information about production ergonomics and the tasks that have been classified

Ergonomic classifications:

- Red – High risk of strain injuries. All or most of the workers will experience problems either short or long term.
- Yellow – Likely risk of strain injuries. A significant number of workers will experience problems either short or long term.
- Green – No risk. This is the target level. None or a few workers are at risk of physical work-related problems.

Error types:

- Not performed – Some aspect of the task has not been performed at all
- Wrong part – The wrong component has been assembled
- Placed incorrectly – A component has been positioned wrong
- Performed incorrectly – The assembly itself has been performed wrong

GL – Team leader (Gruppledare in Swedish)

Go to gemba – A method used in Lean production. Its meaning is to "go see for yourself" in order to get a better understanding of the situation or the problem and decrease the risk of misunderstandings.

Lean production – A philosophy and way of working within a company to increase productivity, quality and engagement by the personnel and to reduce the waste of resources. Developed by Toyota under the name Toyota Production System.

Off line – areas in the plant that follows after section six of the assembly line. At this point the truck is completed and can be driven of the line.

Overhead cost – costs that are independent of the level of production and are shared by many different departments. It is therefore not possible to state how much they each contribute to the specific cost.

Pareto diagram – A bar chart where the values have been sorted from the largest to the smallest.

Payback time – The time it takes to re-gain an investment.

Qulis – Quality Information System, a computer program that is used by Volvo to gather and store data about quality defects within the production.

SAM – Sequence Based Activity and Method Analysis. A pre-determined time system where standard times are used to calculate the time an assembly sequence is estimated to take.

Section – an administrative part of the line. Line 21 is divided into eight sections and six of them are included in the study.

Six Sigma – A management system method for overseeing processes and evaluating how well they perform. Focuses on quality and uses statistical tools.

Sprint – An IT system with information about assembly tasks and materials for the trucks produced at Volvo.

Tact (Tact time) – The amount of time available for the workers to conduct their assembly tasks before the truck moves into the next station.

Tied-up capital – Value of raw material, components, semi-finished products, finished goods that has not yet been shipped, etc.

TQM – Total Quality Management. A management philosophy where the customer is in focus.

VPS – Volvo Production Systems. Volvo's version of Toyota Production Systems.

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Summary

There are numerous studies that discuss the subject of ergonomics in the contexts of sick leave and social expenses. However, there are much fewer that relate production ergonomics to other factors such as quality and productivity. There is still a need to put production ergonomics in a larger financial context, and this study was aimed at doing that.

The project has been carried out at Volvo Trucks' production plant outside Gothenburg in Sweden, as a pilot study. The objectives have been to show that there is a relationship between production ergonomics and product quality in the plant, and to present this information in a financial context. This has been done by performing a retrospective analysis of data collected over a period of 37 production weeks. A number of assembly tasks were selected and the errors associated with these tasks were examined. The tasks had been classified by the company ergonomist as either ergonomically suitable or ergonomically harmful for the workers.

The difference in the number of errors associated with the respective ergonomic categories showed that there are over twice as many errors connected to the ergonomically unsuitable tasks compared to the tasks where the ergonomics are appropriate.

The results were then put into a financial context by investigating the times that were needed to correct the errors. Among other things, the correction time correspond to personnel costs for the workers that are correcting the errors. It was not possible to trace any other costs to the individual errors, but the difference between the ergonomically suitable tasks and the harmful tasks is still significant.

The result serves as an indicator of the relationship between production ergonomics and product quality and the hope is that the financial figures will encourage the plant management to further investigate the matter. This is not about saving money, but rather about using resources for value adding work and increasing the amount of products being made right the first time. Several recommendations are provided in the report as how to continue the work with production ergonomics at Volvo Trucks.

Keywords: Quality, Ergonomics, Manual assembly, Cost of inadequate quality, Truck manufacturing, Ergonomics in a financial context.

Contents

1 Introduction

Production ergonomics is most often connected to the health of the personnel and to social expenses, while other factors that might be affected by inadequate ergonomics are seldom taken into consideration. The cost of improving production ergonomics in companies is rarely put into a larger context and compared to what can be saved by increased productivity and better quality.

This project aims at focusing on other possible savings and improvements that can come from improved production ergonomics. The results seek to broaden the horizon for the management and put more focus on production ergonomics by placing it in a context that it usually is not displayed in. The results of the study aspire to show that production ergonomics needs to be better included in the everyday work within companies and in their strategic work.

1.1 Background

The effect of production ergonomics on production performances is a relatively new area of interest. The findings so far have proven a connection between production ergonomics and quality performance [1] [2].There is, however, a need for more studies to create a broader knowledge base and a more thorough understanding of this connection. By finding the same relationship in different production environments and at different companies, it can be proven to be a general fact that must be considered.

For Volvo Trucks in Gothenburg, this study is a part of the work in putting more focus on production ergonomics. The intent is to make it a part of the ongoing work with strategic improvement and the Volvo Production System (VPS). There is also a need to show what potential savings can be drawn from investments in production ergonomics. This, in turn, may hopefully result in an increased interest and involvement of the management and hence production ergonomics can get more attention and funding.

By tracing costs related to quality problems that arise because of the ergonomic situation of the assembly personnel, the cost of bad ergonomics is highlighted at Volvo Trucks. It also provides a financial figure that can later be compared with the cost of improving the situation. These cost comparisons can put ergonomics in a new context and it is easier to communicate the importance of production ergonomics to management levels. It is equally important to convey the message to the product development departments, since the design of the product provides the base for the ergonomic situation in the production plant.

When initiating this project, Volvo Trucks' goal was to facilitate the communication and draw attention to the area of production ergonomics. By approaching Chalmers University of Technology, Volvo Trucks shaped the project into a master's thesis within the field of production engineering.

1.2 Purpose and objectives

By showing the relationship between production ergonomics and the quality outcome, the benefits of ergonomics can be described as decreasing cost of inadequate quality. This thesis is intended to show Volvo Trucks the potential derived from improving the assembly ergonomics at the plant in Gothenburg specifically, but also in a more general aspect. It also contributes to the range of studies that present a connection between production ergonomics and factors other than health and social expenses.

The purpose of the study is to show a way to communicate the importance of production ergonomics to managers as well as to product developers. It is also to present additional data that confirms the connection between production ergonomics and product quality in more general terms. This is much needed since the financial benefits of production ergonomics is still a field of limited research.

In summary, the objectives of the project are to:

1. Show a relationship between production ergonomics and the quality of the product in truck assembly.
2. Present the results and the importance of production ergonomics in a way that facilitates the communication to decision makers.

In addition, the thesis report should also include recommendations for the continuation of the project as well as for how a more extensive study can be performed. This project is considered to be a pilot study and should highlight the possibilities and limitations that can be expected in the continued work. It is also meant to warrant further investigation concerning production ergonomics at Volvo Trucks in Gothenburg.

1.3 Delimitations

Only physical ergonomics will be included in the project. Aspects belonging to the area of cognitive ergonomics – such as mental stress, information processing and autonomy – have been excluded from the study but will be commented on since they are closely related to physical ergonomics. No initiatives have so far been made to map the cognitive ergonomics at Volvo Trucks, and the lack of a knowledge base prevents from addressing the cognitive ergonomics at this stage.

The ergonomic situation in the production has been partially mapped already and the assembly work has been divided into tasks and sub-tasks. The ergonomics of the tasks have been classified into three levels and these levels will be the basis for selecting tasks for the project. A complete mapping of the ergonomic situation will therefore not be performed. Further studies of the ergonomics will only be done if they are needed to ensure that the classification is valid and up to date.

1.4 Guide for reading the report

Depending on previous knowledge, different parts of this report will be of more or less interest. Therefore, a guide is presented to direct the reader to the chapters that are believed to be of most interest.

If the reader is experienced in the field of ergonomics, *2.2 Basic theory on ergonomics* will be of less interest. A reader who is familiar with Volvo Trucks in Gothenburg and VPS can skip *3 Prerequisites at Volvo Trucks*. If the interest merely concerns Volvo, *2.1 Previous studies* can also be omitted. Instead, the reader can focus on *5 Results*, *6 Analysis* and *8 Recommendations*, where the situation at Volvo specifically is treated more thoroughly. For a reader with a more academic viewpoint, chapters *4 Method*, *6 Analysis* and *7 Discussion* may be of high interest.

2 Theory

This chapter describes some of the existing studies and the methods that have been used to highlight the connection between the production ergonomics and the quality of the output. It also presents how economic benefits from ergonomic improvements have been mapped and communicated to management levels. These studies and their findings served as a base for deciding the goals and the limitations for this study, as well as for making the selection of methods. There is also a short theory section about ergonomics for readers less familiar with the area.

2.1 Previous studies

There are – in comparison with other areas – few studies that aim at finding and pointing out a connection between production ergonomics and the quality of the output. Those that exist all succeed in pointing out a connection between production ergonomics and quality.

The traditional approach to improving quality has been to look into the design of the product and production process in order to reduce variability. With the introduction of several systems and methods – such as Total Quality Management (TQM), Six Sigma and Toyota Production System – there has been a change towards involving the whole organization in the work with quality improvements. There is a difference in how a company works with quality and with production ergonomics; quality movements stretch higher up to a strategic level while ergonomics usually stays at the technical level. [2]

2.1.1 Quality and production ergonomics

In a study by Lin et al [2], it was found that quality could be directly related to two ergonomic variables: time pressure and postural stress. The study was made at a camera manufacturer and their two paced production lines, an older non-automated and a newer semi-automated line. Errors per week were counted and the defect causes were investigated to find which of the errors could be traced back to a work station. The ergonomic variables that were of interest were the time required to complete the task and the posture of the body. The results showed that more errors were predicted to occur if the task required more time than average and therefore resulted in stress and time pressure, and if the postures was ergonomically unsound.

The study by Falck [1] at a car manufacturer also showed that an ergonomically insufficient work task resulted in considerably more faults than an ergonomically sound work task. The study started with a mapping of the ergonomic situation. The work tasks were divided into three different classification levels depending on the ergonomic situation. These levels were constructed as a traffic light with green representing good ergonomics, yellow representing neither good nor really bad and red representing a harmful ergonomic situation. A random selection of work tasks was made, with the numbers of tasks spread as equally as possible over the different classification levels. Errors caused by these selected work tasks were then traced. It was found that the amount of time it took to conduct each work task differed between the classification levels, with most of the time associated with yellow tasks and the green classification having the least time. Therefore, the numbers were adjusted so that a comparison could be made. The result showed considerable fewer errors associated with the green work tasks than with the red or yellow ones, indicating that ergonomics has an impact on the quality output.

A general concern among many ergonomists is that the ergonomic aspects are not included in the beginning of a design process. They are rather being addressed after strategic decisions have already been made, at a point where any change increases the cost dramatically. The result of this is that only minor adaptations are made to improve the ergonomic situation and the whole process of ergonomics is viewed as a time-consuming and cost intensive activity. Another problem is that the feedback from insufficient ergonomics is often received much later, even several years after the design process has been completed, in the form of sick leave, injuries and so on. This makes the connection to design unclear for the management. Additionally, the design team almost never receives this feedback and it is therefore difficult to gain organizational learning. [3]

A comparison made by Auburn Engineers, a US ergonomic consulting firm, shows that if the ergonomists are included in the project from the beginning, the cost is about 1 % of the budget, but if they are brought in after the system is put into operation, the cost is more than 12 % of the budget. The reason for the difference in cost is that if the problems are addressed before the system is implemented, changes are easier to make and they will be less costly. [4]

2.1.2 Presenting economic potentials from ergonomic improvements

To show the benefits from ergonomic improvements in a study by Yeow and Sen [5], the revenue before and after an ergonomic improvement was compared. It was found that there was a possibility of savings in rejection cost, repairs and scrap. It was also found that the output increased and in this case made it possible for the company to meet the customer demands and hence increase their revenues further. [5]

In another study, by Beevis and Slade [6], it was proved that by changing the environment for the operator the cost of damages was reduced by at least £30 per week. The changes cost the company £270, which gives a payback time of only nine weeks. Usually when it comes to improvement of the ergonomic environment, it is often the cost of different solutions that are compared. The possible cost savings within the system that is being improved are not identified. The reason is that the benefits – for example, reduction in anticipated accidents or errors – are difficult to assign and cost out. Another explanation is that ergonomics might be an integral part of a larger improvement and its specific contribution cannot be separated from the total effect. Beevis [7] identified three categories of financial benefit:

- Improved performance – identifying what the problem is that really needs to be solved. Here, ergonomic applications can help in finding the right problem and solve it and thus have a positive effect on the overall performance.
- Avoided costs – costs that might be anticipated in the future unless action is taken to avoid them. For example, minimizing technical support calls, investigating customer complaints, returns or loss of sales.
- New opportunities – providing a new capability or expanding the market potential of a product or process.

In a study conducted by Eldrige and Dale [8] aiming at quantify quality costs, general classifications of cost of quality were used to choose which costs should be included and to present the results. The four classifications were:

- Prevention – all costs concerned with preventing an error from occurring, for example, quality planning costs, new product review costs, process control costs and quality audit.
- Appraisal – costs incurred by identifying poor quality products before shipment to customer, for example, incoming inspection and testing costs, in-process inspection and testing costs, and final inspection and testing costs.
- Internal failure – costs associated with defects that are found before shipment of the product to the customer, for example, scrap costs, loss costs, rework costs, failure analysis costs and downgrading costs.
- External failure – costs incurred because of errors found after shipment of the product to the customer, for example, warranty charges costs, complaint adjustment costs, returned material costs and allowance costs. External failure also exposes the company to the risk of possible loss of future business.

Other costs that increase because of faults are those associated with inventories, such as costs for storage facilities, handling of parts and also interest costs of tied-up capital in material and semi-finished products. The reason for this is that additional material is needed to replace scrap, which means that additional transportation and more storage is needed to hold the extra material. Also, since the products are not finished in time, the tied-up capital in material increases since more materials are in use than if the product had been correctly assembled and had been possible to ship to the customer. [9]

It was found by Eldrige and Dale [8] that it was time consuming to divide the cost into the four categories and underlying headings. Another finding was that it was difficult for management to use the results since it had little or no connection to their knowledge base. The categories are mainly concerned with bookkeeping and the management had little or no knowledge in that area. In the second phase of the study, the costs were instead divided into the functions where they occurred. This method reduced the time spent on processing information as well as improved how the results could be used to gain understanding on the management level. The focus was on direct costs, since it was found that management could easily understand that any improvement in a specific area would reduce or remove these costs. Hence, the benefits of investing the potential elimination of a quality error were more directly communicated to management levels. This was also connected to what was classified as quality costs: activities were said to be quality related if they could be reduced through quality improvements. [8]

This shows that to be able to communicate the need to solve a problem, quality cost should be assigned to actions or departments that cause the costs and where the costs occur [10]. Activity-based costing is a well-known method that tries to allocate costs by identifying what activity it is that causes or increases the costs. Activity-based costing measures the cost of using an activity or resource; it does not, however, measure how much it costs to have the service at readiness. [11]

It can be argued that an ergonomic proposal must be presented in business terms. All costs must be justified with clear economic benefits if the funds are to be provided by the managers [4]. A common problem with this is that the managers want to see the value of ergonomics, but often they cannot provide the information required to perform any kind of cost analysis [7]. Even if the potential value cannot be put in exact numbers, one should discuss the potential benefits that can be made. Therefore, it is important to clearly identify, if possible, the costs and economic benefits that can be expected and also outline how they can be measured. [4]

2.2 Basic theory on ergonomics

Ergonomics is a very wide concept that includes all factors that affect humans. In a workplace, it comprises everything from physical loads and the temperature of the room, to the social relationships with the colleagues. However, such an all-embracing term is not very practical to work with. Therefore, the subject of ergonomics has been divided into *physical* and *cognitive ergonomics*. Physical ergonomics concerns the physical influences on the body from objects and the environment, while cognitive ergonomics concerns mental aspects, such as information processing, stress and the psychosocial context. However, these two areas are closely related and cannot be isolated from each other in practice. Humans are constantly affected by both areas and the perception of one is often influenced by the other. [12]

Cognitive ergonomics is not included in this project but the close relationship between physical and cognitive ergonomics cannot be completely ignored. Since this project focuses on quality problems originating from errors made by the assembly workers, basic theory about human errors is also needed.

2.2.1 Physical ergonomics

Physical ergonomics can be further divided into two areas: environmental aspects and physical loads. Naturally, they affect each other to a great extent but in the workplace the environment is often controlled and optimized. In the factory setting of this project, environmental aspects such as temperature, general lighting, and air pollution are not considered problems. Therefore, they are not treated and will not be described here. [12]

Physical ergonomics includes a vast range of different aspects and there are many factors that need to be considered for each part of the human body. To simplify the topic, physical ergonomics can be described as a combination of three factors: time, force, and posture. Together they form what is called the *cube model*, see Diagram 4. These three aspects cannot be separated since they make no sense on their own; they interact and jointly constitute the ergonomic situation. [13] [14]

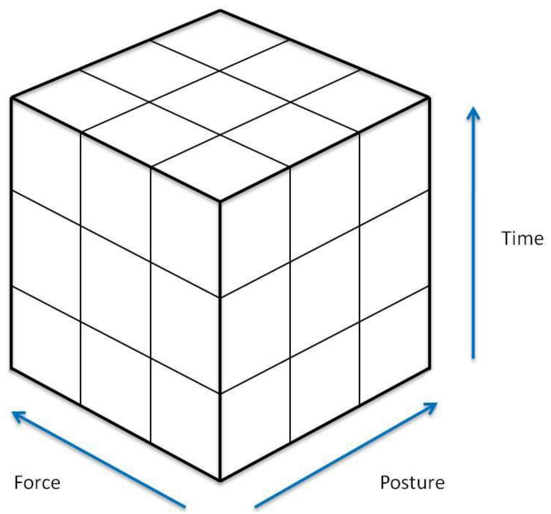


Diagram 1. The cube-model with the three variables that can be used to describe physical ergonomics

- Time – Time is a crucial aspect when dealing with ergonomics. If a very strenuous activity is only performed for a few seconds each time and only done once a month, it is not likely to be very harmful. If the same activity were to be executed for an entire day, it would cause fatigue, pain and the body would not be able to perform the task. [12]

  The body needs to recover and the recovery time is as important as the activity time. Heavy tasks can be done if enough recovery time is allowed. If the recovery time is taken away, the performance capacity is drastically reduced. [12]

  The repetition of a task—that is, the alternation between the task and recovery—is also considered to be part of the time factor. Repetition is not harmful if the recovery time is sufficient for complete recovery. When that is not the case, the repetition creates the same harmful impact on the body, with the only difference that the time to injury may be prolonged. Pain and injuries resulting from repetition can take years to manifest themselves, but will nonetheless be the reality if the recovery time is not sufficient. [12]

- Force – The forces and the load on the body is the second aspect. If the load is too large, there will be immediate damage to the musculoskeletal system. The time factor will be irrelevant since the body cannot handle excessive forces. But below this limit the amplitude of the force will determine the possible duration before fatigue or injury occur. [12]
- Posture – The position of the body has a great effect on the strength and the endurance of the muscles. Tasks that are easy to perform in one posture can be impossible to do in another. The posture also affects precision and can add to the static loads on the body. [12]

Static loads are very harmful to the body since they, by definition, do not allow for recovery. Even very small loads can be harmful when they affect the human for a long period of time. One common source of static loads is holding the body or a body part in a fixed position. For example, even if no external weight is added, holding an arm away from the body can be very tiring and cause pain after doing so for a more than a few minutes. And even if the tasks are varied and include handling and assembling of different parts, the postures can still be static. In that case, variation of the tasks – for example, by rotation – will not be an effective solution to the problem with static loads. [12] [15]

Arbetsmiljöverket (Swedish National Board of Occupational Safety and Health) provides general guidelines for how an ergonomically sound work environment can be provided. However, it is up to the employer to ensure that the guidelines are followed and that ergonomics is an area of interest within the company [12] [16]. At many workplaces, the union also plays an active role in the work with ergonomics.

The guidelines from Arbetsmiljöverket include recommendations about the factors included in the cube model: for example, how much weight that can be lifted and for how many times a day. Posture is to some extent covered by pictures with the distance-zones that are considered acceptable or non-acceptable, as seen in Diagram 2. [17]

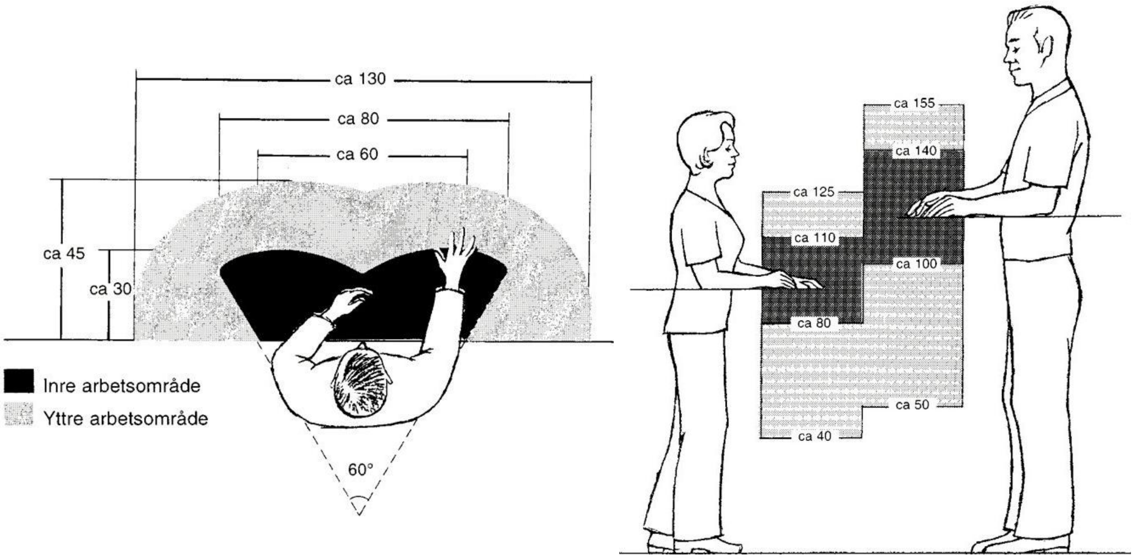


Diagram 2. Example of guidelines provided by Arbetsmiljöverket. The zones represent appropriate and less appropriate heights and distances. (Image source: Arbetsmiljöverket [17])

However, these guidelines are very vague and associated with formulations such as “will add to the risk of injury” and “should be avoided if possible”. There are no exact rules for forces and times; each situation must be examined individually. Each human being is also different and has different prerequisites. It is simply not possible to give exact numbers of what is acceptable and what is harmful [12] [17]. Therefore, no more specific information about what constitutes good physical ergonomics will be provided here. Instead, the reader is referred to existing books on the subject.

2.2.2 Human errors

According to the SRK-model, any human action is generated on one of three levels: *Skill-based*, *Rule-based* and *Knowledge-based* actions. Skill-based actions are things we do automatically and do not have to think about, such as opening a door. Rule-based actions are based on existing rules on how the situation should be handled, using a well-known computer program for example. Knowledge-based actions on the other hand, require problem solving and are used when faced with new and unfamiliar situations. The human brain tries to operate on a low level since problem solving is a relatively slow and demanding task. It therefore often tries to use pre-existing rules in a new situation. It tests different theories and combinations of rules and hopes that a familiar plan of action will work in the new situation as well. [12] [18]

The GEMS-model (Generic error-modeling system) developed by James Reason [19] is based on the SRK-model. It assigns errors to the three skill levels and categorizes them according to the reason for the error. Errors on the Skill-based level are called *Slips* and *Lapses*. A Slip is when you perform the action wrong; for example, trying to enter a screw but dropping it on the floor. A Lapse is when the memory fails and the wrong action is performed; for example, pushing instead of pulling when trying to open a door, even though the same door has been opened many times before. [12] [19]

Mistakes can be made on both the Rule-based and the Knowledge-based levels. A Mistake is made when the mind chooses the wrong rule to solve the problem, either when faced with an unknown situation or when performing a task that is familiar but can be performed in different ways. When presented with a new door that is to be opened, it is visually examined for clues that can reveal if it is to be pulled or pushed. It can be, for example, the type of handle or lock or the position of the edge of the door relative to the door frame. Based on this, the brain selects the rule that is most likely to apply. If that rule is incorrect, it will try the next most likely and so on. If neither pushing nor pulling seems to do it, the next logical step is to check if the door is locked, and if so, if it can be unlocked. [12] [19]

An additional form of error is *Violations*; that is, when a human knowingly performs an error. It can be without bad intentions—for example, skipping a safety rule in order to save time and hoping that nothing will go wrong that particular time—but it can also be with the intention of causing damage, such as vandalism. [12] [19]

There are various factors that increase the risk of errors in a work place. Besides personal factors – such as age and tolerance to stress – there are several others that can be controlled by the management. There are many aspects that are less obvious than, for example, the need for breaks and having the correct tools for the job. Such factors include for example the overall workload, the pace and long-term stress as well as the leadership and the psychosocial environment. Yet another factor is feedback. If the human does not receive feedback or if the feedback is received too long after the error occurred, it will increase the risk of making errors. The perceived importance of the task that is being performed will also affect the risk of making errors. Being able to put the task into a larger context increases the motivation and the probability of performing it correctly [12].

