BACHELOR THESIS

Increasing the arc-on time for the welding robots at ASN Holten

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ASN GROUP

Colophon

Title	Increasing the arc-on time for the welding robots at ASN Holten
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Summary

Problem Context

At ASN Holten salt distributing vehicles are assembled. Part of the assembly is the welding of the hopper of the salt distributing vehicles. The welding is done manually and with two identical welding robots. The welding department of ASN has noted that the percentage of time the welding robot spends welding versus other activities is too low. This percentage is known as arc-on time. The arc-on time of the welding robots at ASN is 50%.

Goal of the Research

The main goal of the research is to analyse the motions made by the welding robot and to find wasteful motions. A secondary goal is to provide recommendations that ASN can use to decrease wasteful motions and thus increase the arc-on time.

Approach

To find the wasteful motions of the welding robot all the motions of the welding robot were analysed. Also, an extensive literature study on the optimization of the welding robots was conducted. Based on the results of the analysis and the findings of this literature study the motions were categorized, and the definition of wasteful motions was determined. Then, a time analysis of the motions per category was completed by performing a simulation with DTPS. The accuracy of DTPS was tested after comparing the simulation time results of two products with the time results from video footage of the welding robot. Once the definition of wasteful motions was defined, and a time analysis of the motions per category was completed, the optimization possibilities for the reduction of wasteful motions were investigated.

Findings

In terms of arc-on time all motions not directly related to welding the welding joints are defined as wasteful. There are three groups of wasteful motions: measuring, maintenance, and moving. The results of the two product simulations showed that the robotic welding cycle in DTPS is 9% shorter than in reality. The time analysis through simulation using DTPS has shown that the arc-on time is 65%, meaning 35% of the time is spent on wasteful motions. Measuring has the most impact: 17%, while moving contributes 11%, and maintenance 7% to the wasteful motions.

Recommendations

Based on the findings ASN should consider to:

1. Optimize the measuring process or find an alternative for the measuring process as it is responsible for the largest share of wasteful motions.
2. Optimize the frequency of maintenance subs by removing the four instances where maintenance subs are used too frequently.
3. Optimize the moving group by removing the two instances where moving happens unnecessarily. Investigate possibilities to implement software which can help with optimizing the motions between welding joints.
4. Improve the data collection system related to arc-on time.

Preface

This bachelor thesis is the result of my bachelor graduation assignment at Aebi Schmidt in Holten. The graduation assignment is part of the Bachelor of Science Industrial Engineering Management at the University of Twente.

I would like to thank Aebi Schmidt Holten and my two supervisors at Aebi Schmidt, Arne Meengs and Bart Leferink, for providing me the opportunity to complete my graduation assignment at Aebi Schmidt as well as supporting me during the assignment. Furthermore, I would like to thank my supervisor of the University of Twente, Leo van der Wegen, for providing extensive feedback and support during my graduation assignment. Lastly, I would like to thank Eduardo Lalla-Ruiz for making time to be the secondary supervisor for my thesis.

Rutger J. Haan

Enschede, 2019

Table of Contents

Definitions and Abbreviations

Active position – An active position is a position where the robotic arm is far away from the product so there is low risk that the robotic arm collides with the product.

Arc-on time – Is the arc-on time M divided by the cycle time of the welding robot. Arc-on time is expressed as a percentage.

ASN – Aebi Schmidt Netherlands.

Belt/Worm – Two types of systems used to push the salt out of the hopper towards the tail piece where a spray mechanism is attached. The Belt is a conveyer belt system. The Worm system acts like a worm drive.

Cycle time – Is the time to perform an operation or task.

DTPS – Desk Top programming and Simulation system. Which DTPS users can create and edit robot programs as well verify robot motion**.**

Entry/Exit position sub – The entry/exit position of a sub is a location between the active position of a sub and the first welding joint. Is the position the welding robot is in when it starts moving to the individual welding joints in a sub. The Entry and Exit position of a sub is defined in a manner to minimize the collision of the welding robot with the product.

Final position program – Is the position the welding robot is in when a program has been completed. No maintenance can be done on the final position.

Home position – The position the welding robot has to be in at the start and end of the robotic welding cycle.

Main – The highest order in the programming of the welding robot. The main is made up of three programs, maintenance subs, and position commands.

Maintenance position – The maintenance position is the position of the robotic arm when the torched is cleaned, the wire is cut, or the wire is changed. maintenance is always done on an active position.

Maintenance subs – Subs pre-programmed by the manufacturer of the welding robot. There are 5 types of maintenance subs.

Position Commands – Position command is the code used to define how the robot moves between two robotic positions.

Program – A program is a subset of a main. There are three types of programs in the main; the Lower-bin program, the Frame program, and lastly the Connecting program. Every product has a unique program.

Robotic Arm – The main component of the welding robot. It manipulates the tip of the welding wire with a millimetre precision using six rotary joints. The robotic arm also houses the maintenance station used to cut and calibrate the welding wire, and to clean the welding torch.

RW – Robotic welding

Robotic Welding Cycle – Is the process which the welding robot has to go through to complete one task.

Roro/Attached – Two types of ways the hopper interacts with the transporting vehicle. The Roro system allows the hopper to be fully removed from the transporting vehicle. The Attached system has to be fully attached to the transporting vehicle.

Sub – The building block in the program of the welding robot. A sub contains a logical cluster of welds and is a subset of a program.

S3 – Stratos 3. The newest salt spreader of ASH.

TCP – The outer point of 17mm welding wire is the Tool Center Point (TCP) of the robot.

Welding Joint (WJ) – An edge or point where two or more products are joined together through welding. In this report a welding joint means that it has yet to be welded.

3600 Attached-Worm Kasko Stratos 3 – A variant on the Kasko of Stratos 3 with length 3600 mm, with a mechanism that attaches to the transporting vehicle, and with a worm drive to move the salt.

1. Introduction and Research Design

In this chapter an introduction to Aebi Schmidt and Robotic Welding is given (Section 1.1). Then the problem is discussed, and a core problem is chosen (Section 1.2 and Section 1.3). Finally, the research design is discussed in Sections 1.4, 1.5, and 1.6.

1.1 Introduction to Aebi Schmidt and Robotic Welding

ASH group - short for Aebi Schmidt Holding - is an international manufacturer of products and services developed for the removal of snow or other unwanted material. The majority of products ASH offers are snowploughs and salt spreading equipment. Other products offer solutions for street cleaning, specialized rail and airport cleaning, and smaller agricultural vehicles. The clients of ASH are governments (municipalities or large cities) and large companies which maintain private infrastructure such as airports or railroads. The head office is in Switzerland as the group has strong roots in Switzerland.
Aebi Schmidt Nederland (ASN) is part of the ASH group and is located in Holten, the Netherlands. The facility in Holten serves mainly as a production line for salt spreading equipment. The production capacity is up to 3000 units per year. A salt spreader consists of multiple components, the largest of which is the hopper. A hopper consists of four modules as can be seen in Figure 1. The mounting system is the mechanism that connects the hopper to the carrier vehicle. The lower bin houses the mechanism to move the salt to the tail. A spreading mechanism is connected to the tail. The upper-bin completes the hopper and is designed to add storage capacity.

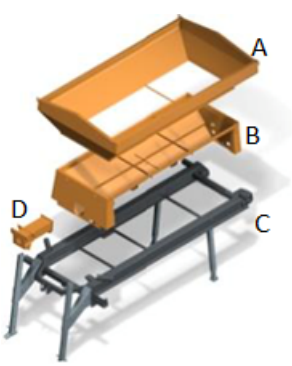


Figure 1: A) upper-bin, B) lower-bin, C) mounting system, and D) tail piece. (Source: Aebi Schmidt)

Welding of the hopper is an important activity within ASN. Welding is done by robots and by employees in the welding department. The main drivers behind implementing robotic welding at ASN were the shortage of welders, long term cost saving of robotic welding and quality advantages robotic welding brings. An image of a partial hopper during and after robotic welding can be found in Appendix A.

The welding robots are programmed offline by the welding coordinator. DTPS (Desk Top programming and Simulation system) is the tool used to write the code for the welding robot. DTPS is an integrated programming and simulation software package for robotic welding. Thus, DTPS can be used to simulate the motions of the welding robot.

Robotic Welding Cycle

A brief description of the working of the welding robot is given by describing what occurs during the robotic welding cycle.
The robotic welding cycle starts when the welding robot is turned on and a product is on the fixture in the workstation. The robot does not know which product is placed in the workstation. It will first use its touch sensor to identify the product. In the near future ASN will introduce a scanning system (QR code) which will make the product identification stage the welding robot carries out obsolete and thus will be ignored in this project. After identification the robot will load the specific programs and variables needed to perform the welding process. Now, the robot knows where the welding joints are located and knows which welding parameters (velocity of welding, distance and angle of the wire to the joint, etc.) have to be used during the welding of the joint. However, the theoretical location of a welding joint is rarely the same as the actual location of the welding joint. The difference comes from manual assembling the hopper and from inaccurate dimensions of the parts. Room for error is extremely low as a few millimeters of displacement could create a faulty weld. The welding robot will use its touch sensor to determine the actual position of the welding joint. After the position is determined, it will carry out the actual welding. During the robotic welding cycle maintenance processes are carried out such as cleaning the torch or cutting the welding wire. The robotic welding cycle ends when all the welds have been completed and the robot is back in its home position.

1.2 Problem Identification

ASN takes pride in its constant drive to improve its production processes. Lean production techniques form a basis for achieving more efficient production processes. One measurement of efficiency in the welding department is the arc-on time of the welding robots.

Definition of Arc-on Time

Arc-on time is the time that the welding torch is on divided by the robotic welding cycle time. Arc-on time is expressed in a percentage. The robotic welding cycle time is the time it takes to complete a robotic welding cycle. What happens during the robotic welding cycle is defined in Section 1.1.1. As stated in this section, the robot is turned on only if there is a product ready for welding in the workstation and will be turned off if all the welds are completed and the robot is back in its default position. Failures experienced by the robot are ignored in this study, because it requires an in-depth technical understanding of the welding robot and collision free pathing. In reality failures have an impact on the robotic welding cycle time.

The welding department has identified that the arc-on time of the welding robots has room for improvement.

Currently the yearly average of arc-on time is estimated at 50% while literature shows that the arc-on time could be around 70-80% (Cortina, 2010) for a welding robot. ASN stated that the robot is making too many unnecessary or wasteful motions. There has been no study done about what motions the welding robot makes, and if they are wasteful. During the preliminary study it was determined that the robot indeed made some wasteful motions such as moving from point A to B in an inefficient manner and moving from point A to B while it should have moved from point A to C.

1.3 The Core Problem

The problem given by ASN is that the arc-on time for its welding robots is too low. However, this is not the core problem as the reasons why the arc-on time is too low are not known. ASN has stated that the arc-on time is too low because the robot makes too many wasteful motions.
Finding the correct core problem is of utmost importance as solving the wrong problem will not be beneficial for ASN. Furthermore, finding the core problem also helps to narrow down the scope of the project. Therefore, a preliminary research at ASN to find out reasons why the arc-on time is too low, has been conducted. The preliminary research included a full day of observing the workings of the welding process and multiple interviews with the welding coordinator. The problem cluster can be seen in Figure 2.

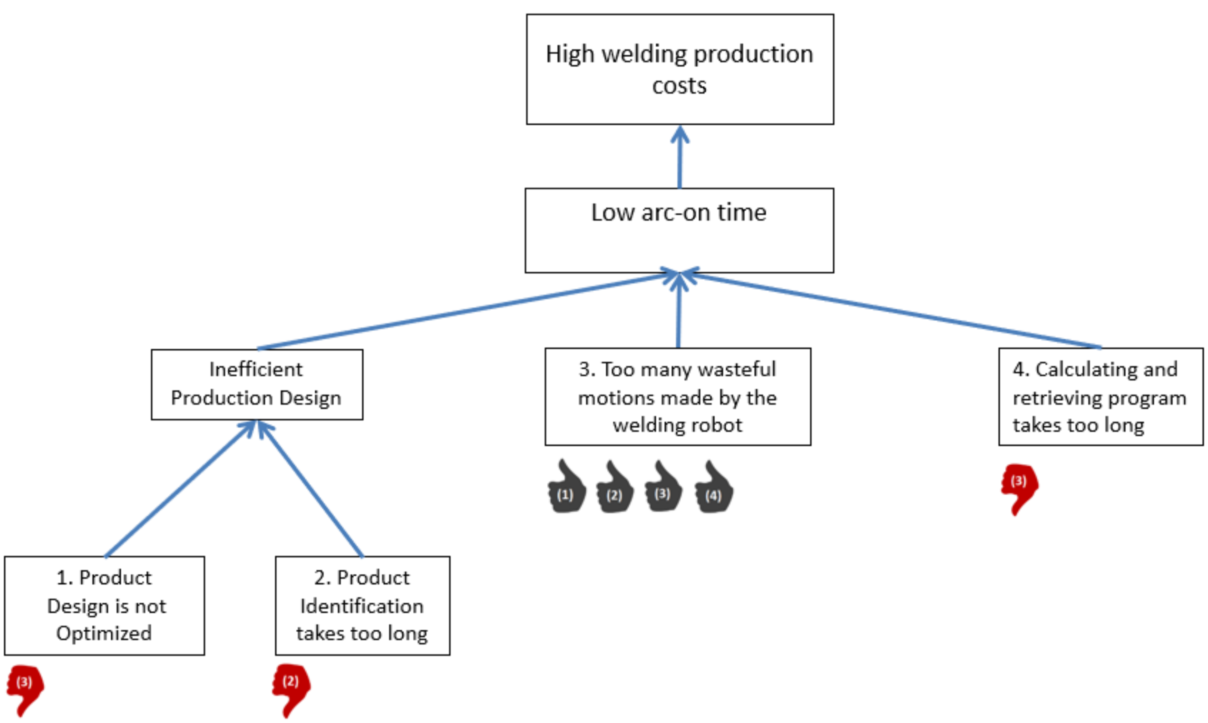


Figure 2: Problem Cluster for ASN low arc-on time.

The four rules of thumb have been used to identify the core problem:

1. The core problem must have no other lower problems.
2. The core problem must be a real problem.
3. The core problem must be solvable and an IEM problem.
4. If there are multiple core problems that fit rules 1 through 3, the problem that has the most impact will become the core problem.

There are five lower problems identified which could be responsible for the low arc-on time. Problem 1 is cannot be solved within 10 weeks thus is not solvable. Furthermore, it is related to industrial design and not IEM. Problem 2 is not a real problem as ASN will introduce a scanning system for identifying the product. Problem 4 is not solvable nor an IEM problem as it is related to computer technology. Problem 3, too many wasteful motions made by the welding robot is the only problem which passes the four-thumb rule. Therefore, the core problem defined for this project is **"Too many wasteful motions made by the welding robot".** This is a two-part problem, as what the wasteful motions are has never be defined globally

1.4 Research Questions

The main research question is:
"How can the arc-on time for the robotic welding department at ASN be increased by reducing the wasteful motions?"

In order to tackle the main research questions the following sub-research questions are defined:

1. What products will be analysed?
ASN produces three products in the welding department with multiple variants per product. It is not possible to analyse all products and product variants in 10 weeks. Therefore, it is first necessary to choose which products to analyse.

2. What is the current situation?
2.1 How do the welding robot and DTPS work?
2.2 How does ASN program the welding robot?
Once it is known which products will be analysed a general understanding of the welding robot and the programming tool DTPS is necessary. Then an analysis can be made on how ASH programs the welding robot using DTPS to weld its products. Describing the current situation will provide information on the motions made by the welding robot.

3. What are the motions of the welding robot and how can the motions be categorized?
By answering research question two, the current situation, a list of motions made by the welding robot can be created. Grouping motions will allow for the motions and wasteful motions to be analysed. However, before wasteful motions can be analysed they should be defined first.

4. What are the causes of wasteful motions in literature and what is the definition of wasteful motions for this project?
Using the knowledge gained through a literature study about sources of wasteful motions, and the groups of motions from research question 3, a definition for wasteful motion in this project will be given.

5. What is the best method to measure the time and what share of time does a group of motions take up?
Now that an overview of motions is made, by answering research question 3, the groups of motions can be analysed in order to find wasteful motions. However, due to time restrictions not every category can be analysed to the same extent. A definition of wasteful motions in research question 4 will only limit the groups of motions to be analysed to a small extent. It is therefore important to measure how much time a category of motion takes up, so choices can be made on which motions will be analysed in depth. It is currently unclear what the best method is to collect time data on the motions of the welding robot.

6. What can ASN do to reduce the wasteful motions found?
Based on the findings of research question 5 recommendations will be given to ASN on how to reduce wasteful motions.

1.5 Theoretical Framework

ASN utilizes lean methods to make its business processes more efficient. The core problem "too many wasteful motions made by the welding robot" and the goal to reduce wasteful motions are lean as well as efficiency based. The perspective of the project is efficiency.

1.6 Research Design

In the section Research Design an explanation will be given as to how the research questions will be answered.

The Type of Research

The research will be explanatory as ASN has stated that the arc-on time is too low because of wasteful motions. However, they do not know what causes the wasteful motions. There is also little data available on the working of the welding robot or the time it takes to complete a product. Therefore, the motions of the welding robot will be described, and time data will be collected.

The Research Population

The goal is to research the motions of the welding robot. The motions the welding robot makes depend on the product variant the welding robot is working on. It will not be possible to analyse all products, therefore by answering research question two, what will be analysed, the research population will be determined. There are two identical robots, and both are utilized to gather data.

The Methods of Data Gathering

The method of data gathering depends on the research question being answered. The vast majority of data and information is gathered on the motions and wasteful motions of the welding robot by using DTPS.

Research Question	Data Method Gathering	Chapter
RQ 1	Production data of the welding department. Discussions with the welding coordinator and supervisor.	2
RQ 2	Observation of the welding robot, analysing the programming method displayed in DTPS and discussions with the welding coordinator.	3
RQ 3	Data from answering research question 2. Discussion with welding coordinator.	4
RQ 4	Literature to provide concept on wasteful motion. Apply concept on the motions of the welding robot from RQ 3. Discussion with supervisor.	4
RQ 5	DTPS time simulation, timing the welding robot, time elements such a speed of welding robot from the welding coordinator/manufacturer information. Verification with welding coordinator and supervisor.	5
RQ 6	Literature and based on own insights. Discussion with welding coordinator and supervisor if certain solutions are possible.	6 and 7

The bulk of the data will be collected using DTPS. Observation of the welding robots and discussions with the welding coordinator and the company supervisor will also provide information. If certain aspects of DTPS need to be explained the welding coordinator can explain them.

The Methods of Data Processing

Microsoft Excel will be used for storing and data processing. The data will be used in the report and presentation.

Validity and Reliability and Limitations of the Research Design

A potential issue with the design of the project will be the use of the simulation software DTPS for the measurement of arc-on time and motion analysis of the hoppers. It is currently unclear how accurate the simulation represents reality. The department of welding has stated that it is quite accurate to the reality, however the degree of accuracy is unknown. Therefore, during the time present at ASN the results of arc-on time derived from DTPS with the actual arc-on time of the welding robot will be compared. This will be done for more than one hopper.

2. Product Selection for Analysis

It is not possible to analyse the motions the welding robot makes for every product and its variants due to time constraints. Chapter 2, product selection for analysis, describes which product and which variants will be selected for further analysis. ASN wants to improve the arc-on time systematically meaning that any wasteful motions and subsequent solutions found, should be applicable to the product and product variants which are welded the most by the welding robot.

2.1 Choosing the Product

There are three products which are welded by the welding robot (WR) as shown in Table 1. The yearly production numbers of the welding robot in 2017 can also be found in this table. In Appendix J an explanation is given as to how the production numbers of the welding robots are determined.

Robotically Welded Products	Production Number '17 WR
Kasko S3	(x)
Upper-bin S3	(x)
FST/DST	(x)

Table 1: The total production number per product. Data Confidential: Data edited (e) or removed (x).

In order to choose which product will be analysed for this project, the product with the highest impact on average yearly arc-on time will have to be chosen. This is the product that spends the most time in the welding robot on a yearly basis.

Product	Production Number '17 WR	RW Time h:m	Yearly RW Hours
Kasko S3	(x)	(x)	2,509
Upper-bin S3	(x)	(x)	161
FST/DST	(x)	(x)	105

Table 2: The total yearly robotic welding hours per product. Data Confidential: Data edited (e) or removed (x).

Column 'Yearly RW' hours of Table 2 shows the yearly robotic welding hours per product. This is calculated by multiplying the RW production numbers of 2017 and the time the welding robot takes to produce one unit of a product. The robotic welding (RW) time is estimated by the welding coordinator.

The total yearly robotic welding hours of the Kasko S3 is astronomical compared to the Upper-bin S3 and FST/DST. It is clear that Kasko S3 has the highest impact on average yearly arc-on time and therefore will be the product that will be analysed.

2.2 Selecting Product Variant

Product Kasko S3 has 12 main variations made up of the combination of:

- Three different sizes; 3000, 3600, and 4200 mm
- Two types of mounting systems (Attached or Roro)
- Two types of salt transportation systems (Belt or Worm)

After deliberation with the welding coordinator and preliminary research a decision has been reached to analyse the 3600 Roro-Belt and the 3600 Attached-Worm. This is due to the fact that the motions necessary to weld the two chosen Kasko S3 also cover the motions needed to weld all 10 other variants.

