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MASTER'S THESIS

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Ann Kristin Håvås
Haugesund, 14.06.2018

Abstract

The right maintenance strategy is vital to achieve cost-effective maintenance over the entire asset lifetime. Industry 4.0 and the corresponding technologies e.g. advanced robots have revolutionised the production processes and maintenance as well. One of the modern emerging technologies is the use of advanced robots in smart warehousing systems, and AutoStore AS has become a pioneer in that. AutoStore offers to their customers a smart warehousing system that utilise robots to store, move, pick, and manage their items in a more efficient manner and less spare occupying than with traditional warehousing.

However, since the AutoStore system are quite new and were implemented in several different sites, several errors has emerged over the last couple of years. The error estimations have proven to be unacceptable with some unexpected failures and more replacements done than what was estimated. AutoStore would like to see if a preventive maintenance program can be a better and more reliable program for them to reduce maintenance cost in a lifetime and stabilize the uptime in the systems. Therefore, Autostore think it is timely to study the errors data and determine the right maintenance action for each critical error. Fortunately, Autostore systems have advanced control and data collection systems called logfiles that collect information about errors. It has based on input information, knowledge and logfiles been set up an estimated maintenance program that are used by the distributors and customers today.

Thus, the purpose of this thesis is to analyse the error database and determine the right maintenance action to eliminate or monitor the cause behind those errors.

In order to achieve the desired goal of the thesis, the error database was systemically analysed to determine the critical site, critical systems within the entire warehousing system and the critical errors. Later, the pattern in the error occurrence over the time was analysed using Weibull method. Finally, the recommended maintenance actions were proposed. The entire systems analysis and associated cost analysis were performed through a case study related to DHL-TI Singapore and specifically focused on robot type 5.

By using the developed method, error data was analysed, and the related cost analyses conducted. The most critical errors were defined through the analysed data and defined in relation to cost and stops in the facility.

The data turned out to be inconclusive. Due to a short analyses interval, too early in the life cycle of the selected system and too many updates and enhancements cannot the historical data conclude in a specific maintenance program. A longer future analyse interval is suggested, also to enhance the learning outcomes from the individual learning approach that are existing in practice today, to a more organizational learning approach. Service personnel is encouraged to share their experienced so that a holistic learning approach can be achieved.

Some solutions were suggested to the described problem, and it was suggested to continue with the historical data analyses in the future years and to use real-time data by using condition monitoring to predict and act on occurring errors based on actual, real-time data. Common for all solutions are that the root causes for the critical errors must be known. There is too little knowledge about what are causing the different errors, and that is reflected by the inconclusive results. By using more time and resources to root cause - analyses will a better understanding of the error be achieved, and that way can a better and more accurate maintenance strategy be set up, that are taking a basis in the actual condition of the robot and the related components.

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List of abbreviations

A.S.	AutoStore
CBM	Condition Based Maintenance
CM	Condition Monitoring
MDC	Main distributor contact
MTBF	Mean time between failure
MTTF	Mean time to failure
MTTR	Mean time to repair
MTTRc	Mean Time to Recover
RCA	Root cause analysis
TPM	Total productive maintenance

1. Introduction chapter

This chapter shall cover the history of maintenance, the description of the selected problem, research question and the selected methodology.

In systems with high demands for reliability and uptime, the correct selection of maintenance program is very important to ensure good operational reliability. A good maintenance program can be both time and cost efficient.
AutoStore had a desire to evaluate their current maintenance program to see if it can be improved. They are of the opinion that the current program had some potential for improvement and want to use the new potential program in the future strategy for AutoStore.
The selected case of the AutoStore system is a large topic, so some delimitations are necessary to be able to provide a possible solution to the selected problem.