Factors that are external – for example the lighting, the work pace and the leadership – are often called *latent conditions*. In order to reduce the amount of human errors, it is necessary to target these conditions and not the humans that are making the errors. It is easy to blame the human factor when errors occur but doing so will not solve the underlying problem and remove the source of the errors. This is important to keep in mind when designing a system: a machine, computer software or a workplace, for example. There will always be human errors if the system is not designed in such a way that it is impossible to make them in the first place [12].

3 Prerequisites at Volvo Trucks

In order to make the methods and results more understandable, a description of the general prerequisites at Volvo Trucks is needed. In this chapter, Volvo Trucks in Gothenburg is presented, its production system and its general work with production development, quality and ergonomics. For readers familiar with Volvo and Volvo Production Systems (VPS), this chapter can be left aside. All information in this chapter originates from internal documents provided by Volvo and consultations with personnel at Volvo Trucks.

Volvo was founded in 1927. Today, Volvo Trucks is part of the Volvo Group together with several other Volvo companies, and the truck operations account for about two-thirds of the total sales within the Volvo Group. Volvo Trucks is represented in more than 140 countries all over the world and it has factories in Sweden, Belgium, USA, Brazil, South Africa, Australia and India. The factory in Tuve, in Gothenburg, Sweden, was built in 1978 and today it employs 1800 people and produces about 100 trucks per day. [20]

All trucks that are produced in Gothenburg are tied to a specific customer order and made to customer specifications. This means that there is a broad variety of trucks produced on the same production line. It takes about two days from the entering of the steel material into the factory until the truck leaves, completed and ready for delivery. [20]

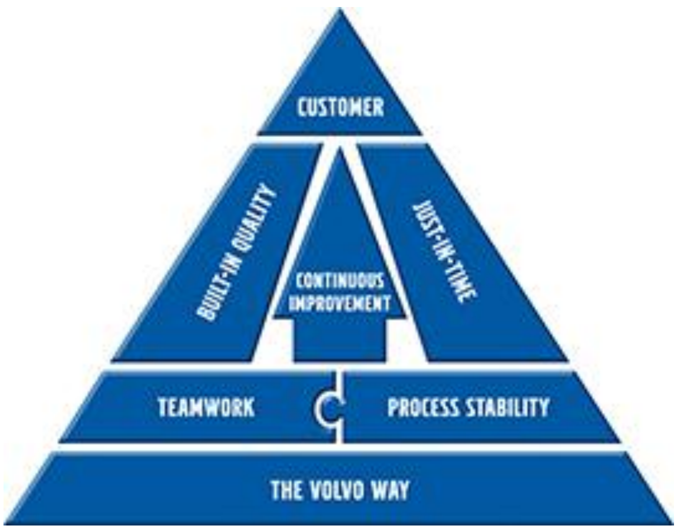


Diagram 3. The VPS-pyramid. (Image source: Volvo Trucks [20])

In 2007 Volvo Production System, VPS, was introduced. It is a model that consists of principles that aim at creating value for the customer by improving quality and assuring delivery, focusing on safety, the environment and people. The VPS system has its origins in the Toyota Production System and is based on the philosophy of Lean production. As seen in Diagram 3, quality is one of the cornerstones that the system is founded on. Volvo describes that quality can be assured by doing the right things from the beginning instead of correcting errors afterwards. By not passing problems to the next step in the process, time can be saved and the process can be stable. [20]

3.1 The production plant

In 2009, Volvo made a big change from building trucks at production cells to the use of a driven line. Today there are two parallel lines that each produces about 50 trucks per day. They are called Line 21 and Line 22. They have some differences in product range due to a turn that the lines have to make because of the physical limitations of the building. The trucks produced on Line 22 have a length limitation since Line 22 has the inner line in the turn. Line 22 is also a bit shorter and has a different number of stations, and the assembly operations are in some cases not distributed in the same way as in Line 21. As will be described in greater detail later, this project is only concerned with Line 21 and therefore it is this line that will be described further.

3.1.1 The assembly line

Volvo Trucks in Gothenburg produces trucks of 16 tons and above. While the engines, gearboxes, wheel axles and cabs are pre-assembled in other production plants in Sweden, the frames are produced at the factory in Gothenburg. Some additional pre-assembly is conducted on the engines, gearboxes, axles and cabs before they are added to the main assembly. There are also stations where kitting and pre-assembly of other details are performed. The tact time is about 9 minutes and each line produces 50 trucks per day. This tact has been used at Line 21 since March 2010. [20]

3.1.1.1 The plant layout

The lines are divided into main assembly and pre-assembly areas. The pre-assembly areas produce more or less complex sub-assemblies that are delivered to the main assembly flow. Everything is built in sequence and the pre-assembly areas transport the components to the main assembly in the correct order. Some pre-assembly is carried out using a paced line, where the product moves from work station to work station but stands still during assembly.

The main production lines consist of eight sections, each with approximately six or seven stations. Each section constitutes an administrative division and the borderlines can in most cases not be seen in the production plant. The entire main assembly flow for each line is laid out as one unit with pathways between stations only where necessary for forklift transportation. A schematic overview of the production flow can be seen in Diagram 4.

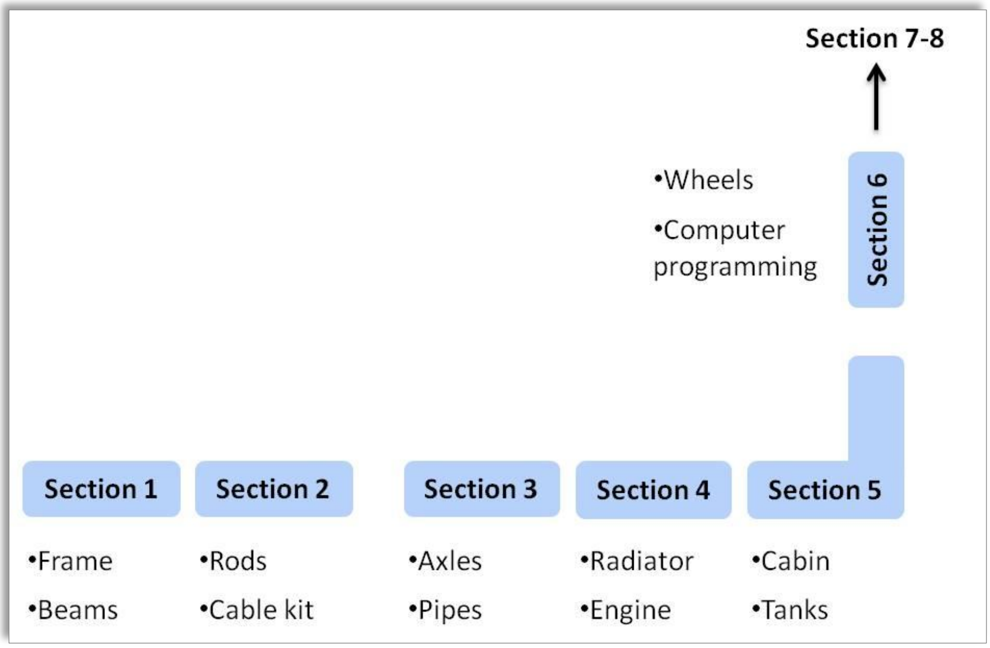


Diagram 4. Schematic representation of the production flow at Line 21

Most of the assembly-operations are performed in sections one through six. Section seven and eight are mainly for filling of fluids, controlling the quality and functions of the truck and correcting minor errors.

The first two sections have a paced flow, where the carriers that the chassis are placed on stand still during assembly operations. When the cycle time has passed, the carrier automatically moves forward to the next station. After the second section, there is a buffer for two chassis and section three starts with marrying the chassis with the axles. From here on, the line becomes a driven line, which means that the truck is constantly moving forward while assembly operations are performed. The last station in section six includes the removal of the carrier that the truck is resting on and the truck is then capable of transporting itself. Sections seven and eight are therefore considered to be off line since the truck is largely completed and ready to drive.

If the truck does not conform to the standards, and the errors cannot be fixed within a relatively short period of time, the truck is sent to the Adjusting department, where errors are corrected. The Adjusting Department has a fixed position layout, where the entire truck can be disassembled and reassembled again if necessary.

3.1.1.2 Sprint and assembly times

All technical information about the assembly process – such as the sequence of assemblies, the times they are expected to take and the work instructions for the assembly personnel – is gathered in an IT system called Sprint. The time estimations are based on the pre-determined time system SAM (Sequence Based Activity and Method Analysis). The purpose of a pre-determined time system is to obtain time estimations in a quick and easy way. The times are calculated based on pre-determined times for individual movements, which are then added together to constitute entire assembly sequences. As a result, the real times are not measured in the actual production plant. [21]

Volvo has adapted SAM to better fit its system and processes. There are, for example, extra times added for certain known problems, where the estimated times need to be longer to conform to reality. Some of the smaller elements have also been combined into larger modules for simplicity. [20]

When calculating the assembly times, it is necessary that the assembly is performed in the same way every time; otherwise the times will be incorrect. However, Volvo Trucks in Gothenburg has no standardized way of working. New assembly personnel are taught the tasks by more experienced workers, but many of the tasks are performed in different ways by different workers, so no consistent methods are used. The work instructions in Sprint only contain the components that are to be assembled and in what sequence the assembly should be made, but no details on how the assembly should be performed. This gives the operator the freedom to perform the task as it suits him or her best, but it also creates a source of error regarding the assembly times.

3.1.1.3 Assembly personnel

Sections one to six of Line 21 consist of 40 workstations, and at each station there is between one and six workers. There is space for up to eight workers in each station if necessary with concern to the production pace. Every section has a quality control station with at least one quality inspector who examines the truck and checks for errors that are known to occur frequently.

Each section also has two team leaders, GL, and one to three Andons. The GL has the coordinating role and is in charge of the communication with other departments. The GL also helps out when a problem occurs, and serves as backup if a worker for some reason needs to step away from his/her station.

The Andons are the ones that correct errors at the assembly line. These are smaller errors that do not take a lot of time to correct, often less than the cycle time. In some cases, prioritized errors – that will be very time-consuming to correct later on, or prevent other crucial components to be assembled on the truck – are allowed to require more time or more than one Andon. This is, for example, the case with errors originating from section one where the riveting is made. These errors cannot be corrected in any other department, so the personnel are very anxious to correct them before the truck leaves the section.

The Andons mainly correct errors within their own section, but sometimes they are called to a subsequent section to correct errors that have occurred at their own section, but are not discovered until later. Depending on how far down the production flow an error is discovered, the Andon makes the decision whether he can correct the error within a reasonable timeframe, or if it is better to send the truck to the Adjusting department. If the Andon decides to correct the error, it will take longer time to do so in a subsequent section compared to if the error was corrected in the section where it originated. This is partly because the Andon has to walk further, but also because the workers in the subsequent section are performing their jobs at the same time. The workers and the Andon might get in each other's way. There may also be components in the way of the part that the Andon is trying to access.

3.1.2 Departments that correct errors off line

Volvo aims at sending a maximum of 30% of all trucks to the Adjusting department; this includes errors both due to assembly mistakes as well as material defects and late deliveries from suppliers. To relieve the Adjusting department, two additional areas have been created where it is possible to correct smaller errors: one in section seven and one in section eight. Independently of which of these three departments the errors are corrected at, the truck is complete, and it will therefore take much longer times to correct the errors. As long as the truck is off line, and thus completed and standing still, it will take approximately the same time to correct a particular error independently of where it is done.

Section seven deals with minor errors that take no more than twice the cycle time, about 18 minutes, to correct, while section eight can handle more time-consuming errors. In section eight, they usually only perform work that takes less than one hour, but they can make exceptions if they do not have a lot of work waiting. They can perform most jobs but do not have all the necessary equipment to do heavy tasks like removing the engine or the wheel axles from the truck. At the end of the day, no trucks are kept at section eight, so any work that has not been completed is finished at the Adjusting department.

The trucks cannot be taken directly to the Adjusting department, so while they are waiting for an empty space in the department area, or waiting for material to be delivered, they are parked outside. This means that they are exposed to weather conditions, especially during the winter, and have to be cleaned before the work can begin. The order in which the trucks are handled by the Adjusting department depends on their delivery date to the customer.

There is no documentation showing the times needed to correct an error in the Adjusting department. However, since the personnel who handle the adjustments are experienced, they have a feeling for how long time an operation takes. These time estimates are used by the Adjusting department when they plan their work and usage of resources.

There are 41 people working at the Adjusting department, of which 24 are performing correction work while the others have more administrative tasks. Several of the adjusting-workers have some sort of special competence, such as painting or sheet-metal work, and all of them have several years of experience with assembly work within the factory. The only error that they do not have competence for is advanced engine-work. This competence is only available at the engine factory in Skövde. Therefore, personnel from there have to come to Gothenburg when errors of this sort have occurred.

3.1.3 The department that handles the consequences of scrapped material

There is a small department, commonly called "Varjburen", which is a sub-department of the Material handling department and can be described as a material buffer. It handles all material that is needed when something gets damaged within the production or when a faulty component is delivered by a supplier. It has a small buffer stock of material that is used frequently, and is in charge of placing some specific types of orders for material. If nothing would ever go wrong within the factory or with deliveries from suppliers, this department would not be needed.

There are currently three full-time workers in the department. They do not use the same computer system for registration of errors as the rest of the plant, but instead get a notification from the Material handling department that a new part has been ordered so that they can await the delivery. They then notify the awaiting department when the component is planned to arrive, and arrange for transportation of the detail. Often, the parts are sent to the Adjusting department since the time available on the production line is usually too short for components to be exchanged there. Instead, the truck is taken to the Adjusting department to have the error corrected.

3.2 The work with ergonomics so far

EMD (Ergonomic Mapping Device) is a tool that has been developed within Volvo Trucks and has been used since 2009. It consists of a Microsoft Excel spreadsheet that is used to map the ergonomic situation in the production plant. Assembly sequences are analyzed with different factors taken into consideration. So far the assessments have been done by an ergonomist, but the goal is for the assembly personnel to get a greater responsibility for the process. When possible, they will do the analysis and register the result in EMD, only consulting the ergonomist if needed.

It is never the entire work cycle that is being assessed at any one time since the cycle time is so long. Recovery time or work rotation is also not included in the analysis; the tasks in EMD have been judged individually and isolated from each other. There are no criteria written down for the classifications but they are based on general ergonomic knowledge, recommendations from Arbetsmiljöverket (Swedish National Board of Occupational Safety and Health), Volvo's own requirements and the experience of the ergonomist.

The sequences that are assessed are often focused on a component that is being assembled. A sequence in EMD can, for example, be to pick different components from a pallet, perform a small sub-assembly, place the parts on the truck and finally assemble them on the truck using a power tool.

An assembly sequence is being assessed with respect to factors such as time, weight and repetition. The weights of the components that are being assembled are considered, as well as the position of the body of the worker. Any focused strain on a certain body part, for example, the hands or neck, is analyzed. The duration of the assembly sequence and any static postures are considered, as well as the number of repetitions of individual tasks within the sequence, for example entering screws. Since static postures and repetitions are important factors, a long and time consuming task is more likely to get an undesirable classification than a task that takes short time to perform.

The postures are greatly affected by the working height, and the analysis is therefore performed with three different workers in mind: one short, one of average length and one tall. When all the considerations have been made, the ergonomist classifies the assembly sequence as red, yellow or green for the three different heights of the workers. Consequently, the analysis will produce three results for each assembly sequence. The representations of the three colors are [22]:

- Red – High risk of strain injuries. All or most of the workers will experience problems in either short or long term.
- Yellow – Likely risk of strain injuries. A significant number of workers will experience problems in either short or long term.
- Green – No risk. None or a few workers are at risk of physical work-related problems. This is the target level.

The assembly sequences that have been analyzed are seldom chosen by the ergonomist. Instead, an assessment is made when the workers, team leaders or production engineers have complaints or questions about a certain task or sequence. Only a small minority of all assembly sequences have been evaluated and hence been included in EMD. Since the investigations are often triggered by complaints, the majority of the tasks in EMD are red or yellow, since they are what workers notice as difficult and strenuous. Thus, there is an overrepresentation of tasks that are immediately tiring or cause immediate pain. In this context, immediate is considered to be within weeks or months, as opposed to work-related problems that do not appear until the same tasks have been performed over a period of several years. There is also a considerable lack of green assembly sequences, as these rarely generate any complaints. Therefore, EMD does not yet present an extensive mapping of the general situation in the production plant; EMD is still only a small sample of some of the tasks that are being performed there.

The general work with ergonomics has only begun, and has not yet become an integrated part of the continuous development of the production process; it is still an isolated piece of the puzzle. Officially, everyone is responsible for the creation of a sound ergonomic environment, but in practice, it is not a prioritized topic, and only a few people are actively working with ergonomics. The work that is being done is generally reactive as opposed to proactive. Ergonomic issues are dealt with when the problems are already there, and changes are made in the form of additional tools and aides in order to solve the problems. While designing the current production process and layout, ergonomics issues were addressed to a very small extent. Now, there are a great variety of different ergonomic aids and tools developed after the production design had already been implemented. These tools are seldom used since they are complicated and often heavy and, above all, do not solve the original problem.

A lot of the work concerning ergonomics that is being done originates from EMD. There, the potentially most harmful tasks are collected and evaluated as a basis for improvement work and development. The red tasks and assembly sequences have the highest priority and can be dealt with first. EMD is, therefore, an important base for further actions towards a better ergonomic situation.

3.3 The work with quality

To Volvo, quality is of the utmost importance and they are constantly working on it. Volvo Production Systems includes procedures for how errors can be tracked and how plans can be made to avoid them in the future.

When an error is discovered in the production plant, it is noted on a card that follows the truck throughout the entire production line. At the end of each section is a control station, where the errors on the card are entered into a computer program called Qulis (Quality Information System). This is done manually by the inspector stationed there. The error is entered with information such as which component is faulty, which part of the truck it is attached to and what position it has on the truck. All of this is done using pre-selected choices in drop-down menus. There is also a text field for comments or further explanations.

All of this would generate a complete database with all errors if it was used exactly as planned. But since there are deviations from the procedure at each step of the process, the database is far from complete. Not all the errors are noted on the card, and not all the errors on the card are entered into Qulis. The method used to enter an error into Qulis also differs greatly from inspector to inspector, from section to section and even from time to time. There are many combinations of entries that mean the same thing, while at the same time there are errors that are very hard to describe with the pre-selected choices available. The terminology in Qulis is not the same as the one that is used in the production plant, and it can sometimes be difficult for the inspector to know which term to use. Many errors are logged with such general terms that it is impossible to trace them back to their origin and know what component was faulty and what the error consisted of. For example, a pipe for the break system that is attached to an air tank can be logged with or without the index 'brake', and sometimes even the coordinates are missing. Since there are multiple air tanks on the truck, with multiple pipes in each and not just for the brake system, there is no way of knowing which pipe it is after the error has been entered and the workers have forgotten about it. When later trying to trace the error, it will be impossible.

When performing searches in Qulis in order to obtain information about certain types of errors, a number of different choices can be made and different terms can be used. Some of them will be explained here to provide the reader with basic information that will facilitate the understanding of the methods described later. Only the ones that were used in the project are mentioned; there are many features in Qulis that were not used at all.

The function called *Remark list* was the main one used in the project, since it offers the opportunity to combine several search terms and leave others blank. The search result is presented as a list that can be exported to Excel and hence be processed to contain only the information of interest.

The terms that are of interest in the study are:

- *Problem detail* – the item that has the problem or error, chosen from an extensive list in a drop-down menu.
- *Help object* – the object that the problem detail is attached to, or that is attached to the problem detail. This is also chosen from a list.
- *Position* – specific location on the truck where the error is positioned. The truck is divided into segments, and these are assigned a combination of letters and numbers; for example, "cc03".
- *Built date* – the date when the truck was assembled.
- *Report date* – the date that the error was registered in Qulis. It is likely to be the same as the *Built date* but can be different. Either *Built date* or *Report date* must be stated when performing a search.
- *Production line* – the line where the truck was built, which can be Line 21 or Line 22. If left blank, the search will include trucks from both lines.
- *Remark type* – the nature of the error. This is also chosen from a long list and can be for example: missing, placed wrong, leakage, too short, not treated.
- *Fault description* – text that is manually written when registering an error and that is used to further describe it and where it is situated on the truck. This text is also used by some sections of the line for tracing their errors to a specific station, and for some to enter information on whether they have corrected the error or passed it forwards to the next section. It is very useful to read the *Fault description* after a search has been performed to better understand the errors that were retrieved.
- *Problem owner* – the section of the line that is responsible for the error in one way or another, most often the section that is assembling the component in question. When tracing errors from a specific section, this option is used.
- *Reporting area* – the section or department that has discovered the error. Sometimes, it is the same department that has caused the error. It can also be a subsequent section, or even the Adjusting department.

4 Method

This chapter will start with a very broad and non-detailed description of the work process throughout the project. The chronological order will also be presented, while each part of the process is described in detail in subsequent chapters.

Overall, the project has been divided into two main parts:

- Information gathering
- Information processing and documentation

The main reason for this is that the project extended over the summer vacation and no information gathering was possible during that time. Since the end of the vacation and the project deadline were fairly close together, there was no time after the vacation for additional information gathering. Therefore, the vacation period had to be spent on documenting the project.

The main goals have been constant throughout the project but there has been some flexibility when it comes to the way of reaching them. Since this is a relatively new field of study and Volvo Trucks had never done any research in this area, it was not possible to foresee the difficulties that were encountered, nor the results that have been reached. Therefore, flexibility in the choice of methods was necessary. The difficulties and their impact on the study and the result are more thoroughly discussed in chapter 7, especially *7.3 Limitations in the result.*

During the information gathering, an iterative way of working was used. Since the project has been focused around the production line, which is divided into eight sections, it has been natural to work with one or two sections at a time at each step in the process. Two or more steps have been performed in parallel, but never in the same section, since the next plan of action has often been dependent on the previous results. When one of the main stages of the project has been performed at a section of the line, valuable lessons have been learned. Before the same stage of the project has been performed at another section, the methods have been revised and improved. Therefore, the work has gone more smoothly for each section that has been completed. Several of the project stages have been completed before another one has started, thus utilizing a serial work procedure. Other stages have instead been continued throughout the majority of the information gathering time period and have hence been performed in a parallel way.

It has been very important throughout the project to aim for a result that is as certain and reliable as possible from a statistical point of view. All the numbers acquired should be well-founded in the data and the real situation. Because of this objective, it has been considered better to obtain numbers that are too low rather than too high. This has been a basis for all decisions during the entire information gathering process, whether it is the number of errors, times or cost. For example, where there has been any doubt if an error should be included or not, it has been excluded. And when in doubt regarding which time or cost to choose, the lower has been selected. This ensures that the final result is the lowest possible; the times and costs can only be higher in reality.

Another methodology that has been used throughout the project is the Lean principle *Go to Gemba* [23]. The principle originally means “to go to the source of the problem”, but can be expanded to a more general meaning of “go see for yourself” [23]. The authors have spent a lot of time on the factory floor, consulting people who are working there. Only a small part of the non-computerized data has been gathered from so-called white collar personnel; the majority has been collected from interviews and consultations with workers and team leaders. The reason for this is that it was quickly discovered that management and engineers do not have a full understanding of the situation on the factory floor. In order to collect the correct data, understand it and analyze it, it was necessary to speak to the people working in the production on a daily basis and that are actually performing the tasks that were investigated.

A representation of the process can be seen in Diagram 5 on the next page. The project has been built up of nine main steps but they have not been performed entirely in order. The first three steps were necessary to create a foundation for the project and for selecting the assembly tasks to be included, as seen in Diagram 5. Together with the following three steps, they provided enough data to show that there is a connection between production ergonomics and product quality at Volvo Trucks. If the only goal of the project was to show that connection, this would have been enough and the project could have been terminated at this stage. But in order to communicate the message to the plant management it was necessary to put the result into a context and to focus on economic issues. Therefore, the final three steps in the project were included as well. That gave the result practical and not just theoretical meaning.

The dark arrows in Diagram 5 represent the iterative way of working. There was an information loop between steps five and six and there was also information acquired during steps five and six that changed the selection of tasks made in step four.