2.3 Selecting the Material

The products are made of steel or stainless steel. The type of material has no impact on the motions the robot makes. So, the motions the welding robot makes to weld a 3600 Roro-Worm Kasko S3 made of stainless steel are the same motions the welding robot would use to weld a steel 3600 Roro-Worm Kasko S3. However, the material type has impact on the welding time as when a stainless steel Kasko S3 is welded two more wire switches take place of 16 seconds each. Furthermore, the type of material has impact on some welding parameters such as the speed of welding, electricity need, type of shielding gas, and the type of wire used for welding.
The majority of robotically welded Kaskos S3 are made from steel; 716 against 56 from stainless steel. Thus, the steel version of the Kaskos will be analysed.

2.4 Summary

The product selected for this study is the Kasko S3. The two variants chosen are the Kasko S3 3600 Roro – Worm and Kasko S3 3600 Attached – Belt. Only the steel version of the variants will be simulated. Since the two chosen variants cover all other variants, any wasteful motions found in the two variants will be found in the variants not selected.

3. Current Situation

In order to get a clear scope on what contributes to wasteful motions, the current situation must be described first. How the welding robot works and what motions it makes has not been studied before by ASN. In this chapter the workings of the welding robot and what motions it makes will be explained using DTPS as a simulation tool for the motions and the welding coordinator to explain or provide missing information related to the workings of the welding robot. The goal is thus to give an overview of the current situation of the welding robots in relation to the motions during the robotic welding process. The chapter starts with explaining the configuration (Section 3.1), activities (Section 3.2) and position commands (Section 3.3) of the welding robot. The second part of Section 3 explains DTPS, and how ASN uses DTPS to program the robot in order to weld its products (Section 3.4).

3.1 The Configuration of the Welding Robot

The welding robot is made up of two parts: the robotic arm and the external axes. The external axes are made up of the rotary manipulator for the product, the gallows on a 16-meter linear track, and the belt track on top of the gallows. The robotic arm hangs from the gallows and it has six joints which can rotate nearly independently.

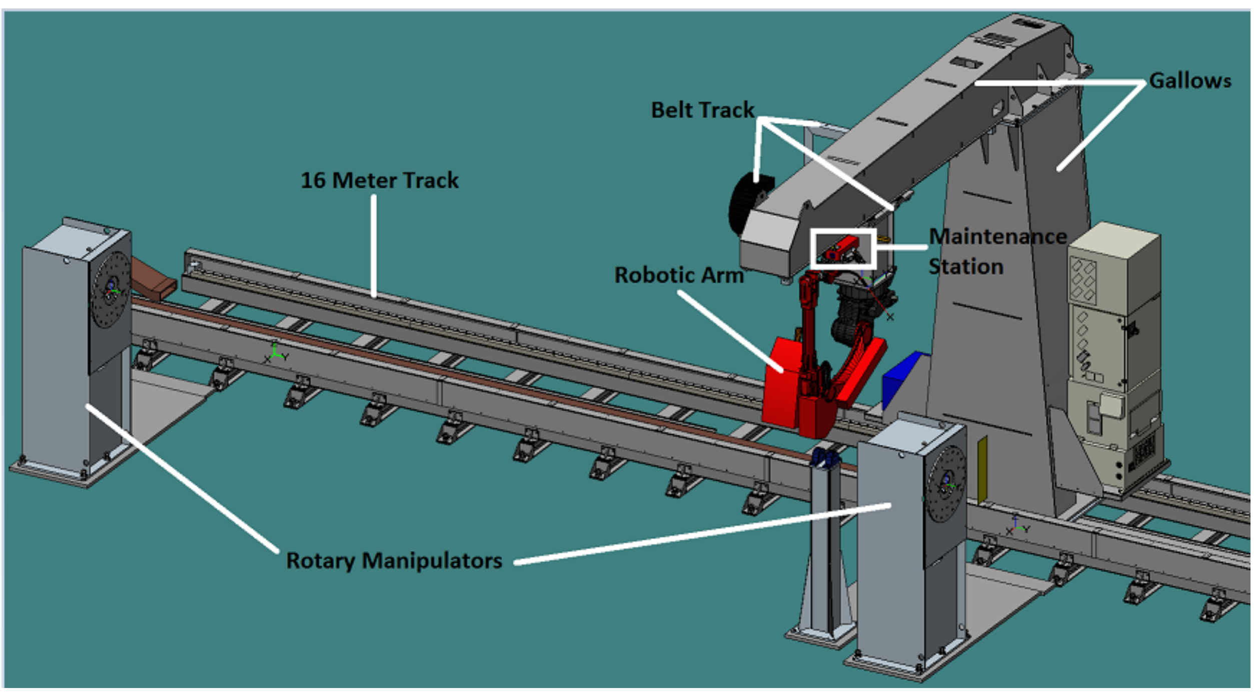


Figure 3: A representation of the components of the welding robot at ASN.

At the end of the robotic arm there is a torch attached. The torch contains the welding wire which feeds the material for the weld. The welding wire sticks out 17mm from the torch so that the torch does not hit the product. The outer point of 17mm welding wire is the Tool Center Point (TCP) of the robot. The maintenance station is connected to the upper part of the gallows.
Figure 4 below completes Figure 3 with the product on the rotary axes.

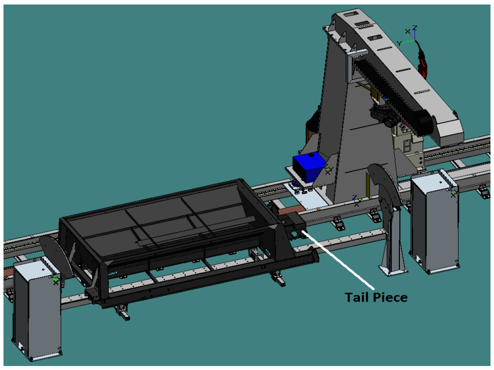


Figure 4: Welding robot at home position with 3600 Roro-Belt on the rotary axis.

3.2 Activities of Welding Robot

The basic function of the robot is to complete movements. There are three main activities which the robot performs during the movements: welding, measuring, and maintenance.

Welding

The main activity of the robot is to weld products. To make a weld the location must be known, and the welding parameters must be determined. Important welding parameters are the angle and distance of the torch to the welding joint and the welding velocity. These parameters are stored in the program.

Measuring

DTPS tells the robot where the welding joints are located. However, the theoretical location of a welding joint is rarely the same as the actual location of the welding joint. The difference comes from the manually assembled hopper and the inaccurate dimensions of the parts. Room for error is extremely low as a few millimetres of displacement could create a faulty weld. The welding robot will use its touch sensor to determine the actual position of the welding joint. In Appendix B additional information on measuring is given. It is impossible to describe the measuring process in detail within the scope of this project as it would require detailed knowledge of welding and product design which would take at least a year. Measuring is still a key process so instead of an analysis of the motions that take place during measuring the process as a whole will be evaluated.

Maintenance

There are five types of maintenance activities:

- Mechanical Cleaning. A welding torch can become blocked due to molten material bouncing back into the torch during the welding process. After a specific welding time the torch will be cleaned in the maintenance station.
- Wire cut. In-order for the welding robot to measure the X, Y, Z coordinates of a welding joint, it needs its welding wire to be exactly at a length of 17mm. During welding the wire changes in length as the rate of depletion is never the same as the rate of supply. Therefore, every time a welding joint must be located the welding wire has to be cut if the previous activity was welding.
- Wire Switch. When there is a change in the welded material from steel to stainless steel or vice versa the welding wire needs to be changed for a different type. After the wire has been changed a Wire cut will take place.
- The Clean-Cut maintenance sub is a combination of Mechanical Cleaning and Wire cut.
- ATC is the last and fifth type of maintenance sub. In the ATC maintenance sub the calibration of the robotic arm is checked.

All the maintenance activities are done in the maintenance station.

3.3 Robotic Position and Position Command

To complete all the activities to weld a product, the robot must make thousands of movements of the TCP between two points in the 3-dimensional space. The robot does this by changing the robotic position. One robotic position corresponds with one position of the TCP in the 3D space. A robotic position is described by the position of all six joints of the robotic arm (R) and the position of the three external axes (E). Table 3 below shows a randomly selected robotic position.

R		E	
Joint	Angle	Joint	Position
RT	-111	G4	5553
VA	128	G5	500
FA	-192	G6	-45
RW	352		
BW	-50		
TW	-71		

Table 3: Example of a Robotic position.

The R column in Table 3 shows the list of angles of the six joints of the robotic arm. The E column contains the location of the gallows along the track (G4), the position of the robotic arm hanging from the gallows (G5), and lastly the degree of rotation of the product on the rotary axis (G6).

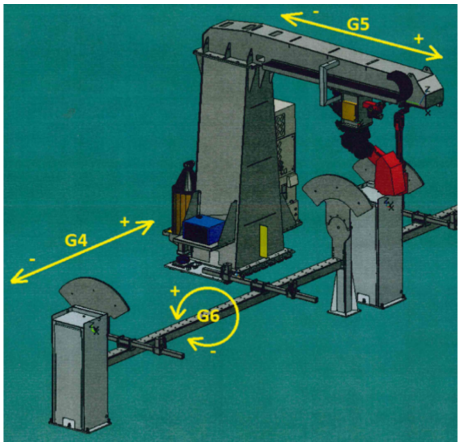


Figure 5: The external axis of the welding robot labelled.

The location of the TCP in the 3-dimensional space is determined by R, G4 and G5. G6 rotates the product and determines the location of the product in the 3-dimensional space.

Position command is the code used to define how the robot moves between two robotic positions. It includes the movement R (robotic arms all six joints) and E (three external axes).
The position command can be used to:

- rotate the product only (G6)
- move the gallows only (G4 and/or G5)
- move the R joints of the robotic arms only
- a combination of the above

The position command also contains what kind of activity (mode) should be performed between two robotic positions and the travel parameters (speed). The welding robot can use three modes. In the first mode the welding robot can turn on its touch sensors in order to locate the exact position of the weld. In the second mode the torch is turned on in order to weld. The third mode is a neutral mode where the robot just moves between robot positions without turning on the touch sensors or torch.

In neutral mode the robot can move the TCP at a maximum speed of 120 meters per minute. The speed is reduced for the neutral mode when moving near the product to 15 m/min in order to avoid collisions. The speed for mode two, welding, depends on the material but for steel the minimum speed is 0.5 m/min and the max is 1 m/min. Lastly, the speed of the welding arm for locating the welding joint is 2 m/min. The slowest moving part of the robot is the gallows which moves at a speed of a maximum of 13.2 m/min.

3.4 DTPS

Desk Top Programming and Simulation system (DTPS) is an integrated programming and simulation software package for robotic welding. ASN uses DTPS primarily to program the

welding robots. A secondary function of DTPS is that it can simulate the motions of the welding robot. The user inputs robotic positions and position commands. DTPS outputs the code based on the Robotic positions and positions commands to the robot.
If the user wants to simulate the process of the welding robot the user can import a Computer Aided Design (CAD) file of the product in DTPS. Geometrical details of the actual workstation (fixture and robot) are also available in DTPS. The user can then simulate the motions of the welding robot based on the inputs given and verify if the motions are feasible. DTPS was used as the main source of data to create an overview of the current workings and motions of the welding robots.

Below in Figure 6 the result of a simulation is shown. It shows the movements of the TCP during measuring (green), welding (pink), and normal (blue).

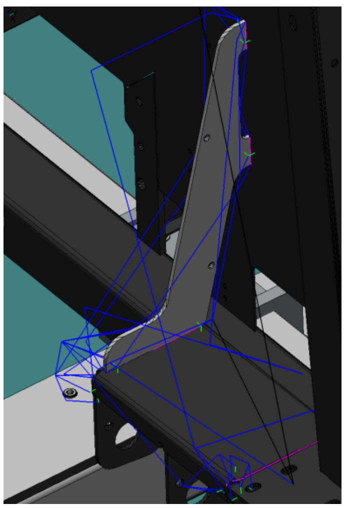


Figure 6: The sub VRBL from the 3600 Roro-Belt showing the line which the TCP follows.

3.5 Modular Programming

The products of ASN are designed to be modular. The modular design is most visible in the programming structure for the welding robot. To increase efficiency of programming, ASN has developed standardized modules which can be used for different types of hoppers.

The full code for one hopper is found under the main, which is split up in three programs where each program has multiple subs as can be seen in Figure C-1 and C-2 in Appendix C.

The main is made up of three programs:

- Frame program takes care of welding the frame of the hopper. Two frame programs used in our analysis are Roro and Attached. The product variants dictate how the hopper interacts with the transporting vehicle.

- Lower-bin program takes care of welding the lower-bin of the hopper. In this study Kasko S3 has two Lower-Bin programs; Worm and Belt. The product variant relates to how the salt is moved in the hopper.
- Connection program takes care of the welding of the lower-bin and frame together. The Connecting program is based on the four combinations formed by Roro/Attached and Belt/Worm.

A program is split up in multiple subs. A standard sub is a logical cluster of welding joints in an area of the product. A sub can be used in different programs and thus in different products. In Table E-1 in Appendix E an overview of the subs per program can be found.

The robot uses the following standard robotic positions to facilitate safe and effective movement between mains, programs, subs, and welding joints:
- home position main
- active position main
- active position for each program
- final position for each program
- active position for each sub
- entry/exit position for each sub

The home position is located such that employees can remove the Kasko S3 from the workstation without damaging the welding robot.

An active position is a position where the robotic arm is far away from the product so there is low risk that the robotic arm collides with the product. ASN has defined 1 active position for the main, 1 active position for each program, and 1 active position for each sub. Subs and programs can have the same active position. To perform a maintenance operation the robot needs to be in an active position. To move between a main and program, or program and sub, or sub and the entry/exit position the robot needs to be in the active position.

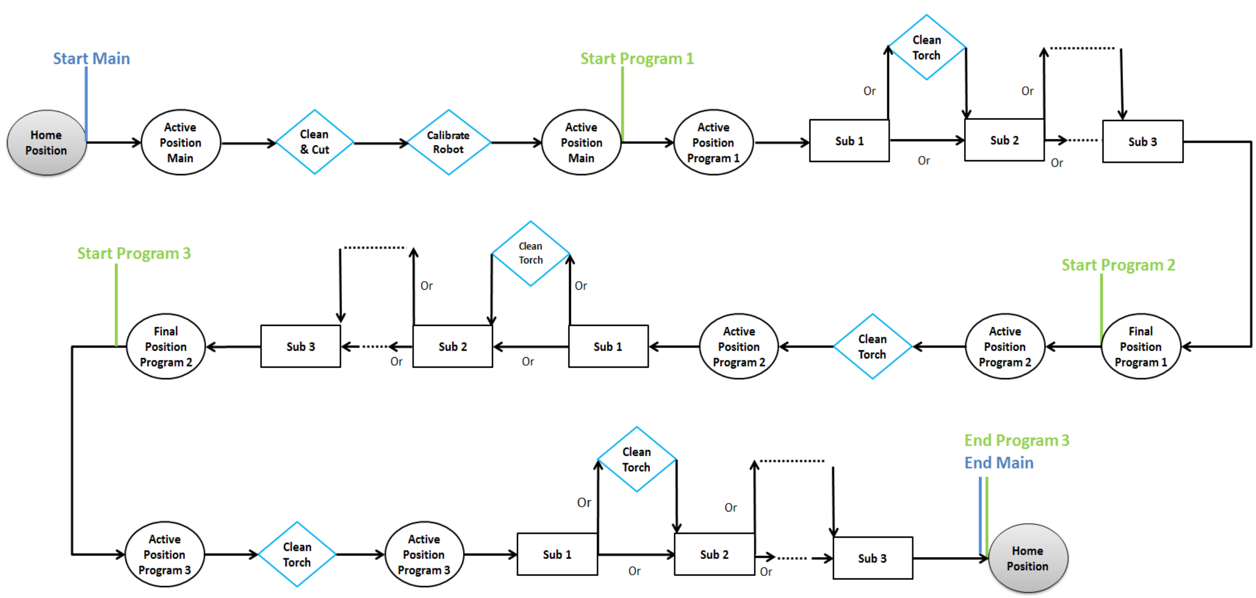
To move from a current program to the next program the robot needs to be in the final position of a program. The final position is similar to an active position except that no maintenance can be conducted in the final position.
The entry/exit position of a sub is a location between the active position of a sub and the first welding joint. The movement from the active position of the sub to the entry/exit position (vice versa) can be done with high speed. The movement from the entry/exit point to the first welding joint is done at low speed as the robotic arm is closer to the product.

3.5.1 Details of Main

The main has two functions. First it sets up the robot and secondly it decides which three programs are run. In order to set up the robot the main moves the robot from its home position to the active position. It will then activate three maintenance subs to make sure the welding robot is ready to operate effectively. The main will then select the three programs belonging to a product variant and activate the first program. From there on the three programs dictate how the welding robot operates. When a program is finished, the main will activate a new program. The main is in control of the order of three programs. After the third and final program the main makes sure the welding robot moves back to the home position.

3.5.2 Details of a Program

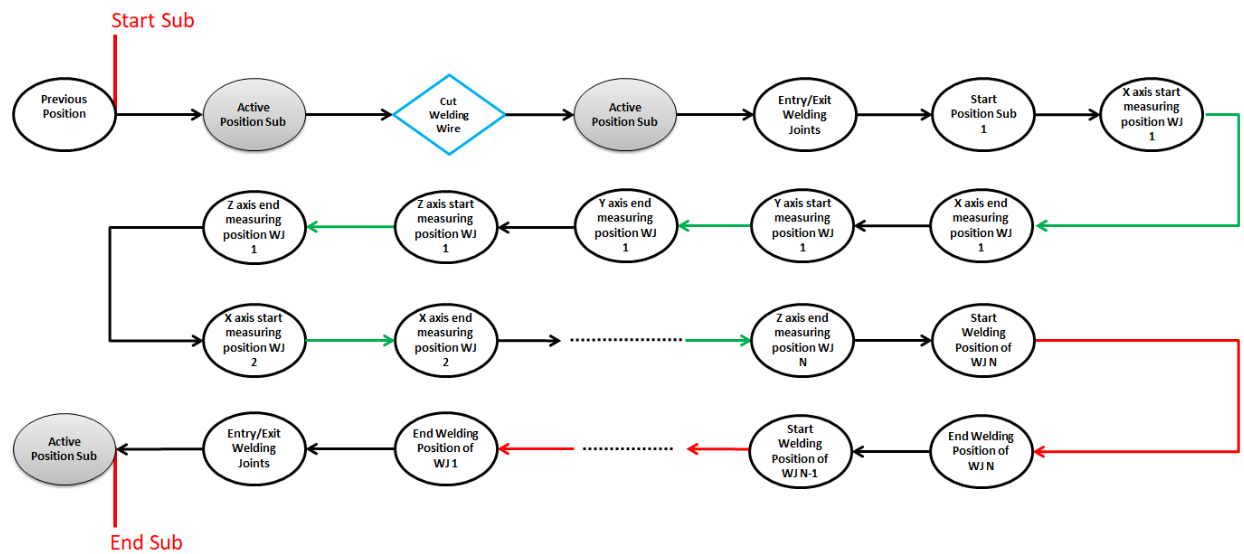
A program is made up of subs, maintenance subs, and position commands to rotate the G6 axis when required. At the start of every program the welding robot moves to the active position. The next step is to switch the wire and clean the torch if necessary. It then moves back to the active position. After these steps have been completed the program will work down a long list of subs with Mechanical Cleaning intertwined every two subs on average. Flowchart 1 clarifies the motions between a main, program, and sub. Table E-2 in Appendix E shows what happens in a main and in each program per product variant.



Flowchart 1: Flowchart for the motions in one main and 3 programs. The legend for the flowchart can be found in Appendix D.

3.5.3 Details of a Sub

The subs are the building blocks for the programming of the welding robot. A sub is a logical cluster of welding joints in a particular area of the product. In subs the majority of code is stored. Flowchart 2 shows the motions that occur in a sub. At the start of the sub the welding robot moves to the active position. It then cuts the welding wire after which the robot moves back to the active position. From the active position it moves to the entry/exit position of the sub. From the entry/exit position it moves to measure the first welding joint and all other welding joints. After all welding joints have been measured it welds the joints in reverse order. Once the last welding joint is welded the robot moves to the entry/exit position from which it moves back to the active position. Once back at the active position is reached the sub has ended. The entry/exit position and active position is created so that the welding robot can reach the location of the sub. However, sometimes the TCP can only reach the sub when the product is rotated on the G6 axis.



Flowchart 2: Flowchart for the motions in one sub. The Nth counter represents the number of welds in a sub. The X, Y, and Z coordinates of both positions (start/end) of a welding joint need to be measured. Only then can the welding robot move to the next welding joint. The legend for the flowchart can be found in Appendix D.

3.5.4 Order of Subs Inside a Program

The ordering of the subs in a program is based on the active position of the sub not the physical location of the welding joints as the welding robot starts and ends each sub in the active position. The subs are first grouped by program, then inside a program they are grouped by the angle of the rotary axis (G6) of their active position. The subs with the same rotary angle are grouped together and the order in a group is decided by which sub is nearest to the previous sub on G4 axis. The ordering based on the G4 axis is not always done correctly.