1.1 Problem background

Warehousing business have changed drastically over the resent years. Traditional warehousing with many human workers, using forklifts and needing a lot of shelves has in increasing numbers been replaced with modern, smart warehousing. Increased customer demands to larger assortment, prices and delivery time requires modern, effective and cost-effective solutions for warehousing businesses. Using modern intelligent warehousing can be an effective solution to meet the changing demands. Using robotics in warehousing will help increase efficiency and meet the growing demand in online retail [1]. This change in warehousing processes also requires a modern and cost-effective maintenance process. Maintenance processes and strategies must be updated to interact efficiently with warehousing robots.

Maintenance have been an important agenda in all industrial sectors for a long time and will not become less important in the years to come. With having a good maintenance program, the goal is to reduce unexpected downtime and the unscheduled maintenance costs. The future of both the warehousing industry and industry in general involves less manual work, and more automated processes. The use of automation and more digital production and operations will continue to increase in the future. With more and more automated systems the demands for efficient and high, stable operating uptimes increase. Because of this, an effective maintenance program is of high importance.

The first generation of maintenance existed up to Wold War II. Then the machines were easy, there was low requirements to both uptime and to prevent failure. In addition to that machines were fairly easy to both operate and repair, maintenance was not considered important. Things changed drastically during World War II. During the war a demand for a high production volume grew along with a need for short production time. In combination with low availability in manpower, more and more production processes became mechanised. By the 1950' was effective production dependent on machines, and with that grew a focus on downtime and how to prevent this. Preventive maintenance was implemented, and maintenance were done on intervals of running times on the machine.

With an increasing focus on cost efficiency, managers wanted to maximize the life of the assets and started to consider other maintenance procedures. Since the mid 70's did changes started to happen [2]. But in the 70's and 80's maintenance was still considered “a necessary evil” by some, and the effects of doing maintenance were underestimated. In the following years it became an increased focus on reliability, quality, safety and the environment. Combined with a focus on maintenance cost and operating costs, have the importance of a correct and effective maintenance strategy only continued to grow. With the development and use of online condition monitoring it is also much easier to evaluate when maintenance should be done [3].

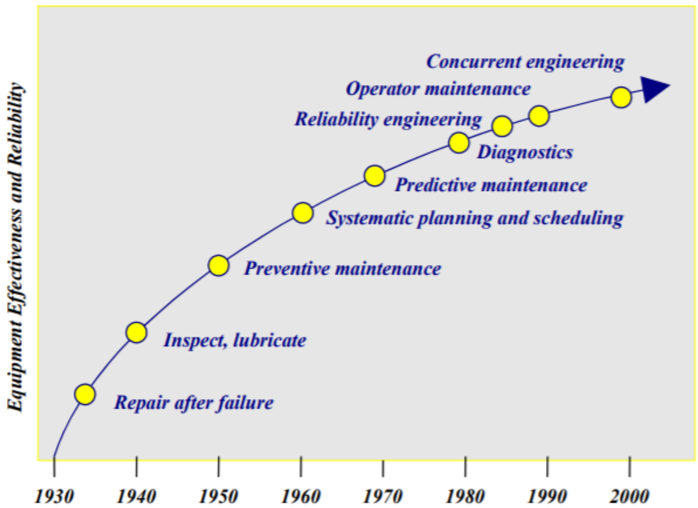


Figure 1 - Changes in reliability and maintenance concepts [4]

The Figure 1 shows a historical timeline with the different stages of maintenance development

This project was initiated in collaboration with Autostore to look at the possibility to implement preventive maintenance as a better and more reliable maintenance program in a cost-effective manner. The AutoStore system is a reliable and redundant system, and AutoStore wishes to deliver a system with the highest uptime that is practically possible. By comparing failure data to the existing maintenance program, this thesis aims to see if preventive maintenance can be a more suitable maintenance program and enlighten the irregularities in maintenance and repair that AutoStore are experiencing today.