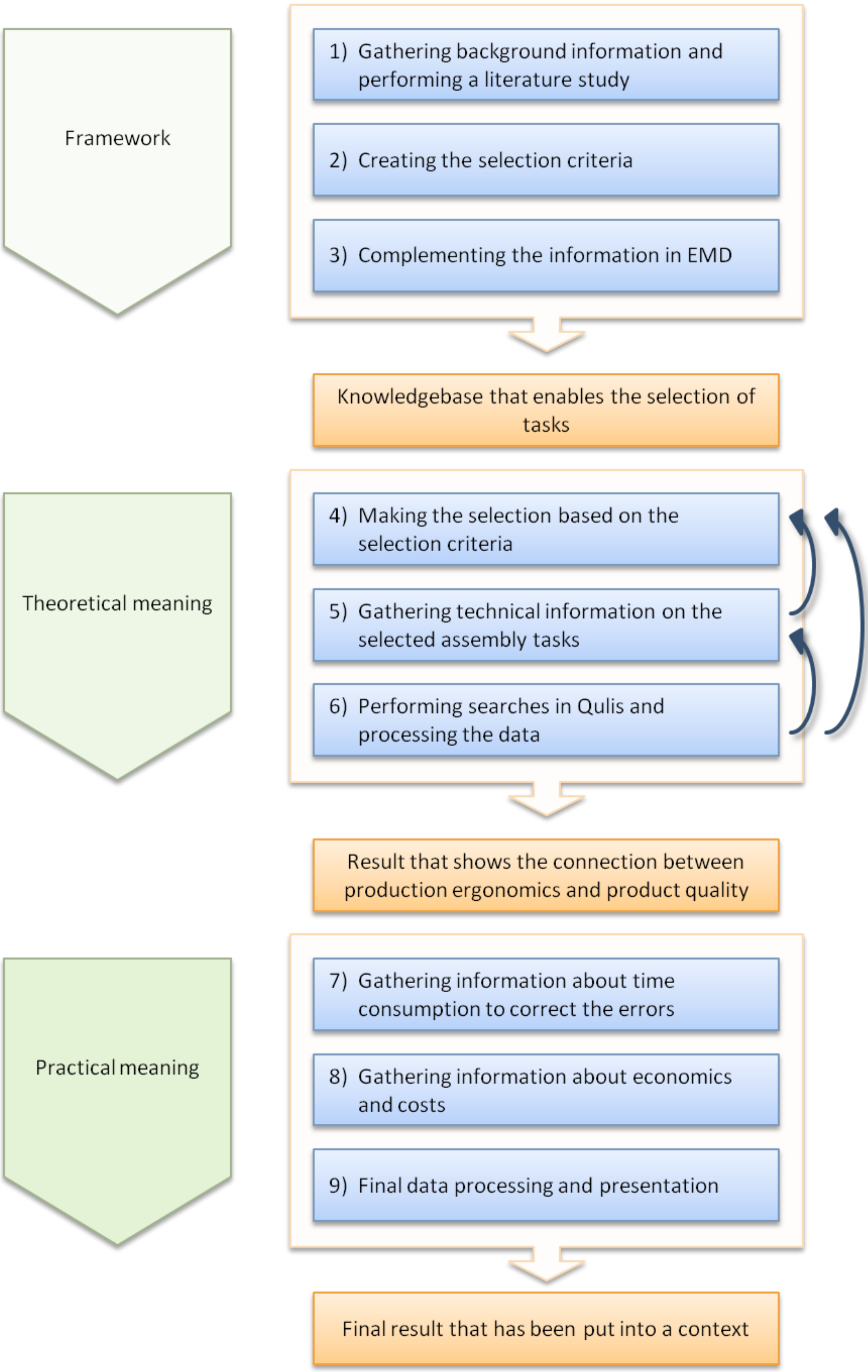


Diagram 5. A representation of the working procedures used in the project

4.1 Chronological description of the working procedures

The project started with the gathering of the theoretical data, step one in Diagram 5. This research was done in order to create a foundation for the subsequent work since production ergonomics and its possible connection to quality is still a new area of research. Therefore, it was important to know what had been done in other studies and what could be expected, as well as what was possible to do within the given timeframe.

When a base had been obtained, the framework for the project was decided together with the project owners at Volvo. Since they did not have set notions of what the project would include but rather a main goal and a plan for how to use the results, the theoretical base was of great assistance at this stage. The information gathering process could then begin with examining the ergonomic situation in the production plant. EMD served as the main source of information in this case but the company ergonomist was also consulted. When a general understanding of the ergonomics had been achieved, the assembly tasks were selected.

Since EMD only focuses on ergonomics, it was important to also develop an understanding of the more technical aspects of the assembly tasks, for example: what exactly is being done, in which order and which errors may occur. For this reason, the team leaders for each section of the production line were consulted.

As soon as a section had been covered, the information gathering about quality errors for that section was initiated. The search for technical information and quality data was not a serial process, but was rather iterated throughout the production line. A method for treating the data in a consistent way was established. Since new questions undoubtedly arose during the information gathering, several additional consultations were made with the team leaders in the production plant. Consultations and computerized information searches were alternated, as shown by the dark arrows in Diagram 5.

When the main part of the information gathering of quality data was finished, the next principal stage of the project was to retrieve information about how much time was needed to correct the errors. The information was acquired through consultations and interviews with team leaders, Andon, staff in the Adjusting department and workers in the production line. It was necessary to complete the search for quality data before this step could be initiated since the questions asked were based on the search result. This was also made for one section of the line at a time as soon as the previous step was completed and therefore it was an ongoing process for a long period of time.

When all data had been retrieved from the production plant, the economic data were gathered. Since the need for various economic factors depended on the outcome of the previous steps, this part of the project was done late in the process. Even though it could have been enough to show the time needed to correct errors, it is always of interest to take an economic perspective of the data.

When all available data had been gathered, it was then processed in order to show the result in a compact and easily understandable way. Several different aspects were of interest and the data were combined in different ways to show those.

4.2 The selection of assembly tasks

This chapter concerns steps two and four in Diagram 5.

It was decided early in the project to only use tasks that had been classified by the company ergonomist as red and green, thus excluding the yellow. This was done because the yellow classification includes such a wide range of task characteristics and is not a homogeneous group. There are yellow tasks that are bordering on green and others that are bordering on red and so there is a risk that the span of properties of the yellow tasks is too large to provide a consistent result. The purpose of the project is not to map the entire potential savings in time and money by reducing all red and yellow tasks to green, but rather to show a connection between production ergonomics and product quality and provide recommendations for more extensive studies. Therefore, it is in this case not necessary to include the yellow tasks to achieve the project goals.

As mentioned in *3.2 The work with ergonomics so far*, the entire production line has not been mapped when it comes to the ergonomic situation; only a small part of all assembly tasks have been studied and classified. Since it is the workers and team leaders themselves that initiate an ergonomic investigation, red tasks rather than green tasks had been mapped when the project started. In order to obtain green tasks, the ergonomist had to complement EMD with new assembly tasks. This work was done in a hurry and the methods differed somewhat from the original mapping of tasks in EMD. A discussion on how this have affected the project can be found in *7.2.2 Discussion of the selection of work tasks*

Since not all of the production line was mapped and there was a lack of green assembly tasks, the population of tasks is unknown. One important aspect of making a selection is that it should be a good representation of the total population. With an unknown population this is of course very difficult. Many assumptions have had to be made and the selection has been made according to the principle of "a little bit of everything" in order to include as many different circumstances as possible. For example, it was desirable to include red assembly tasks that had been classified as red for different reasons, not only due to heavy lifting, as is often the focus of attention in the plant.

When selecting samples of red and green tasks respectively, that are later going to be compared, these two samples obviously need to be comparable. To illustrate the problem an example is given:

> In order to show which one has the best quality, two car models are being assessed by examining a number of cars of each model. The conclusion is that the cars of model A have 200 errors while the cars of model B have 500 errors. Model A is, therefore, thought to be of better quality. But this is only true *if the same number of cars of each model* where included in the study. If there were 50 cars of model A but 150 cars of model B, the result is not obvious at all. A simple solution in this case is to instead count the average number of errors per car. 200 errors per 50 cars equals 4 errors per car for model A, while 500 errors per 150 cars equals just over 3.3 errors per car for model B. In this scenario, model B consequently is of better quality.

This problem is present in this project too since the assembly tasks are not equal. When performing a task it takes a specified amount of time. Since it is not the entire cycle time at a station, but rather individual assembly tasks and sequences that are being assessed, all the tasks have their own individual time. Naturally, performing a task over a longer period of time provides time for making more errors than for a task that takes a very short time to complete. Therefore, it is not enough to ensure that there is an *equal number of tasks* in the study; the samples of tasks must instead take an *equal amount of time*. Generally, green tasks take a shorter time than red due to different levels of complexity as well as the nature of the classification criteria – see *3.2 The work with ergonomics so far* for further details – so it is necessary to have more green tasks than red. But the lack of green tasks in EMD turned this into a problem that was very difficult to solve within the timeframe of the project. Instead, the problem needed to be avoided if possible. Just as for the example with the two car models above, one solution is to divide the result with the available assembly time. This time will be different for red and green tasks but the division will make the two samples comparable. The main unit for presenting the number of errors is therefore errors per minute. The connection between production ergonomics and product quality can thus be shown if the red tasks have a larger number of errors per minute than the green tasks.

4.2.1 Selection criteria

In order to only select suitable assembly tasks for the study, selection criteria were created to clearly state what characterized such tasks. It also set the boundaries for the data that was collected. The basics of each criterion are described in bold text, while the subsequent text can be read for a deeper understanding. They are formulated as causes of action to take in different circumstances in order to cover all possibilities.

1) The time period that was studied is 2010-05-17 to 2011-03-04

In order to attain a statistically valid result, the study had to include a sufficient number of trucks. This was to ensure that the possible errors that can occur have had a chance to do so even if the probability of an error is small. The time period should preferably have been about a year but it was limited by events and changes in the production process. The process must have been fairly stable during the selected time span and in this case the process was not sufficiently stable until May 2010. The selected time period consists of 37 weeks of production and during this time 7 864 trucks were manufactured by line 21.

2) The tasks were selected from line 21 only

As explained in *3.1.1 The assembly line*, the two lines in the factory are quite different. They have also had a very different history and evolution. Even if the tasks are performed in the same way today at both line 21 and line 22, they might not have been so in the past. Despite all products being trucks, the models have large differences and there are differences in the model range of the two production lines. All of this means that it is not possible to equate a task on line 21 with the corresponding task on line 22. In order to include tasks from line 22, an additional ergonomic mapping of the tasks there would have been necessary. Since Qulis clearly separates the errors originating from line 21 from the ones from line 22, there was no practical reason to include line 22 in the study.

In the pre-assembly areas the way of working is in most cases very different to the situation on the assembly lines. None, or very limited, ergonomic investigations have been made here and the prerequisites are completely different. Therefore, the pre-assembly stations could not be included in the study.

The pre-assembly of the engines and wheel shafts are more similar to the assembly line since they are assembled in sequence and with a similar tact. However, the working conditions and the products are very different and the assembly workers have different tools and aids. The ergonomic situation is very different from the situation on the main assembly lines. If the engine and shaft lines had been included, the statistical errors would have increased due to the mixing of populations. If the pre-assembly lines were to be studied, this should be done separately. For these reasons, they have not been included in the study.

3) ***The tasks were chosen from sections one to six of line 21***

The main assembly is done in sections one through six of the assembly line. When the truck leaves section six, it is almost finished and can drive off the line by itself. After section six, any assembly is mainly of exterior trim and there is checking of the performance. The truck is also filled up with fluids; a task that is not considered as assembly. It is also submitted to extensive quality checks. Therefore, the workers conducting these tasks are not performing assembly operations in the same way that the assembly personnel in the rest of the production line are. They have more varied tasks and have a different takt time since the line is split up into two branches after section six. The working conditions and the small number of assembly operations resulted in the exclusion of sections seven and eight in the study. The assembly tasks chosen were therefore only selected from sections one to six.

4) ***When choosing the tasks, they should as far as possible be evenly distributed along the production line***

In order to ensure that the result from the study was not distorted due to other factors than the ones studied, there could not be considerably more tasks chosen from one section of the line than from the others. It was not necessary to have perfect equality between the sections and the exact same number of tasks but there could not be a very large deviation. The balance of red and green tasks should preferably also be fairly even but, where this was not possible, a deviation could be accepted. The primary goal when choosing tasks was to obtain the desired number for the study and the distribution of tasks between the sections of the line was not allowed to hinder this goal. When the primary goal had been achieved, then the next target was to create balance throughout the line. However, this criterion did not affect the sample of chosen tasks.

5) ***If there had been more task than needed in some sections of the line, a random selection should have been made to exclude tasks.***

In order to create the above mentioned balance between sections of the line, it could have been necessary to exclude assembly tasks. If this had been the case, the tasks should first have been analyzed and categorized according to the properties that were important for the study, such as the ergonomic classification and the reasons for that classification. Since a balance was strived for when it came to these properties as well, this might have been reason enough to choose between the tasks. If no such reasons could have been found the tasks would have been randomly selected. This would ensure that the selection of tasks was not subjective. This criterion was never used since all tasks that conformed to the other criteria were included in the study.

6) ***The ergonomic classifications of the chosen tasks are distinct and not bordering on yellow***

When selecting tasks that are red or green, they had to be good representatives for their respective populations. Therefore, the tasks had to be clearly classified irrespective of the height of the assembler. None of the three height classifications were allowed to be yellow.

7) The classification of a task could not be allowed to depend on the material properties of the parts that are being assembled, if these properties vary over time

The ergonomic classification of some of the tasks depends on the material properties of the parts that are being assembled. The material properties can make it easy or hard to perform the assembly task correctly. It can, for example, be difficult to insert a pipe into a valve if the material of the components creates a lot of friction between the objects. An unsuitable shape or size can also make it difficult to assemble parts. If material properties like these are not constant, but rather changing over time, it can change the ergonomic classification. One batch of material can be very easy to assemble, resulting in a green classification, while another batch can be much more difficult, resulting in a yellow classification. If this is the case for a task, the task was excluded from the project.

8) The classification of a task was not allowed to depend on the use of ergonomic aids or tools

When a task is classified, the classification is made as if the ergonomic tools that are provided are always being used. However, this is not the case. Many of the tools and aids are never used and therefore the classification is not representative for the actual situation in the production. Unfortunately, many of the tasks that have been classified as green suffer from this problem. They are not really green when considering how the workers are actually performing their task. Since the classification of the tasks had to be constant in the project, these green operations were excluded.

9) The chosen tasks must have had a constant classification during the selected time period

As mentioned above, it was very important to have constant classifications of the tasks. Therefore, the classifications could not have changed during the time period selected for the study. If changes have been made to the tasks and the production process, they may only be so small that they did not change the classification.

For documentation reasons, the classification had to be the same when the project was executed, even if the selected time period ended in March 2011. It also made it possible to look at the situation in the factory and see how it has been during the entire selected time period.

10) The chosen tasks have to be performed on at least 90 % of the vehicles on the production line

In order to get ergonomic consistency, it was necessary to choose tasks that were common on the production line. If a red task is performed only once a month, it is not that tiring and damaging to the body. Similarly, if a green task is very uncommon it will not serve as a chance of physical recovery. Rare tasks will also be more cognitively demanding as it will be hard to remember how to perform them and the risk of making a mistake will increase. Therefore, the study only includes routine tasks that are very familiar to the workers.

Choosing frequent tasks also ensured that the tasks had been repeated a sufficient number of times within the chosen time frame. If more uncommon tasks were chosen, a longer time span would have to be selected in order to allow errors to occur even if the probability of a particular error is very low. To simply be on the safe side while still allowing for slight differences in frequency of the tasks, the limit was set at 90 %. Many of the tasks are performed on less than 90 % of the trucks and this limit is therefore very strict. However, it was necessary in order to ensure statistical validity of the study and to remove possible sources of error.

11) Only tasks that are assembly tasks and thus add to the value of the product were selected

There are tasks that are only considered to be material handling, for example: placing and replacing tools and carriers, handling handcarts, and climbing into the truck cabin. These are tasks that are isolated as material handling and do not include assembly. They do not in themselves add value to the product and potential errors while performing these tasks are not logged. Consequently, it is not possible to track errors and compare the outcomes of these tasks with assembly tasks.

Material handling is also part of the assembly tasks. However, there is a distinction between the pure material handling and the form of material handling that is included in the tasks. The worker picks the material and parts needed and then assembles them on the truck. This form of material handling is included as part of a complex task. It is sometimes the picking of a heavy part that is the reason for a red classification of a task. Including the picking of a part also enables the inclusion of errors connected to it, such as picking the wrong part. Therefore, it is not possible to exclude this from the tasks when it has been included in the ergonomic classification.

12) The chosen tasks had to be validated by the ergonomist so that the classifications were correct and up to date

Since the mapping of the ergonomic situation in the production plant is an ongoing process, not all classifications are up to date at any given time. There is also constant change in the production and small details are modified continuously. In order to make sure that any changes have not affected the classification, the ergonomist made a quick evaluation to validate the classification. It was not necessary to do this in written form but rather to perform an overall visual inspection in the plant to see if the classifications were still valid. If there were any doubts regarding the classification of a task, it was excluded from the study.

13) The chosen tasks were also validated by the team leaders etc. to ensure that the tasks are carried out in the specified way

Since the ergonomist does not have all technical information, the tasks also needed to be validated by someone who has a deep knowledge about the production process. This could be done by team leaders, safety representatives, and production engineers. These employees were able to verify the specified data given for each task and if it confirmed to the selection criteria.

14) The sample of tasks classified as red should have a roughly even distribution between tasks that are harmful for different areas of the body, as well as between tasks with heavy operations, static postures and precision work

To only include certain types of tasks – for example, heavy lifting – would not have provided a representative sample for the population. The sample should include all types of issues that result in a red classification. There should also be tasks that are harmful to different areas of the body; for example, the back, neck, shoulders, arms and hands. Again, this is to obtain an appropriate sample from the population of tasks.

15) It had to be possible to trace quality issues back to the selected tasks

This criterion placed demands on both the tasks and the errors that could be included in the study. The tasks must be distinct and separated from each other. It was not possible to select a task where one component is assembled if another identical component is assembled in the same place on the truck but in a completely different station. The components must have names, placements or some other means of identification that separate them from each other. In some cases, both tasks can be selected if the assembly and the classification are the same; for example, when the exact same assembly is being performed on both sides of the truck, requiring the same amount of time.

The types of errors that were included were also limited by the demand of traceability. Very general errors that may have originated from any station along the line were not included; one example of this is surface scratches. Errors that have been committed at a specific station, but where it is not possible to pinpoint which assembly task they originated from, were also excluded for this reason.

4.2.2 Making the actual selection

The selection was made based on the criteria above. In the end, all tasks that conformed to the criteria were included in the study. Therefore, the criterion regarding exclusion of tasks based on there being more tasks than was necessary, criterion number five, were never used. Neither was criterion number four, stating that the assembly tasks should be evenly distributed throughout the line, since they were sufficiently distributed without interference through selection. The dispersion of red and green tasks was however not evenly distributed, but compared to the goal of obtaining as many assembly tasks as possible this issue was considered to be inferior.

The selection of tasks was not an isolated event. When deeper understanding and knowledge of the tasks were gained throughout the information gathering process, the selection was changed. No new tasks were included, but tasks were excluded when reasons for doing so were discovered. It was considered very important to only include suitable tasks in the final result and therefore much thought was put into the selection of tasks.

4.3 Gathering information about the assembly tasks

This chapter concerns steps three and five in Diagram 5.

After the selection had been made, the information about the assembly tasks was gathered over several steps. It was necessary to gradually build up an understanding of the assembly line, as well as of the product and its various components. Not only the components in the selected tasks were investigated, but also components with similar names or that are located close to the components of interest. It was crucial to eliminate all misunderstandings and misinterpretation of data, and that could only be done through learning as much about the production and the product as possible. Since this knowledge was nonexistent at the beginning of the project, initially a lot of time was spent on this. The authors have spent much time in the production plant getting to know the process by consulting the staff working there. At first, guided tours by safety representatives were provided and the questions to the staff were of a very general nature. As the knowledge grew, it was possible to ask more specific questions and the answers provided were greatly improved by the fact that the authors learned to use the same vocabulary as the workers.

It was also necessary to consult the production engineers in order to retrieve the information required to decide if the tasks conformed with the selection criteria in chapter *4.2.1 Selection criteria* or not. An example of the information obtained from the production engineers was the percentage of the trucks that a particular task is performed on and the time each task is calculated to take. Further information, more general in nature, was concerned with how the assembly times are calculated and how the balancing of the production line is carried out. Similar general information about how Volvo is working with quality and how quality defects are traced were acquired from the quality coordinators.

In order to be able to perform searches in Qulis, an educational session was held with the person responsible for Qulis and for educating personnel working with Qulis. The basics and how to use the program effectively were covered in order to provide a base for the information searches. Later, occasional consultation with the same person provided helpful tips for the searches. He, along with the quality coordinators, team leaders and assembly personnel, also provided information about how Qulis is used in practice in the production plant.

The information retrieved from Qulis had to be complemented with input from the staff in the production plant. Since it is possible to log an error in many different ways, as described in *3.3 The work with quality,* it took a lot of knowledge to understand which errors were of interest for the study and which were not. As a result, this part of the project was highly iterative and searches in Qulis were alternated with consultations in the production plant in order to ensure that the errors were treated correctly. Focus was on one section of the production line at a time, starting from section number one and working towards the end of the line. The entire line was processed several times in order to collect all the necessary data. Since the knowledgebase was considerably lower when the project started, it was necessary to go back to the first two sections and complement the previous work. By doing this, information was retrieved that was not discerned the first time.

The staff in the production plant made time available out of their daily tasks in order to answer questions from the authors. The team leaders always have to be on call in case a worker needs assistance and therefore seldom have more than ten or fifteen minutes to spare. The workers all had their tasks to complete and had to answer questions while continuing to work. Therefore, it was not possible to ask lots of questions at a time. A specific area of interest had to be selected and concrete questions formulated. Also, the questions should not result in long and verbose answers since that would have taken too long. Instead, several short interviews were performed with the same people on different occasions. On isolated occasions, the team leaders were able to step away from the production line and answer more general questions but mostly the interviews were held in the production environment with constant interruptions by colleagues or phone calls.

4.4 Searching for the quality data in Qulis

This chapter concerns step six in Diagram 5.

As mentioned in the previous chapter, the searches in Qulis were alternated with consultations with the team leaders. There were two main reasons for this. The first reason is that Qulis does not use the same vocabulary as the workers in the production plant and neither does it use the same as EMD. Instead, it uses the terminology from the Sprint system as much as possible, although there are exceptions. The vocabulary in EMD is a mix of terminology from the plant and the Sprint system and therefore it is sometimes difficult to understand. By asking the person responsible for education in Qulis, as well as team leaders, workers and quality coordinators, it was possible to gain knowledge about which terms from the different systems are used to describe the same object or type of error.

The second reason is the inconsistency in registering the errors, as described in *3.3 The work with quality*. This made it necessary to understand a great variety of ways to describe the same error. No misunderstandings were allowed regarding which errors truly mean the same thing and which mean something slightly different. It was also vital to be aware of the established practices regarding the registration of errors that exist in some sections of the line. The sections have created their own standards for how to log certain errors, and the vocabulary and terms in Qulis may have different meanings for different sections.

Since the same type of error can be logged in a great variety of ways, it was necessary to create a consistent way to deal with the inconsistencies. It was also crucial to decide which type of errors should be included and which should not. When searching in Qulis, several options should be selected in order to create a search result with all, and only, the necessary data. These options are (for an explanation of the terms used, see *3.3 The work with quality*):

- *Production Line* set to Line 21, in order to only get data from the selected production line.
- *Build Date* set for the selected weeks. Build date should not be confused with *Report Date* since the errors might be registered outside of the selected time period.
- *Problem Owner* selected as the section of the line that is of interest for a particular assembly task. This reduces the risk of misinterpretation, as similar components might be assembled in different sections. Since errors are sometimes logged at the wrong section by subsequent sections, this option might exclude search results that should have been included. However, when asking the team leaders and quality coordinators about this issue, it was explained that the risk of this is fairly slim. If an error is logged incorrectly, it is often moved by the section that received it but did not own the problem. The benefits of searching with only the correct section selected outweighed the risk of excluding the rare wrongly registered errors.
- The options of showing *Fault Description* should be selected since reading the written descriptions in that field creates an opportunity to understand the nature of the error much better.
- The option of showing the *Date of Registration* should be selected. If the dates only covers a limited period of time, it is an indicator that there is something exceptional about the errors and that further investigation is needed before it can be decided if the errors should be included in the study or not.

The methods for extracting the errors and the rules for deciding if they should be included in the study are the following.

- Due to the inconsistent registration of errors, several separate searches had to be performed for each component of interest. A minimum of two searches had to be made, one with the component as *Problem Detail* and one with the component as *Help Object*. Searches were also made for similar words or parts of words that might generate a desirable result. For example, if the component was a lamp cable, an additional search for 'cable' only was made.
- All means possible were used when trying to determine if the error should be included or not. For example, the position on the truck, the *Fault Description* or the *Reporting Area* helped to give clues on what the problem was.
- Since the combination of *Problem Detail* and *Help Object* is selected from a list with predetermined options and not always selected with great care, the *Fault Description* is often a better report of the problem. Therefore, the text in the *Fault Description* took precedence over the other options when there were doubts regarding the nature of an error.

- Only errors that with a reasonable level of certainty could be proven to originate from the assembly task of interest were included in the study. If it was not possible to prove that the error was made by the worker performing the task, it was excluded. It was preferred to exclude errors rather than include uncertainties in order to create a result that is reliable even if it is lower than if all errors were included.
- Some type of errors were never included, such as: errors due to lack of material because the worker did not order the material in time or because the delivery was late; errors that are reported by departments that handle the object before it reaches the production line; and errors that are due to material defects originating from an internal or external supplier.
- The errors have to be connected to the ergonomic evaluation. If retrieving the component is a part of the evaluation, then errors committed in this phase of the assembly task were included; for example, retrieving the wrong component. If this is not the case, then these errors were excluded. There are, for example, tasks that only consist of tightening screws that are already put in place. Errors in placement of the screws were then not included since it is not part of the assembly task.
- When correcting errors on the assembly line, there are sometimes complications that result in damages on other parts. These errors are sometimes registered separately. In these cases, the errors were only included if it was clearly stated in the *Fault Description* that the damage is a result of an error committed by the worker performing the task of interest.
- When considering errors regarding the threads of screws and holes, it was investigated if there is a known problem with the material in the components. If so, the errors were not included. On the other hand, if there are indications that the threads are damaged due to mistakes made during assembly, the errors were included.
- There is a lot of wiring, cables and plastic pipes in the truck and these must be placed correctly in order to have a suitable length, and for it to be possible to connect them in both ends. The majority of the cables are handled by several stations throughout the line and any mistakes in placements can therefore not be traced. There is also the possibility of them being too short to begin with, a common problem for the plastic pipes. Regarding these types of components, the errors were only included if there were strong reasons to believe that it is the worker at the station of interest that is responsible.