A special requirement for the sequence of the subs is that there is a set of subs in the Frame which must be welded before the Kasko can be turned by more than 45 degrees (G6). For the Roro-Belt and Attached-Worm these subs are listed below:

- Roro-Belt: S3FRO_**VPV** and S3FRO_**VPA**
- Attached-Worm: S3AF_**KVZL,** S3AF_**KVZR,** S3AF_**VZ**

If the subs should be ordered in a different way, for example by removing the program structure, the subs listed above should be welded before the Kasko turns more than 45 degrees.

3.5.5 Order of Welding Joints in a Sub

The strategy of ordering the welding joint in a sub is to select the nearest welding joint from the previous welding joint. Because measuring happens from WJ 1 until WJ N and welding happens from WJ N to WJ 1 the order of welding joint is circular. The method of deciding the nearest welding joint is done by eye and thus is therefore not always optimal.

3.6 Conclusion

The motions of the two identical welding robots are based on the programming of DTPS. The welding coordinator programs the welding robots to measure and weld the product, maintain the torch, and conduct any motions between measuring, welding, and maintenance. The welding robot must weld different products which share modular components. The modular design of the products results in modular programming which is reflected in the build-up of subs into programs and programs into a main.

4. Groups of Motions and Wasteful Motions

Now that an overview of the current situation is given, the motions can be analysed, and wasteful motions can be found. However, there are thousand position commands and robotic positions which dictate the motion of the welding robot for one product. It is impossible to analyse each individual motion. Therefore, the purpose of this chapter is to first define the motions of the welding robot and group them (Section 4.1). Furthermore, in order to find wasteful motions, a definition of wasteful motions needs to be determined. By combining the groups of motions (Section 4.2) and the findings of the systematic literature review (Section 4.2) a definition for wasteful motions is determined (Section 4.3).

4.1 Motions of the Robot

In order to help with grouping and defining wasteful motions for this project the motion instances of the welding robot will be defined first. The Figures D-2 and D-3 in Appendix D are used to compose the list below.

Motions in a main or in a program

a) Moving from the home position to the main active position for the maintenance of the torch.
b) Moving to complete the maintenance of the torch in the main from and back to the active position of the main.
c) Moving from the main active position to the program active position for the maintenance of the torch.
d) Moving to complete the maintenance of the torch in the program from and back to the active position of the program.
e) Moving from the program active position to the active position of the first sub.

Motions in a sub

f) Moving to complete the maintenance of the torch in the sub from and back to the active position of the sub.
g) Moving from the active position to the entry/exit position of the welding joints.
h) Moving from the entry/exit position of the welding joints to the first welding joint.
i) Moving between the welding joints to be measured. From the first welding joint until the last welding joint (N).
j) Moving to measure all the welding joints (1 → N).
k) Moving between the welding joints to be welded. From the final welding joint measured (N) until the first welding joint measured.
l) Moving to weld all the welding joints (N → 1)
m) Rotating the product after a set amount of welding joints have been welded/measured.
n) Moving from the first welding joint to the entry/exit position of the welding joints.
o) Moving from the entry/exit position to the active position of a sub.

p) Moving from the active position of the previous sub to the active position of the current sub.
q) Moving to any maintenance actions or rotation of the product in between subs until the last sub.
r) Moving to complete the maintenance of the torch between subs.
s) Moving from the last sub to the final position of the program.
t) Moving from final position of program 1 or 2 to the active position of program 2 or 3.
u) Moving from program 3 back to the home position.

Out of the motions listed above the following groups are formed:

1. **Moving** in/in between main, programs, subs, and welding joints. (a, c, e, g, h, k, m, n, o, p, r, s, t, u).
2. **Moving to maintain the torch** (b, d, f, q).
3. **Moving to measuring** the welding joints and moving between measuring the welding joints (i, j).
4. **Moving to weld** the welding joints (l).

These groups will be used again in Section 4.3.

4.2 Findings of Systematic Literature Review

It is important to define wasteful motions as the process of defining it creates a better understanding of the project for the author, reader, and client. In order to help define what wasteful motions are a literature study has been completed. The goal of the study was to find a useful definition of wasteful movements and investigate the causes of wasteful motions in industrial robots. Appendix I describes the literature study protocol. The concepts found in the literature study are listed below.

Concept 1: Supportive and effective movements
There are two types of movements which are effective movements and supporting movements. Effective movements are any movements made by the welding robot that are directly related to welding. Supportive movements are all movements that support the welding movements but are not directly related to welding. Supporting movements contain the majority of wasteful movements and therefore can be optimized easier. Effective movements are more rigid due to the tasks they have to complete such as welding a seam and thus are harder to optimize (Alatarsev and Ortmeier, 2013) (Alatarsev and Ortmeier, 2014) (Alatarsev, 2015).

Concept 2: Overly specified effective tasks
It is possible for effective movements to be overly specified. For example, a start point for an effective task is typically fixed but not always positioned in the most efficient place in terms of movement optimization. Thus, overly specified fixed tasks can result in wasteful movements (Alatarsev and Ortmeier, 2013). When going from an overly specific to a relaxing effective task essentially a degree of freedom is added for the optimization of the robot. This therefore increases

the ability to optimize the movements of the robot and thus reduces wasteful movements (Alatarsev, 2015).

Concept 3: Lack of use of sophisticated programs for optimizing motions
Current practice is that engineers program both effective and supportive movements. However, it is possible to utilize sophisticated programs which optimize the supportive and effective movements in terms of scheduling and make sure movements are collision free. Making use of such programs is not done enough and results in an efficiency loss (Alatarsev and Ortmeier, 2013). Furthermore, not utilizing sophisticated programs to optimize effective and supportive movements results in an increase in costs and errors (Alatartsev, Stellmacher and Ortmeier, 2014).

Concept 4: Sub-optimal choice of base location of the robot
Another issue that can result in wasteful movements is the location of the robot. If the base location of the robot is chosen incorrectly than it is possible that all other efforts to optimize the robot will be ineffective (Alatarsev and Ortmeier, 2013). If this occurs then all efforts to reduce wasteful movements have been in vain. It might help to mount the robot on a rail to further increase the degree of freedom of the robot. Furthermore, it is important to know the position of the tool center point (TCP) and its orientation in order to increase robot optimization (De Maeyer, Moyaers and Demeester, 2017). If this is not done the optimization of movements is limited and therefore resulting in wasteful movements.

Concept 5: Sub-optimal path collision constraint algorithms
Sub-optimal collision constraints can result in wasteful movements because the robot can be forced to make unnecessary movements in order to avoid colliding with its surroundings. It is difficult to create algorithms to calculate collision free paths which are efficient, meaning that such algorithms are more expensive (Alatarsev and Ortmeier, 2013). Having a redundant robot with more degrees of freedom (DoF) than necessary results in it being able to complete its work more dexterously than non-redundant robots. Having the extra DoF can be used to complete supportive tasks such as collision avoidance (Alfs, Ivlev and Graeser 2000).

Concept 6: Sub-optimal task sequence optimization.
Typically, a robot has to perform a set of tasks. If the sequence of the task is incorrectly calculated than this would result in wasteful movements (Alatartsev, Stellmacher and Ortmeier, 2014). The optimal task sequence can be determined by applying the traveling salesman problem (TSP) (Alatarsev and Ortmeier, 2013), (Alatarsev, 2015).

Conclusion: Concept 1: Effective motions versus supportive motions is the most relevant finding related to defining wasteful motions for this project. The other five concepts could be used to find the causes for wasteful motions. The different authors propose different causes of wasteful motions and different solutions.

4.3 Definition of Wasteful Movements

In Alatarsev and Ortmeier (2013) there are two types of movements which are effective movements as well as supporting movements. Effective movements are movements when the welding torch is turned on, thus when the movement required to weld the welding joint. Supporting movements are in between or after effective movements and are not directly needed to complete the welding joint. However, supporting movements are necessary to complete a sequence of effective movements.

This definition is similar to the lean concept of value activity categories. According to lean principles a process can fall in one of the three following labels: value adding, non-value adding but necessary, and non-value adding and unnecessary (University of Iowa, 2018). The non-value adding and unnecessary types of motions are also completely wasteful. These two concepts have been applied on the motions groups the robot makes during the robotic welding cycle.

Types of Motions the Welding Robot Makes During the Welding Cycle	Effective or Supporting Movements	Lean Activity Categorisations
Moving in/in between main, programs, subs, and welding joints.	Supportive	Non Value Added but Necessary
Moving to maintain the torch	Supportive	Non Value Added but Necessary
Moving to measure the welding joints and moving between measuring the welding joints	Supportive	Non Value Added but Necessary
Moving to weld the welding joints	Effective	Value Added

Table 4: The instances of motions the welding robot makes categorized by effective or supporting motions and the lean activities.

For this project there is only an interest in increasing arc-on time through the reduction of wasteful motions. Therefore, the definition of wasteful motions for the welding robot is any motion that is not directly related to welding the joint. In other words: supportive, non-value added, non-value added but necessary are all seen as wasteful in the perspective of increasing arc-on time.

These motions can be necessary for the overall welding process and will thus never be zero. However, the goal of this project is to minimize the three supportive motions. A simplistic view of wasteful motions allows for the non-value added but necessary motions to be analysed and critiqued. After all they might be necessary now but not in the future. For ASN the motions that fit the definitions of wasteful motions is maintenance, moving between, and measuring.

4.4 Conclusion

To conclude the motions of the welding robot of ASN can be split up in four main groups: welding, moving, measuring, and maintenance. The definition of wasteful motions is any motion that is not directly related to welding. Supportive motions are defined as wasteful while effective motions are not in the perspective of arc-on time optimisation. The three groups of motions: moving, measuring, and maintenance are all wasteful motions as they are supportive motions. Thus, the goal of ASN should be to minimize these three groups of wasteful motions.

5. Time Simulation and Result

In Chapter 4 the following three groups have been determined to be wasteful motions: measuring, moving, and maintenance. In order to know the impact of the wasteful motions on the arc-on time, a time analysis of the motions is needed. Before a time analysis can be done a system for performing the time analysis needs to be selected (5.1), and the accuracy of the system selected needs to be verified (5.2). The setup of the time analysis is described in Section 5.3 and lastly the result of the time analysis is given in Section 5.4.

5.1 Selection of the System to Perform the Analysis

There are three data sources which can be used for the time analysis:

- A software system which shows the daily, weekly, monthly, and yearly average arc-on time, and total occurrence of errors. The data cannot be sorted by type of product or by motion group. Therefore, there is no data available on arc-on time per product or time taken to weld a certain product.
- Observing and timing the welding robot in real time (video).
- DTPS has a motion tool which calculates the following; total time (s), welding time (s), arc-on time (%), welding length (m), number of welding joints and measuring time.

The first option does not deliver enough detailed data. The video option is incredibly time consuming to measure as the time keeping will have to be done by hand. Therefore, it means that the accuracy and reliability of the measurements would be very poor or unreliable. The only realistic option is simulation with DTPS, however ASN has never used the simulation tool of DTPS to measure time elements. It is unclear if DTPS is an accurate representation of reality thus a small experiment in Section 5.2 will be conducted to verify the accuracy.

5.2 Verifying Performance of DTPS

Experiment Set Up

The simulation time performance of DTPS will be done by comparing the total time a Kasko S3 will take to complete in reality and in the simulation. There is no data available on the time it takes for the welding robot to complete one robotic welding cycle. However, there was existing footage of the welding robot welding two variants of the Kasko S3 captured by a go-pro. The two Kasko S3 (3600 Roro-Worm and 3600 Attached-Belt) were not the same variant as the ones chosen in Chapter 2 (3600 Roro-Belt and 3600 Attached-Worm). Filming the correct Kasko S3 was not possible due to limited physical access to the welding robots. Measuring the welding time by observation was not practical and would not deliver reliable data. Thus, the choice has been made to compare the time simulation in DTPS of the 3600 Roro-Worm and 3600 Attached-Belt versus the real time.

Result

Kasko Variant	Real Time (hrs:min:sec)	Simulation Time (hrs:min:sec)	Difference %
3600 Roro-Worm	x	x	9
3600 Attached-Belt	x	x	9
Total	x	x	9

Table 5: The total robotic cycle time measured by simulation and video (Real time) for the 3600 Roro-Worm and the 3600 Attached-Belt. Data Confidential: Data edited or removed (x).

As can be seen in Table 5, the simulation time is 9% shorter than the measured real time for both the 3600 Roro-Worm and 3600 Attached-Belt. This result shows that simulation time is faster than the robot is when performing the tasks. All the reasons behind the difference in time is unknown. The difference in speed is partially due to the fact that the top speed of the tip of the welding wire is 180 m/min in the simulation while it is 120 m/min in reality. It is also possible that the welding robot is slower in general due to the friction in the joints. Lastly, the maintenance actions in the simulation time are faster than in reality. The maintenance activities cannot be simulated by DTPS. Instead, when such actions occur DTPS uses a timer set the duration the action would take in practice. The time in DTPS was not in line with actual times resulting in some inaccuracies. Thus, a correction had to be made when gathering time data from DTPS by using the values in Appendix M. The 9% time difference means DTPS is not an optimal representation of reality. However, it is the most effective timing tool available.

5.3 Time Simulation Set Up

The goal of the time simulation is to see how the three categories of wasteful motions impact arc-on time. As discussed in Section 5.1 the motion tool of DTPS will be used to collect the time data. The motion tool calculates the following six elements:

1. Total time = Robotic Welding Cycle Time(s)
2. Total welding time (s)
3. Arc-on time (%)
4. Total measuring time (s)
5. Total moving time (s)
6. Total maintenance sub time (s)

The motion tool only yields data on the six elements when run on a sub level. Therefore all 72 subs in the two chose product variants are simulated individually. The data of the 72 subs have been stored in Microsoft Excel. The maintenance sub time is corrected since the maintenance sub time is different in DTPS as discussed in Section 5.2. With additional data on the motions in the program and main, gathered through manipulating DTPS, the data base is completed. The simulation will be run twice to collect the full-time data from the 36 Roro-Belt and 36 Attached-Worm. An example of the raw data collected for subs can be found in Figure K-1 and K-2 of Appendix K and the manipulated data in K-3.

5.4 Simulation Time Results

By manipulating the data and taking the two averages of both product variants the average share of time per motion group has been calculated and is shown in Figure 7. The average of both products has been taken as the share of time per motion group is almost identical as can be seen in Figure 8.

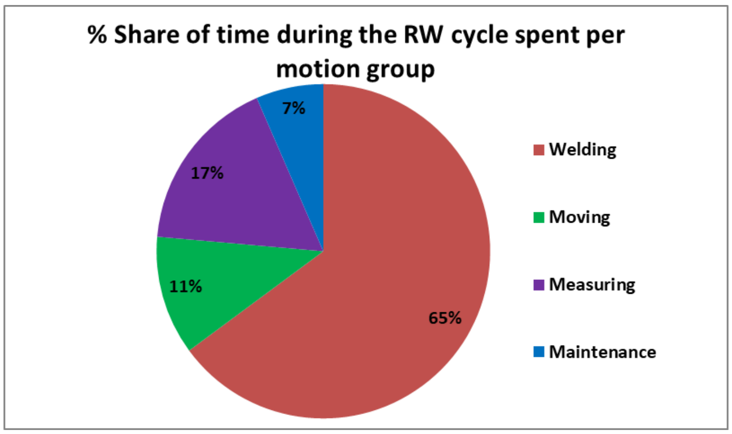


Figure 7: The share of time during the RW cycle spent per motion group.

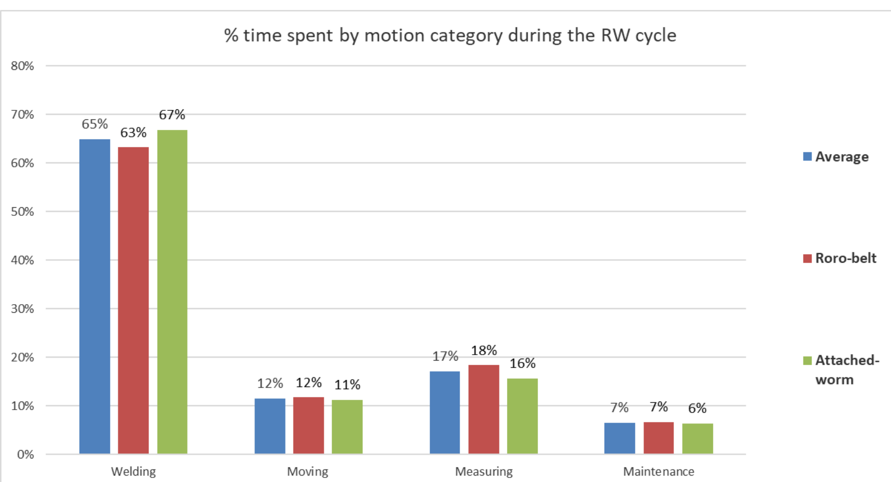


Figure 8: The share of time during the RW cycle spent per motion group.

Most of the time is spent on welding which takes up 65% of total time. This means that the arc-on time for the time simulations is 65%. Thus, wasteful motions take a share of 35%. This made up of 7% total time spent on maintenance activities, 17% on measuring the welding joints, and 11% on moving.

5.5 Conclusion

In this chapter the time elements for the four groups of motions have been determined. The motion tool of DTPS is selected as the best method of gathering time elements of the welding robot. The other methods of gathering time elements related to arc-on time lack accuracy or cost too much time to carry out. A verification experiment of DTPS versus reality has shown that in DTPS the RW cycle is 9% shorter. Some of the causes of the difference have been identified and corrected in the simulation results. Although an attempt has been made to improve the time measurement capabilities of DTPS, it is still insufficient in certain areas. The accuracy is good enough for an overview of the time elements of the welding process, but if a more detailed analysis is to be made of certain time elements it is lacking. A tool to measure more detailed time elements and measure them frequently (real time data on arc-on time of the welding robots) would be desirable. By simulating the two product variants of the Kasko S3 the percentage of time spent per motion group of the total robotic welding time has been determined. The optimization possibilities of all three wasteful motions groups will be analysed in Chapter 6.

6. Optimization Possibilities and Other Findings

Now that the impact of the three groups of wasteful motions is known on arc-on time optimization possibilities that reduce the wasteful motions can be formulated. The chapter starts of by describing the steps taken to generate the optimization possibilities in Section 6.1. Optimization possibilities are given for measuring (Section 6.2), moving (Section 6.3), and maintenance (Section 6.4). Other findings are discussed in Section 6.5. In Section 6.6 the challenges of the optimization are given.

6.1 Generating Optimization Possibilities

The three categories of wasteful motions identified are: measuring, maintenance, and moving. Per category possible solutions are formulated through brainstorming. The number of optimization possibilities found depend on the category of motion. In general, the more the motions of a category are understood or documented the more optimization possibilities are formulated. All formulated optimization possibilities are discussed with the welding coordinator and company supervisor during multiple discussion sessions. No optimization possibilities were offered by the welding coordinator or company supervisor. The discussions of the welding coordinator and company supervisor resulted in one optimization possibility removed in the maintenance category as it had no impact.

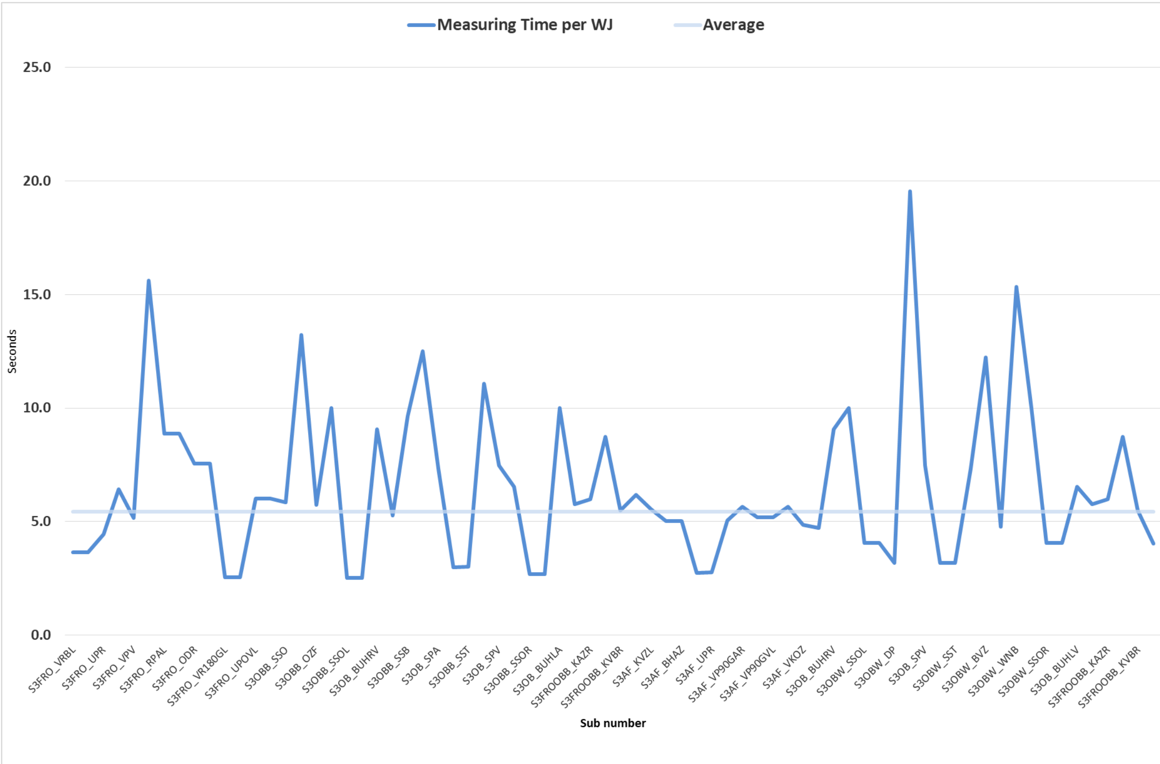
The measuring process is not understood well and undocumented. Only two generalized optimization possibilities were formulated.