1.2 Problem formulation

The AutoStore system is online on a continuous basis when the system is running. The robot sends and receives information at all time when it is in operating state and communicates with the AutoStore controller through access points. All information received by the controller are then written as logfiles. These files will be stored in a database at AutoStore, so they have information about the different systems around the world. This provides them with a lot of system - and failure information. To this day they have roughly based on input information, knowledge and logfiles, set up an estimated maintenance program for the distributors and customers. These estimations have proven to be a bit inaccurate with some unexpected failures and some serial failures and AutoStore would like to see if a preventive maintenance program can be a better solution for them to use.

The robot is the most complex component with the highest amount of spare parts needed in a life cycle. The whole process is reliant of functioning robots with a high availability rate, and there are some unexpected failures and parts in the robot that have a shorter lifetime than expected. These observations and evaluations formed the basis for this thesis with a focus on the robot5.

They have a significant amount of data available, and this thesis will analyse data and system failures related to the Robot5 to look at the possibility that using a preventive maintenance program can provide AutoStore with the tools needed for a more reliable system with less downtime and unexpected failures. This may reduce the amount of corrective maintenance done and the corrective maintenance costs in the long run. If a preventive maintenance program can more accurately give estimations about the expected lifetime of the robot and its parts, then a more accurate replacement program of spare-parts in the robot can be set up. The thesis will also conduct cost analysis to give estimations about the failure cost and try to estimate the cost of current and a possible new preventive maintenance program. These analyses can be used in the evaluation of a possible preventive maintenance strategy. The goals are to reduce downtime by identifying failures before they occur and the maintenance costs in a robot's life cycle [5].

1.3 Research question and project objective

1.3.1 Project objective

The main objective for this thesis is to analyse the existing error data for critical subsystems and use the necessary analytical tools to compare this with the existing maintenance program. By doing analyses on the logfiles, this thesis intents to evaluate if preventive maintenance can be a cost-effective maintenance program for the smart warehousing robots. To evaluate the current program, the failure and repair history of the selected system will be used, and the important milestones mapped.

The sub-objective for this thesis will be to explore if the uptime and reliability can be increased. This will be used to help answer the main objective.

1.3.2 Research question

The research question to be answered in this thesis are formulated as follows:

- *"How can the maintenance program for the critical system of the smart warehousing system be improved in a cost-effective manner?"*

Through this thesis different tools and techniques will be used to try to provide a solution to this question.

1.4 Methodology

A method is defined as 'a manner or mode of procedure, especially an orderly, logical, or systematic way of instruction, inquiry, investigation, experiment, presentation, etc' [6]. Methodology is important when conducting and writing a scientific thesis. The method is a tool and technique for examining the chosen field, and scientists uses different methods for different field of work [7].

1.4.1 The Inductive Approach

Lodico, Spaulding and Voegtle defines the inductive approach with that "inductive reasoning is often referred to as a "bottom-up" approach to knowing, in which the researcher uses observations to build an abstraction or to describe a picture of the phenomenon that is being studied" [8].

The inductive approach starts with observations and ends with possible proposed theories at the end of the process as opposed to the deductive method, where one start with a hypothesis or a theory, and makes analyses to prove the hypotheses that were set in the start of the research process [9].

With no hypotheses in the start the researcher can change direction of studies during the process by the use of the results obtained so far [10].

The goal of the inductive method is to get a theory by analysing data sets to identify patterns and relationships, but it does not mean that one cannot use an existing theory to formulate the research question [11].