Unfortunately, it is not always possible to connect the errors in Qulis to a specific task. There are different tasks that deal with the same components and are performed very close together on the production line; for example, in two subsequent stations. However, when all of the tasks that the error could possibly belong to have been selected for the study and also have the same ergonomic classification, then the error can still be included. This is possible through grouping some of the assembly tasks together into assembly *elements* with two or more tasks in each element. If both the assembly times and the number of errors are added together for the tasks in question, the final result of the sum of errors per minute will still be the same.

When a search had been made in Qulis, the data was exported to Microsoft Excel by using the built-in function in Qulis. There, it was processed and examined very closely in order to decide exactly which errors were to be included in the study and which were not. Every line of the search results were read multiple times. In Excel, lines that were of no interest were deleted, and additional information retrieved from other sources was added. Color codes were used for different types of errors to allow for easy survey of the material. Excel also has useful functions for searching and isolating data and these were frequently used. Overall Excel was considered to be a very suitable tool for the task.

4.5 Gathering information about time consumption

This chapter concerns step three and seven in Diagram 5.

Time is a crucial variable in the study. This chapter describes the information gathering process regarding the time to perform the assembly tasks, as well as the time needed to correct the errors.

4.5.1 Time to perform the assembly tasks

A very important base for the study was the knowledge of the time needed to perform each assembly task that was chosen for the project. This was required in order to develop a common unit for the data to allow for comparisons. It was also needed as general information of the extent of the study.

EMD served as a base for all technical data regarding the assembly tasks, including the calculated assembly time. Unfortunately, at the beginning of the project, EMD was not completely up to date and there was information missing. Additionally, the new green assembly tasks that were classified specifically for the project were originally not included in EMD and the information about those were therefore not available and had to be retrieved from the Production Engineering department. They were provided with the description of the task, the station number and the names of the components that were being assembled. When possible the reference numbers to the Sprint system were also included which made the search easier. The production engineers could then retrieve the assembly times from the Sprint system based on the information received, see *3.1.1.2 Sprint and assembly times* for more details about the matter.

One difficulty that was discovered was the great variety of trucks and the resulting variance in assembly times. Depending on the model, the assembly time for a specific task can vary significantly. For example, one truck model can have eight screws to tighten during a certain task while another model just has four. These variations needed to be dealt with in a consistent way in order to obtain comparable results. One option is to make a weighted average value of the time for each task dependent on the product variations. However, this would have required much time and work for the production engineers and that time was not available. It would also not have provided much additional information for the project result since all values, both red and green, would have been affected to the same extent. It was decided that the assembly times should be used for what is considered to be a time consuming and difficult truck model to assemble. Since a truck model can be considered time consuming at one section but quick and easy at another, the assembly times might not be for the same truck model throughout the line. The production engineers were instructed to select a difficult truck model but were free to pick the one they thought were most suitable for their specific section. Which model they chose were not of interest and were not documented since their experience and expertise made the data that they provided considered as reliable.

By selecting a time consuming truck model, the assembly times retrieved were relatively long. When the number of errors per minute were calculated this resulted in a low value since there were fewer errors per minute than if the times had been short. This in term later provided a value for the cost of the errors that were too low rather than too high, which is the preferred choice in a study like this.

4.5.2 Gathering information on the time needed to correct errors

There are four different options for where an error can be corrected:

- On the same section of the line as it originated from
- On a subsequent section of the line
- Off the line at section seven or eight
- In the Adjusting department

These four options in turn generate four different possible times for each individual type of error, and therefore, it had to be traced where the errors had been corrected. This was done mainly by analyzing the different properties of the errors in Qulis. If, for example, an error were discovered and registered in Qulis by a subsequent section, it was obviously not corrected at its point of origin. It is also customary to note in the problem description if the problem was sent onwards after discovery. This is done with the notation "ÖPx" where the x is exchanged for the number of the section that passed the error forwards (ÖP stands for the Swedish words "Öppen punkt"). The notation "ÖP6" means that the error at least was corrected off line, while "ÖP8" means that the error was definitely sent to the Adjusting department. In many cases, it was not possible to decide where an error was corrected. As a consequence, a consistent way of assigning the errors was developed in order to at least assign each error to a group:

- An error which was registered by the same section as it originated from was assumed to be corrected there, as long as no notification of "ÖP" was present.
- An error that was registered by a subsequent section and that did not have any notations of "ÖP" was assumed to be corrected where it was registered.
- An error that was registered by section six were assumed to be sent on to section seven since the team leader at section six stated that they do not correct errors from other sections. The only exception to this was errors from section five that were corrected at section six to a minor extent. These were consequently assumed to be corrected as section six.
- An error with the notation "ÖP6" or "ÖP7" but without "ÖP8" was assumed to have been corrected off line at section seven or eight.
- An error with the notation "ÖP8" or "Justeringen" was assumed to have been sent to the Adjusting department.

The notations are not always used consistently, so there are undoubtedly errors that have been assigned wrong. However, the rules assign errors to the category with the shortest possible time; again making the sums of time and money smaller, rather than larger, than possible.

In addition to the information in Qulis the team leaders, Andon and the personnel in the Adjusting department were consulted about the existence of errors that are always treated in the same way.

For example, errors that are always sent on to the Adjusting department because it is too time-consuming or difficult to correct them on the assembly line. If this is the case, the rules in the list above were set aside. The assembly personnel also provided information about the limit for when an error can no longer be corrected at the production line. At a certain point, the part is simply built in and blocked by other components to the extent that it is no longer reasonable to try to access it. An error discovered after this limit is consequently always sent to the Adjusting department.

It was also necessary to obtain the time for correcting the individual types of errors in each group. The methods for retrieving this information are described below. The times needed to correct errors are not documented by Volvo in any way, so the only way to obtain this information was to speak to the people responsible for this type of work. It is important to understand that there is no correct answer to the questions about how much time is needed to correct the errors; there is only personal perception about the time consumptions.

When collecting the correction times, it had to be assumed that the error in question was the only error on the truck, and that the time needed was for correcting that specific error only. This was clearly stated during the consultations with the workers. No possible consequential errors caused by the original error were considered since these can vary greatly from time to time.

4.5.2.1 Times to correct errors in section one to six of the production line

When collecting the data about the times needed to correct the errors on the production line, team leaders and Andon personnel were consulted. For each type of error, they were asked about the time needed to correct it in their own section and the time needed if it was corrected at a subsequent section. They have experience with correcting the errors and a good knowledge of how long an error usually takes to correct. However, since this time can vary it is difficult to give an exact answer even for an experienced worker. All times provided are estimations and were often presented as an interval. When the span was small, for example, “two to three minutes” the lower value was chosen. When the interval was larger, for example, “two to five minutes” the mean value was chosen. This insured that the resulting calculations were too low rather than too high.

In some cases the production personnel could not provide a time at all for correcting an error since the times were varying too much for each occasion. Some were also reluctant to give an answer that they were not completely sure about. In some cases the authors had to make assumptions themselves since there was no information available. In these cases the times were set considerably lower than actually believed to ensure that too high numbers were not used.

Only one person per section were consulted, either the team leader or an Andon. It might be desirable to have answers by multiple people to each question, but it would have been too time consuming to collect all data multiple times. It is also doubtful if it would have contributed to the result; there are not many people working as team leader and Andon in each section so adding a few more estimations to an already estimated value would not necessarily have improved the accuracy of the result.

While gathering the information about correction times, the production personnel were also consulted on how the errors were treated and if there were any general guidelines for specific types of errors. This information was useful for understanding how errors are treated and which factors are affecting the correction of errors.

4.5.2.2 Times to correct errors off line in section seven and eight

The correction times that were provided by the Adjusting department were also the foundation for the estimated times for errors that was corrected at section 7 and section 8. The situation in these two sections is very similar to the Adjusting department: the truck is complete and standing still. It would have been much too time consuming to gather information about each type of error from two additional departments. Instead, the team leaders of the two sections were asked if they believed the times given by the Adjusting department in general were representative for their respective sections as well.

The team leader of section seven explained that due to the time pressure they experience, the workers at section seven works faster than the ones at the Adjusting department. He gave examples of errors and the times it took to correct them in section seven and the Adjusting department respectively. Based on this, the times for the errors that are believed to have been corrected at section seven have been reduced by 25 percent. The time available to correct errors in section seven is a maximum of eighteen minutes. When the correction time for an error is more than this after the reduction by 25 percent, the error is considered to not be corrected at section seven. This was assumed independently of the notations in Qulis, since these notations are not completely reliable.

The team leader at section eight on the other hand, believed that it takes slightly longer times to correct errors there than at the Adjusting department. This is because they do not have all the proper tools and as much experience. However, because of the before mentioned aim of having too low numbers rather than too high, no adjustments of the correction times were made. The times at section eight and at the Adjusting department are considered to be the same.

4.5.2.3 Times to correct errors at the Adjusting department

The Adjusting department was sent the questions in advance, concerning one or two sections of the line at a time. The workers at the department are experts of one or two sections of the line each, and therefore the team leader had to be able to prepare a suitable worker beforehand. Then a meeting was held and the questions were answered by an experienced worker. Together with specific correction times, general questions were asked to better understand the relationship between the production line and the Adjusting department, as well as the process of work at the Adjusting department.

It was made clear to the consulted workers that the desired times were the complete times from when the truck was brought into the department until it was completely ready to be transported out again. It was assumed that the error in question was the only error on the truck so that the time should not be divided between several errors. If fault-localizing is needed, that should be included in the time. Also, if fluids need to be drained and then refilled, the time for that should also be included.

The times obtained from the Adjusting department were often much more vague than from the production line. The span could be “one to two hours” instead on expressed in minutes. The same logic regarding the intervals were used here as for the times from the production line but the differences between the different truck models are much greater. Every presented time is an estimation, but it is as good as it gets. It can also be noted that the Adjusting department uses the same estimations to plan their daily work.

4.6 Data processing

This chapter concerns step six and nine in Diagram 5.

Since the searches in Qulis generated one individual line of text for each registered error, the data was not presented in an informative way. There was no way of taking in the whole situation by reading the individual lines. Therefore, the data needed to be processed in order to present the information to the reader. This was done in two main steps, as presented below. The same basic data generated by Qulis was used in both steps; it was just combined in different ways and complemented with information about the times needed to correct the errors. Furthermore, it was also of interest to evaluate the extent of the study.

4.6.1 Connecting ergonomics to quality

Only the errors conforming to the inclusion criteria were left in the Excel documents after sorting the errors. The total amount of errors for each assembly element was then added together. In order to obtain the errors per minute, the number of errors was divided with the total assembly time for each element respectively. Consequently, each assembly element was associated with a particular number of errors per minute.

To calculate the errors per minute for the two groups of red and green elements respectively, all of the errors were summed up, and so were the assembly times. The sum of errors was then divided with the sum of times to obtain the mean value of errors per minute for the red and the green category respectively. The two mean values was the information needed to state whether there is a connection between production ergonomics and product quality at Volvo Trucks in Gothenburg.

4.6.2 Putting the result into a context

It was not considered to be enough to only present the connection without putting the importance of production ergonomics into a larger context. Therefore the times to correct the errors were needed. However, the results from the red tasks and the green tasks are not immediately comparable since the assembly times for the two categories are not the same. This is yet again the problem described in the example with the two car models in chapter *4.2 The selection of assembly tasks*. Up until now, this issue has been solved by dividing the results with the assembly time in order to create a unit that includes the attribute “per minute”. The problem with this is that it does not show the big picture very well, and it is a very poor method of communicating the result in a way that is intuitively understood. It only provides a comparative number and has no information about the size or context of that number.

To facilitate easy communication, another method of comparing the results had to be used. It was desirable to keep the size of the result, i.e. if a number is in the tens of thousands, it should not be reduced to a single digit. To do this, the result from the green tasks can be multiplied by a factor in order to correct the imbalance in the assembly times. That is the same as saying: “if the assembly time of the green tasks were as long as the time of the red tasks, the result would look like this”. Since it is the difference between red and green that is of interest, this method is acceptable. The factor that the results associated with the green tasks should be multiplied with is the same as the quotient between the original assembly time for the red tasks and the green tasks:

$$\frac{\text{total assembly time of the red tasks}}{\text{total assembly time of the green tasks}}$$

To sum up: *either t*he results from both red and green tasks can be divided with their respective assembly time, *or* the results from the green tasks can be multiplied with this factor based on the quotient between the assembly times. The situation will decide which option is suitable, but using one of these two options is the only way to obtain a comparable result. The first option is more academically correct, while the second provides a better view of the bigger picture and hence is of interest in this project.

Besides being separated according to their ergonomic classification, the errors were also separated based on where the particular error had been corrected: on the line, off the line at section seven or eight or in the Adjusting department. By adding the times together and adjusting the result from the green tasks with the above mentioned factor, information was obtained regarding how much time errors associated with red and green tasks respectively took to correct in different parts of the production plant. This was useful to show whether there were not only more errors originating from red tasks, but if these errors also took a longer time to correct.

To further investigate the result, the errors were separated into four different categories based on the nature of the errors. These categories are:

- Not performed – Some aspect of the task has not been performed at all
- Wrong part – The wrong component have been assembled
- Placed incorrectly – A component has been positioned wrong
- Performed incorrectly – The assembly itself has been performed wrong

By adding up the number of errors belonging to red or green tasks respectively, information was provided concerning the difference in nature of the errors in red and green assembly tasks. Consequently any pattern regarding if one type of error was more common than another was discovered.

One of the most common errors is *cable not tied*: a cable tie is missing or has not been tightened. Volvo is very aware of this issue and is working with it in various ways. All of the errors with missing or loose cable ties belong to the first category: *Not performed*. That makes the result somewhat skewed. All errors of cable not tied were therefore removed and the new result was displayed separately in an additional sub-category called *Not performed, excluding cable not tied.* This was done to provide a more nuanced result where one well-known type of error was not allowed to dominate. Therefore, all five categories are presented for each aspect of the result.

When both the times and the nature of the errors had been investigated, it was desirable to combine the results. By using Excel and creating a database with the errors, it was possible to cross reference the times with the nature of the errors. In that way, information on the times that each type of error took to correct could be presented. A schematic representation of this can be seen in Diagram 6. Of course, this result also needed to be adjusted with the factor based on assembly times. By making this cross reference it was possible to see if the difference between the times to correct the errors belonging to red and green tasks respectively were larger than the difference in the number of errors.

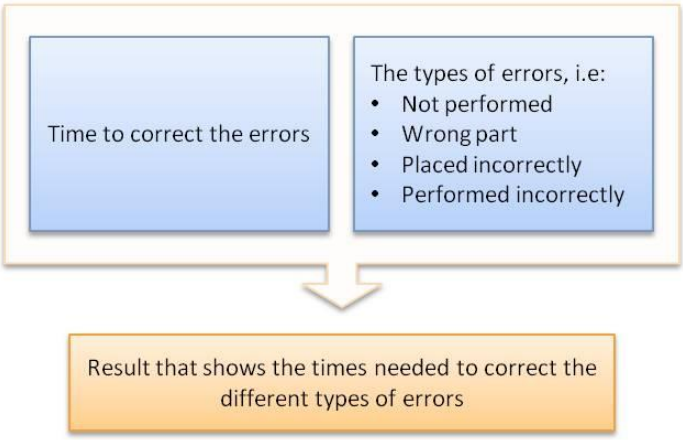


Diagram 6. Schematic representation of the combination of data that resulted in the times needed to correct the errors divided into types

4.6.3 Evaluating the extent of the study

When making a study with a sample of a population, it is obviously important to know the size of the sample. Since the total number of assembly tasks in the production line are not known and neither is the distribution between red and green assembly tasks, the extent of the study could not be determined in this way. Instead, the total amount of assembly time in the sections of the line that are included in the study was obtained. This was done by selecting an average production week and examining the average calculated assembly time that was needed for the trucks produced that week. The obtained average assembly time could then be compared to the assembly times for the tasks included in the study.

It was realized early in the project that the sample of tasks would not be large enough to draw any conclusions about the entire population. By calculating the standard deviation this could be confirmed; the dispersion of the result is large, which is usually the case when the sample used is too small. For example, if the mean value of a sample is 5 and the standard deviation is 4, it means that the average deviation from the mean in the population is 4 points. The mean in the population can therefore vary between 1 and 9. If the numbers can range from 0 to 10, and the population is assumed to be normally distributed, this does not really provide much information. It is because the sample is too small: a larger sample must be selected in order to reduce the standard deviation.

The standard deviation was calculated using the common formula:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

where n is the number of assembly tasks in each sample, meaning red or green assembly elements. x_i is the number of errors per minute for each individual element and $\bar{X}$ is the mean value of errors per minute in the sample.

Because of the size of the standard deviation, no other statistical methods have been used in the project since it was not regarded as meaningful.

4.7 Method for economical calculations

This chapter concerns step eight in Diagram 5.

Time is certainly both interesting and important, but in order to communicate with financially focused plant managers everything needs to be expressed in financial terms. The difference in errors from red and green work tasks provides the basis for possible savings. If these errors do not occur, costs that are connected to correcting them do not occur either. The cost of correcting the errors associated with green assembly tasks is therefore considered to be the minimum cost. The costs associated with assembly tasks that are not green are unnecessary and constitutes potential savings.

The term for these costs is *Failure cost* since the only reason it exist is that the product fails to satisfy the quality demands stated by the company and the customer. Failure costs can be divided into *Internal* or *External* costs. This project is only concerned with the internal failure costs since all errors included in the study are discovered within the factory.

It is only *Direct costs* that are of interest since it has been found that the connection between these costs and improvements is easier to communicate to management levels as discussed in *2.1 Previous studies*. When costs are traced and shown in the same manner as would be the case in book keeping, it is difficult to grasp how changes can affect the level of the costs. This is because both overhead costs and direct costs are included, but also because of how they are displayed. If the quality of the product is improved for example, this will lower the level of several inputs in the book keeping display of costs. It is difficult to know which of the entries will be lower and therefore the effects from the change are not comprehended by the management, who at best only has a basic understanding of the processes behind book keeping [8].

By only including direct costs and displaying them by the department or the activity that cause them, they can be communicated and put into a context as described in *2.1.2 Presenting economic potentials from ergonomic improvements*. Since that is one of the objectives of this project, it was decided to trace activities that occur when an error is detected and what these activities cost the company. Consultations with the Economy department at Volvo Trucks gave the information that the largest posts are almost always those of cost for personnel. The Economy department also provided information about what the hourly standard personnel cost is for the departments that are involved in the work with correcting errors.

The activities that may occur during the correction of an error, and that generates direct costs, include:

- Correction of the error
- Scrapping of material if that is needed, including the activities:
  - Placement of an order of substitute material. The order can either be directed to a supplier or to a preceding section of the assembly line.
  - Transportation of the new material
  - Transportation and disposal of scrapped material

When the times for correcting the errors had been collected, they were multiplied with the hourly standard cost of personnel in order to obtain a total cost. The results from both the red and the green category were multiplied with the same number, so this step does not provide any more information in itself. It is simply done in order to facilitate communication and speak the same language as the management.

The costs for scrapping of material – for example, placement of orders and transportations – were not possible to trace. This is due to the fact that the cost of a separate order placement is not known and neither is the cost of a forklift to do a delivery route. The cost of scrapped material was not possible to trace either, since it was associated with the department that first handles the detail, not the department that causes the damage to the detail. For example: if a sub-assembly of components that has been assembled in a pre-assembly area is damaged in the production line, the scrapping of the components is associated with the pre-assembly station, not the appropriate section of the line.

It was possible to find total costs for a department, but it is not always clear what is included in these total costs and how much of the total sum that is originating from inadequate quality. Therefore, it was not possible to draw any conclusions about how much of the cost that could have been caused by the errors included in the study. Since it is important to only include costs that can be proven to be caused by these errors, it was decided to only include the cost of the man-hours needed to correct the errors. This provides a minimum cost difference between red and green assembly tasks and shows what possibilities lies within improving the production ergonomics.

5 Results

The result will be presented in several different ways: number of errors, nature of the errors, correction times and cost of correcting the errors. All will be divided into the two ergonomic classifications so the result can be compared and conclusions drawn. Additionally, there is also a section in the end of this chapter about the extent of the study.

5.1 Errors in red and green assembly elements respectively

When the final selection had been made, 39 assembly tasks were selected to be included in the study. Of these, 25 are classified as red and 14 are classified as green. As described in *4.4 Searching for the quality data in Qulis*, the 39 assembly tasks were grouped into 29 assembly elements, of which 15 are red and 14 are green. To compare the two groups of assembly elements, the errors per minute was calculated for each assembly element using the following division:

$$\frac{\text{number of errors}}{\text{assembly time [min]}}$$

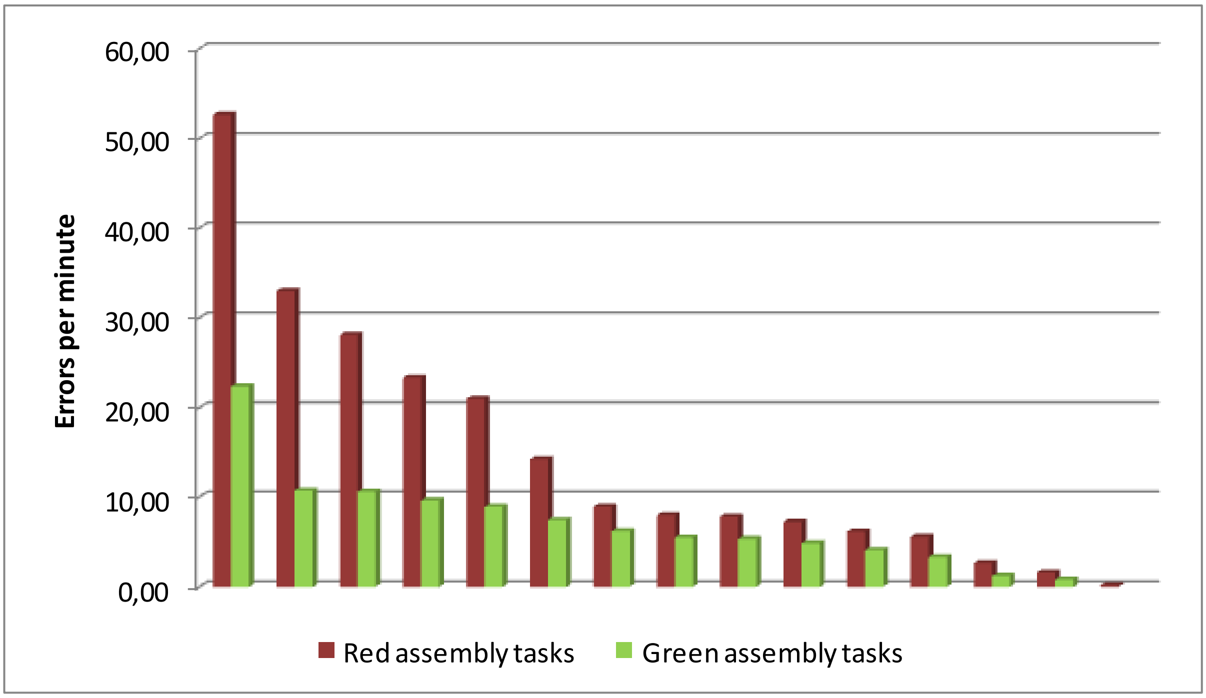
The assembly elements are presented in Table 1, along with the assembly times, the number of errors and the number of errors per minute.