The motion category moving was understood better but still partially undocumented. Multiple optimization possibilities were generated.

Maintenance is well documented but only when maintenance subs need to be used are understood. Multiple optimization possibilities are generated with four concrete optimization possibilities. One optimization possibility was removed due to having no impact.

6.2 Measuring Optimization Possibilities

The measuring activity takes on average 17% of the total RW time and is therefore the wasteful motion that has the most impact on arc-on time. The issue with the measuring process is that it is incredibly complex as concluded in Appendix B and in Section 3.2. The measuring process can be optimized by the welding coordinator. Graph 1 is a good indicator in which subs the measuring process is inefficient compared to the average. The welding coordinator could use Graph 1 to select subs for analysing the measuring process. Subs with an average of 15 seconds or more to measure a welding joint (S3FRO_VPV, S3OB_SPV, and S3OBW_SSOR) could be analysed first to see why their average is so high. An analysis of subs with an average below 5 seconds is useful for finding out what goes right and if that can be applied to the other subs.



Graph 1: The average measuring time of welding joints per sub.

Another optimization possibility is to remove the measuring process from the robotic welding cycle. There are solutions on the market which could scan the location of the welding joints of a product before it is even placed on the welding robot. The issue with a scanning solution is that during the welding process the location of welding joints changes due to slight deformation in the product. Finding an adequate scanning solution is therefore quite hard and would require a large investment. However, in terms of reducing arc-on time it would be worth it as the welding robot is very inefficient in measuring the welding joints. The measuring process takes up 17% of the total robotic welding time. Furthermore, the maintenance sub wire cut at the start of each sub is no longer necessary if the welding robot measures the welding wires. Removing the Wire cut maintenance sub would save an addition 4% of time in the robotic welding cycle. By removing the measurement process altogether, the robotic welding cycle time would be reduced by 21%, and the arc-on time would increase to 81%.

6.3 Moving Optimization Possibilities

Moving takes up an average 11% of the RW cycle time.

Moving can be categorized in three activities:

1. Moving between active positions of the main, programs, and subs.
2. Moving between welding joints (sub level).
3. Moving between active position of a sub and the location of the welding joints of a sub.

Activity one is responsible for 2% of the RW cycle time. Activities two and three are responsible for the remaining 9%. The share of time taken up by activity two or three could not be calculated using DTPS. It is estimated that on average activity 3 takes up 10 seconds per sub as explained in Appendix K. Thus activity 3 is responsible for 3% of the total RW cycle time and activity 2 is responsible for 6% of the total RW cycle time.

6.3.1 Moving Between Active Positions

A main, every program, and every sub has an active position. The movements between these active positions are not always optimal. Two possibilities for optimization were found in the motions between the active positions between the main and programs. The explanation behind the wasteful motions between the active position is complex and can be found in H-1 and H-2 of Appendix H. A total of 193 minutes per year could be saved by optimizing these movements. It is possible to improve the active positions further, but this would require more analysis. Active positions take up almost no

6.3.2 Moving Between Welding Joints

Moving between welding joints takes an estimated 6% of the robotic welding cycle time. It is possible to optimize the motions between the welding joints. As described in Section 3.5.5 there is a strategy to determine the order of the welding joints, but it is not always followed correctly. It is also not clear if the current strategy is optimal for reducing the motions between welding joints. The average number of welding joints per sub is nine with a maximum of 27. Although optimization is possible it is clear that it is only possible to optimize the time spent with a sophisticated software program.

6.3.3 Moving Between Active Position of a Sub and the Location of the Welding Joints of a Sub.

The location of the physical welding joints in a sub is not the same as the location of the active position of the sub. As the active position of a sub is the starting and final position of a sub the welding robot has to move from the active position to the location of the welding joints and after the welding joints have been welded it moves back to the active position. This can be seen in Flowchart 2, Section 3.5.2. These motions take up an estimated 3% of the total RW cycle time. The difference of location is so that the welding robot has the room to manoeuvre in a collision free manner towards the location of the welding joints. The active position of each sub and the location of the welding joints of each sub have been collected in Appendix F.
To significantly and systematically optimize the time these movements take is very complex as a high number of collision free paths and robotic positions need to be determined. A sophisticated software program would be required for such a task.

6.4 Maintenance Optimization Possibilities

An average of 7% of the total RW time is spent on maintenance activities of which 4% is due to Wire-cut maintenance subs and 3% due to cleaning subs. The maintenance sub ATC (calibration) and Clean Cut is only used once and thus negligible. As maintenance subs are processes created by the manufacturer it is not possible increase the efficiency of each maintenance operation. However, within the scope of this project it is possible to optimize the frequency of the maintenance subs. Four instances where the frequency of maintenance subs can be optimized are discussed in Appendix H, H-3 to H-6. These instances have a potential to save 938 minutes on a yearly basis.

6.5 Other Findings

There are two findings that are not directly related to the reduction of the three wasteful motions but are nonetheless important to mention. First, there is a high variety in arc-on time per sub (6.4.1) and secondly, there is not enough data or accurate data available to measure the robotic welding process in detail (6.4.2).

6.5.1 High Variety in Arc-on Time per Sub

On average 95% of the total RW time is spent in subs as can be seen from Figure 9. The motions occurring during subs have the largest impact on arc-on time.

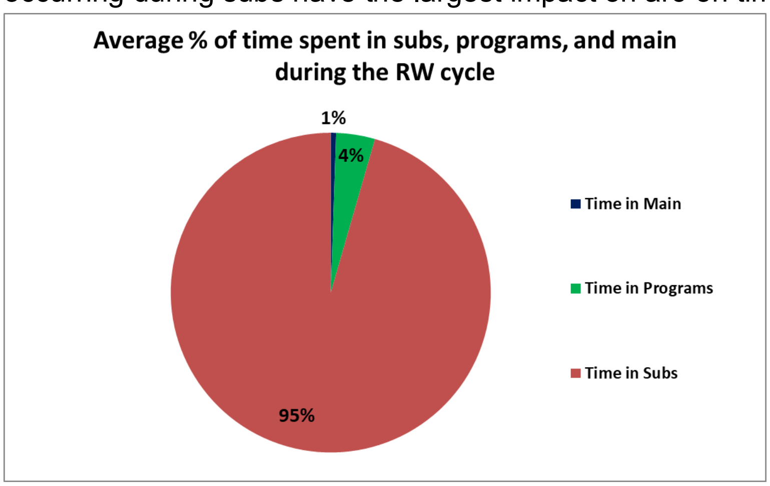
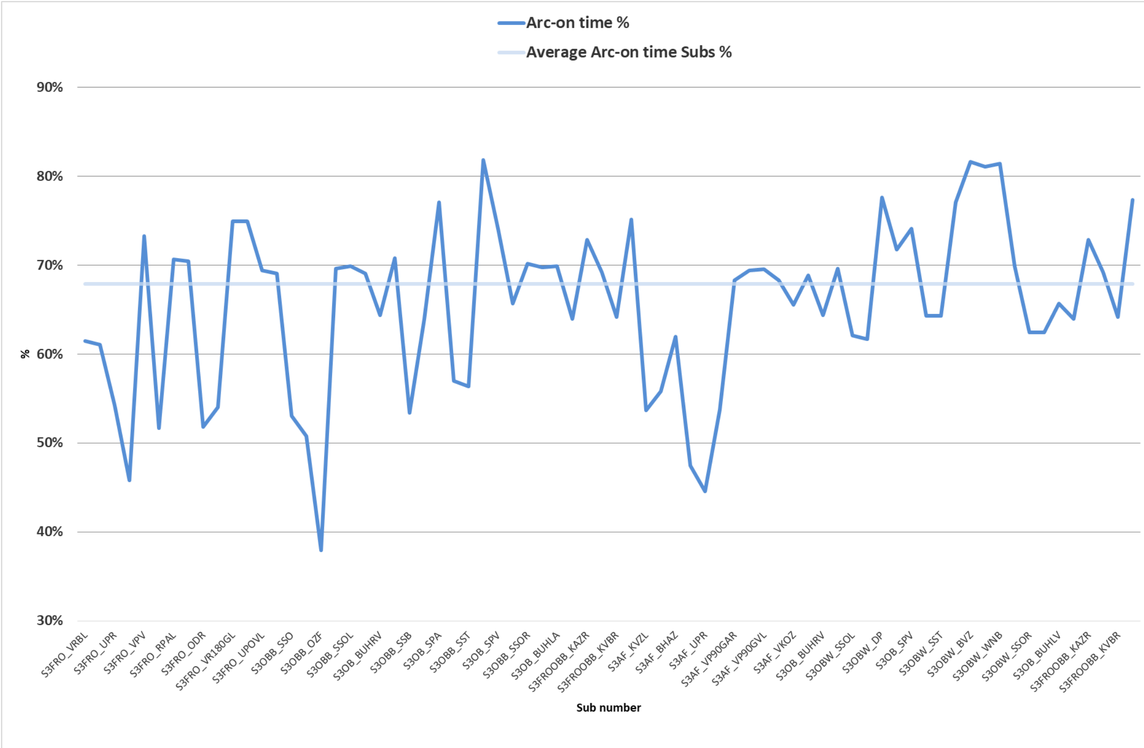


Figure 9: Percentage of time spent in main, programs and subs during the RW cycle.

When comparing the arc-on time per sub and the average arc-on time per sub it is noticeable that the certain subs have an arc-on time far higher or lower than the average as can be seen in Graph 2. The subs with the lowest arc-on time could be analysed by an experienced person to see what can be improved.



Graph 2: Arc-on time per sub compared to the average sub arc-on time.

6.5.2 Time Measurements of DTPS not Accurate

There are almost no data sources available on arc-on time and the time elements of the robotic welding cycle. In this study DTPS has been used to simulate the motions of the welding robot. The disadvantage of DTPS is that the inaccuracy is 9% and, that certain time elements can only be calculated through data manipulation which is time consuming. If ASN implements solutions to minimize wasteful motions and thus optimize arc-on time a better information system is needed. Currently the information system does not track arc-on time in real time per product. Time elements related to the four categories of motions are also not tracked.

6.6 Optimization Challenges

According to Concept 6 of the literature findings in Section 4.1 the Travelling Salesman Problem (TSP) algorithm is the preferred way to solve the optimization sequence problem of the robot and thus minimizing wasteful movements. The algorithm calculates the optimal route of towns (points) the salesman has to follow. The time of the path between each town is the input for the algorithm. If the number of towns increases, the number of calculations increases exponentially. A translation of the TSP problem for the robot would be: the robot or TCP leaves the home position, has to weld a number of welding joints and returns to the home position.

A major problem is the time required to determine an optimal collision free path between two welds. This calculation needs to be done for all the paths between each pair of welds. The number of calculations is depending on the number of welding joints. Table 6 below gives the number of paths for two optimization cases. In Appendix L the calculation methodology is explained.

Case 1- Optimizing subs and WJ in subs			**Total**		**Total Paths**
Subs			38		1,406
Welding Joints in Sub			369		4,496
				Total	5,902
Case2- Optimzing WJ , no subs			**Total**		**Total Paths**
Subs			0		-
Welding Joints in Kasko			369		135,792
				Total	135,792

Table 6: Number of paths per case for Kasko S3, Roro-Belt.

In case 1, the 38 subs are optimized and the welding joints per sub are optimized. For this case already 5902 collision free paths have to be calculated. If all the welding joints are optimized individually – this is case 2 – the number of paths grows to 135,792. It is clear that this can't be done manually but needs to be done by a sophisticated software program. The input for such a program is another challenge; how to get all data of the Kasko S3 and of the robot with the axes into the system. However, this is the most efficient way of reducing wasteful movements in the motions group. At this stage it is not possible to give a clear cost benefit analysis of such a program. Further evaluation is needed if there is software available which ASN could use and if it would be useful for ASN.

6.7 Conclusion

To conclude, there are optimization possibilities for ASN to reduce the three groups of wasteful motions and thus increase the arc-on time. There are six instances, two of which are related to the moving category and four related to maintenance activities, which could be implemented and result in an estimated total yearly saving of 1131 minutes (<1% of total yearly production time). The impacts of other optimization possibilities are harder to estimate and implement. The challenge of this problem is to calculate the number of optimal collision free paths. A sophisticated program is required for this. A more reliable information system that also tracks time elements related to arc-on time in real time is needed.

7. Conclusion, Recommendations, and Discussion

In the following chapter the conclusion and discussion of the bachelor project is given. In Section 7.1 Conclusion the main research question is answered, and the results are summarized. Recommendations are given in Section 7.2. The results of the bachelor project are discussed in Section 7.3.

7.1 Conclusion

In this bachelor project the main research question was:
How can the arc-on time for the robotic welding department at ASN be increased by reducing the wasteful motions?

To answer the main research question, the wasteful motions had to be defined and measured first. By describing the current motions of the welding robot, discussions with the welding coordinator, and a literature review the wasteful motions for the welding robot of ASN were determined to be all motions related to the measuring process, maintenance, and moving. After simulating the motions of the welding robot and measuring time elements with DTPS the impact of the wasteful motions on arc-on time was determined. The arc-on time measured using DTPS is 65% while ASN estimates it to be around 50%. Measuring takes up 17% of the total robot welding cycle time with moving and maintenance taking up 11% and 7% respectively.
With wasteful motions defined and measured, solutions were offered as to how ASN could reduce the wasteful motions in order to increase arc-on time. The three wasteful motions, with a high priority on measuring, should be reduced. Chapter 6 discusses the optimization possibilities for the wasteful motions found. Removing the measuring process would save 21% of the RW cycle time thus increasing arc-on time. Optimizing the motions in maintenance and moving results in less drastic savings. Software which calculates the collision free shortest path is required to optimize the motions between welding joints from the moving group.
An indirect solution to the reducing of wasteful motions is the implementation of a better time measurement system for arc-on time and other time elements. The 9% difference in DTPS time measurement with reality needs to be solved. Furthermore, an arc-on time of 65% is found while ASN says it is around 50%. The difference in arc-on time is also a result of poor time measurement system.

7.2 Recommendation

Now that optimization possibilities have been listed the recommendations for ASN as to how ASN could consider reducing arc-on time through reducing wasteful motions formulated. There are four lists of recommendations. The first three correlate to the three wasteful motions group, moving, measuring, and maintenance. The final recommendation list is related to the data collection system of ASN.

7.2.1 Recommendation for the Moving Group

- Remove the two instances of wasteful motions as described in H-1 and H-2 Appendix H by editing DTPS.
- Investigate possibilities to implement software which can help with optimizing the motions between welding joints.

7.2.2 Recommendation for the Measuring Group

- Analyse why certain subs have a high ratio of measuring time over number of welding joints as shown in Graph 1 in Section 6.3.
- Investigate alternatives for measuring the location of the welding joints. The measuring takes up 17% of the total RW cycle time. The Wire-cut activities (4%) can also be eliminated if the robot no longer measures the location of the welding joints. This would reduce the RW cycle time by 21% and increase the arc-on time from 65% to 81%.

7.2.3 Recommendation for the Maintenance Group

- Remove the four instances of wasteful motions as described in H-3 until H-6 in Appendix H by editing DTPS.

7.2.4 Improve the Data Collection System Related to Arc-on Time

- Update DTPS with new maintenance time values given in Table 6, Section 5.6.
- Investigate the realization of an improved monitoring system. Using DTPS as a simulation tool is time consuming. Although the inaccuracy (9%) is within reasonable limits, a monitoring system with direct input from the robots will improve the accuracy. A monitoring system should also be able to allocate the actual time spent to the different activities.

7.3 Discussion

This study has managed to define the wasteful motions of the welding robots at ASN within the scope of arc-on time. Furthermore, the impact of the wasteful motions on arc-on time was also determined. Lastly, solutions and recommendations were given as to how the wasteful motions could be reduced in order to increase arc-on time. However, the study has its limitations and further research is needed to eliminate some of these limitations.

7.3.1 Limitations

There are three main limitations that limited the extend of the study and the results of the research; time, expertise, and data availability.
The limited amount of time available to study the motions and to improve the wasteful motions of the welding robot meant that in depth analysis of the wasteful motions was not possible. This is especially relevant for the wasteful motion group moving. A lack of time also resulted in a study that focusses on motion processes instead of individual motions and on general solutions instead of detailed solutions.
A lack of expertise in industrial topics such as welding, steel product design, and torch maintenance limited the analysis of wasteful motions related to maintenance and measuring.

7.3.2 Further Research

Further research can be done on any of the three categories of wasteful motions and their subsequent recommendations. The required expertise and time for further research depends on the chosen category of wasteful motions. To improve the maintenance motion group an expertise of maintenance of the welding robot is required. To describe and improve the measuring processes would require far more time; an expertise in product design, welding, industrial measuring systems, and in-depth knowledge of the capacity of ASN. Further research related to the wasteful motion group moving, would require more time and knowledge on collision free and motion optimization software.

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Appendix A Images of a Hopper

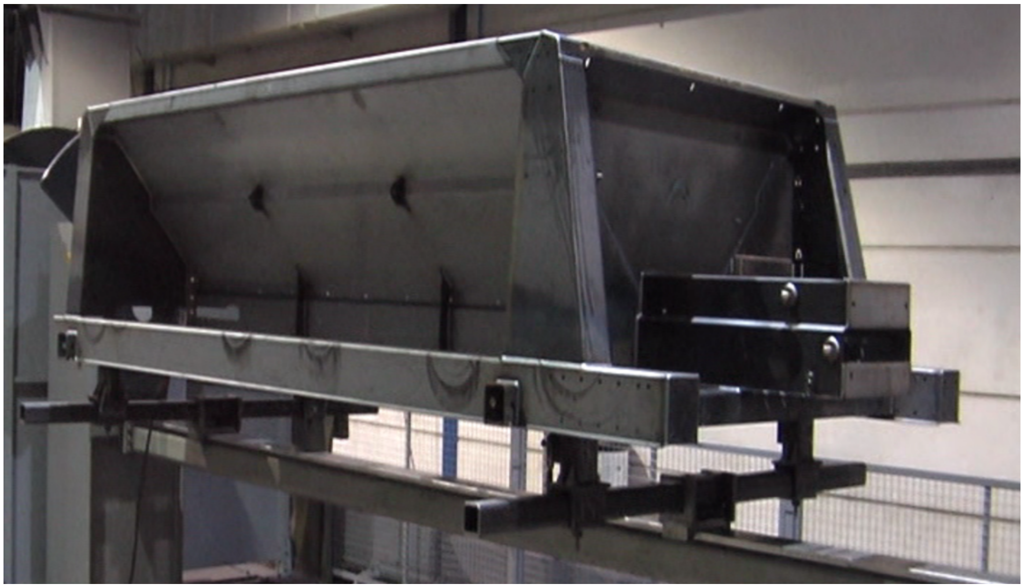

Image A-1: A fully welded Kasko S3 on a fixture in one of the welding robot work stations. (Source: Aebi Schmidt)

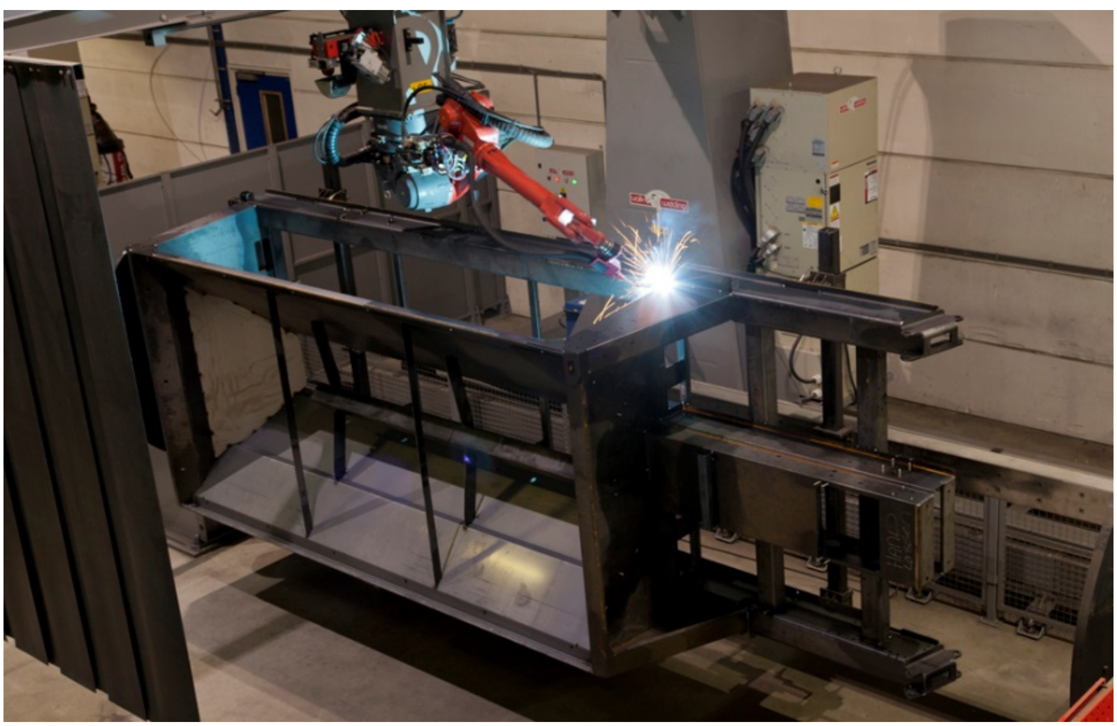

Image A-2: The robotic welder in action with a 90-degree rotated fixture. (Source: Aebi Schmidt)

Appendix B   Measuring the Welding Joint

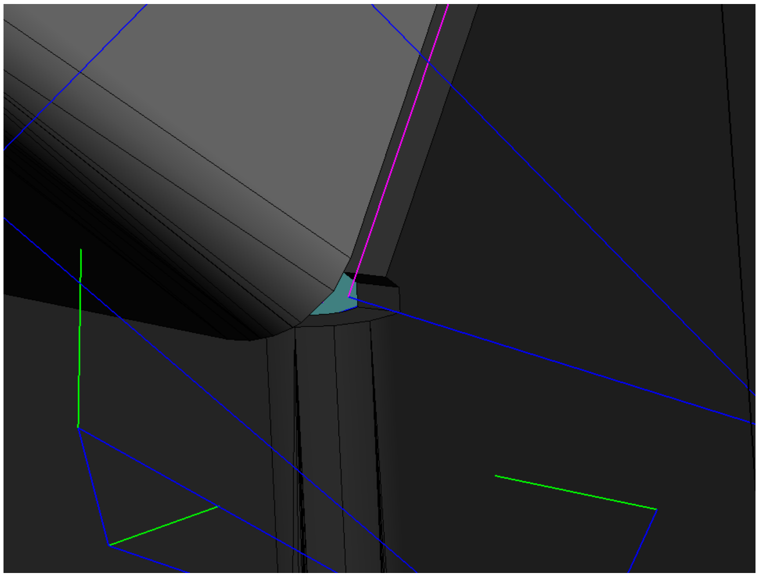

Figure B-1: measuring movements (green) and normal movements (blue) needed to measure part of weld (pink).