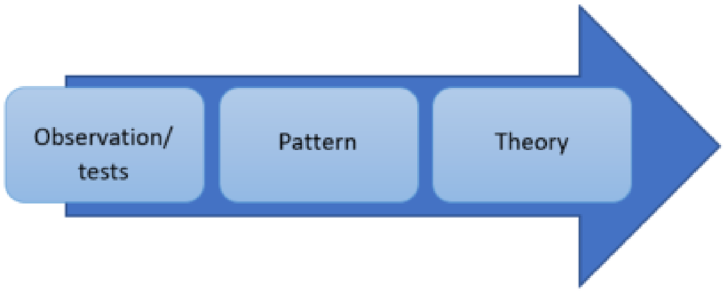


Figure 2 - Inductive approach [10]

The Figure 2 shows a representation of how the inductive approach works

The inductive approach is generally linked to the qualitative method of data collection and analysis, and the deductive reasoning is usually in relation with quantitative methods. However, it is not an absolute fact, and one can have an inductive approach with the quantitative method. [10]. Table 1 shows the correlation between the approaches, and Table 2 shows information about the deductive and inductive method.

Table 1 - Correlation between inductive/deductive and qualitative/quantitative method [9]

	Qualitative	**Quantitative**
Inductive	Grounded theory	Exploratory data analysis
Deductive	Qualitative comparative analysis	Structural equation modelling

Table 2 - Deductive and inductive method [9]

Attribute	Deductive	Inductive
Direction	"Top-Down"	"Bottom-Up"
Focus	Prediction changes, validating theoretical construct, focus in “mean” behaviour, testing assumptions and hypotheses, constructing most likely future	Understanding dynamics, robustness, emergence, resilience, focus on individual behaviour, constructing alterative futures
Spatial scales	Single (one landscape, one resolution)	Multiple (multiple landscape, one resolution)
Predictive vs. Stochastic accuracy	High – Low (one likely future)	Low-High (many likely futures)
Data intensity	Low (group or partial attributes)	High (individual or group attributes)

1.4.2 The applied method

In the compilation of this thesis the use of the inductive approach and conduct a quantitative research has been chosen as the best methodology. There are massive data from the logfiles available which will be analysed, with aims to construct an alternative future maintenance program. By analysing the logfiles and robot failures, this thesis aims to identify failure patterns and the high impact errors within the robot so that those results can be used to present a more reasonable and better solution. It will not start with a hypotheses and work to prove this, so a bottom-up approach seems more reasonable.

Since interviews and observations will not be the main focus and the data that will form the basis for the analyses are specific and already exists today, a quantitative research will be the best method for this thesis [12].

There will used some tools and data programs in the data handling and analysis process in this thesis.

Core9 will be used in the system structure analysis, to look at the systems functions and make visible the physical structure of the system and the robot. Core9 was provided through the University supervisor at the University in Stavanger.

The logfiles provided by AutoStore must be read in a proprietary software, called AsLogReader. This software has been made available so that the logfiles can be opened and analysed.

In the work with analysing the files and the systems failures Microsoft Excel will also be used as a part of the process. When conducting cost analyses will Excel will be the most important tool. The current analyses of cost and maintenance procedures are done in Excel, and the existing analyses will be used in the work with this thesis.

The troubleshooting manual and AutoStore Service Guidelines are available in AutoStore's own database called AutoStore Service Portal. An account was provided so that the necessary information could be retrieved.

1.4.3 Project methodology

The research methodology consists of several stages:

- Collect – *find relevant data*
- Analyse – *find critical system and critical site, analyse the data*
- Assess – *find critical error(s)*
- Conclude – *Present findings and recommended steps*