Table 1. The data for the green and red assembly elements respectively

Green assembly elements					
	Assembly element	Number of assembly tasks that the element contains	Number of errors associated with the assembly element	Total assembly time for the element [min]	Errors per minute
	G1	1	18	3,71	4,85
	G2	1	90	12,09	7,44
	G3	1	32	26,13	1,22
	G4	1	15	4,51	3,32
	G5	1	14	2,26	6,19
	G6	1	23	2,58	8,92
	G7	1	29	2,74	10,58
	G8	1	30	1,34	22,36
	G9	1	7	1,28	5,49
	G10	1	32	2,99	10,70
	G11	1	110	20,62	5,34
	G12	1	31	3,22	9,62
	G13	1	5	6,18	0,81
	G14	1	36	8,81	4,09
Sum	14	14	472	98,46	-

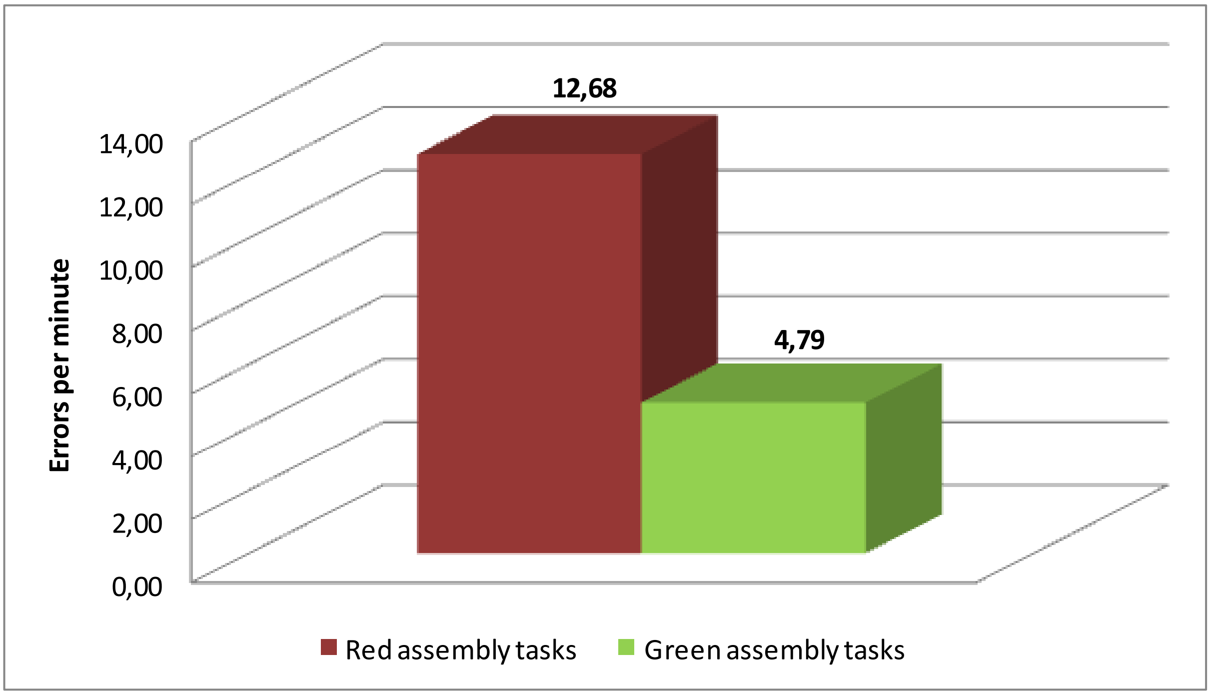
Red assembly elements					
	Assembly element	Number of assembly tasks that the element contains	Number of errors associated with the assembly element	Total assembly time for the element [min]	Errors per minute
	R1	1	32	20,13	1,59
	R2	1	231	16,27	14,20
	R3	2	277	31,04	8,92
	R4	1	6	2,26	2,65
	R5	1	54	8,78	6,15
	R6	5	421	75,71	5,56
	R7	1	2	10,04	0,20
	R8	2	490	17,43	28,11
	R9	5	2030	96,65	21,00
	R10	1	116	14,53	7,98
	R11	1	95	12,14	7,82
	R12	1	123	2,34	52,65
	R13	1	115	4,93	23,31
	R14	1	96	2,91	32,98
	R15	1	122	16,86	7,24
Sum	15	25	4210	332,03	-

The errors per minute can also be displayed in a Pareto diagram as in Graph 1 in order to provide a more general view. A Pareto diagram is a bar chart where the values have been arranged from the largest to the smallest.



Graph 1. Pareto diagram of the number of errors per minute for each assembly element in the study

The mean value of errors per minute for the red and green assembly elements respectively are shown in Graph 2:

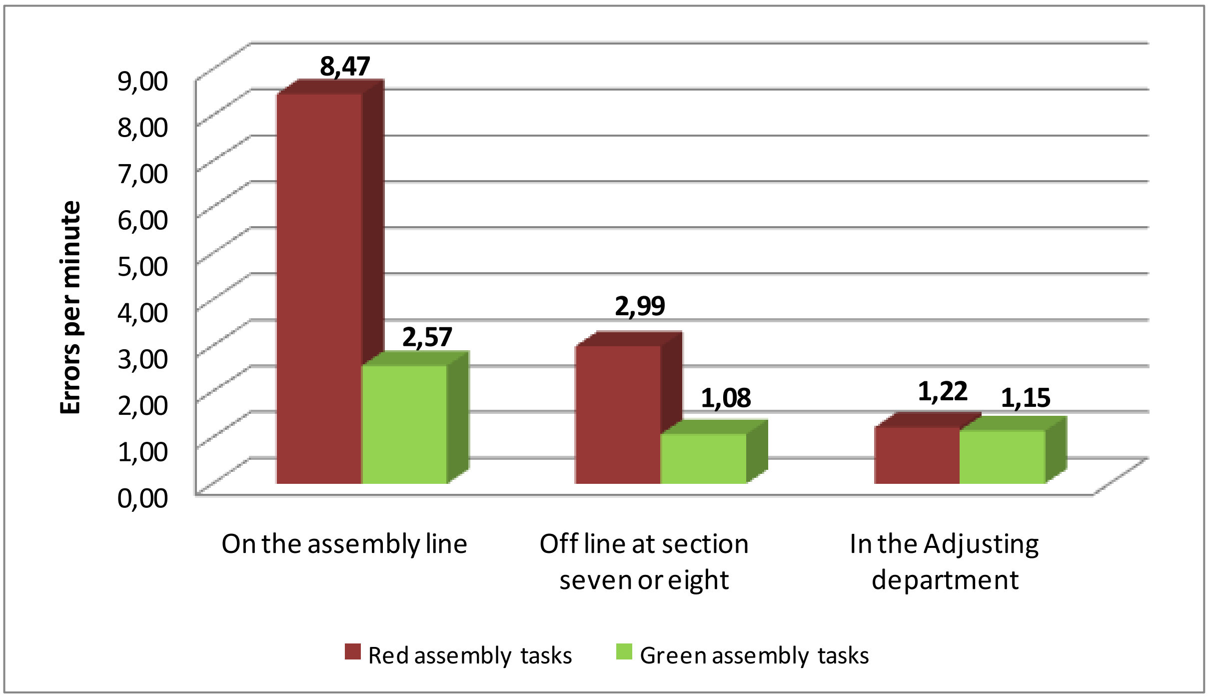


Graph 2. The mean values of errors per minute for the red and green assembly tasks respectively

The mean values are the result that shows the level of connection between assembly ergonomics and product quality. This fulfills objective number one for the project, as stated in *1.2 Purpose and objectives*.

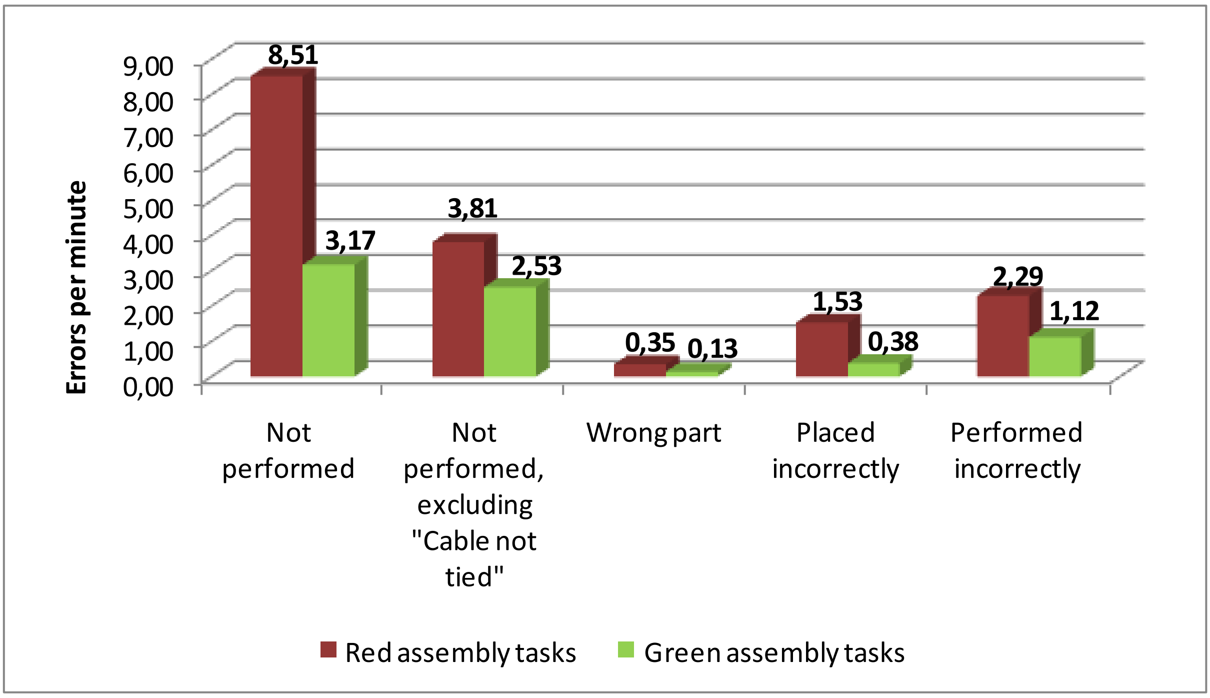
5.2 The characteristics of the errors

The errors were categorized according to where they were corrected. This can either be on the production line, off line in section seven or eight, or in the Adjusting department, as seen in Graph 3. These values were also divided with the assembly times in order to obtain figures for comparison.



Graph 3. The mean values of errors per minute depending on where in the plant the errors were corrected

The errors were also categorized according to type. The four types chosen, as described in *4.6.2 Putting the result into a context*, are presented in Graph 4. The sub-category where *cable not tied* has been eliminated from *Not performed* is also included.



Graph 4. The mean values of errors per minute depending on the type of the errors

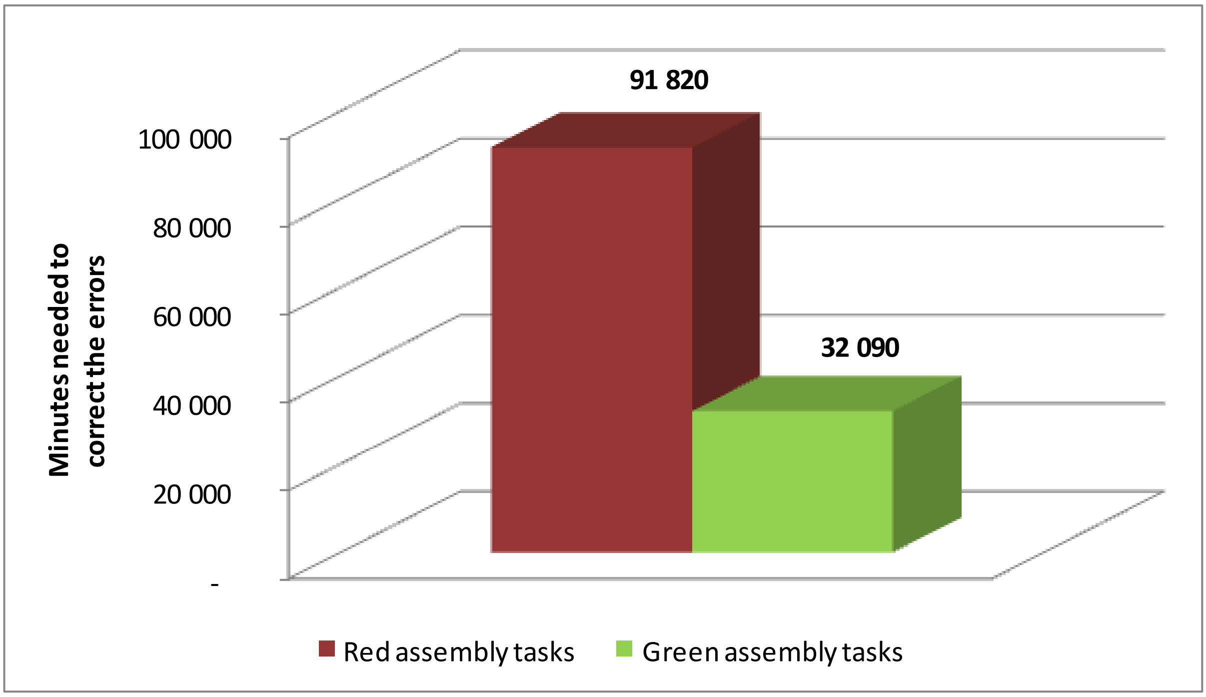
5.3 Time to correct the errors

In order to fulfill objective number two, the result needed to be put into a larger context. This was done by calculating the times needed to correct the errors. However, since the total assembly time for the green tasks is lower, the numbers needed to be adjusted, as described in *4.6.2 Putting the result into a context*. The correcting factor was calculated as:

$$\frac{\text{total assembly time for the red tasks}}{\text{total assembly time for the green tasks}} = \frac{332}{95.5} = 3.37$$

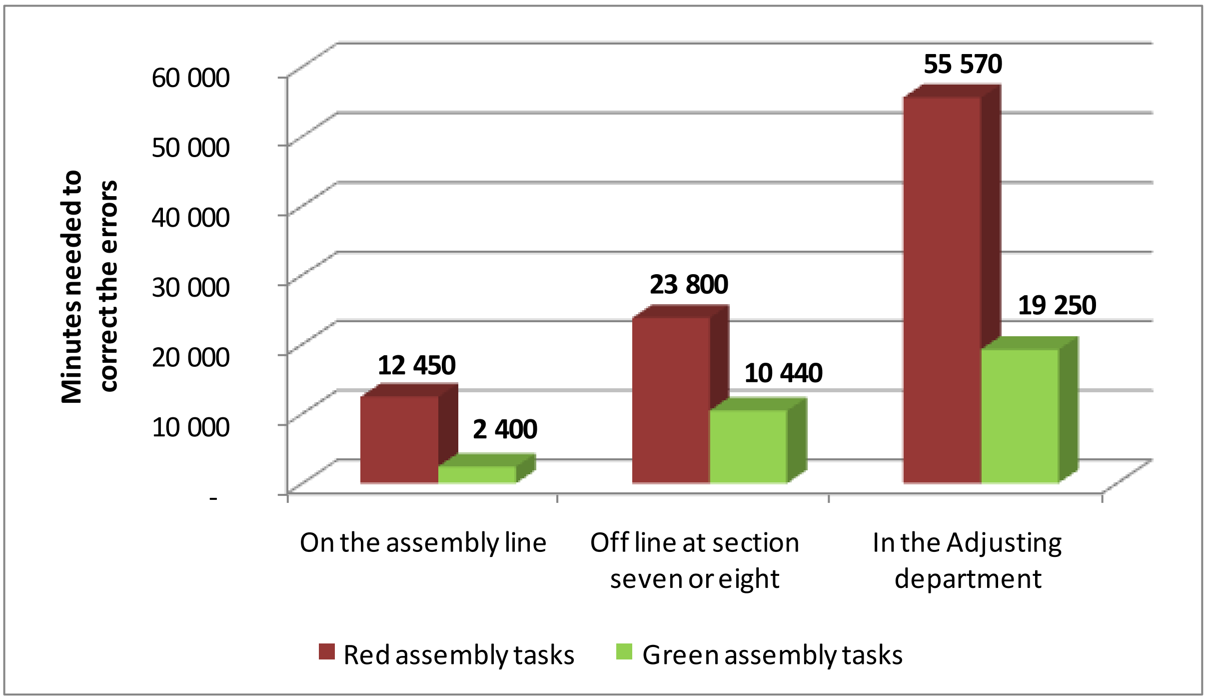
The times to correct errors for the green assembly elements were then multiplied with this factor of 3.37 in order to obtain comparable results. This was done consistently with all correction times for the green assembly element and will hereby not be stated separately for each graph.

It is important to note that the stated correction times are for the 37 weeks of production that were included in the study, and not for a full production year of 47 weeks. The results for red and green assembly tasks respectively are presented in Graph 5.



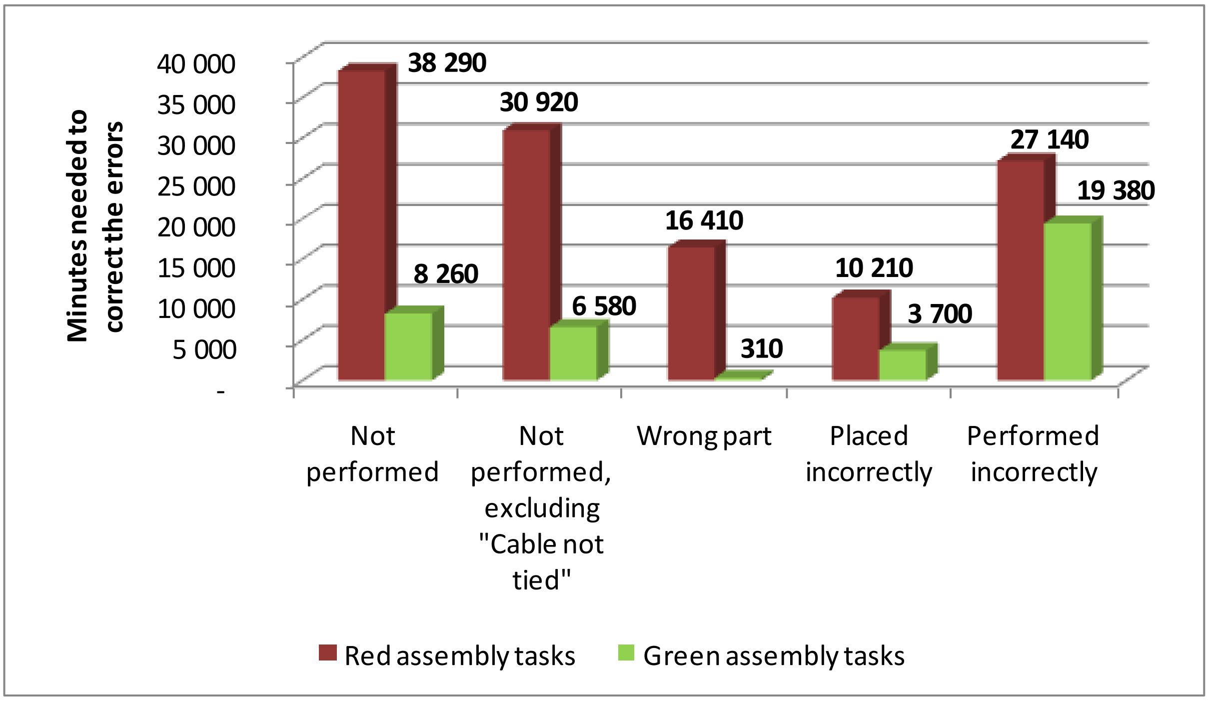
Graph 5. The times needed to correct the errors included in the study

The distribution of errors at the different locations in the production plant – on line, off line at section seven and eight or in the Adjusting department – was then combined with the times to correct the errors. This visualized the times needed to correct the errors depending on how late in the production process the errors were treated. The result is presented in Graph 6 on the next page.



Graph 6. The times needed to correct the errors depending on where in the plant the errors were corrected

The times to correct the errors were also combined with the information about the four different types of error, the result is shown in Graph 7. Again, the sub-category where *cable not tied* has been eliminated from *Not performed,* is included.

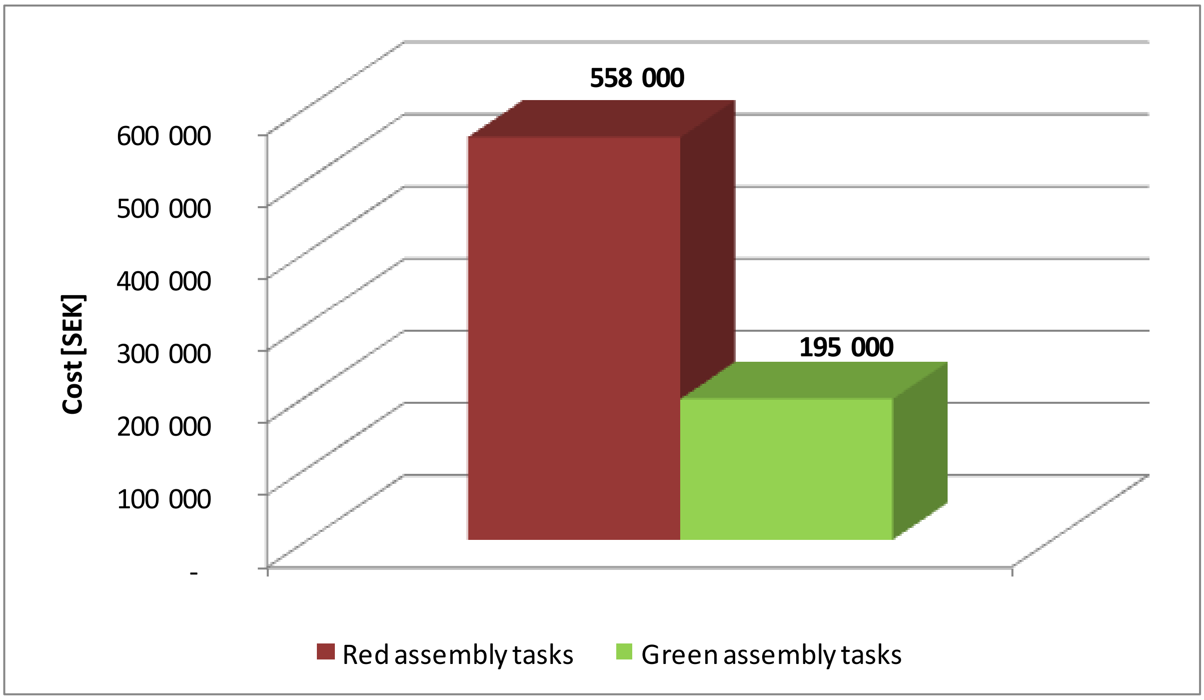


Graph 7. The times needed to correct the errors depending on the type of the errors

5.4 Cost of correcting the errors

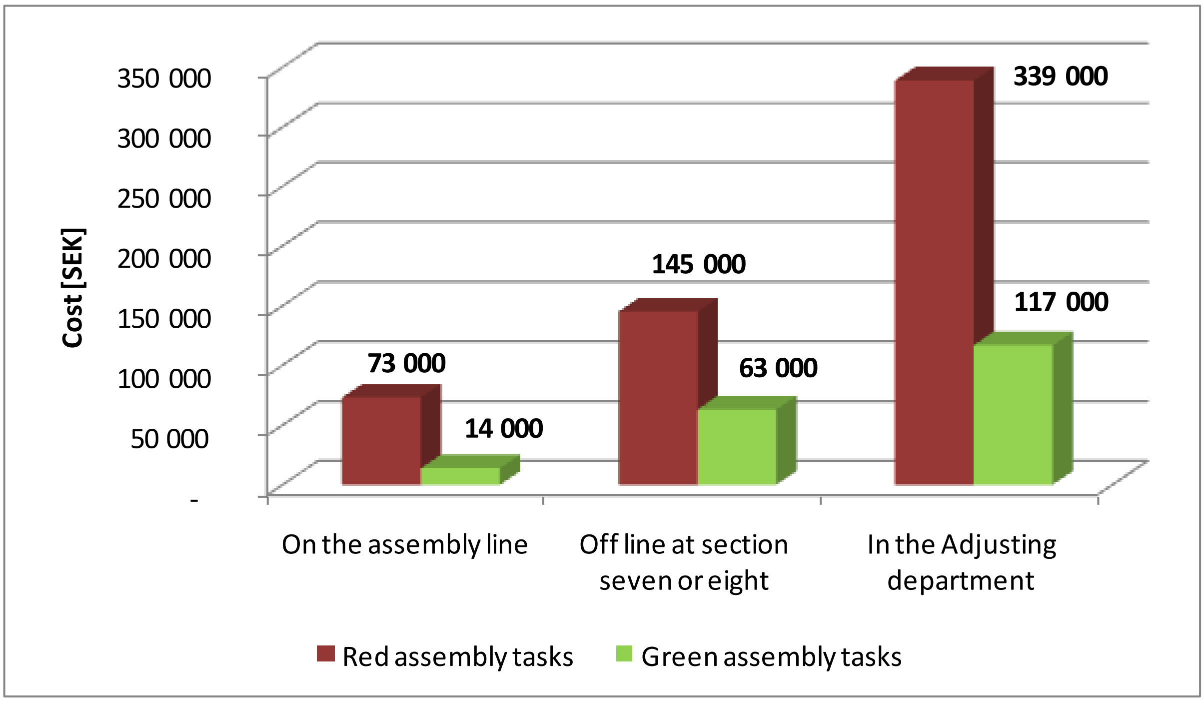
For this project it was not enough to point out how much non-value-adding activity were caused by bad production ergonomics, it was also necessary to put this into financial terms. This was done by using the times presented in *5.3 Time to correct the* errors and an average standard cost for a blue collar employee at Volvo Truck. As described in *4.7 Method for economical calculations*, other costs were not included due to difficulties in associating them with individual errors.