The measuring of the joints can be done in several ways. In the Image above the three green lines are the lines the welding wire follows with measuring mode on. The welding wire moves along the first green line and only stops when it contacts the product. Once it makes contact it writes down the coordinates for the X coordinate. It then repeats this process twice more at the remaining green lines to measure the coordinates in the Y and Z direction. The starting point of the joint is now determined. The sequence of measuring XYZ can be in any order. After the X, Y, and Z coordinates have been saved the welding robot repeats the process to determine the end point of the welding joint.

Another possibility is that the robot uses the length of the joint together with the starting point to determine the location of the complete joint. The length is stored within the program. With the length and the starting coordinates in the form of X, Y, and Z the welding robot can weld the welding joint.

It is sometimes possible to only have to measure one or two dimensions to find the location of the welding joint. This happens in two scenarios. If the components are always in the same exact location there will be no reason to measure one, two or three of the dimensions (X,Y, Z). The second scenario is that the location of the welding joint has already been partially or fully determined by the measuring of a previous welding joint close by. An example of this is would be two plates in an L shape which has to be welded from the inside and outside (shown in Figure B-2). It is only necessary to measure the location of one welding joint to weld both joints as both joints are defined by the same X,Y and Z coordinates. It is also possible to have scenarios where one or two dimensions need to be determined.

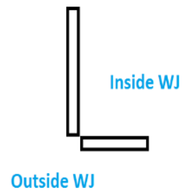

Figure B-2: L shaped formed by two plates. With a welding joint on the inside of the L and outside.

To conclude, every welding joint is measured differently and only the welding coordinator knows what information is needed for each welding joint. It would take weeks for the welding coordinator to explain the entire measurement process and this is simply not possible within the scope of this project.

Appendix C The Modular Design

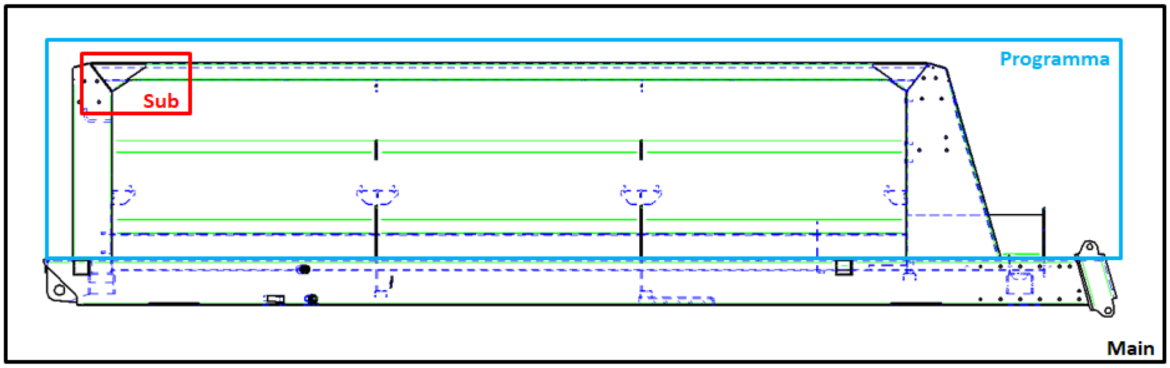

Figure C-1: The modular design of a hopper. The entire hopper is called the main. An example of a program is the upper part of the hopper as shown in blue. A sub is part of a program as shown in red. (Source: Aebi Schmidt)

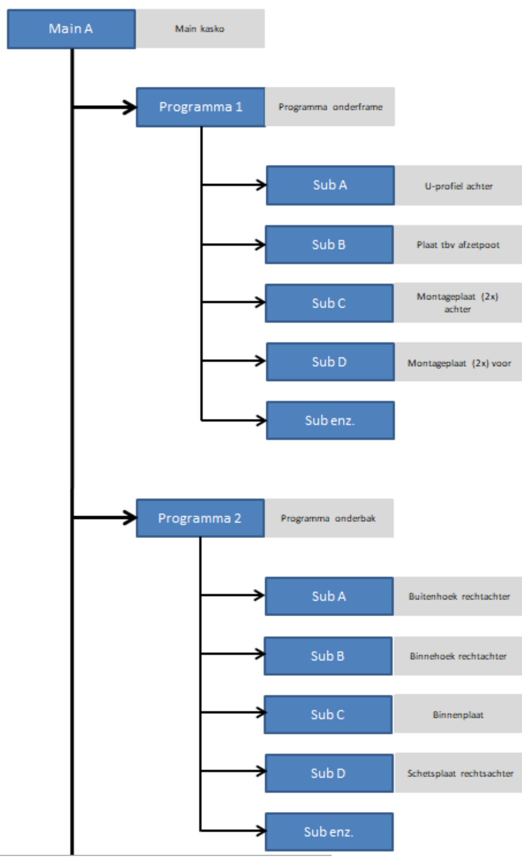

Figure C-2: The modular design as would be run by DTPS and the welding robot. It runs through program 1 and all its related subs first. Once the subs are completed program 2 would start. (Source: Aebi Schmidt)

Appendix D Flowcharts

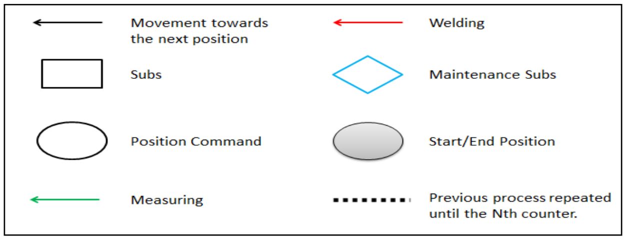

Figure D-1: Legend for the flowcharts.

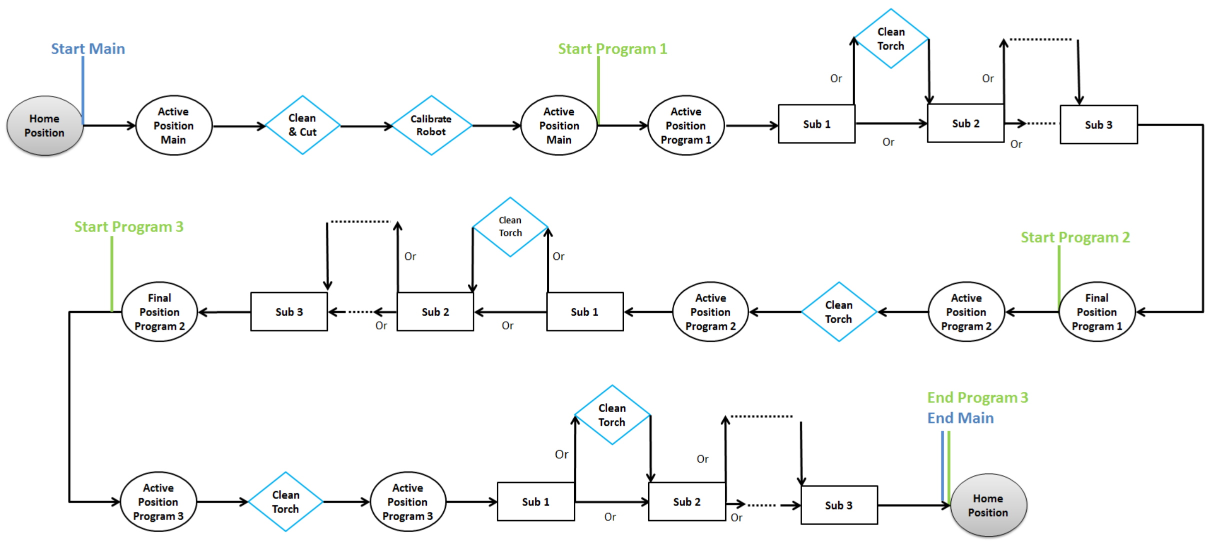

Figure D-2: Flowchart for the motions in one main and 3 programs.

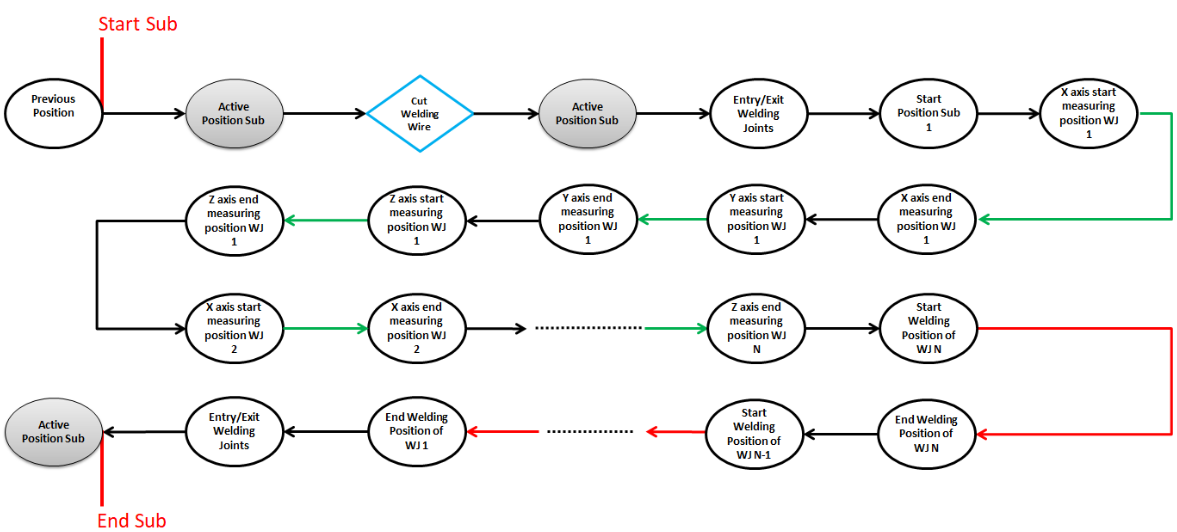

Figure D-3: Flowchart for the motions in one sub. The Nth counter represents the number of welds in a sub.

Appendix E List of Subs

	3600 Roro-Belt				3600 Attached-Worm		
	Frame	**Lower-bin**	**Connecting**		**Frame**	**Lower-bin**	**Connecting**
Number	1184591-6	1184370-3-3	FRO_OBB_Main	**Number**	1184542-6	1185100-7	FRO_OBB_Main
1	S3FRO_**VRBL**	S3OBB_**SSO**	S3FROOBB_**KVBL**	**1**	S3AF_**KVZL**	S3OB_**BUHRV**	S3ROOBB_**KVBL**
2	S3FRO_**VRBR**	S3OBB_**BSS**	S3FROOBB_**KAZR**	**2**	S3AF_**KVZR**	S3OB_**BUHRA**	S3ROOBB_**KAZR**
3	S3FRO_**UPR**	S3OBB_**OZF**	S3FROOBB_**KAZL**	**3**	S3AF_**BHAZ**	S3OBW_**SSOL**	S3ROOBB_**KAZL**
4	S3FRO_**UPL**	S3OB_**BUHRA**	S3FROOBB_**KVBR**	**4**	S3AF_**UPL**	S3OBW_**SSOL**	S3ROOBB_**KVBR**
5	S3FRO_**VPV**	S3OBB_**SSOL**	S3FROOBB_**KABL**	**5**	S3AF_**UPR**	S3OBW_**DP**	AFOBW_**KABR**
6	S3FRO_**VPA**	S3OBB_**SSOL**		**6**	S3AF_**VZ**	S3OBW_**BAZ**	
7	S3FRO_**RPAL**	S3OB_**BUHRV**		**7**	S3AF_**VP90GAR**	S3OB_**SPV**	
8	S3FRO_**RPAR**	S3OBB_**SS90G**		**8**	S3AF_**VP90GVR**	S3OBW_**SST**	
9	S3FRO_**ODR**	S3OBB_**SSB**		**9**	S3AF_**VP90GVL**	S3OBW_**SST**	
10	S3FRO_**ODL**	S3OBB_**BZA**		**10**	S3AF_**VP90GAL**	S3OB_**SPA**	
11	S3FRO_**VR180GL**	S3OB_**SPA**		**11**	S3AF_**VKOZ**	S3OBW_**BVZ**	
12	S3FRO_**VR180GR**	S3OBB_**SST**		**12**	S3AF_**AZF**	S3OBW_**SSW**	
13	S3FRO_**UPOVL**	S3OBB_**SST**		**13**		S3OBW_**WNB**	
14	S3FRO_**UPOVR**	S3OBB_**BP**		**14**		S3OB_**BUHLA**	
15		S3OB_**SPV**		**15**		S3OBW_**SSOR**	
16		S3OB_**BUHLV**		**16**		S3OBW_**SSOR**	
17		S3OBB_**SSOR**		**17**		S3OB_**BUHLV**	
18		S3OBB_**SSOR**		**18**			
19		S3OB_**BUHLA**		**19**			

Table E-1: Order of subs per program for the product 3600 Roro-Belt and 3600 Attached-Worm.

The sequence of the sub execution is top to bottom for Frame, top to bottom for Lower-bin and top to bottom for Connecting.

Main
Move
Wire Switch
Clean Cut 17 VWPR
ATC VWPR

3600 Roro-Belt

Frame	Lower-bin	Connecting
1184591-6	1184370-3-3	FRO_OBB_Main
Moving	Moving	Moving
Wire Switch	Wire Switch	Wire Switch
S3FRO_**VRBL**	Mech Cleaning	Mech Cleaning
S3FRO_**VRBR**	S3OBB_**SSO**	S3FROOBB_**KVBL**
Mech Cleaning	S3OBB_**BSS**	S3FROOBB_**KAZR**
S3FRO_**UPR**	Mech Cleaning	Turning/Moving
S3FRO_**UPL**	S3OBB_**OZF**	Mech Cleaning
Mech Cleaning	Turning/Moving	S3FROOBB_**KAZL**
S3FRO_**VPV**	S3OB_**BUHRA**	S3FROOBB_**KVBR**
S3FRO_**VPA**	Mech Cleaning	Turning/Moving
Mech Cleaning	S3OBB_**SSOL**	Mech Cleaning
S3FRO_**RPAL**	S3OBB_**SSOL**	S3FROOBB_**KABL**
Mech Cleaning	Mech Cleaning	Move Back
S3FRO_**RPAR**	S3OB_**BUHRV**	
Turning/Moving	S3OBB_**SS90G**	
Mech Cleaning	Turning/Moving	
S3FRO_**ODR**	S3OBB_**SSB**	
Turning	S3OBB_**BZA**	
S3FRO_**ODL**	Mech Cleaning	
Turning/Moving	S3OB_**SPA**	
Mech Cleaning	S3OBB_**SST**	
S3FRO_**VR180GL**	S3OBB_**SST**	
S3FRO_**VR180GR**	Mech Cleaning	
Mech Cleaning	S3OBB_**BP**	
S3FRO_**UPOVL**	S3OB_**SPV**	
S3FRO_**UPOVR**	Turning/Moving	
Move Back	S3OB_**BUHLV**	
	Mech Cleaning	
	S3OBB_**SSOR**	
	S3OBB_**SSOR**	
	S3OB_**BUHLA**	
	Move Back	

3600 Attached-Worm

Frame	Lower-bin	Connecting
1184542-6	1185100-7	FRO_OBB_Main
Moving	Moving	Moving
Wire Switch	Wire Switch	Wire Switch
S3AF_**KVZL**	Clean Cut	Mech Cleaning
S3AF_**KVZR**	Turning	S3ROOBB_**KVBL**
S3AF_**BHAZ**	Mech Cleanning	S3ROOBB_**KAZR**
Mech Cleaning	S3OB_**BUHRV**	Turning/Moving
S3AF_**UPL**	S3OB_**BUHRA**	Mech Cleaning
S3AF_**UPR**	Mech Cleanning	S3ROOBB_**KAZL**
S3AF_**VZ**	S3OBW_**SSOL**	S3ROOBB_**KVBR**
Turning/Moving	S3OBW_**SSOL**	Turning/Moving
Mech Cleaning	Turning/Moving	Mech Cleaning
S3AF_**VP90GAR**	Mech Cleanning	AFOBW_**KABR**
S3AF_**VP90GVR**	S3OBW_**DP**	Moving Back
Turning/Moving	S3OBW_**BAZ**	
Mech Cleaning	S3OB_**SPV**	
S3AF_**VP90GVL**	Mech Cleanning	
S3AF_**VP90GAL**	S3OBW_**SST**	
Turning/Moving	S3OBW_**SST**	
Mech Cleaning	Mech Cleanning	
S3AF_**VKOZ**	S3OB_**SPA**	
S3AF_**AZF**	S3OBW_**BVZ**	
Move Back	S3OBW_**SSW**	
	S3OBW_**WNB**	
	Turning/Moving	
	Mech Cleanning	
	S3OB_**BUHLA**	
	S3OBW_**SSOR**	
	S3OBW_**SSOR**	
	S3OB_**BUHLV**	
	Move Back	

Table E-2: The list of maintenance activities, movements/ rotations, and subs in the programs.

This is another view on the sequence of the subs but with movements and turns of the external axes (G4, G5 and G6) made are highlighted in green while the maintenance subs are highlighted in blue. Normal subs are in black with the most important naming factor highlighted.