The values have been adjusted to show the costs for an entire production year and not only the 37 weeks that were included in the study. The rounded costs for correcting the errors are shown in Graph 8 below:



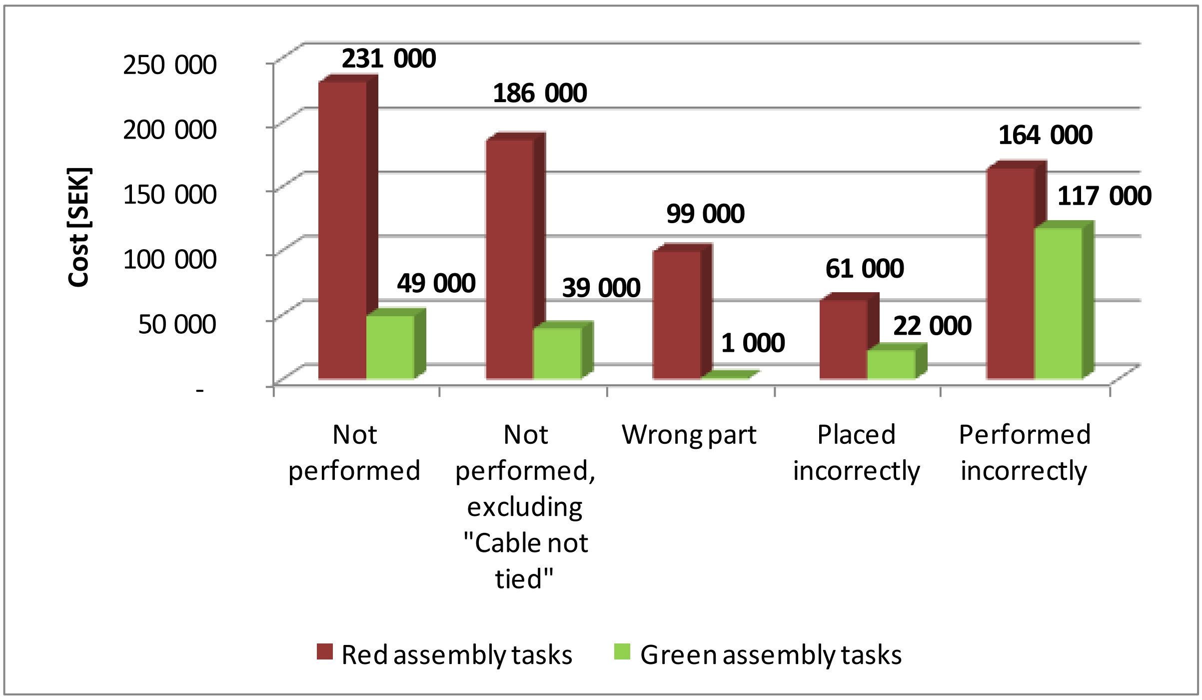
Graph 8. The total cost in a year for correcting the errors associated with red and green assembly tasks respectively

Since the times for correcting the errors have been divided with respect to where the errors have been corrected and the type of the errors, so can the financial data. Graph 9 on the next page shows the rounded costs of correcting the errors depending on where in the factory they were corrected.



Graph 9. The total costs in a year for correcting the errors depending on where in the plant the errors were corrected

Finally, the rounded costs for correcting the errors divided into types are presented in Graph 10.



Graph 10. The total costs in a year for correcting the errors depending on the type of the errors

5.5 The extent of the study and statistical information

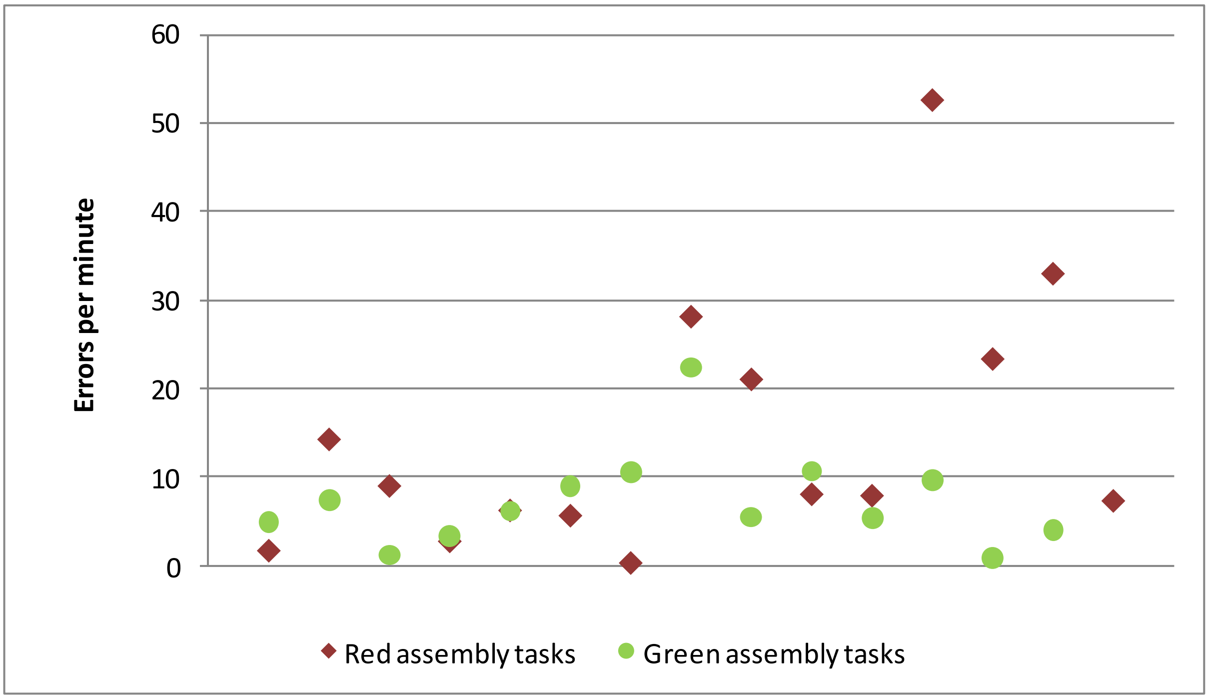
A total of 4 682 errors are included in the study and the total assembly time for the selected tasks is 430 minutes, which equals just over seven hours. In comparison, it takes in average about forty hours of assembly time to complete one truck from section one to section six of the assembly line. That means that the study includes 17.5% of the total assembly time. However, since the assembly times obtained are for types of trucks that are considered to be especially difficult and time consuming to assemble, the real percentage is actually lower.

The exact percentage and size of the sample of assembly tasks is not of interest though, since it is too small to be able to say anything about the population anyway. This was known early in the project but it was decided that some statistical information should be calculated in order to prove it. The standard deviation was therefore calculated, since it is a measurement of the distribution of the data in a statistical study. If the standard deviation of the sample is large, it means that a larger sample is needed to draw conclusions about the population. The standard deviation for the mean value of errors per minute for the red and green assembly elements respectively are presented in Table 2.

Table 2. Standard deviation for the mean values of errors per minute of the red and green assembly tasks respectively

Standard deviation	
Red assembly tasks	14,62
Green assembly tasks	5,94

By displaying the individual values of errors per minute in a scatter plot it is also possible to see the distribution of the values. This is presented in Graph 11.



Graph 11. Scatter plot of the individual values of errors per minute for the assembly element in the study

6 Analysis

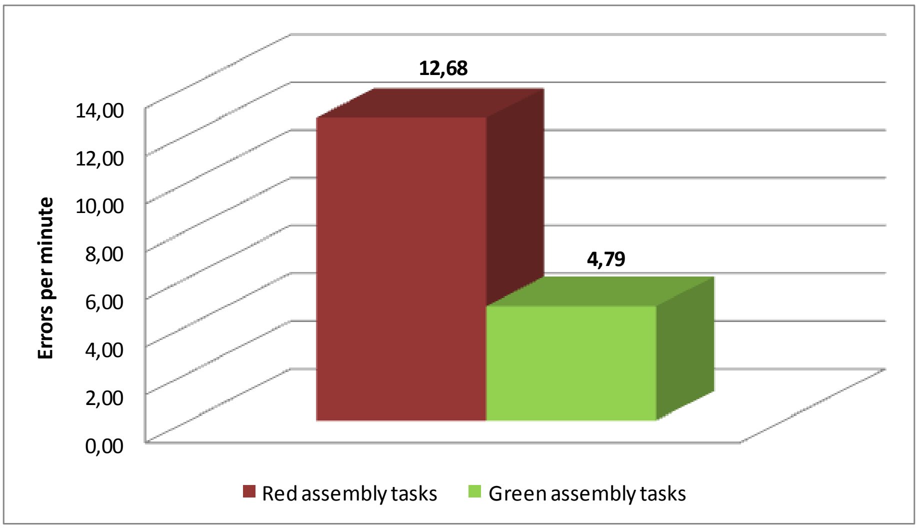
In order to fully understand the result and what it means, it needs to be analyzed. This chapter provides a deeper understanding of the result, as well as a sensitivity analysis. The sensitivity analysis discusses the underlying data and its reliability and investigates the consequences of any incorrect input data.

6.1 Analysis of the result

There are several important and interesting conclusions that can be drawn from the data when different results are compared to each other. In order to make it easier to follow the analysis, some of the graphs shown in chapter *5 Results* will be repeated here.

6.1.1 The connection between production ergonomics and product quality

One of the most important conclusions is that there are more errors associated with assembly tasks that have been classified as red than with the tasks that have been classified as green. There is a difference of 165% between the two categories. This can also be expressed as there being 2.65 times more errors for the red tasks compared to the green. In other words, for every one hundred errors associated with green assembly tasks, there are 265 errors associated with red assembly tasks.



Graph 12. A repetition of Graph 2. The mean values of errors per minute for the red and green tasks

This information shows the connection between production ergonomics and product quality. Since the mean value of errors per minute is higher for red assembly tasks than for green, it has been shown that a relationship between production ergonomics and quality is present at Volvo Trucks in Gothenburg.

6.1.2 Analysis of the number of errors and the times needed to correct them

Another very interesting relationship is the one between the number of errors and the time it takes to correct them. While the difference between the number of errors for red and green assembly tasks are 165%, the difference between the correction times are 186%. If the number of errors were the only aspect that was different, these two figures would have been the same. Since the percentage for the correction times is even larger, each error associated with a red assembly task on average takes longer time to correct than an error associated with a green assembly task.

This relationship can be seen even more clearly when the result is divided into different categories. If the graphs displaying the categories of where the errors have been corrected are compared – as in Diagram 7 – the difference between the number of errors and the times they take to correct becomes very clear.

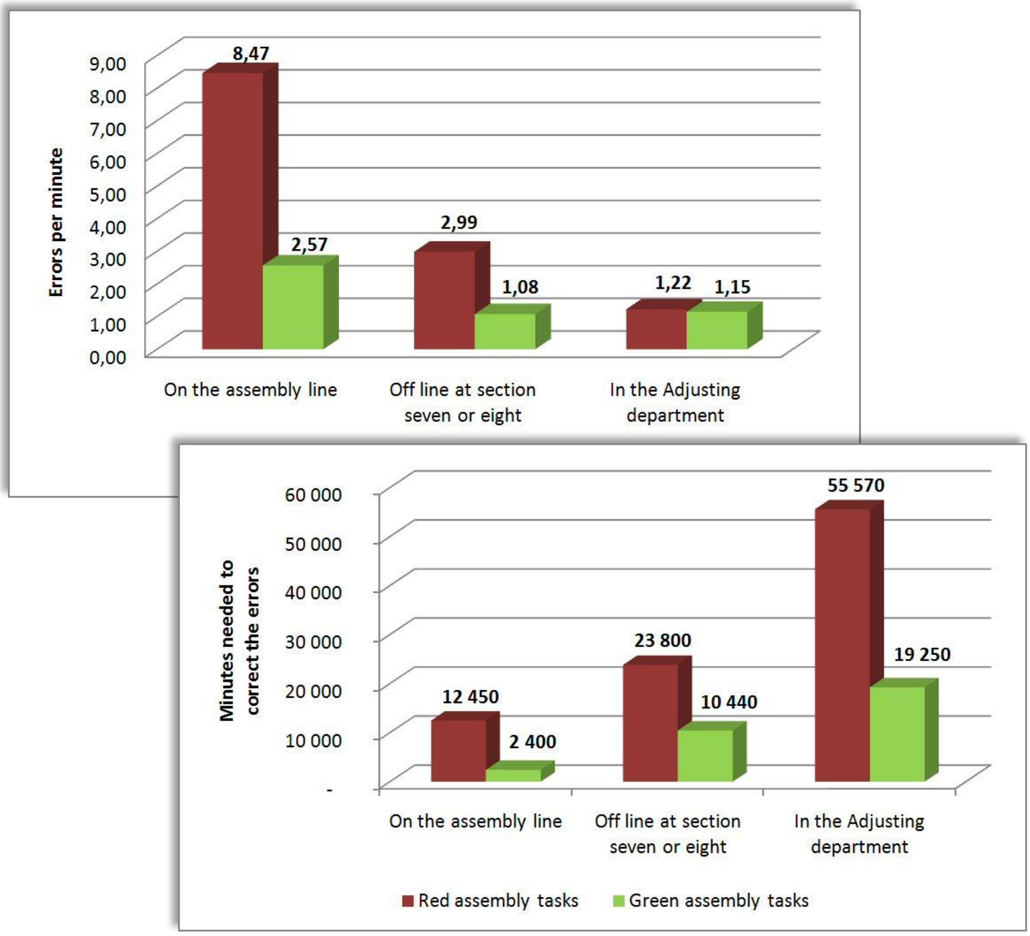


Diagram 7. The uppermost graph is Graph 3 and the one at the bottom is Graph 6, both from chapter *5 Results*. They are presented for comparison of the number of errors and the time it takes to correct them in different areas of the production plant.

While most errors are corrected on the assembly line, the longest times for correcting the errors are present at the Adjusting department. This is not surprising, since it is much more time consuming to correct errors on a completed truck where parts often need to be disassembled and reassembled again. The difference in the number of errors in red and green assembly tasks that are corrected in the Adjusting department are only 7%. Still, the difference in correction times is 189%. This unmistakably shows that the errors associated with the red assembly tasks takes a lot longer to correct at the Adjusting department than the errors associated with the green tasks. Since the costs are based on the correction times, this also means that it is more expensive to correct an error at the Adjusting department than at the assembly line. A consequence that follows from this is that an error that originates from a red assembly task will in average cost more to correct than an error that originates from a green assembly task.

At the production line a similar situation is present, but here the difference in time to correct errors is even larger than in the Adjusting department. It takes just over five times as long to correct the errors connected to the red tasks than the errors connected to the green tasks. However, since the times are relatively short compared to when the errors are corrected at sections seven or eight or in the Adjusting department, there are not as much potential savings in this area when considering the absolute values.

Another way to display the difference between number of errors and the time it takes to correct them is to separate the errors depending on type, as described in *4.6.2 Putting the result into a context*. The difference between red and green tasks when it comes to the times needed to correct the errors are larger than the difference in the corresponding mean values or errors per minute, as can be seen in Diagram 8.

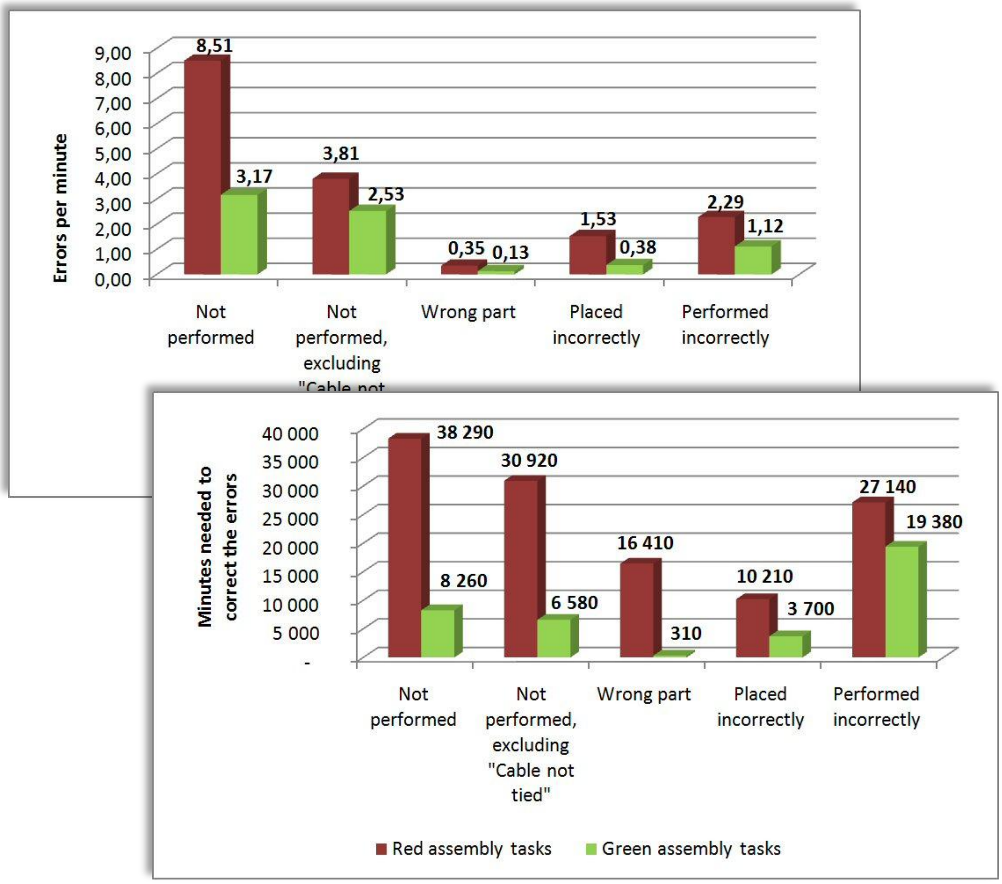


Diagram 8. The uppermost graph is Graph 4 and the one at the bottom is Graph 7, both from chapter *5 Results*. They are presented for comparison of the number of errors and the time it takes to correct them depending on the type of the errors

When viewing this separate display of the errors and time to correct them, another interesting aspect can be found. When comparing the category *Not performed* with the category *Not performed, excluding cable not tied* the number of errors is reduced by 55%, but the time to correct the errors is only reduced by 19%. This difference can be seen by comparing Graph 4 and Graph 7 in chapter 5, and the relevant sections of these graphs are therefore shown below in Diagram 9. This means that even if the cable ties are causing a high number of errors, they do not take a long time to correct and hence are not very expensive. However, there might be other good reasons for trying to reduce this type of error, beyond the scope of this project.

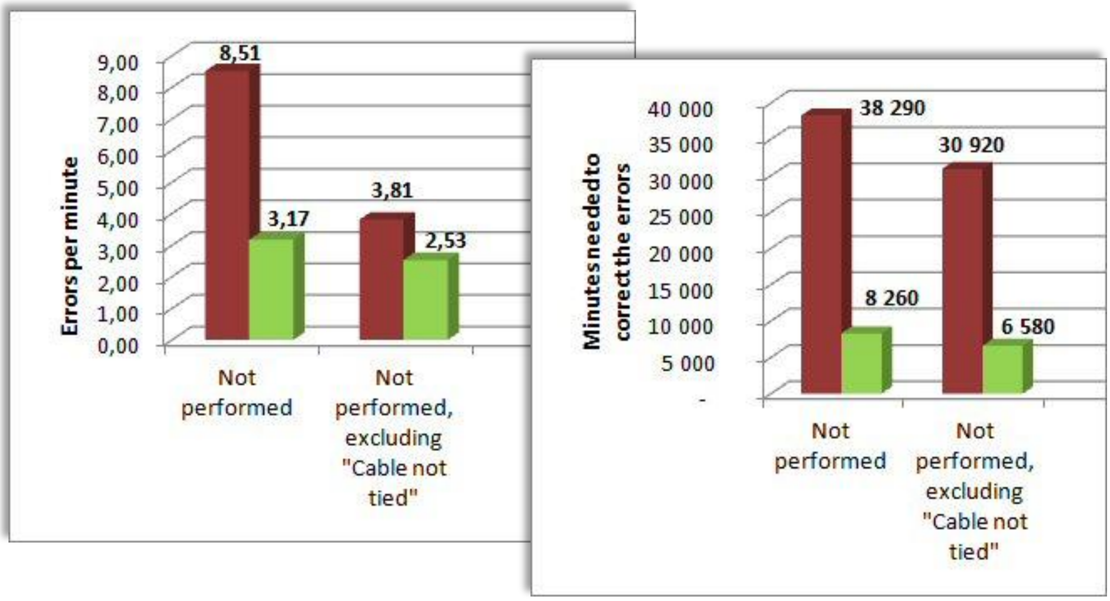
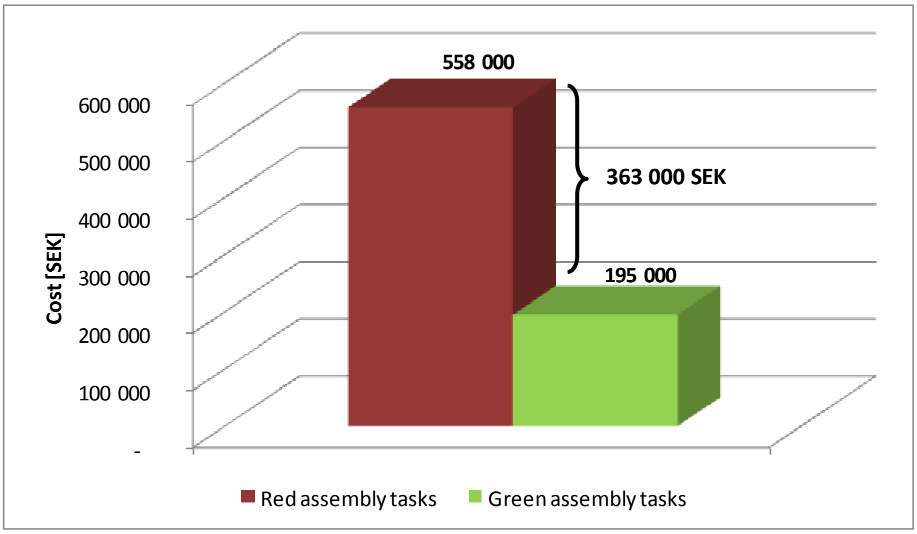


Diagram 9. Parts of Graph 4 (left) and Graph 7 (right) from Chapter 5. When comparing the two red bars in each graph, the difference between the bars is larger in the graph to the left - showing the mean value of errors per minute - than in the graph to the right, showing the correction times.

6.1.3 Analysis of costs to correct the errors

The percentage differences in costs for red and green assembly tasks are the same as the differences in time to correct the errors, since the data for both the red and green categories have been multiplied with the same financial data. The difference in financial terms is 363 000 SEK in a year in personnel cost only, as seen in Graph 13. Since the study consists of less than 17% of the total assembly time, the potential of decreasing the cost for inadequate quality by investing in production ergonomic improvement is possibly even larger.



Graph 13. A repetition of Graph 8 in chapter 5. It shows the total cost in a year for correcting the errors associated with red and green assembly tasks respectively.

The difference in cost for red and green assembly tasks respectively can be viewed as an unnecessary cost of inadequate quality that is caused by insufficient production ergonomics. If the red tasks included in the study could be changed and improved enough to be reclassified as green, this cost has the potential to be eliminated. This will free financial, as well as personnel, resources that could be invested in other areas to take preventive measurements and further improve the production ergonomics and the quality level.

6.1.4 Conclusions that can be drawn from the result

Since the sample of assembly tasks is small, it is not possible to draw any conclusions about the entire population of tasks in the factory based on the study. However, it is likely that there are potential savings in the rest of the plant that has not been studied. Since the indication of a connection between production ergonomics and product quality is strong, it is also highly likely that the same relationship to varying extent is valid throughout the entire production line, and not only for the tasks that are included in the study. Without further investigation it is not possible to make any statements for the rest of the production plant, but for line 21 the conclusions seems to be well founded.

6.2 Sensitivity analysis

A sensitivity analysis is made in order to show how the input data affects the result. If the input data is incorrect, it is important to understand how that may affect the output and even the conclusions. In this case there are three main variables that constitute the results and potentially affect the conclusions: the assembly time of the tasks, the number of errors included in the study, and the time it takes to correct the errors. If these three variables are altered it is possible to see which of them will affect the result the most and if there is a risk of having drawn the wrong conclusions.

More details of the calculations in the sensitivity analysis can be found in Appendix A.

6.2.1 Sensitivity analysis of the assembly times

First, the assembly times were altered. In this context, it is not interesting to examine if the difference in mean values of errors per minute for the red and green tasks increases, only if the difference decreases. One way of achieving this is to alter the input data so that the mean value of errors per minute for the red tasks is lowered and the mean value for the green tasks is raised. This would mean that the assembly times for the red tasks would be increased and the assembly times for the green tasks would be decreased. However, the assembly times obtained are for a time consuming and difficult truck model. Therefore it is not realistic that the assembly times for the green tasks would be even lower than what is currently stated. Instead, the assembly times for the green tasks were held constant and the assembly times for the red tasks were altered.

The result of this showed that it would be necessary to change the assembly times by 25% in order to obtain a change in the output data by 20%. That means that the assembly times are generally not a factor with a high level of influence on the output. In order to lose the relationship between production ergonomics and product quality – that is, have mean values of errors per minute that are the same for both red and green tasks – the assembly times of the red tasks would have to be wrong by 62%. It is extremely unlikely that such a large error is present in the data.

6.2.2 Sensitivity analysis of the number of errors

Second, the number of errors in the study was altered. In this case both the number of errors for the red tasks and for the green tasks was altered by the same percentage. The number of errors associated with the red tasks was lowered while the number of errors associated with the green tasks was raised.

The result showed that the number of errors included in the study have to be changed by 11% in order to change the output data by 20%. It is therefore a factor that affects the output more than the assembly times. It is possible that a deviation by 11% have been made since it has been very difficult to trace the errors. Many errors have been excluded from the study since it has not been possible to ensure that they are associated with the tasks of interest. Therefore, the likely scenario is that there are many errors missing for both the red and the green tasks. However, this would not decrease the difference between the mean values of errors per minute since it is highly likely that it affects the data in the same way for both categories.

If the number of errors would be changed until the relationship between production ergonomics and product quality were removed all together, the change would have to be 45%. That is, the errors associated with the red tasks would have to be reduced by 45% while the errors associated with the green tasks would have to be increased by 45%. Such large deviations from the true values working together to close the gap between the mean values are not likely.

6.2.3 Sensitivity analysis of the times to correct the errors

Third, the times to correct the errors were altered. The same method as before was used here as well: the values of the red tasks and the green tasks were changed by the same percentage and the mean value of the red tasks was decreased while the mean value of the green tasks was increased.

Again, an alteration by 11% would be needed to change the output by 20%. Since the times are only estimations, it is possible that the estimations are off by a total of 11%. To obtain the same mean value of errors per minute for both the red and the green tasks, it would be necessary to change the correction times with just over 80%. This, on the other hand, is not a realistic error to have been made.

6.2.4 Sensitivity analysis of where the errors have been corrected

Finally, the location for correcting the errors was altered. The errors have been separated based on where they have been corrected: on the assembly line, off line in section seven or eight, or in the Adjusting department. This has been based on information from Qulis and from the assembly personnel. It is supposed to be noted in Qulis if an error is sent to section seven or eight or to the Adjusting department. This is not always done and can therefore be a source of error in the study. In the sensitivity analysis the number of errors that have been sent to these correction departments was increased. The number of errors that was corrected on the assembly line was lowered by a percentage and the number of errors in the other two areas was increased by half of the errors each. For example, if 100 errors were removed from the assembly line, 50 were reassigned to section seven and eight while 50 were reassigned to the Adjusting department. The correction times are so similar at section seven and eight compared to at the Adjusting department that the area is not of very high importance, just as long as the errors are removed from the assembly line.

This shows that it is necessary to reassign 17% – a relatively high number in this context – of the errors in order to obtain a change in the output by 20%. In this case, the change would be an increase in the difference between red and green assembly tasks and the conclusions would consequently be strengthened. The reversed situation: that a worker has noted that he has sent an error to a correction department when he has in fact corrected it himself is considered extremely unlikely and was therefore not analyzed.

6.2.5 Conclusions that can be drawn from the sensitivity analysis

The sensitivity analysis shows that the output data is more sensitive to incorrect input data when it comes to the number of errors and the times needed to correct them than when it comes to the assembly times. In order to obtain a change in the output data by 20%, a smaller change in the input data is needed for the number of errors and the correction times than for the assembly times.

In some cases it is possible that errors in the input data have caused the result to be wrong by 20%. However, this would only affect the resulting figures and not the conclusions. Very large errors have had to be made in order for the main conclusion – that there is a relationship between production ergonomics and product quality – to be incorrect. It is considered to be very unlikely that such large errors have been made. This relationship is therefore considered to be valid at Volvo Trucks in Gothenburg.

7 Discussion

All uncertainties and how they affect the result cannot be explored by calculations. These uncertainties are instead discussed in this chapter. Differences in the result from this study compared to other studies are also discussed.

7.1 Consequences of the prerequisites at Volvo Trucks

The prerequisites at Volvo Trucks have naturally influenced the study to a great extent and therefore need to be discussed, especially since they contribute to the unique aspects of the study. It is important for both Volvo and others to understand how the prerequisites have affected the project and the result.

7.1.1 Information about the production ergonomics at Volvo Trucks

Production ergonomics has traditionally not been an area of high interest for improvement at Volvo Trucks in Gothenburg, and hence the knowledge has been limited up to this point. The approach so far has been to find and work with the acute issues that the assembly personnel have brought attention to. The knowledge gathered in EMD is limited to these urgent problem areas and therefore, it is not a good representation of the entire assembly line.

This became evident at the beginning of the project when the selection of tasks was to be made. There was a significant lack of green assembly tasks in EMD since it has not been of any interest to map these. Therefore, it was necessary to find green assembly tasks urgently. It proved difficult to find as many green tasks as red tasks, and the difference in assembly time was even larger. Even if this work provided more information about the production system, it is still just a small fraction of the entire production line. Hence, it is not possible to state what the distribution is between red, yellow and green assembly tasks.

Since it is often the assembly personnel themselves who initiates an ergonomic investigation, the data gathered in EMD mostly concerns tasks that result in immediate physical problems, such as heavy lifting or having to bend the joints in extreme angles. Many postures and movements will not harm the body until they have been repeated over a longer time period, and therefore, the assembler might not connect the pain with a particular assembly task. Then the problem is at risk of being unexplored since no one is complaining specifically about it. There is a possibility that there are several unknown tasks that are worse, from an ergonomic point of view, than the ones that have been identified so far, simply because the consequences have not yet manifested themselves. Instead of allowing the assembly personnel to be solely responsible for determining which tasks are most harmful, it is important to take an ergonomist's point of view and utilize the knowledge he or she has.

7.1.2 The usage of Qulis in the project

Qulis was used to find the errors that originated from the selected assembly tasks. A lot of information is stored in Qulis and it is used daily by production personnel and the quality department. However, in this study Qulis was used in a way that it is not intended for and problems have therefore arisen. Since it is a system specifically designed for and by Volvo, it is not intended to be used by people that are unfamiliar with the product and the production process. There is a lot of knowledge that it is presupposed that the user has. In the daily work with Qulis this is not a problem, but when a new project is started this is an issue that needs to be taken into consideration. In order to know what terminology to use when searching for information and processing data, the vocabulary of the production plant first needs to be adopted by the user. In this case the initial information gathering was slowed down due to communication difficulties between the program and the writers.

Further, Qulis was not designed to trace errors to a specific assembly tasks as far back in time as have been necessary in this project. When Qulis is used on a daily basis, the amount of information that is being dealt with is a lot smaller. The quality coordinators use Qulis to search for errors in a similar way to what has been done in this project, and they categorize the information in order to, for example, present statistics on the most common errors. But when they do so, they are usually looking at much smaller timeframes and therefore much fewer errors. Additionally, when the quality personnel are working with Qulis on a daily basis, they have the advantage of examining the errors shortly after they were registered. That means that if there are any questions regarding a specific error, they can contact the assembly personnel that registered it and get more information about it. This was not possible during the project since the data was registered over a year ago. No one is able to answer specific questions regarding minor events that took place that long ago, and this issue has had a continuous effect on the project.

When statistical data is collected by the quality coordinators, the exact meaning of each error – that is, where it originated and why – is usually not of interest. They are looking at tendencies and the overall situation. When trying to find a solution to a certain type of error it is enough to target the majority of the errors in a category, it does not matter if not every single error is analyzed. For this approach, Qulis is working excellently, but this was not an option in this project since the data needed to be analyzed much more thoroughly. After having performed searches in Qulis, it was necessary to go through all errors and analyze them one by one since it was not possible to perform searches that resulted in the sought-after data only. As explained in *4.4 Searching for the quality data in Qulis*, some options have been used to narrow the search result, but for each search performed there were still data that should not be included, and there were additional data that were missing from the search result. The vast quantity of data made the processing of the search results very time consuming and difficult.

Another reason for the difficulty of finding the errors that were of interest in the study – and of knowing which errors to include and which to exclude – is the vocabulary used to describe the errors. Qulis mostly uses the same notations on components as the Sprint system does, while EMD uses a mix of this and the jargon used by the assembly personnel. This means that some names on parts used by EMD does not exist in Qulis and vice versa, which makes it very difficult to know what terminology to use when conducting searches in Qulis.

Adding to this is the many different words used for describing the same error. The meaning of these words can also change depending on which section of the production line that reported the error. Each predefined term found in Qulis has a specific meaning and should be used in a specific context, but this knowledge is lost at some point in time between the educational sessions in Qulis and when the operators are doing their entries during the everyday work. This does not seem to be viewed as a very big problem in general, since those who use Qulis have the needed knowledge to understand different variations in registration of the same error. However, in any kind of study where deeper knowledge of the individual errors is needed, this will undoubtedly be a problem.

Another aspect that must be considered when doing a study that relies on data obtained from Qulis, is that not all errors are registered as they are supposed to. Even if an error is noted on the card that accompanies the truck through the production process, it might not be registered in Qulis. There will undoubtedly be many errors that are never even noted on the card, especially errors that are very quick and easy to correct and that are discovered in other areas than at the control stations. If it is easier for the assembly workers to correct the error than to note it on the card, they will likely chose the easier option. In this case however, it is possible that the times to correct the errors are so short – just a few seconds – that it would not have affected the end result very much either way. Still, not having all errors registered in Qulis will be a factor that needs to be taken into consideration when performing a study.

7.1.3 Using estimations of the assembly times

As described in *3.1.1.2 Sprint and assembly times*, the assembly times in the system called Sprint are calculated based on standardized times. Even if additional times are added if necessary, the times are still based on calculations and not on actual measurements. This means that the assembly times will only be estimations of the real situation.

Additionally, there are no standardized ways of working at the production line. Every worker is free to perform the tasks as he or she sees fit. The work instructions available will only provide information about which components to assemble and in which order to do so, but not on how the assembly should be performed. This results in a great variation in how the tasks are performed; the actual assembly times will therefore vary as well.

When gathering the assembly times, it was consequently not possible to obtain the real values. The information on how much time is actually spent on each assembly task is simply not available. This has not been considered as a problem since the objectives of the study concern the *difference* in quality between red and green assembly tasks, and the difference will be constant as long as both categories are treated the same. When calculating the errors per minute this is simply used as comparative figures in order to compare the two categories. If there are deviations from reality, it does not affect the result, only the absolute numbers; the difference between them will still be the same. Therefore, it is not of high importance to obtain the real assembly times. Time estimations will be sufficient, as long as the same method has been used when calculating the assembly times for both red and green tasks.

Another difference from reality is that the assembly times that have been used in the project are not representing the variety of trucks that are assembled on the production line. The assembly times are based on a time consuming truck model in order to obtain longer times and thus low values of errors per minute. It was not possible to obtain values for the real distribution of truck models since it would have been extremely time consuming for the production engineers to present that information. Therefore, it was decided to use the assembly times for time consuming models and make a simplification of the situation. Again, this is acceptable since both categories are treated the same. The result of the simplification is likely to be that the mean values are too low, but since they are both too low the difference will not be affected to a significant extent.

Even if all of these factors were to be important, the sensitivity analysis still shows that the assembly times are not a variable that affects the result very much. As seen in *6.2.1 Sensitivity analysis of the assembly times*, it is necessary to have a large error in order to obtain a deviation of the result that actually matters. To sum up; the simplifications that have been made regarding the assembly times have not affected the end result.

7.1.4 Financial factors that could not be included in the study

Numerous economic factors were of interest in this study and initially several were intended to be included. Unfortunately, it was not possible to obtain all the desired information, simply because it does not exist at the detailed level that was needed for the calculations. This is probably a situation that exists in many companies and is the reason why other researchers has noted that even if the information about costs that could be reduced when improving production ergonomics is much needed, it cannot be presented. The situation that follows is that economic effects from ergonomic investments cannot be argued for in financial figures to any greater extent.

One factor that would have been interesting to include is cost of scrapped material. As described in *4.7 Method for economical calculations*, there are several types of costs associated with scrapped material. None of these costs are recorded in a way that makes it possible to associate them with individual errors, or even with sections of the line. When a component is scrapped, it is registered as associated with the section that first handled it. Often that is a pre-assembly area and not a section of the line. It is not recorded where the error was found or where the component was scrapped. That makes it impossible to trace the scrapped components and use the information in this project. Similarly, the material handling associated with the scrapping is untraceable as well.

The only cost that was possible to use in the project is the cost for the personnel that is working in the production plant to correct the errors. No administrative cost could be included, even despite there being administrative personnel that do extra work because errors occur within the production plant. An example is the new material needed when a part is scrapped. New material needs to be ordered, the material needs to be transported within the factory and the scrapped material needs to be taken care of. All these activities need planning and hence result in paper-work, which is not recorded and could hence not be included in the calculations. Similarly, the extra time that fork-lifts uses to transport new material and scrapped material is not traced.

Other cost that would have been of high interest is tied-up capital. The trucks that are being corrected at the Adjusting department represent high value semi-finished goods that cannot be delivered to a customer and thus not be translated into revenues. Since these trucks have left the production line, they could have been sent to the customer, providing that they had been correctly assembled. This means that there is a risk of delayed deliveries and even the risk of losing customers that are not satisfied with the lack of delivery accuracy.

If all these additional costs had been possible to trace and include in the study, the resulting figures would likely have been much higher than the presented cost for personnel.

7.2 Consequences of the methods and the work process

It is not only the prerequisites at Volvo that have affected the study. The methods that were chosen have also influenced the project and the result. These also need to be discussed in order to learn from the outcome and improve the methods further before a similar study is made.

7.2.1 Gathering data and sorting information

The single aspect that has influenced the project the most is the fact that the study has been retrospective. This was not a choice, since the timeframe of the project did not allow for any other options, and it has been the most difficult issue to deal with during the project. All information has been gathered long after the events have taken place. The errors that have been analyzed occurred over a year ago and there is no additional information about them than what is stored in Qulis. It is impossible to ask the assembly personnel questions about individual errors since no one will remember them.

It was necessary to select a long period of time for the study in order to obtain a valid result. If a shorter period had been selected, there would have been a risk of choosing a period when there were fluctuations in the production process. The result would then not have been representative for the general situation at the production line. By selecting a longer time period, the impact of such deviations was minimized. It was desirable to include all 47 production weeks in a year, but when the project started the process had not been stable for the last year. Therefore, it would have been unsuitable to include more than the 37 production weeks that were chosen.

The long period of time resulted in a very large number of errors. There are over 4000 errors included in the study but several thousands more have been examined and excluded. All of these errors have been treated manually. The information about them has been read and a decision has been made regarding if they were to be included or not. During this manual work, mistakes will undoubtedly have been made. It is not likely to be enough to alter the result, but it is still a source of error.

The retrospective methodology and the large number of errors have made it necessary to make simplifications and generalizations. One example of this is that it has not been possible to ask the assembly personnel at the line and in the Adjusting department how long every individual error has taken to correct. Obviously this is the case for the 4000 errors, but it is also true for all of the different types of errors. When gathering the information on the correction times, it was necessary to generalize the questions to a large extent. Instead of asking how long it takes to exchange a particular pipe for example, it was asked how long it generally takes to exchange any pipe in that area on the truck. The errors were also collected into groups of likely correction measures. For example, all errors that would result in the component being replaced were gathered up together, and the questions were not asked for the individual types of errors, but rather for all errors that resulted in replacement. In that way the number of questions could be reduced to a manageable amount.

When all individual errors were associated with a correction time, more assumptions were necessary. There were inevitably errors that were not possible to group together with others, that seemed unique. Even if there were not many of these errors for each component, there were a large number of them when all the components were considered. Therefore, it was still not possible to ask the assembly personnel and the workers in the Adjusting department questions about all these errors. Generalizations and assumptions have had to be made. Similar errors – both in the same section and in other sections of the line – were used as guidance and likely correction times were associated with the errors. As a general rule, low values were used in order to obtain too low numbers, rather than to high numbers, in the end.

This last statement is also very important. Throughout the study, it has been a general rule to always make choices that result in lower values rather than higher values. The aim has been to obtain a result that is well-founded and reliable. When presenting the result it should be possible to state that it is minimum numbers: the result might be larger, but it is not smaller. Since the study is dealing with financial figures, this is essential. When presenting data in the form of possible savings in an area, it is wise to be sure of those numbers. If the savings then turns out to be larger it will only be positive, but they should not be smaller than stated. Otherwise, the managers are less likely to agree to any other similar investments in the future. This minimum-level approach has been used for both the relationship between production ergonomics and quality, as well as for the financial figures. It is possible that the relationship is even stronger: that the difference in mean values of errors per minute is even larger than what is claimed in the study. It is also possible – and very likely, as was discussed in *7.1.4 Financial factors that could not be included in the study* – that the financial savings are larger than what is proposed. But every possible action has been taken to ensure that they are not smaller.

The sensitivity analysis showed that both the number of errors and the times to correct them are important factors. Even a change in the input data of only 11% would alter the output by 20%. As stated in the sensitivity analysis, it is not unlikely that the input data is incorrect by 11%, but it is not very likely that it is incorrect in a way that actually makes the difference in quality output between the red and the green assembly tasks smaller. The likely scenario is that there are a lot of errors missing from both the red and the green tasks. In that case, the difference in the result between the red and the green tasks will either be constant or increase. It will not decrease since there are most likely much more errors missing from the red assembly tasks than from the green. There are currently more errors associated with the red tasks and therefore more margin of error for that category. If the two categories of red and green tasks were both increased by 11%, then the difference between them would increase by *more* than 11%. Again, the aim of finding the minimum value is present.

The iterative work method was a good way of working throughout the project since it gave the possibility of testing a method, reviewing it, learning from the outcome and then to make smaller changes so that a better way of working could be utilized next time. This can be compared to the PDCA-cycle (Plan-Do-Check-Act) that is a common tool in Lean production. This also worked well together with the *Go to gemba* approach, since it was found early in the project that an understanding of the data could only be reached by learning about the production system by observing and by talking to the assembly personnel.

7.2.2 Discussion of the selection of work tasks

The fact that there is only red and green assembly tasks included in the study has naturally affected the extent of the result. In order to obtain a more nuanced description of the situation, assembly tasks that have been classified as yellow should also be included. However, the conclusions that can be drawn from the study are not affected by this delimitation. The goal was to show the relationship between production ergonomics and product quality and in order to do that, yellow tasks does not have to be included. It is also not necessary to include yellow assembly tasks when showing that there is potential savings in the form of lowered cost for inadequate quality. It is only the magnitude of these savings that may be changed by the inclusion of yellow assembly tasks.

Because of the lack of green assembly tasks when the project started, a number of green tasks had to be identified quickly. Therefore, the investigation of green tasks was done slightly differently than what is usually the case when the ergonomist is mapping the assembly tasks. The analysis of the task was not as thorough as usual and the work was not documented with all the information that is usually included. Therefore, the mapping of the green assembly task is a source of error in the project. There is a slight possibility that some of the tasks might have been classified wrongly because of the lack of in-depth analysis and time available for the work. The writers have complete faith in the work of the ergonomist and cannot question the classifications, but if an additional study were to be performed, it would be desirable to analyze the green assembly tasks more thoroughly.

7.2.3 Discussion of the time to correct errors

When gathering the information about the times needed to correct the errors, only one person was consulted in each section of the line. It would have been statistically desirable to obtain the same information from multiple sources, but due to the time constraints this was not possible. As described in *4.5.2 Gathering information on the time needed to correct errors*, the assembly personnel had to take time away from their regular work tasks in order to answer questions, and therefore, it was not possible to interrupt more people than absolutely necessary. In some cases it was also difficult to find just one individual that had the knowledge to answer the questions. It takes a lot of experience to be able to provide information about average times to correct specific errors and the workers that can provide this information are, for obvious reasons, often the busiest.

For these reasons, the variation in data between different members of the staff is unknown. There is a possibility that the times to correct errors will vary greatly between different workers. However, since multiple people have been consulted throughout the line as a whole, it is likely that the variations will have cancelled each other out. If particularly long correction-times have been obtained for one section, particularly short times will probably have been obtained for another.

The correction times will also vary depending on the truck model. That means that there are much uncertainties in the correction times already, and further investigation about the times would not likely have provided better estimates anyway. For a pilot study like this is, the depth of the analysis of the correction times is enough.

7.3 Limitations in the result

There are a number of factors that have not been investigated in the study and that put limitations on the result and conclusions. Physical ergonomics is naturally not the only factor that influences the quality of the product. Some of the more obvious aspects – for example, suppliers delivering defective materials or delivering components late – have been excluded from the study, but other factors could not be isolated and their influence on the result still exists.

- As mentioned several times, it is not possible to make any statements about the entire population of assembly tasks, only about the tasks that are included in the study. Since EMD only provides information about a fraction of the assembly tasks in line 21 – and no information at all about the tasks anywhere else – there is not even any way of knowing what the population looks like. The study cannot claim to have found a relationship between production ergonomics and product quality in the entire production plant; it can only state that a relationship has been found for the assembly tasks that have been analyzed.

Additionally, because of the strength of the relationship, it is likely that it is generally present at section one to six of Line 21. No claims can be made regarding the rest of the plant.

- The result is also limited by the lack of yellow assembly tasks in the study. For a pilot study, excluding the yellow tasks was a good approach since the goal was to find a general relationship, and the resolution of the result did not have to be any higher. But it also means that the result cannot show potential gains from minor improvements in production ergonomics. In reality, improvements are initially often of smaller proportion, such as changing a red assembly task so it can be reclassified as yellow. Additional studies will have to be made before the potential savings in cost for inadequate quality for the entire population of assembly tasks can be presented.

- Since there is no standardized work in the production plant, the workers are free to perform the tasks to the best of their abilities. That means that there are likely methods that result in errors more often than others. The work of the individual assembly workers will therefore affect the quality of the product as well.

- As explained in *2.2 Basic theory on ergonomics*, ergonomics is a much wider field than just physical ergonomics. Errors are being made due to the cognitive situation as well. Latent conditions like the work pace, long term stress and the psychosocial environment will affect the quality of the work as well. The personal situation of the workers will also affect their work. For example, some of the errors in the study might have been made because one of the workers are going through a divorce, and is having trouble concentrating on the task at hand. The point is that there is no way of knowing the real reasons for the errors. While any questionable errors have been excluded, there are many more that might have another cause than the *physical* ergonomics.

- The complexity of the product and the components in each assembly will also influence the quality of the outcome. If the complexity is high, the likelihood of making errors will increase. The complexity has not been studied separately in the project, but the general impression is that there is a connection between the production ergonomics and the complexity of the assembly. This can also be seen in the fact that the red assembly tasks generally takes longer to perform than the green tasks. This relationship needs to be investigated much more thoroughly, but it is likely that the issues of inadequate production ergonomics and high complexity can be targeted using the same cause of action. In that way, it will be possible to gain the benefits of solving both problems with one solution, that is, kill two birds with one stone.

7.4 The result in comparison to other studies

Even if there are only a limited number of studies concerning the relationship between production ergonomics and product quality, they all show the presence of such a relationship. It was therefore assumed that the result of this study would do the same, and this has also been confirmed by the result and the sensitivity analyses. However, most other studies show a stronger relationship. The result in this study is that there are over twice as many errors associated with tasks that have been classified as belonging to the ergonomically worst group of tasks. Other studies that were reviewed at the beginning of this project showed results of up to six times as many errors originating from assembly tasks with harmful production ergonomics compared to tasks where the production ergonomics were good [1] [2] [5]. The previous studies set the level of expectations on the result from this project, and therefore, it was somewhat unexpected to not reach the same magnitude in the numbers as in those studies.

This difference could be explained by different conditions in the examined production environments, as well as differences in the methods used. In most other studies it has been possible to include longer time periods as well as a larger share of the assembly tasks; some of them have been able to include the entire assembly line in question. Previous studies have also been performed in real time and thus not been dependent of historic data that might be more or less complete. Most of the studies that have been found have also been performed over a longer time period. A master thesis should be completed within approximately six months, while other projects have had a time span of over a year.

There is also a matter of the preconditions at the company that the study is being performed at. Different products allow for different situations. The tact time and what is included in each assembly task also affects the result. How well the ergonomic situation is mapped and the overall level of ergonomics also contributes to differences at different companies. If the ergonomics is generally good, the tasks that are considered to be the worst are likely to be better than the worst tasks at a company where the general situation is very poor. Even if ergonomics are not a relative science, it is difficult to ignore relative levels when classifying assembly tasks. There can also be a cultural difference at the companies when it comes to the willingness of reporting errors or certain type of errors.

Another factor that can result in the difference between this study and previous studies is the target of presenting the minimum levels of the result. It might be possible that other writers have had the opposite aim when performing their studies: to present the highest level in order to show high potential savings and in that way convince the management that ergonomics is an important area. There is no right and wrong when it comes to this, but the difference in approach can explain the differences in the result.

As a conclusion, there are multiple explanations for the slightly lower figures in the result compared to other studies. It is also believed that if this study had been performed under the same conditions as the other more extensive studies, the results would have been more similar.

This study tried to put the result into financial terms. This has been done in some of the previous studies, but mostly the area has been discussed in terms of which costs should be included and why. Therefore the financial result from this study cannot be compared to previous findings. The difficulties in gathering information about costs, so that the correct amounts can be associated with production ergonomics and quality, have been described in some of the studies. The challenge of this has been confirmed in this study.