Main

Main
Wire Switch
Clean Cut
ATC

3600 Roro-Belt

Frame	Lower-bin	Connecting
1184591-6	1184370-3-3	FRO_OBB_Main
Wire Switch	Wire Switch	Wire Switch
Wire Cut	Mech Cleaning	Mech Cleaning
S3FRO_VRBL	Wire Cut	Wire Cut
Wire Cut	S3OBB_SSO	S3FROOBB_KVBL
S3FRO_VRBR	Wire Cut	Wire Cut
Mech Cleaning	S3OBB_BSS	S3FROOBB_KAZR
Wire Cut	Mech Cleaning	Mech Cleaning
S3FRO_UPR	Wire Cut	Wire Cut
Wire Cut	S3OBB_OZF	S3FROOBB_KAZL
S3FRO_UPL	Wire Cut	Wire Cut
Mech Cleaning	S3OB_BUHRA	S3FROOBB_KVBR
Wire Cut	Mech Cleaning	Mech Cleaning
S3FRO_VPV	Wire Cut	Wire Cut
Wire Cut	S3OBB_SSOL	S3FROOBB_KABL
S3FRO_VPA	Wire Cut	
Mech Cleaning	S3OBB_SSOL	
Wire Cut	Mech Cleaning	
S3FRO_RPAL	Wire Cut	
Mech Cleaning	S3OB_BUHRV	
Wire Cut	Wire Cut	
S3FRO_RPAR	S3OBB_SS90G	
Mech Cleaning	Wire Cut	
Wire Cut	S3OBB_SSB	
S3FRO_ODR	Wire Cut	
Wire Cut	S3OBB_BZA	
S3FRO_ODL	Mech Cleaning	
Mech Cleaning	Wire Cut	
Wire Cut	S3OB_SPA	
S3FRO_VR180GL	Wire Cut	
Wire Cut	S3OBB_SST	
S3FRO_VR180GR	Wire Cut	
Mech Cleaning	S3OBB_SST	
Wire Cut	Mech Cleaning	
S3FRO_UPOVL	Wire Cut	
Wire Cut	S3OBB_BP	
S3FRO_UPOVR	Wire Cut	
	S3OB_SPV	
	Wire Cut	
	S3OB_BUHLV	
	Mech Cleaning	
	Wire Cut	
	S3OBB_SSOR	
	Wire Cut	
	S3OBB_SSOR	
	Wire Cut	
	S3OB_BUHLA	

3600 Attached-Worm

Frame	Lower-bin	Connecting
1184542-6	1185100-7	FRO_OBB_Main
Wire Switch	Wire Switch	Wire Switch
Wire Cut	Clean Cut	Mech Cleaning
S3AF_KVZL	Mech Cleanning	Wire Cut
Wire Cut	Wire Cut	S3ROOBB_KVBL
S3AF_KVZR	S3OB_BUHRV	Wire Cut
Wire Cut	Wire Cut	S3ROOBB_KAZR
S3AF_BHAZ	S3OB_BUHRA	Mech Cleaning
Mech Cleaning	Mech Cleanning	Wire Cut
Wire Cut	Wire Cut	S3ROOBB_KAZL
S3AF_UPL	S3OBW_SSOL	Wire Cut
Wire Cut	Wire Cut	S3ROOBB_KVBR
S3AF_UPR	S3OBW_SSOL	Mech Cleaning
Wire Cut	Mech Cleanning	Wire Cut
S3AF_VZ	Wire Cut	AFOBW_KABR
Mech Cleaning	S3OBW_DP	
Wire Cut	Wire Cut	
S3AF_VP90GAR	S3OBW_BAZ	
Wire Cut	Wire Cut	
S3AF_VP90GVR	S3OB_SPV	
Mech Cleaning	Mech Cleanning	
Wire Cut	Wire Cut	
S3AF_VP90GVL	S3OBW_SST	
Wire Cut	Wire Cut	
S3AF_VP90GAL	S3OBW_SST	
Mech Cleaning	Mech Cleanning	
Wire Cut	Wire Cut	
S3AF_VKOZ	S3OB_SPA	
Wire Cut	Wire Cut	
S3AF_AZF	S3OBW_BVZ	
	Wire Cut	
	S3OBW_SSW	
	Wire Cut	
	S3OBW_WNB	
	Mech Cleanning	
	Wire Cut	
	S3OB_BUHLA	
	Wire Cut	
	S3OBW_SSOR	
	Wire Cut	
	S3OBW_SSOR	
	Wire Cut	
	S3OB_BUHLV	

Table E-3: All the subs and maintenance subs in the main for a 3600 Roro-Belt and 3600 Attached-Worm.

The maintenance sub Wire cut has been placed outside of each sub in order to visualize the ordering of maintenance and normal subs.

Appendix F Locations of Subs and Active Position

Introduction

The location of the different subs of program Connecting for the Attached-Worm variant are visualized in Fig. F-1a All the welding joints of a sub are within a rectangle or on a line. The Y axis has the same direction as the gallows (G4) and the X axis has the same direction of G5. The dimensions in the Z direction (depth) are ignored as the movements in this direction are relatively small compared to the X and Y directions. Movements in this direction are more done by the fast robot arm and less by the slow movements of G4 and G5. The G6 movements are monitored.
In Appendix F-1 all locations of the subs per program per product variant are given. In the Appendix F-2 this is done for the coordinates of the subs and in Appendix F-3 the coordinates of the active positions are listed.

F-1 Locations of subs by program by product variant

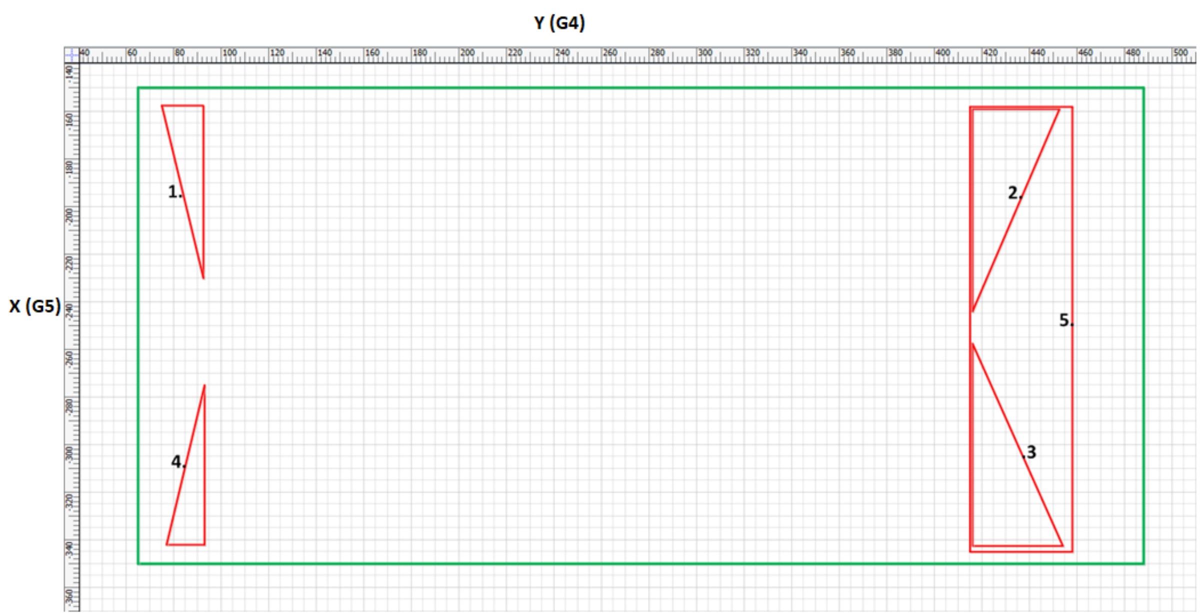

Figure F-1a: Placement of subs for the program Connecting of the 3600 Attached Worm

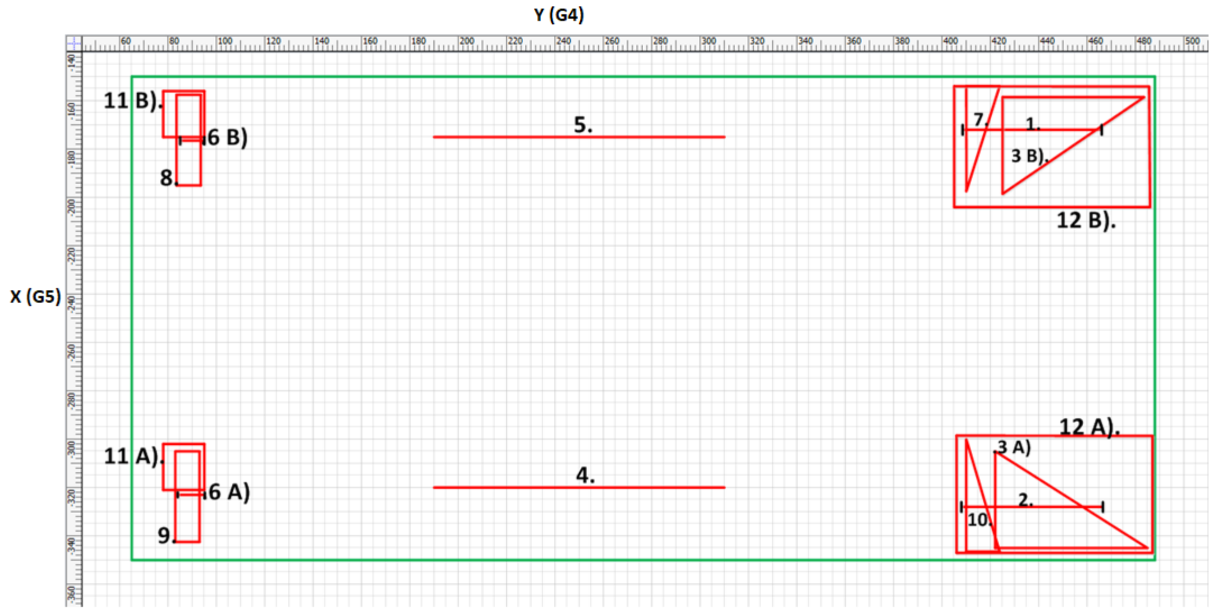

Figure F-1b: Placement of subs for the program Frame of the 3600 Attached Worm

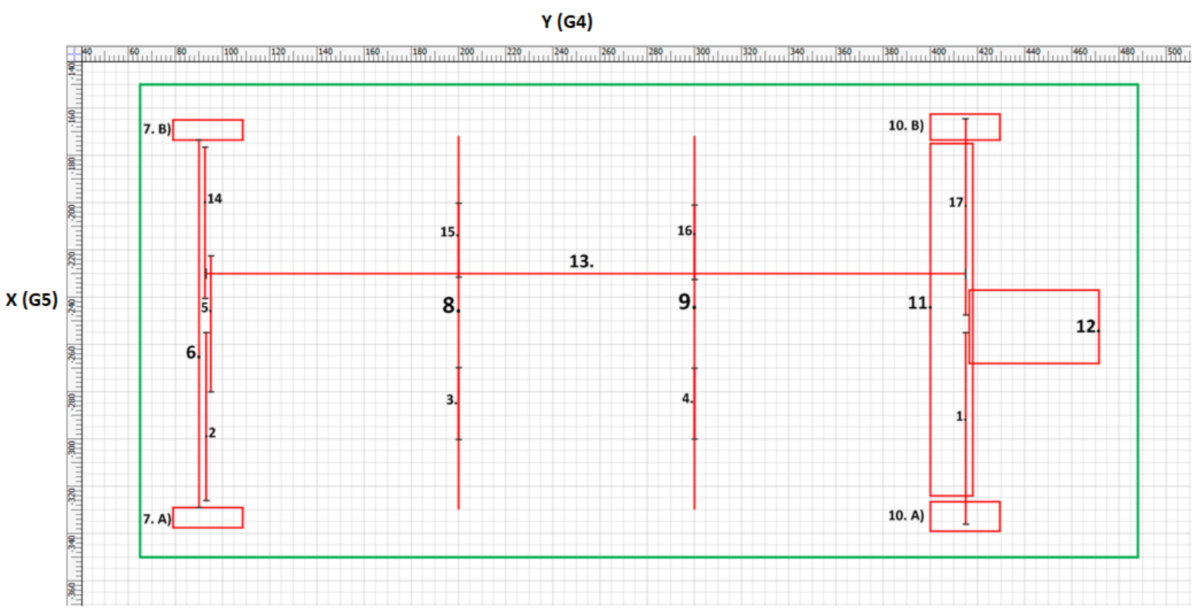

Figure F-1c: Placement of subs for the program Lower-bin of the 3600 Attached Worm

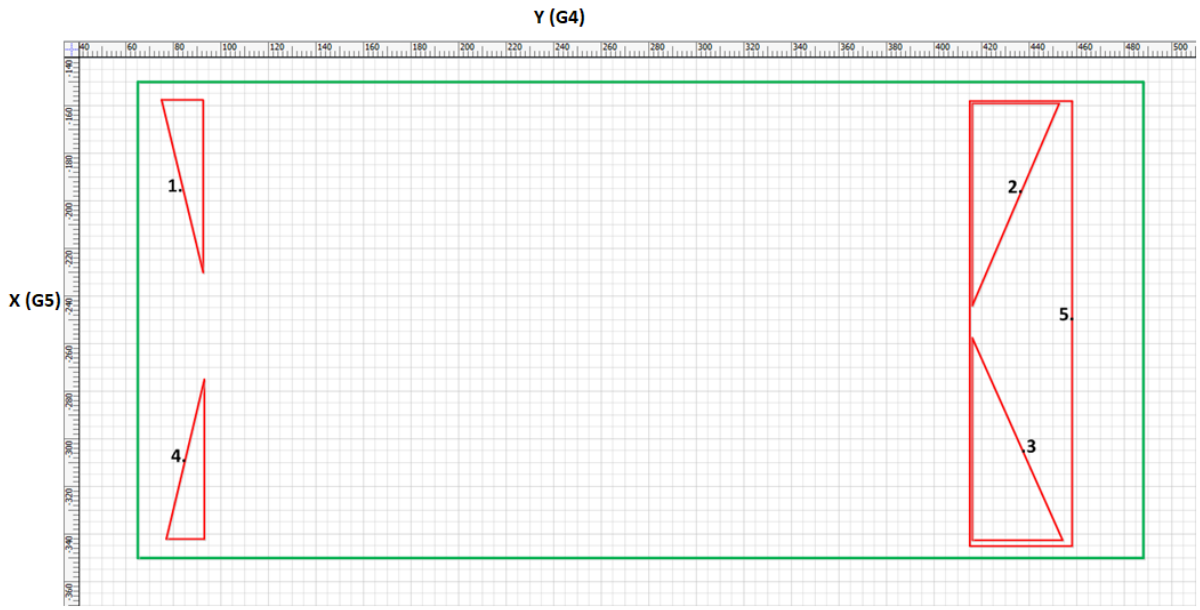

Figure F-1d: Placement of subs for the program Connecting of the 3600 Roro-Belt.

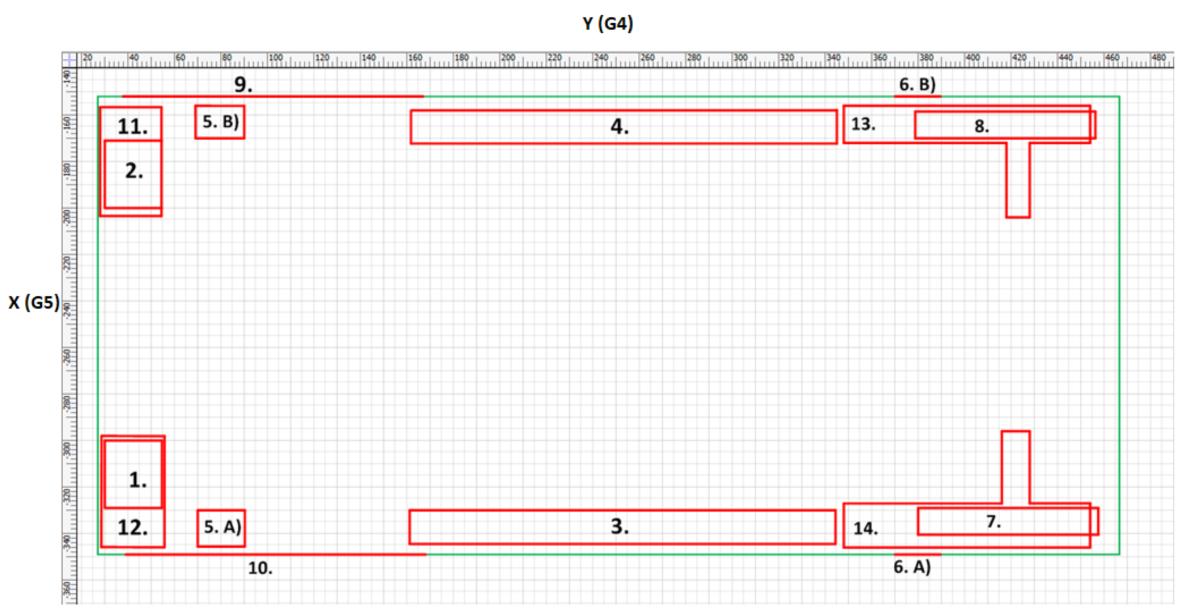

Figure F-1e: Placement of subs for the program Frame of the 3600 Roro-Belt.

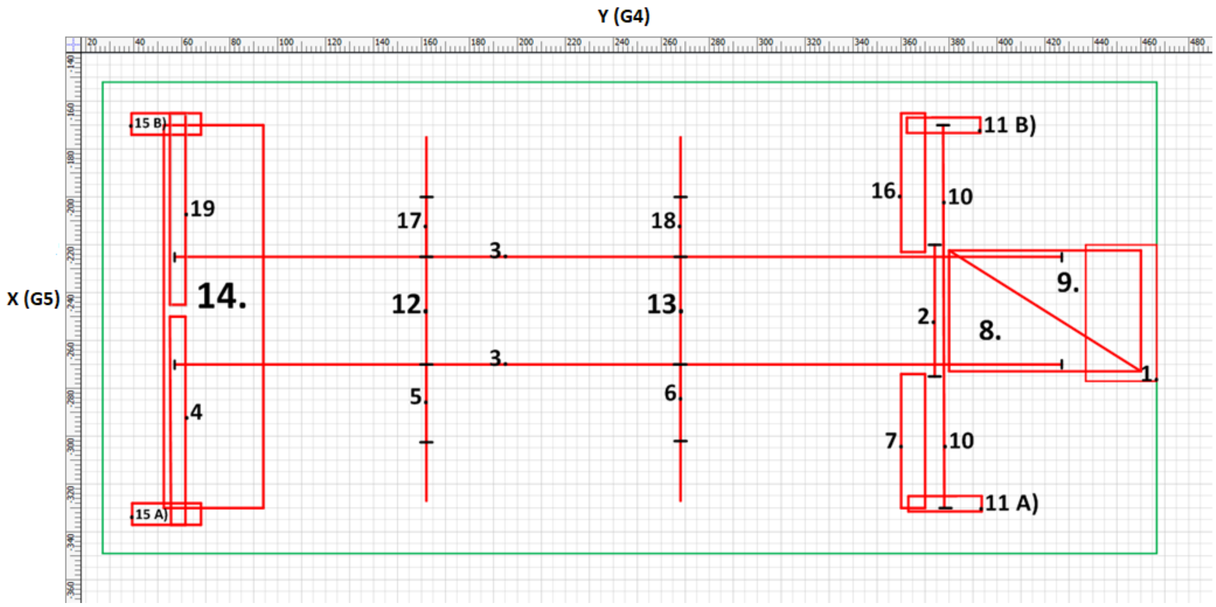

Figure F-1f: Placement of subs for the program Lower-bin of the 3600 Roro-Belt.

F-2 Coordinates and Angles of subs by program by Product Variant

3600 Attached-Worm Connecting						Angle:
						-90
	Connecting					
	FRO_OBB_Main	1	S3ROOBB_**KVBL**			
Number				Width (X)	Length (Y)	
1	S3ROOBB_**KVBL**		Pos 1	1571	775	
2	S3ROOBB_**KAZR**		Pos 2	2357	929	-90
3	S3ROOBB_**KAZL**					
4	S3ROOBB_**KVBR**	2	S3ROOBB_**KAZR**			
5	AFOBW_**KABR**			Width (X)	Length (Y)	
			Pos 1	1580	4142	
			Pos 2	2434	4522	90
		3	S3ROOBB_**KAZL**			
				Width (X)	Length (Y)	
			Pos 1	2586	4141	
			Pos 2	3430	4521	90
		4	S3ROOBB_**KVBR**			
				Width (X)	Length (Y)	
			Pos 1	2760	775	
			Pos 2	3433	932	0
		5	AFOBW_**KABR**			
				Width (X)	Length (Y)	
			Pos 1	1584	4148	
			Pos 2	3434	4524	

Table F-2a: sub Coordinates and angles for the program Connecting of the 3600 Attached-Worm.

3600 Attached-Worm Frame

Number	Frame 1184542-6
1	S3AF_**KVZL**
2	S3AF_**KVZR**
3	S3AF_**BHAZ**
4	S3AF_**UPL**
5	S3AF_**UPR**
6	S3AF_**VZ**
7	S3AF_**VP90GAR**
8	S3AF_**VP90GVR**
9	S3AF_**VP90GVL**
10	S3AF_**VP90GAL**
11	S3AF_**VKOZ**
12	S3AF_**AZF**

No.	Sub	Program	Angle:	Pos 1 Width (X)	Pos 1 Length (Y)	Pos 2 Width (X)	Pos 2 Length (Y)
1		S3AF_**KVZL**	0 (-45)	1722	4141	1722	4653
2		S3AF_**KVZR**	0 (45)	3290	4140	3290	4650
3	a	S3AF_**BHAZ**	0	3051	4236	3446	4864
3	b	S3AF_**BHAZ**	0	1574	4236	1966	4875
4		S3AF_**UPL**	0 (45)	3200	1993	3200	3115
5		S3AF_**UPR**	0(-45)	1750	1980	1750	3115
6	a	S3AF_**VZ**	0	3290	840	3290	930
6	b	S3AF_**VZ**	0	1723	840	1723	930
7		S3AF_**VP90GAR**	-90	1526	4130	1985	4230
8		S3AF_**VP90GVR**	-90	1566	837	1984	939
9		S3AF_**VP90GVL**	90	3046	838	3448	939
10		S3AF_**VP90GAL**	90	3046	4130	3448	4228
11	a	S3AF_**VKOZ**	180	1568	773	1757	950
11	b	S3AF_**VKOZ**	180	3250	773	3450	945
12	a	S3AF_**AZF**	180	2972	4060	3445	4870
12	b	S3AF_**AZF**	180	1570	4060	1982	4870

Table F-2b: sub Coordinates and angles for the program Frame of the 3600 Attached-Worm.

3600 Attached-Worm Lower-bin

Number	Lower-bin 1185100-7
1	S3OB_**BUHRV**
2	S3OB_**BUHRA**
3	S3OBW_**SSOL**
4	S3OBW_**SSOL**
5	S3OBW_**DP**
6	S3OBW_**BAZ**
7	S3OB_**SPV**
8	S3OBW_**SST**
9	S3OBW_**SST**
10	S3OB_**SPA**
11	S3OBW_**BVZ**
12	S3OBW_**SSW**
13	S3OBW_**WNB**
14	S3OB_**BUHLA**
15	S3OBW_**SSOR**
16	S3OBW_**SSOR**
17	S3OB_**BUHLV**

No.	Sub	Program	Angle:	Pos 1 Width (X)	Pos 1 Length (Y)	Pos 2 Width (X)	Pos 2 Length (Y)
1		S3OB_**BUHRV**	90	2580	4143	3378	4142
2		S3OB_**BUHRA**	90	2533	930	3250	930
3		S3OBW_**SSOL**	90	2720	2000	3000	2000
4		S3OBW_**SSOL**	90	2720	3070	3000	3070
5		S3OBW_**DP**	0	2230	940	2800	940
6		S3OBW_**BAZ**	0	1732	900	3290	900
7	a	S3OB_**SPV**	0	3293	774	3373	1070
7	b	S3OB_**SPV**	0	1654	777	1730	1070
8		S3OBW_**SST**	0	1734	2000	3290	2000
9		S3OBW_**SST**	0	1734	3080	3290	3080
10	a	S3OB_**SPA**	0	3260	4000	3370	4318
10	b	S3OB_**SPA**	0	1650	4000	1760	4318
11		S3OBW_**BVZ**	0	1728	3992	3243	4177
12		S3OBW_**SSW**	0	2385	4150	2685	4700
13		S3OBW_**WNB**	0	2300	934	2300	4150
14		S3OB_**BUHLA**	-90	1722	900	2440	932
15		S3OBW_**SSOR**	-90	2000	2000	2294	2000
16		S3OBW_**SSOR**	-90	2000	3070	2295	3070
17		S3OB_**BUHLV**	-90	1650	3990	2480	4177

Table F-2c: sub Coordinates and angles for the program Lower-bin of the 3600 Attached-Worm.

Connecting 3600 Roro-Belt

Number	**Connecting** FRO_OBB_Main
1	S3FROOBB_**KVBL**
2	S3FROOBB_**KAZR**
3	S3FROOBB_**KAZL**
4	S3FROOBB_**KVBR**
5	S3FROOBB_**KABL**

No.	Name	Width (X)	Length (Y)	Angle
1	S3FROOBB_**KVBL**			-90
		Width (X)	Length (Y)	
	Pos 1	1580	390	
	Pos 2	2277	560	
2	S3FROOBB_**KAZR**			-90
		Width (X)	Length (Y)	
	Pos 1	1586	3760	
	Pos 2	2269	4136	
3	S3FROOBB_**KAZL**			90
		Width (X)	Length (Y)	
	Pos 1	2758	3760	
	Pos 2	3431	4142	
4	S3FROOBB_**KVBR**			90
		Width (X)	Length (Y)	
	Pos 1	2736	390	
	Pos 2	3433	557	
5	S3FROOBB_**KABL**			0
		Width (X)	Length (Y)	
	Pos 1	1583	3986	
	Pos 2	3435	4360	

Table F-2d: sub Coordinates and angles for the program Connecting of the 3600 Roro-Belt.

3600 Roro-Belt Frame

Number	**Frame** 1184591-6
1	S3FRO_**VRBL**
2	S3FRO_**VRBR**
3	S3FRO_**UPR**
4	S3FRO_**UPL**
5	S3FRO_**VPV**
6	S3FRO_**VPA**
7	S3FRO_**RPAL**
8	S3FRO_**RPAR**
9	S3FRO_**ODR**
10	S3FRO_**ODL**
11	S3FRO_**VR180GL**
12	S3FRO_**VR180GR**
13	S3FRO_**UPOVL**
14	S3FRO_**UPOVR**

No.		Name			Angle:		Name			Angle:
1		S3FRO_**VRBL**			0					
			Width (X)	Length (Y)						
		Pos 1	3000	289						
		Pos 2	3290	547						
2		S3FRO_**VRBR**			0					
			Width (X)	Length (Y)						
		Pos 1	2014	546						
		Pos 2	1723	277						
3		S3FRO_**UPR**			0 (45)					
			Width (X)	Length (Y)						
		Pos 1	3289	1612						
		Pos 2	3448	3543						
4		S3FRO_**UPL**			0 (-45)					
			Width (X)	Length (Y)						
		Pos 1	1567	3540						
		Pos 2	1726	1611						
5	a	S3FRO_**VPV**			0 (45)	b	S3FRO_**VPV**			-45
			Width (X)	Length (Y)				Width (X)	Length (Y)	
		Pos 1	3449	903			Pos 1	1700	903	
		Pos 2	3300	692			Pos 2	1564	692	
6	a	S3FRO_**VPA**			0 (45)	b	S3FRO_**VPA**			-45
			Width (X)	Length (Y)				Width (X)	Length (Y)	
		Pos 1	3500	3718			Pos 1	1555	3718	
		Pos 2	3500	3892			Pos 2	1555	3892	
7		S3FRO_**RPAL**			0					
			Width (X)	Length (Y)						
		Pos 1	3291	3797						
		Pos 2	3419	4548						
8		S3FRO_**RPAR**			0					
			Width (X)	Length (Y)						
		Pos 1	1587	3765						
		Pos 2	1730	4552						
9		S3FRO_**ODR**			-90					
			Width (X)	Length (Y)						
		Pos 1	1550	397						
		Pos 2	1550	1679						
10		S3FRO_**ODL**			90					
			Width (X)	Length (Y)						
		Pos 1	3500	397						
		Pos 2	3500	1679						
11		S3FRO_**VR180GL**			180					
			Width (X)	Length (Y)						
		Pos 1	1566	277						
		Pos 2	2028	545						
12		S3FRO_**VR180GR**			180					
			Width (X)	Length (Y)						
		Pos 1	29990	277						
		Pos 2	3450	545						
13		S3FRO_**UPOVL**			180	SC				180
			Width (X)	Length (Y)				Width (X)	Length (Y)	
		Pos 1	1572	3469			Pos 1	1761	4270	
		Pos 2	1706	4532			Pos 2	2027	4170	
14		S3FRO_**UPOVR**			180	SC				180
			Width (X)	Length (Y)				Width (X)	Length (Y)	
		Pos 1	3307	3478			Pos 1	2963	4270	
		Pos 2	3473	4555			Pos 2	3281	4170	

Table F-2e: sub Coordinates and angles for the program Frame of the 3600 Roro-Belt.

Lower-bin 3600 Roro-Belt

Number	Lower-bin 1184370-3-3
1	S3OBB_**SSO**
2	S3OBB_**BSS**
3	S3OBB_**OZF**
4	S3OB_**BUHRA**
5	S3OBB_**SSOL**
6	S3OBB_**SSOL**
7	S3OB_**BUHRV**
8	S3OBB_**SS90G**
9	S3OBB_**SSB**
10	S3OBB_**BZA**
11	S3OB_**SPA**
12	S3OBB_**SST**
13	S3OBB_**SST**
14	S3OBB_**BP**
15	S3OB_**SPV**
16	S3OB_**BUHLV**
17	S3OBB_**SSOR**
18	S3OBB_**SSOR**
19	S3OB_**BUHLA**

					Angle
1		S3OBB_**SSO**			180
			Width (X)	Length (Y)	
		Pos 1	2257	4373	
		Pos 2	2767	4657	
2		S3OBB_**BSS**			180
			Width (X)	Length (Y)	135
		Pos 1	2280	3760	225
		Pos 2	2735	3760	
3		S3OBB_**OZF**			180
			Width (X)	Length (Y)	
		Pos 1	2252	577	
		Pos 2	2750	4271	
4		S3OB_**BUHRA**			90
			Width (X)	Length (Y)	
		Pos 1	2507	550	
		Pos 2	3370	618	
5		S3OBB_**SSOL**			90
			Width (X)	Length (Y)	
		Pos 1	2700	1620	
		Pos 2	3021	1620	
6		S3OBB_**SSOL**			90
			Width (X)	Length (Y)	
		Pos 1	2700	2690	
		Pos 2	3021	2690	
7		S3OBB_**BUHRV**			90
			Width (X)	Length (Y)	
		Pos 1	2740	3600	
		Pos 2	3300	3700	
8		S3OBB_**SS90G**			90
			Width (X)	Length (Y)	
		Pos 1	2290	3800	
		Pos 2	2750	4600	
9		S3OBB_**SSB**			0
			Width (X)	Length (Y)	
		Pos 1	2290	3800	
		Pos 2	2750	4600	
10		S3OBB_**BZA**			0
			Width (X)	Length (Y)	
		Pos 1	1748	3790	
		Pos 2	3291	3790	

					Angle					
11	a	S3OB_**SPA**			0	b	S3OB_**SPA**			0
			Width (X)	Length (Y)				Width (X)	Length (Y)	
		Pos 1	3250	3624			Pos 1	1650	3624	
		Pos 2	3370	3937			Pos 2	1761	3937	
12		S3OBB_**SST**								
			Width (X)	Length (Y)	0					
		Pos 1	1750	1620						
		Pos 2	3280	1620						
13		S3OBB_**SST**								
			Width (X)	Length (Y)	0					
		Pos 1	1750	2690						
		Pos 2	3280	2690						
14		S3OBB_**BP**								
			Width (X)	Length (Y)	0					
		Pos 1	1700	532						
		Pos 2	3300	920						
15	a	S3OB_**SPV**			0	b	S3OB_**SPV**			0
			Width (X)	Length (Y)				Length (X)	Length (Y)	
		Pos 1	3280	393			Pos 1	1650	393	
		Pos 2	3370	682			Pos 2	1740	682	
16		S3OB_**BUHLV**			-90					
			Width (X)	Length (Y)						
		Pos 1	1650	3610						
		Pos 2	2260	3760						
17		S3OBB_**SSOR**			-90					
			Width (X)	Length (Y)						
		Pos 1	2000	1620						
		Pos 2	2280	1620						
18		S3OBB_**SSOR**			-90					
			Width (X)	Length (Y)						
		Pos 1	2000	2690						
		Pos 2	2280	2690						
19		S3OB_**BUHLA**								
			Width (X)	Length (Y)	-90					
		Pos 1	1642	560						
		Pos 2	2266	560						

Table F-2f: sub Coordinates and angles for the program Lower-bin of the 3600 Roro-Belt.

F-3 Coordinates of Active Positions by Program by Product Variant

3600 Attached-Worm Connecting

Number	Connecting FRO_OBB_Main
1	S3ROOBB_**KVBL**
2	S3ROOBB_**KAZR**
3	S3ROOBB_**KAZL**
4	S3ROOBB_**KVBR**
5	AFOBW_**KABR**

1	S3FROOBB_**KVBL**		E
		Joint	Position
		G4	2500
		G5	800
		G6	-90
2	S3FROOBB_**KAZR**		E
		Joint	Position
		G4	2359
		G5	800
		G6	-90
3	S3FROOBB_**KAZL**		E
		Joint	Position
		G4	2359
		G5	800
		G6	90
4	S3FROOBB_**KVBR**		E
		Joint	Position
		G4	2500
		G5	800
		G6	90
5	AFOBW_**KABR**		E
		Joint	Position
		G4	5450
		G5	400
		G6	0

2->3	**Turning/Move**		**E**	
		Joint	**Position**	**Distance**
		G4	**2500**	**141**
		G5	**1000**	**200**
		G6	**90**	**180**
3->4	**Turning/Move**		**E**	
		Joint	**Position**	**Distance**
		G4	**5250**	**2750**
		G5	**1000**	**200**
		G6	**0**	**90**

Table F-3a: Coordinates of active positions for the program Connecting of the 3600 Attached-Worm.

3600 Attached-Worm Frame

Number	Frame 1184542-6
1	S3AF_**KVZL**
2	S3AF_**KVZR**
3	S3AF_**BHAZ**
4	S3AF_**UPL**
5	S3AF_**UPR**
6	S3AF_**VZ**
7	S3AF_**VP90GAR**
8	S3AF_**VP90GVR**
9	S3AF_**VP90GVL**
10	S3AF_**VP90GAL**
11	S3AF_**VKOZ**
12	S3AF_**AZF**

No.	Name	Joint	E Position	Distance	
1	S3AF_**KVZL**	G4	5503		
		G5	1000		
		G6	0		-45
2	S3AF_**KVZR**	G4	5503		
		G5	1000		
		G6	0		45
3	S3AF_**BHAZ**	G4	4000		
		G5	800		
		G6	0		
4	S3AF_**UPL**				45
		G4	1500		
		G5	500		
		G6	0		
5	S3AF_**UPR**				-45
		G4	1500		
		G5	500		
		G6	0		
6	S3AF_**VZ**	G4	2000		
		G5	1000		
		G6	0		
7	S3AF_**VP90GAR**	G4	2593		
		G5	1200		
		G6	-90		
8	S3AF_**VP90GVR**	G4	2593		
		G5	1200		
		G6	-90		
9	S3AF_**VP90GVL**	G4	2593		
		G5	1200		
		G6	90		
10	S3AF_**VP90GAL**	G4	2593		
		G5	1200		
		G6	90		
11	S3AF_**VKOZ**	G4	2000		
		G5	1200		
		G6	180		
12	S3AF_**AZF**	G4	4000		
		G5	0		
		G6	180		
6->7	**Turning/Move**	**G4**	**2500**	**500**	
		G5	**1200**	**200**	
		G6	**-90**	**90**	
8->9	**Turning/Move**	**G4**	**2500**	**93**	
		G5	**1200**	**0**	
		G6	**90**	**180**	
10->11	**Turning/Move**	**G4**	**2000**	**593**	
		G5	**1200**	**0**	
		G6	**180**	**90**	

Table F-3b: Coordinates of active positions for the program Frame of the 3600 Attached-Worm.

3600 Attached-Worm Lower-bin

No.	Name	Joint	E Position	Distance
1	S3OB_**BUHRV**	G4	2506	
		G5	1000	
		G6	90	
2	S3OB_**BUHRA**	G4	2506	
		G5	1000	
		G6	90	
3	S3OBW_**SSOL**	G4	2918	
		G5	800	
		G6	90	
4	S3OBW_**SSOL**	G4	2918	
		G5	800	
		G6	90	
5	S3OBW_**DP**	G4	1500	
		G5	800	
		G6	0	
6	S3OBW_**BAZ**	G4	2268	
		G5	800	
		G6	0	
7	S3OB_**SPV**	G4	2200	
		G5	800	
		G6	0	
8	S3OBW_**SST**	G4	2842	
		G5	800	
		G6	0	
9	S3OBW_**SST**	G4	2842	
		G5	800	
		G6	0	
10	S3OB_**SPA**	G4	2000	
		G5	800	
		G6	0	
11	S3OBW_**BVZ**	G4	4760	
		G5	800	
		G6	0	
12	S3OBW_**SSW**	G4	3136	
		G5	800	
		G6	0	
13	S3OBW_**WNB**	G4	2461	
		G5	800	
		G6	0	
14	S3OB_**BUHLA**	G4	2506	
		G5	1000	
		G6	-90	
15	S3OBW_**SSOR**	G4	2918	
		G5	800	
		G6	-90	
16	S3OBW_**SSOR**	G4	2918	
		G5	800	
		G6	-90	
17	S3OB_**BUHLV**	G4	2506	
		G5	1000	
		G6	-90	
Program	**Turning**	**G4**	**N/A**	**N/A**
		G5	**N/A**	**N/A**
		G6	**90**	**90**
4->5	**Turning/Move**	**G4**	**1500**	**1418**
		G5	**1000**	**200**
		G6	**0**	**90**
13->14	**Turning/Move**	**G4**	**2500**	**39**
		G5	**1000**	**200**
		G6	**-90**	**90**

Table F-3c: Coordinates of active positions for the program Lower-bin of the 3600 Attached-Worm.

Connecting 3600 Roro-Belt

Number	Connecting FRO_OBB_Main
1	S3FROOBB_**KVBL**
2	S3FROOBB_**KAZR**
3	S3FROOBB_**KAZL**
4	S3FROOBB_**KVBR**
5	S3FROOBB_**KABL**

1	S3FROOBB_**KVBL**	**E**	
		Joint	Position
		G4	2500
		G5	800
		G6	-90

2	S3FROOBB_**KAZR**	**E**	
		Joint	Position
		G4	2359
		G5	800
		G6	-90

2->3	**Turning/Move**	**E**		
		Joint	**Position**	**Distance**
		G4	**2500**	**-141**
		G5	**1000**	**-200**
		G6	**90**	**-180**

3	S3FROOBB_**KAZL**	**E**	
		Joint	Position
		G4	2359
		G5	800
		G6	90

4	S3FROOBB_**KVBR**	**E**	
		Joint	Position
		G4	2500
		G5	800
		G6	90

4->5	**Turning/Move**	**E**		
		Joint	**Position**	**Distance**
		G4	**5250**	**-2750**
		G5	**1000**	**-200**
		G6	**0**	**90**

5	S3FROOBB_**KABL**	**E**	
		Joint	Position
		G4	5500
		G5	400
		G6	0

Table F-3d: Coordinates of active positions for the program Connecting of the 3600 Roro-belt.

3600 Roro-Belt Frame

Number	**Frame** 1184591-6
1	S3FRO_**VRBL**
2	S3FRO_**VRBR**
3	S3FRO_**UPR**
4	S3FRO_**UPL**
5	S3FRO_**VPV**
6	S3FRO_**VPA**
7	S3FRO_**RPAL**
8	S3FRO_**RPAR**
9	S3FRO_**ODR**
10	S3FRO_**ODL**
11	S3FRO_**VR180GL**
12	S3FRO_**VR180GR**
13	S3FRO_**UPOVL**
14	S3FRO_**UPOVR**

1	S3FRO_**VRBL**	**E**	
		Joint	Position
		G4	1643
		G5	400
		G6	0

2	S3FRO_**VRBR**	**E**	
		Joint	Position
		G4	1643
		G5	400
		G6	0

3	S3FRO_**UPR**	**E**		Note
		Joint	Position	
		G4	1643	
		G5	400	
		G6	0	45

4	S3FRO_**UPL**	**E**		Note
		Joint	Position	
		G4	1643	
		G5	400	
		G6	0	-45

5	S3FRO_**VPV**	**E**		Note
		Joint	Position	
		G4	2260	
		G5	800	
		G6	0	45/-45

6	S3FRO_**VPA**	**E**		Note
		Joint	Position	
		G4	2343	
		G5	800	
		G6	0	45/-45

7	S3FRO_**RPAL**	**E**	
		Joint	Position
		G4	3490
		G5	800
		G6	0

8	S3FRO_**RPAR**	**E**	
		Joint	Position
		G4	3493
		G5	800
		G6	0

9	S3FRO_**ODR**	**E**	
		Joint	Position
		G4	2800
		G5	800
		G6	-90

10	S3FRO_**ODL**	**E**	
		Joint	Position
		G4	2800
		G5	800
		G6	90

11	S3FRO_**VR180GL**	**E**	
		Joint	Position
		G4	1750
		G5	400
		G6	180

12	S3FRO_**VR180GR**	**E**	
		Joint	Position
		G4	1750
		G5	400
		G6	180

13	S3FRO_**UPOVL**	**E**	
		Joint	Position
		G4	4000
		G5	800
		G6	180

14	S3FRO_**UPOVR**	**E**	
		Joint	Position
		G4	4000
		G5	800
		G6	180

8->9	**Turning/Move**	**E**		
		Joint	**Position**	**Distance**
		G4	**2800**	**693**
		G5	**1000**	**-200**
		G6	**-90**	**90**

9->10	**Turning/Move**	**E**		
		Joint	**Position**	**Distance**
		G4	**2800**	**0**
		G5	**1000**	**-200**
		G6	**90**	**-180**

10->11	**Turning/Move**	**E**		
		Joint	**Position**	**Distance**
		G4	**1800**	**1000**
		G5	**1000**	**-200**
		G6	**180**	**-90**

Table F-3e: Coordinates of active positions for the program Frame of the 3600 Roro-belt.

Lower-bin 3600 Roro-Belt

Number	Lower-bin 1184370-3-3
1	S3OBB_SSO
2	S3OBB_BSS
3	S3OBB_OZF
4	S3OB_BUHRA
5	S3OBB_SSOL
6	S3OBB_SSOL
7	S3OB_BUHRV
8	S3OBB_SS90G
9	S3OBB_SSB
10	S3OBB_BZA
11	S3OB_SPA
12	S3OBB_SST
13	S3OBB_SST
14	S3OBB_BP
15	S3OB_SPV
16	S3OB_BUHLV
17	S3OBB_SSOR
18	S3OBB_SSOR
19	S3OB_BUHLA

		E	
1	S3OBB_SSO	Joint	Position
		G4	3343
		G5	400
		G6	180
2	S3OBB_BSS	Joint	Position
		G4	1900
		G5	1000
		G6	180
3	S3OBB_OZF	Joint	Position
		G4	100
		G5	1000
		G6	180
4	S3OB_BUHRA	Joint	Position
		G4	2506
		G5	1000
		G6	90
5	S3OBB_SSOL	Joint	Position
		G4	3043
		G5	1000
		G6	90
6	S3OBB_SSOL	Joint	Position
		G4	3043
		G5	1000
		G6	90
7	S3OB_BUHRV	Joint	Position
		G4	2506
		G5	1000
		G6	90
8	S3OBB_SS90G	Joint	Position
		G4	5418
		G5	800
		G6	90
9	S3OBB_SSB	Joint	Position
		G4	3343
		G5	800
		G6	0
10	S3OBB_BZA	Joint	Position
		G4	4843
		G5	1000
		G6	0
11	S3OB_SPA	Joint	Position
		G4	2000
		G5	800
		G6	0
12	S3OBB_SST	Joint	Position
		G4	2843
		G5	800
		G6	0
13	S3OBB_SST	Joint	Position
		G4	2843
		G5	800
		G6	0
14	S3OBB_BP	Joint	Position
		G4	2093
		G5	800
		G6	0
15	S3OB_SPV	Joint	Position
		G4	2200
		G5	800
		G6	0
16	S3OB_BUHLV	Joint	Position
		G4	2506
		G5	1000
		G6	-90
17	S3OBB_SSOR	Joint	Position
		G4	3043
		G5	1000
		G6	-90
18	S3OBB_SSOR	Joint	Position
		G4	3043
		G5	1000
		G6	-90
19	S3OB_BUHLA	Joint	Position
		G4	2506
		G5	1000
		G6	-90

		E		
3->4	Turning/Move	Joint	Position	Distance
		G4	2500	-2400
		G5	1150	-150
		G6	90	90
8->9	Turning/Move	Joint	Position	Distance
		G4	3400	-2912
		G5	1150	-350
		G6	0	90
15->16	Turning/Move	Joint	Position	Distance
		G4	2500	-300
		G5	1150	-350
		G6	-90	90

Table F-3f: Coordinates of active positions for the program Lower-bin of the 3600 Roro-belt.