7.5 Fulfillment of the objectives and purpose

The main purpose of the project was to communicate the importance of production ergonomics to the management at Volvo Trucks in Gothenburg. This has been done in the form of this report. Additionally, a presentation/seminar will be held at Volvo Trucks after the completion of the project. It is believed that the message has been – and will be – communicated in a clear and informative way and that the potential of production ergonomics has been shown. However, there is no way of knowing in advance if the study will result in more focus on production ergonomics and additional funding to allow for further studies and improvements.

As stated in *1.2 Purpose and objectives*, the objectives of the project were to:

1. Show a relationship between production ergonomics and the quality of the product in truck assembly.
2. Present the results and the importance of production ergonomics in a way that facilitates the communication to decision makers.

The first objective was fulfilled through investigating the number of errors associated with red and green assembly tasks respectively. Since a clear difference in the mean number of errors per minute was found, it can be concluded that such a relationship exist in the production of trucks in Gothenburg.

In order to fulfill the second objective, the result needed to be put into a financial context. This has been done by investigating the time needed to correct the errors and presenting the personnel costs related to the correction time. The difference in cost for correcting errors associated with red and green tasks respectively has been presented as possible savings in the cost for inadequate quality. This money can be better spent in other areas and on investments that will further improve the quality and the ergonomic situation.

To conclude, the goals and objectives of the study are considered to have been fulfilled.

8 Recommendations

The knowledge gained during the project has resulted in a number of recommendations for the continued work with production ergonomics. They are especially targeted at Volvo Trucks in Gothenburg, but can also be considered and used by other companies and researchers.

8.1 Recommendations for future studies

One of the goals of the study was to present recommendations for performing more extensive studies. These recommendations have been divided into prerequisites on one hand and methods and execution on the other.

8.1.1 Preferred prerequisites

In order to be able to initiate a more in-depth study, there are some conditions that should be fulfilled if possible.

- To ensure that the result from a study can be used within the company, it is important that the goals are clearly stated. As with any study, it is also very important that the company is open for what it might present and is willing to react to the result and make changes if necessary. To only gather information and not use the result is a waste of resources.
- The ergonomic situation should be mapped, preferably completely, but at least to a large extent. Currently, EMD only includes a small part of the assembly tasks within the factory and it is not possible to make any statement about the overall situation. EMD needs to be expanded to include a larger part of the assembly tasks to ensure that a statistically valid result can be presented in an additional study.
- In order to do a cost analysis, it is vital to collect the required information. If not all costs that are of interest can be documented and traced to individual errors, it might at least be possible to present average or standard costs. Then the costs for inadequate quality can be showed much more clearly.
- Since the times to correct the errors are an important variable when calculating the personnel costs, these correction times should be documented in some way. This is not only of interest for a similar study concerning ergonomics, but also for other operations in the plant. Especially the correction times in the Adjusting department should be mapped since it would also make it easier to plan the use or resources in the department.

There are additional aspects that should be considered in the long term. These prerequisites are not possible to fulfill in a short period of time for the entire production line. They should be initiated as soon as possible but completing them will take time.

- A standardized way of working should be developed in the production plant. The benefits of this will go well beyond the field of production ergonomics. All types of planning will become much easier with a standardized way of working. Ensuring a high quality output will also be greatly simplified when the work is always done in a consistent way. The result of an ergonomic study that is performed in an environment where standardized work is utilized will also be much more reliable since the risk of errors due to variations in the work method is reduced.

- A study that examines the relationship between production ergonomics and product complexity should be performed. When this relationship has been analyzed, it will be possible to know even more about where the resources should be allocated in order to gain the most benefits. It is likely that measures that are taken to improve the quality by lowering the level of complexity also have the potential to improve the production ergonomics, and vice versa.
- Not only the *physical* ergonomics will affect the product quality; the *cognitive* ergonomics is an important factor as well. The mapping of the ergonomic situation in the production plant should be expanded to include the cognitive ergonomics. Aspects like mental stress, time pressure, information processing and so on, should be investigated.

8.1.2 How a more thorough study can be performed

Many of the methods that have been used in this study have proven to be suitable and useful. For example, the selection criteria can be reused after slight adaption to the extent and contexts of a new study. The calculations methods are also considered to work well and the same calculations can be made with new data. However, several recommendations can be made on how to make a more in-depth and representative study for the entire production area of interest.

One option is to examine the entire production line and have a random sample of assembly tasks. Then the number of chosen tasks will decide the extent of the study and whether the result will be statistically valid as a representation for the entire line. Another option is to select a defined section of the line and make a more thorough study there. Then a larger proportion of the population of assembly tasks can be included in the study, since the population of tasks is smaller. There will also be fewer errors which mean that each error can be investigated deeper.

The recommendations on how to perform another study are as follows.

- The study should be made in real time, that is, the data should be analyzed as it is recorded in the first place. If all errors associated with the assembly tasks in the study are examined the same day they are registered, the work will become much easier and the result will be more accurate. Instead of only relying on data from Qulis, it will be possible to talk to the assembly personnel about individual errors and gather the correct information.

  More information can also be obtained in cooperation with the assembly personnel. It will be possible to ask them to document how long the errors actually took to correct, instead of relying on general information and average figures. They could also be asked to be even more careful than usual when registering errors and make sure to record all errors that are found.
- Since the pilot study has now been performed, the next study should be made to be representative for the whole population, whether it is the entire production line or just a section of the line. A larger proportion of the assembly tasks should be included, including yellow tasks. This will be possible if a more extensive mapping of the production ergonomics have been made in EMD.
- If possible, an entire year’s worth of production should be included in the study. This will ensure that any fluctuations in the quality outcome due to instabilities in the production process will cancel each other out.

- When gathering the data for the study, focus should be on including the correct errors in the study and not make any inclusions or exclusions incorrectly. Focus should also be on documenting the true times needed to correct the errors. These two factors have the most influence of the result, as shown in the sensitivity analysis, and hence, is it important to ensure that uncertainties concerning this data are kept at a minimum.

8.2 General recommendation for the continued work with ergonomics

Additionally, there are recommendations for how Volvo Trucks in Gothenburg can continue the work with production ergonomics. It is not only the aspect of product quality that needs to be considered. There are also the aspects of productivity, personnel turnover in the production plant, continuous improvements in all areas, and product design, just to mention a few factors.

Production ergonomics should be an integrated part of VPS to a much larger extent than it is today. VPS is based on Lean production and one of the cornerstones of Lean production is *people*. Not only in the form of taking care of the personnel, and in that way lower the levels of sick leave and social expenses. But also to use the human resources in the best way possible, since the potential that all co-workers have – both physical and in the form of ideas and knowledge –should be utilized. To allow for the assembly personnel to get injuries and pain from their work, and therefore not be able to perform their tasks as well as possible, is a waste of resources.

As soon as any changes are made in the production environment or concerning the product itself, ergonomics should be included as an important factor in the consequence analysis. When any form of reconstruction of an assembly station is made, ergonomics should be included from the very beginning and a suitable ergonomic situation should be part of the requirements specification. By including it early, there will be no additional costs for developing an ergonomically sound work environment. By not including it early, the costs will present themselves later and will most certainly be higher than what would have been necessary.

The ergonomic knowledge in the product development process must be greatly improved. The product is the foundation for all assembly work and if the product does not facilitate an ergonomic assembly, no measures that can be taken in the production plant will be enough to ensure a sufficient ergonomic situation. There must be much better communication between the production plant and the product development department. When a product is developed or changed, there must be consideration to the assembly process and production ergonomics.

The only way to make sure that no errors are made is to remove the possibility of making them. If there is a way to assemble a component wrong or otherwise make a mistake, it will happen. When developing a standardized way of working, production and product engineers must work together to ensure that the only way to perform an assembly is the correct way. This way should of course be ergonomically appropriate as well and thus ensure both the product quality and the ergonomic correctness.

It is well-known that Toyota stops their production lines when there is a problem. They do it partly to correct the error, but also to prevent it from happening again. Each error is analyzed and actions are taken to eliminate the source of the error. Volvo Truck in Gothenburg is using the opposite approach. If an error cannot be corrected within the available time, it is sent further down the line and the error is ignored until the truck arrives at section seven or eight or at the Adjusting department. Even if the error is made at section one of the production line, all assemblies are performed as usual until the truck is complete. Then it is transported to the adjusting department and disassembled again. Therefore, all the time spent on assembly on the production line is wasted at non value adding activities.

Naturally, it is not possible to begin stopping the line at the discovery of each error if no actions are taken to eliminate the source of the error. If the error is going to happen over and over again, this approach will only result in a lot of down time. But if the root cause of the errors were investigated and corrected, it will in time be possible to adopt Toyota's method. Since Toyota has clearly made it profitable to stop the line, it can be done at other companies as well.

If the work with ergonomics will be successful, the tools must be developed. Currently, EMD is used as an isolated tool and an addition to all the other computer programs and systems that are used at Volvo. It would be better to integrate the aspect of ergonomics into the Sprint system so that all information is collected in the same place. Then, the ergonomic situation is clearly visible for each assembly task and if something in the task is changed it is less likely that an updated of the ergonomic classification is forgotten.

It would also be desirable to connect EMD to Qulis in a better way. If there was an easy way of cross referencing the assembly tasks between EMD and Qulis, it would be possible to always have updated and reliable statistics about the errors in relation to the ergonomic classifications. Then, it would also be very easy to analyze the quality outcome after an ergonomic improvement has been made.

If all assembly tasks in the production line were to be analyzed and classified in EMD as they have currently been, it will not be possible to do so and still keep the classifications up to date without engaging several additional ergonomists. It will be a massive task and it is doubtful if the benefits will be worth the effort. If instead the assembly personnel become responsible for the assessments and classifications, it will on the other hand be very difficult to obtain consistent classifications without very detailed instructions of how the assembly tasks should be judged. The assembly personnel will undoubtedly make relative classifications, comparing assembly tasks with each other. The most straining and difficult assembly tasks of each section of the line are likely to be classified as red since the workers will experience them as the worst. Without deeper ergonomic knowledge or experience from the entire production plant, it will be very difficult to make an objective analysis.

Additionally, by isolating individual tasks, they are not analyzed in their proper context and the result might be questionable. If eight of the nine minutes of the tact time is spent on tasks that have been classified as red, while the last minute consists of green tasks, there will still not be enough recovery time at the station as a whole. The quality of the green assembly will suffer as well since the worker will already be tired and possibly in pain from the more strenuous tasks. By isolating the assembly tasks this factor will be wrongfully disregarded.

There needs to be a balance in the classification between details and context. When all tasks are to be analyzed, it is important to do it on an appropriate level so that it is possible to keep the classifications up to date without having to spend too much time. Perhaps one option would be to classify the entire work station. The classification could then be based on how much time is spent in different postures and how much time is spent doing potentially harmful movements.

9 Conclusions

The conclusions that can be made based on the study include:

- There is a general relationship between production ergonomics and product quality at Volvo Trucks in Gothenburg. The strength of the relationship throughout the entire production plant has not been determined, but for the assembly tasks that have been examined, the relationship is strong.
- There are potential savings in the cost for inadequate quality. By improving the production ergonomics the quality of the output can be improved and thus resources can be saved and reassigned to other areas.
- Today, it is difficult to collect all the information needed for detailed studies concerning product quality. It is not possible to trace costs to individual assembly stations or tasks. In order to simplify later studies, it should be made possible to document financial figures in a more detailed way.
- Volvo Trucks has made important steps in the work with improving the production ergonomics. By using tools as EMD, a structured work process has been developed. However, there are still many gaps that need to be filled and ergonomics needs to be an area of even more focus in the future.
- It is necessary to continue to investigate the relationships between production ergonomics and areas such as quality, productivity and product complexity. This project has served as a pilot study and provided a lot of useful information, but the main part of the work with ergonomics in relationship to other areas is yet to come.

By continuing to work with production ergonomics, Volvo Trucks in Gothenburg will be able to not only improve the work situation for the assembly personnel, but also improve the quality of the products and save resources. By considering the recommendations provided in this report, and performing additional studies concerning the relationship between production ergonomics and other areas, it can be shown that these savings are likely to be substantial.

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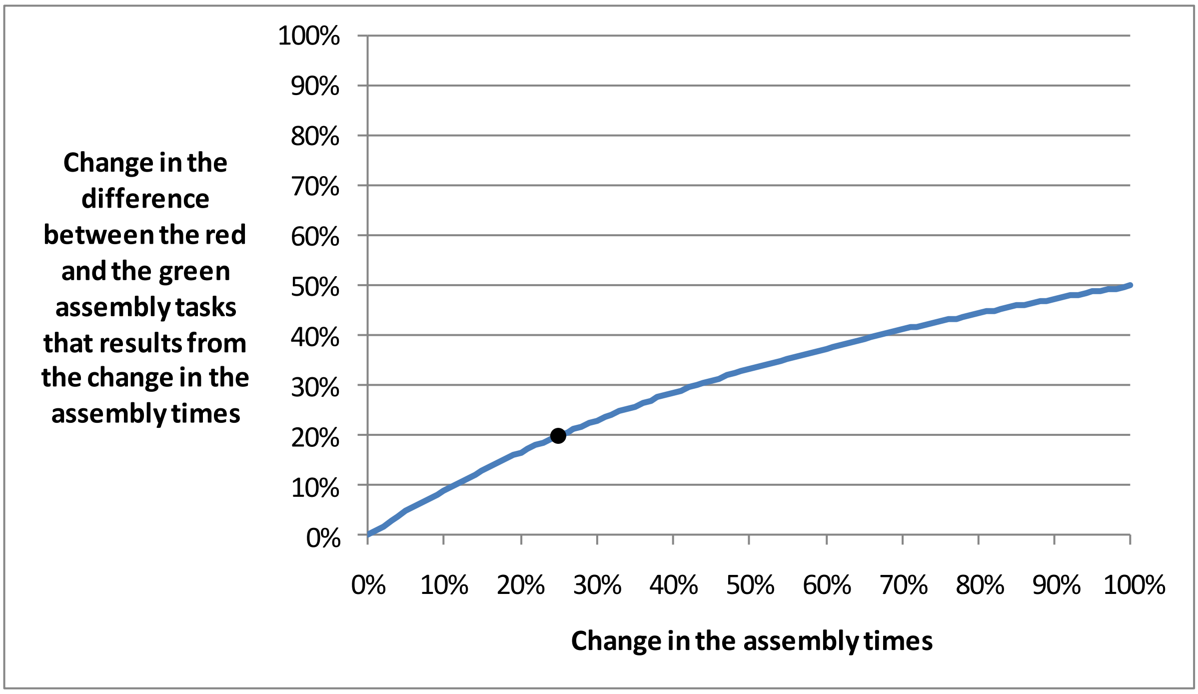
Appendix A – Calculations in the sensitivity analysis

In order to provide more information regarding the background of the sensitivity analysis, some additional data is presented here.

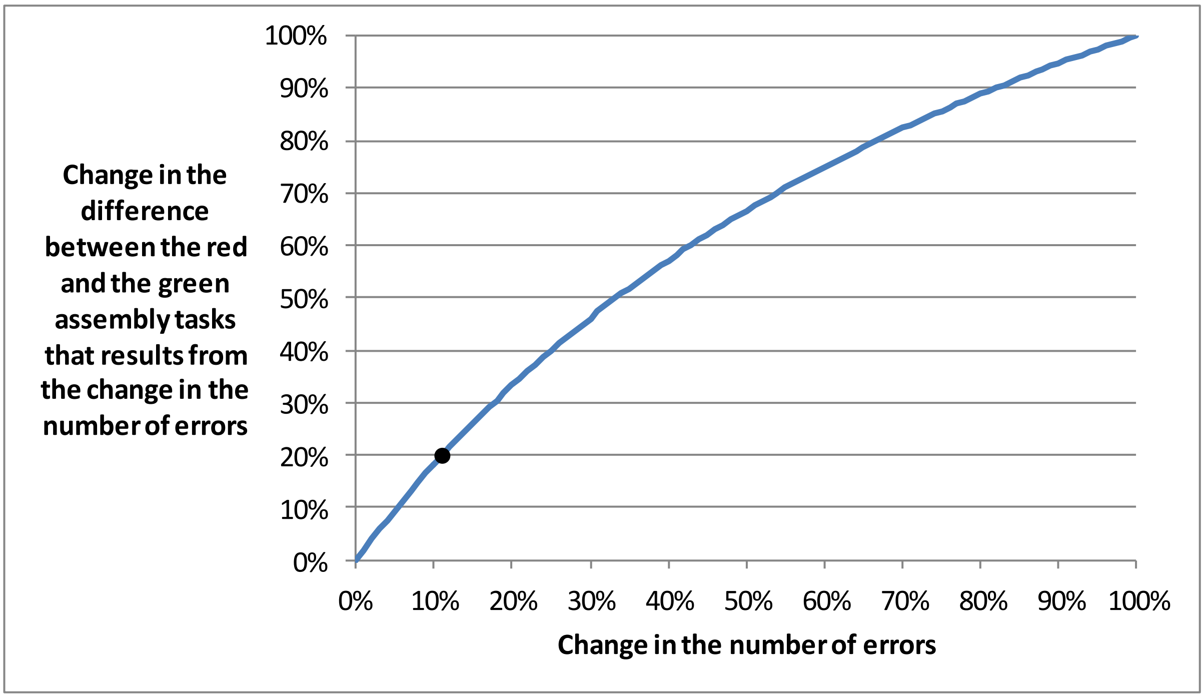
When the assembly times used in the project are altered, the difference between the mean values of number of errors per minute for the red and green assembly tasks will also change. The relationship between the change in the assembly times and the change in the difference between the two categories is presented in Graph 1.



Graph 1. The relationship between the change in assembly time and the change in the difference between red and green assembly tasks. The level where the change in the difference between red and green tasks is approximately 20% has been marked.

The hypothetical assembly time for the red tasks that would result in the same mean value of errors per minute for both the red and the green tasks was calculated. This number was then compared with the actual assembly time for the red tasks. This in turn gave the resulting 62% that represents the magnitude of the necessary error in the input data that is needed to have drawn the wrong conclusions from the study.

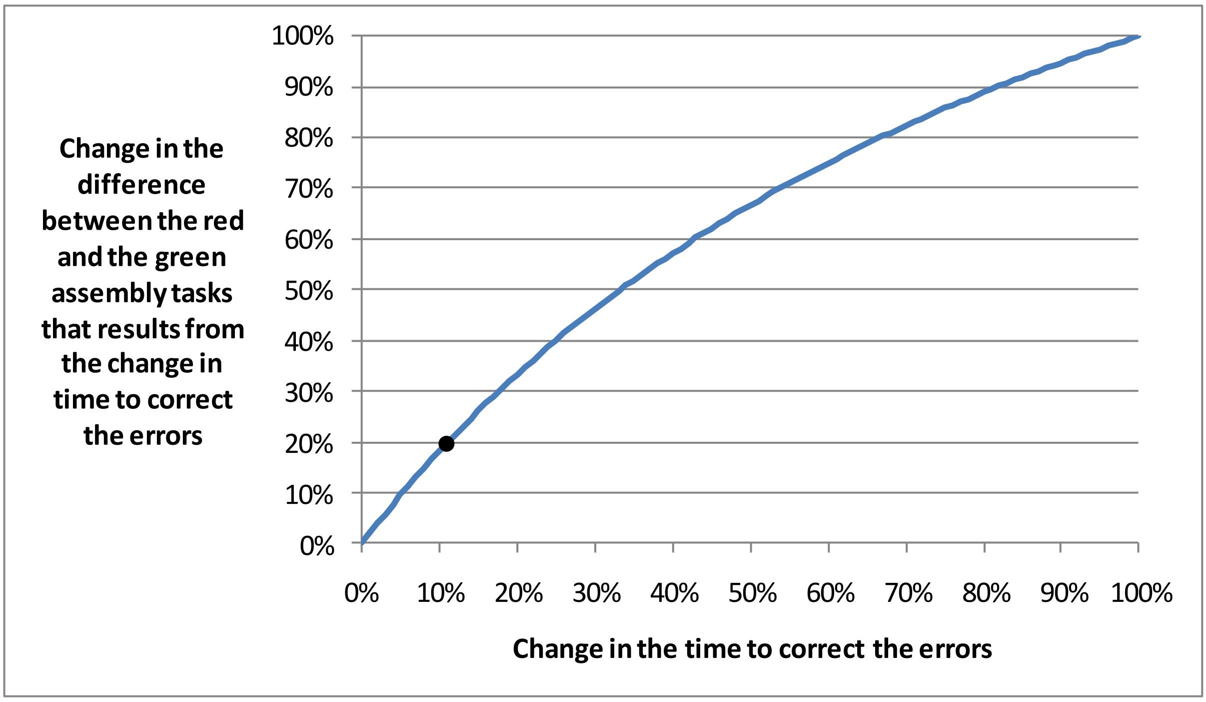
If the number of errors included in the study is changed, the difference between the mean values of number of errors per minute for the red and green assembly tasks will also change. The relationship between the change in the number of errors and the change in the difference between the two categories is presented in Graph 2



Graph 2. The relationship between the change in the number of errors and the change in the difference between red and green assembly tasks. The level where the change in the difference between red and green tasks is approximately 20% has been marked.

The hypothetical number of errors associated with the red and green assembly tasks respectively that would give the same mean values of errors per minute was calculated. The number of errors associated with red tasks was increased and the number of errors associated with green tasks was decreased, using the same factor for both categories. This factor was then calculated and found to be approximately 45%. This represents the magnitude in the error in the input data that is needed in order to have drawn the wrong conclusions from the study.

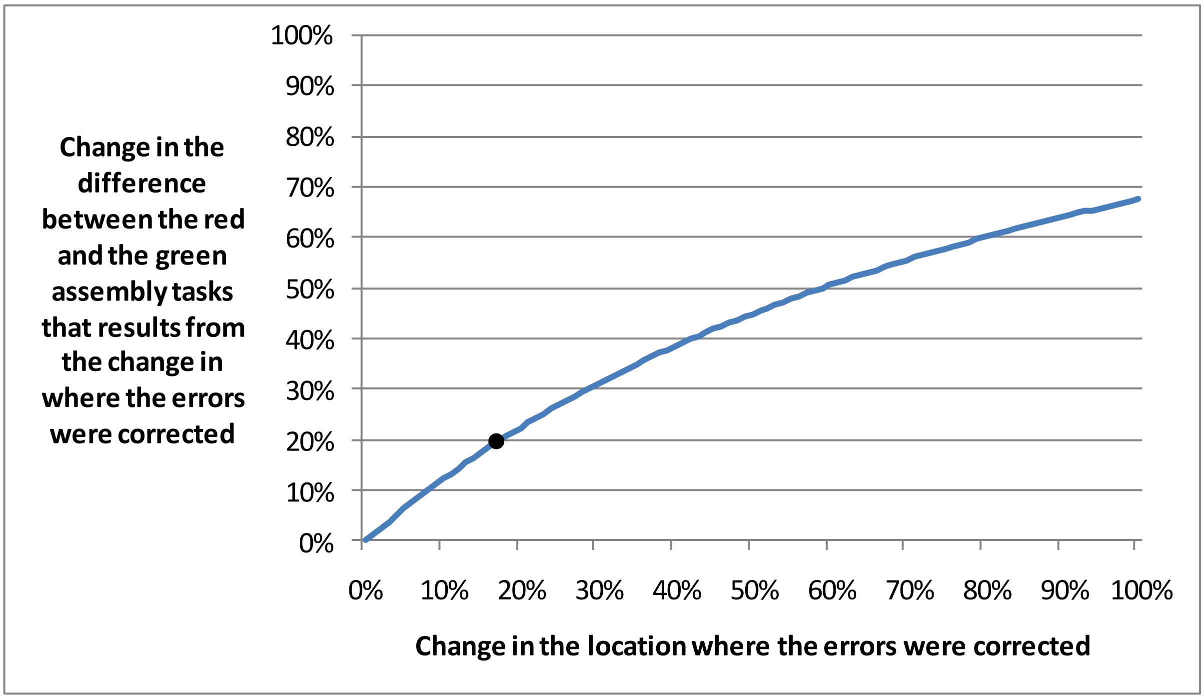
If the time to correct the errors is changed, the difference between the correction times for the errors associated with red and green assembly tasks respectively will also change. The relationship between the change in the correction time and the change in the difference between the two categories is presented in Graph 3



Graph 3. The relationship between the change in the correction time and the change in the difference between red and green assembly tasks. The level where the change in the difference between red and green tasks is approximately 20% has been marked.

The hypothetical times needed to correct the errors associated with the red and green assembly tasks respectively that would give the same correction times for both categories was calculated. The correction time associated with red tasks was increased and the correction time associated with green tasks was decreased, using the same factor for both categories. This factor was then calculated and found to be approximately 80%. This represents the magnitude in the error in the input data that is needed in order to have drawn the wrong conclusions from the study.

Finally, if the location for the correction of the errors is altered, the difference between the correction times for the errors associated with red and green assembly tasks respectively will also change. A percentage of the errors were removed from the assembly line and reassigned equally between section seven or eight and the Adjusting department. The relationship between the change in the location and the change in the difference between the two categories is presented in Graph 4.



Graph 4. The relationship between the change in where in the production plant the errors were corrected and the change in the difference between red and green assembly tasks. The level where the change in the difference between red and green tasks is approximately 20% has been marked.

In this case, the difference between the correction times for the errors associated with red and green assembly tasks will only increase, instead of decreasing as in the previous hypothetical scenarios. This means that the relationship between production ergonomics and product quality will be even more obvious.