Appendix G Position and Position Sequence

Table G-1, G-2 and G-3 show the position of the robotic arm and external axis in multiple scenarios. Table G-1 describes the home position of the main and the previous position of the welding Robot per program. The previous position for each program is the first position the welding robot is in when it starts a program. The previous position for a program is decides by the end position of the previous program. Thus, the previous position of program 2 and program 3 is the end position of program 1 and program 2 respectively. The previous position of program 1 is equal to the active position in the main (Flowchart D-2 in Appendix D).

Type	Description				
Main	Home Position	R0		E0	
	R0,E0	Joint	Angle	Joint	Position
		RT	35	G4	6850
		VA	135	G5	-1240
		FA	-40	G6	0
		RW	25		
		BW	-40		
		TW	0		
	Active Position	R1		E1	
		Joint	Angle	Joint	Position
		RT	0	G4	3000
		VA	65	G5	1100
		FA	25	G6	0
		RW	90		
		BW	-90		
		TW	0		
3600 Attached - Belt					
Program 1	Previous Position	R1		E1	
	R1,E1	Joint	Angle	Joint	Position
		RT	0	G4	3000
		VA	65	G5	1100
		FA	25	G6	0
		RW	90		
		BW	-90		
		TW	0		
Program 2	Previous Position	R1		E2	
	R1,E2	Joint	Angle	Joint	Position
		RT	0	G4	2500
		VA	65	G5	1000
		FA	25	G6	180
		RW	90		
		BW	-90		
		TW	0		
Program 3	Previous Position	R1		E3	
	R1, E3	Joint	Angle	Joint	Position
		RT	0	G4	2500
		VA	65	G5	1000
		FA	25	G6	-90
		RW	90		
		BW	-90		
		TW	0		

Type	Description				
Maintenance Position	Maintenance	R1			
	R1	Joint	Angle	Joint	Position
		RT	0	G4	N/A
		VA	65	G5	N/A
		FA	25	G6	N/A
		RW	90		
		BW	-90		
		TW	0		
3600 Roro - Worm					
Program 1	Previous Position	R1		E1	
	R1, E1	Joint	Angle	Joint	Position
		RT	0	G4	3000
		VA	65	G5	1100
		FA	25	G6	0
		RW	90		
		BW	-90		
		TW	0		
Program 2	Previous Position	R1		E2	
	R1,E2	Joint	Angle	Joint	Position
		RT	0	G4	2500
		VA	65	G5	1000
		FA	25	G6	180
		RW	90		
		BW	-90		
		TW	0		
Program 3	Previous Position	R1		E3	
	R1, E3	Joint	Angle	Joint	Position
		RT	0	G4	2500
		VA	65	G5	1000
		FA	25	G6	-90
		RW	90		
		BW	-90		
		TW	0		

Table G-1: Common positions for the welding robot.

Tables G-1 and G-2 show the three motions in chronological order (1 -> 3) made by the welding robot at the start of each program. Only the movement of the external axis is shown as the robotic arm is always in maintenance position (R1). The welding robot needs to move from the previous position (1) to the starting position of the first sub of the program (3). Before it moves to point 3 the welding robot needs to run some maintenance subs of the program. The programmer of the welding Robot has decided that in order to run a maintenance sub in the program the welding Robot needs to move to the active position. As the robotic arm is already in the maintenance position only the external axis sometimes moves. In program 2 - 3600 Roro-Belt, program 1 and 2 - 3600 Attached-Worm the external axis, mainly the gallows, moves.

3600 RORO-BELT								
1. Previous Position			**2. Active Position Program**			**3. Active Position First Sub of Program**		
Program 1	**E**		Program 1	**E**		Program 1	**E**	
	Joint	Position		Joint	Position	S3FRO_**VRBL**	Joint	Position
	G4	3000		G4	3000		G4	1643
	G5	1100		G5	1000		G5	400
	G6	0		G6	0		G6	0
Program 2	**E**		Program 2	**E**		Program 2	**E**	
	Joint	Position		Joint	Position	S3OBB_**SSO**	Joint	Position
	G4	3000		G4	2500		G4	3343
	G5	1000		G5	1000		G5	400
	G6	180		G6	180		G6	180
Program 3	**E**		Program 3	**E**		Program 3	**E**	
	Joint	Position		Joint	Position	S3ROOB_**KVBL**	Joint	Position
	G4	2500		G4	2500		G4	2500
	G5	1000		G5	1000		G5	800
	G6	-90		G6	-90		G6	-90

Table G-2: Three positions of the robot for all three programs of the 3600 Roro-Belt.

3600 ATTACHED - WORM								
1. Previous Position			**2. Active Position Program**			**3. Active Position First Sub of Program**		
Program 1	**E**		Program 1	**E**		Program 1	**E**	
	Joint	Position		Joint	Position	S3AF_**KVZL**	Joint	Position
	G4	3000		G4	5500		G4	5503
	G5	1100		G5	1000		G5	1000
	G6	0		G6	0		G6	0
Program 2	**E**		Program 2	**E**		Program 2	**E**	
	Joint	Position		Joint	Position	S3OB_**BUHRV**	Joint	Position
	G4	3000		G4	2500		G4	2506
	G5	1000		G5	1000		G5	1000
	G6	180		G6	180		G6	90
Program 3	**E**		Program 3	**E**		Program 3	**E**	
	Joint	Position		Joint	Position	S3ROOB_**KVBL**	Joint	Position
	G4	2500		G4	2500		G4	2500
	G5	1000		G5	1000		G5	800
	G6	-90		G6	-90		G6	-90

Table G-3: Three positions of the robot for all three programs of the 3600 Attached-Worm position of the welding robot for the 3000 and 4200 variants

3000 RORO-BELT

1. Previous Position			**2. Active Position Program**			**3. Active Position First Sub of Program**		
Program 1	**E**		Program 1	**E**		Program 1	**E**	
	Joint	Position		Joint	Position	S3FRO_**VRBL**	Joint	Position
	G4	3000		G4	3000		G4	1643
	G5	1100		G5	1000		G5	400
	G6	0		G6	0		G6	0
Program 2	**E**		Program 2	**E**		Program 2	**E**	
	Joint	Position		Joint	Position	S3OBB_**SSO**	Joint	Position
	G4	3000		G4	2500		G4	2743
	G5	1000		G5	1000		G5	400
	G6	180		G6	180		G6	180
Program 3	**E**		Program 3	**E**		Program 3	**E**	
	Joint	Position		Joint	Position	S3ROOB_**KVBL**	Joint	Position
	G4	2500		G4	2500		G4	2500
	G5	1000		G5	1000		G5	800
	G6	-90		G6	-90		G6	-90

4200 RORO-BELT

1. Previous Position			**2. Active Position Program**			**3. Active Position First Sub of Program**		
Program 1	**E**		Program 1	**E**		Program 1	**E**	
	Joint	Position		Joint	Position		Joint	Position
	G4	3000		G4	3000		G4	1643
	G5	1100		G5	1000		G5	400
	G6	0		G6	0		G6	0
Program 2	**E**		Program 2	**E**		Program 2	**E**	
	Joint	Position		Joint	Position		Joint	Position
	G4	3000		G4	2500		G4	3943
	G5	1000		G5	1000		G5	400
	G6	180		G6	180		G6	180
Program 3	**E**		Program 3	**E**		Program 3	**E**	
	Joint	Position		Joint	Position	S3ROOB_**KVBL**	Joint	Position
	G4	2500		G4	2500		G4	2500
	G5	1000		G5	1000		G5	800
	G6	-90		G6	-90		G6	-90

Table G-4: Three positions of the robot for all three programs of the 3000 and 4200 Roro-Belt.

3000 ATTACHED - WORM

1. Previous Position			**2. Active Position Program**			**3. Active Position First Sub of Program**		
Program 1	**E**		Program 1	**E**		Program 1	**E**	
	Joint	Position		Joint	Position	S3AF_**KVZL**	Joint	Position
	G4	3000		G4	5500		G4	4903
	G5	1100		G5	1000		G5	1000
	G6	0		G6	0		G6	0
Program 2	**E**		Program 2	**E**		Program 2	**E**	
	Joint	Position		Joint	Position	S3OB_**BUHRV**	Joint	Position
	G4	3000		G4	2500		G4	1906
	G5	1000		G5	1000		G5	1000
	G6	180		G6	180		G6	90
Program 3	**E**		Program 3	**E**		Program 3	**E**	
	Joint	Position		Joint	Position	S3ROOB_**KVBL**	Joint	Position
	G4	2500		G4	2500		G4	2500
	G5	1000		G5	1000		G5	800
	G6	-90		G6	-90		G6	-90

4200 ATTACHED - WORM

1. Previous Position			**2. Active Position Program**			**3. Active Position First Sub of Program**		
Program 1	**E**		Program 1	**E**		Program 1	**E**	
	Joint	Position		Joint	Position	S3AF_**KVZL**	Joint	Position
	G4	3000		G4	5500		G4	6103
	G5	1100		G5	1000		G5	1000
	G6	0		G6	0		G6	0
Program 2	**E**		Program 2	**E**		Program 2	**E**	
	Joint	Position		Joint	Position	S3OB_**BUHRV**	Joint	Position
	G4	3000		G4	2500		G4	3106
	G5	1000		G5	1000		G5	1000
	G6	180		G6	180		G6	90
Program 3	**E**		Program 3	**E**		Program 3	**E**	
	Joint	Position		Joint	Position	S3ROOB_**KVBL**	Joint	Position
	G4	2500		G4	2500		G4	2500
	G5	1000		G5	1000		G5	800
	G6	-90		G6	-90		G6	-90

Table G-5: Three positions of the robot for all three programs of the 3000 and 4200 Attached-Worm.

Appendix H Instances of Wasteful Motions

Removed: Confidential

Appendix I Literature Protocol

Search Strings:

The search strings used are a combination of the terms cause, “welding robots”, “industrial robot” “wasteful motion”. For the term “wasteful motion” synonyms or identical phrases are used. Wasteful is substituted with effective or efficient. Motion can be replaced by movement.

Results:

Platform	Search Strings	Hits	Date	Scope
scopus	cause AND "wasteful motion" AND "welding robots"	0	Any	article title, abstract and keywords
scopus	cause AND "wasteful motion" AND "industrial robots"	0	Any	article title, abstract and keywords
scopus	cause AND "wasteful movement" AND "industrial robots"	0	Any	article title, abstract and keywords
scopus	cause AND "effective movement" AND "industrial robots"	0	Any	article title, abstract and keywords
scopus	cause AND "efficient movement" AND "industrial robots"	0	Any	article title, abstract and keywords
scopus	cause AND "efficient motion " AND "industrial robots"	1	Any	article title, abstract and keywords
scopus	cause AND "effective motion" AND "industrial robots"	0	Any	article title, abstract and keywords
web of science	cause AND "wasteful motion" AND "welding robot"	0	Any	topic or title
web of science	cause AND "wasteful motion" AND "industrial robots"	0	Any	topic or title
web of science	cause AND "wasteful movement" AND "industrial robots"	0	Any	topic or title
web of science	cause AND "effective movement" AND "industrial robots"	0	Any	topic or title
web of science	cause AND "efficient movement" AND "industrial robots"	0	Any	topic or title
web of science	cause AND "efficient motion " AND "industrial robots"	1	Any	topic or title
web of science	cause AND "effective motion" AND "industrial robots"	0	Any	topic or title
google scholar	cause AND "wasteful motion" AND "welding robot"	0	Any	anywhere in article
google scholar	cause AND "wasteful motion" AND "industrial robots"	1	Any	anywhere in article
google scholar	cause AND "wasteful movement" AND "industrial robots"	1	Any	anywhere in article
google scholar	cause AND "effective movement" AND "industrial robots"	29	Any	anywhere in article
google scholar	cause AND "efficient movement" AND "industrial robots"	44	Any	anywhere in article
google scholar	cause AND "efficient motion " AND "industrial robots"	197	Any	anywhere in article
google scholar	cause AND "effective motion" AND "industrial robots"	70	Any	anywhere in article
	Total Hits	**344**		

Table I-1: Overview hits per search string and platform.

As can been seen in Table I-1 the term “welding robots” has resulted in 0 hits for all platforms. Therefore, the term “industrial robots” is selected for further combinations with the other search strings. The hits when the term wasteful was included were disappointing. Any platform and search strings that result in 0 hits have been removed for the next stages.

To find more accurate results exclusion and inclusion criteria have been developed as shown in Table I-2.

Number	Criteria	Reason for Exclusion/Inclusion
1	Exclude: Pre 1990 Articles	Robotic Welding only became main stream in the late 1980’s and early 1990’s.
2	Include: Welding	The goal is to find information that can be related to welding. The search string “welding robots” is too exclusive, while “industrial robots” is better but could be too inclusive. Adding the term welding creates balance.

Table I-2: First set of inclusion and exclusion criteria.

The results of applying the inclusion and exclusion criteria 1 and 2 are shown in table I-3 below:

Platform	Search Strings	Hits	Date	Scope
scopus	cause AND welding AND "efficient motion " AND "industrial robots"	0	1990-2018	article title, abstract and keywords
web of science	cause AND welding AND "efficient motion " AND "industrial robots"	0	1990-2019	topic or title
google scholar	cause AND welding AND "wasteful motion" AND "industrial robots"	0	1990-2020	anywhere in article
google scholar	cause AND welding AND "wasteful movement" AND "industrial robots"	0	1990-2021	anywhere in article
google scholar	cause AND welding AND "effective movement" AND "industrial robots"	10	1990-2022	anywhere in article
google scholar	cause AND welding AND "efficient movement" AND "industrial robots"	10	1990-2023	anywhere in article
google scholar	cause AND welding AND "efficient motion " AND "industrial robots"	46	1990-2024	anywhere in article
google scholar	cause AND welding AND "effective motion" AND "industrial robots"	21	1990-2025	anywhere in article
	Total Hits	**87**		

Table I-3: Hits results after inclusion and exclusion criteria 1 and 2.

The total hits in table 4 are still too high. Therefore, a quick scan of the results has been made in order to find more inclusion and exclusion criteria.

Number	Criteria	Reason for Exclusion/Inclusion
3	Exclude Motor Exclude Technical	The articles containing technical information are not useful for answering the research question.

Table I-4: Second set of inclusion and exclusion criteria.

Platform	Search Strings	Hits	Date	Scope
google scholar	cause AND welding AND "effective movement" AND "industrial robots" -technical -motor	5	1990-2022	anywhere in article
google scholar	cause AND welding AND "efficient movement" AND "industrial robots" -technical -motor	3	1990-2023	anywhere in article
google scholar	cause AND welding AND "efficient motion " AND "industrial robots" -technical -motor	12	1990-2024	anywhere in article
google scholar	cause AND welding AND "effective motion" AND "industrial robots" -technical -motor	0	1990-2025	anywhere in article
	Total Hits	**20**		

Table I-5: Hits after applying the inclusion and exclusion criteria 3.

The 20 remaining results will be added to Endnote and any duplicates will be removed. Any article behind a pay wall will be removed.
Next the title, abstract, and key words will be analysed. Not relevant articles will be removed.
The remaining articles will be analysed and any article that contains information relevant to answering the research question will be selected and further discussed. Any articles not relevant to answering the sub question after reading will be removed as well.

Platform	Search Strings	Hits	Date	Scope
google scholar	cause AND welding AND "effective movement" AND "industrial robots" -technical -motor	5	1990-2022	anywhere in article
google scholar	cause AND welding AND "efficient movement" AND "industrial robots" -technical -motor	3	1990-2023	anywhere in article
google scholar	cause AND welding AND "efficient motion " AND "industrial robots" -technical -motor	12	1990-2024	anywhere in article
google scholar	cause AND welding AND "effective motion" AND "industrial robots" -technical -motor	0	1990-2025	anywhere in article
	Total added to Endnote	**20**		
	Duplicates removed	**-1**		
	Behind Paywall	**-2**		
	Removed after reading Title, Abstract, and Keywords	**-7**		
	Removed after reading	**-4**		
	Selected for review	**6**		

Table I-6: Remaining articles selected for review.

The articles that have been selected are listed in the table below:

Article Reference	Article Number
(Alatartseve, Ortmeier, 2013)	Article 1
(Alatartseve, Stellmacher and Ortmeier, 2014)	Article 2
(Alatartseve, Ortmeier, 2014)	Article 3
(Alatartseve, 2015)	Article 4
(De Maeyer, Moyaers and Demeester, 2017)	Article 5
(Alfs, Ivlev and Graeser 2000)	Article 6

Table I-7: Articles selected for review.

Next a concept matrix from (Webster and Watson, 2002) will be made in order to sort the articles. The concepts chosen after reading all the articles are:

Concept 1: Supportive and Effective movements.
Concept 2: Overly specified effective tasks
Concept 3: Lack of use of sophisticated programs for optimizing motions
Concept 4: sub optimal choice of base location of the robot.
Concept 5: sub-optimal path collision constraint algorithms.
Concept 6: sub-optimal task sequence optimization.

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Article 1	X	X	X	X	X	X
Article 2			X		X	X
Article 3	X					X
Article 4	X	X				X
Article 5				X		
Article 6					X	

Table I-8: Concept Matrix

Appendix J Production Numbers of 2017

Removed: Confidential

Appendix K Raw Data Time Simulation

Removed: Confidential

Appendix L Number of Paths Calculation

The number of paths between n welds or n subs is (n)*(n-1). This is because the end point is not the same as the beginning point for a welding joint or sub. This means that distance from weld A to weld B is not the same as from weld B to weld A.

Two possible optimization cases are defined. For case 1 per program for each sub the number of paths is being calculated depending the number of welding joint in a sub. For program 1 the number of paths is 2,494. The number of paths per program is than added for the 3 programs (4,496). In case 1 also the number of paths is calculated needed to optimize the 38 subs. The subs are not optimized per program but for the whole Kasko S3.

In case 2 no subs need to be calculated. Only the paths for the 369 welding joints.

Program 1	Welds in sub	Nr of subs	Nr paths
S3FRO_VRBL	9	1	72
S3FRO_VRBR	9	1	72
S3FRO_UPR	15	1	210
S3FRO_UPL	12	1	132
S3FRO_VPV	6	1	30
S3FRO_VPA	2	1	2
S3FRO_RPAL	5	1	20
S3FRO_RPAR	5	1	20
S3FRO_ODR	8	1	56
S3FRO_ODL	8	1	56
S3FRO_VR180GL	27	1	702
S3FRO_VR180GR	27	1	702
S3FRO_UPOVL	15	1	210
S3FRO_UPOVR	15	1	210
Total	**163**	**14**	**2'494**

Program 2	Welds in sub	Nr of subs	Nr paths
S3OBB_**SSO**	10	1	90
S3OBB_**BSS**	4	1	12
S3OBB_**OZF**	20	1	380
S3OB_**BUHRA**	6	1	30
S3OBB_**SSOL**	10	1	90
S3OBB_**SSOL**	10	1	90
S3OB_**BUHRV**	3	1	6
S3OBB_**SS90G**	6	1	30
S3OBB_**SSB**	6	1	30
S3OBB_**BZA**	4	1	12
S3OB_**SPA**	8	1	56
S3OBB_**SST**	12	1	132
S3OBB_**SST**	12	1	132
S3OBB_**BP**	3	1	6
S3OB_**SPV**	8	1	56
S3OB_**BUHLV**	5	1	20
S3OBB_**SSOR**	10	1	90
S3OBB_**SSOR**	10	1	90
S3OB_**BUHLA**	6	1	30
Total	**153**	**19**	**1'382**

Program 3	Welds in su	Nr of subs	Nr paths
S3FROOBB_	12	1	132
S3FROOBB_	6	1	30
S3FROOBB_	5	1	20
S3FROOBB_	12	1	132
S3FROOBB_	18	1	306
Total	**53**	**5**	**620**

Case 1- Optimizing Subs and WJ in Subs	Total		Total Paths
Subs	38		1'406
Welding Joints in Sub	369		4'496
		Total	5'902

Case2- Optimzing WJ , no Subs	Total		Total Paths
Subs	0		-
Welding Joints in Kasko	369		135'792
		Total	135'792

Table L1: Number of paths for two cases Kasko S3, Roro-Belt.

Appendix M Real Maintenance Activities Time

Removed: Confidential