1.4.4 The developed method

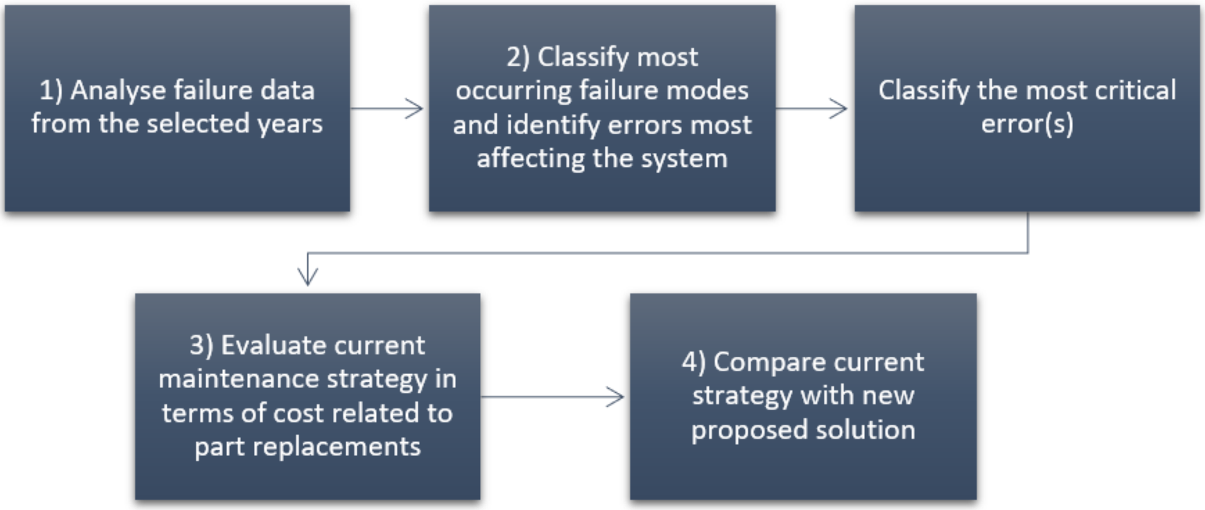


Figure 3 - The developed method

The Figure 3 shows the method that was used for the analyses in this thesis

1.5 Project scope and delimitation

There are several delimitations that have been decided on to ensure a thesis of good quality and demonstrative case study within the limited time and resources. The delimitations started by selecting one critical site, and then one critical system, followed by the analysis time interval, and finally the critical errors.

The first delimitation is the facility selection. Facilities that are in high running categories were selected for further analysis, and DHL-TI Singapore where eventually chosen as the system for analyses. Only one category 4 facility selected for analyses was therefore the first delimitation.

In the AutoStore system, there are several elements, however, the most important are robots, the grid, ports and bins. Out of these, the robot is considered to be the most critical and is what this thesis is going to focus on. The robot is more complex than the grid and bins, and a reliable system are dependent on functioning robots with a high as possible uptime. The highest maintenance and spare part cost during a systems lifetime are also appurtenant to the robot [13].

The second delimitation will therefore be the robot and this thesis will not look at any other parts of the AutoStore system than the robot. It will also not consider failures and errors linked to the robot that is related to user errors. The focus will be on robot5 failures that are technical, mechanical or software related issues.

The third delimitation is related to the time interval on which the analyses were performed. Robot5 were first delivered in May of 2011, and DHL-TI Singapore with AutoStore system started up in 2013. To avoid typical infant mortality and start-up errors were the first years neglected for the analyses in this thesis. Since a category 4 system were selected as a basis for doing the analyses was the years 2015 to 2017 considered sufficient basis for the analysis interval. This was then the third delimitation done.

The last delimitation is related to error criticality. After the analyses where completed was an evaluation done to select the most critical errors in relation to cost, stops and downtime. There were 3 errors that where considered most critical, and out of these was the results focused on the error selected as the most critical, ‘trackshift at stop’.

The externally limitations in the work with this thesis are time and capacity. It is therefore important to do delimitations, and in consultation with both AutoStore and the teaching supervisor at UiS this thesis has chosen the robot as a main component and area of focus.

1.6 Thesis outline

This thesis is consisting of five connected parts. The first part is the theory and literature review chapter where the relevant theories and literature related to this thesis are presented. The first part covers intelligent warehousing theory, maintenance strategies relevant for the thesis followed by the methods and tools used.

The second part contains the collected data related to the case study, with all information necessary to understand the work done in this thesis. This also the information necessary to understand the AutoStore system with how it is built up and how it works. The third part covers all data analyses which then can provide a recommended solution to the described problem. The cost analyses are also covered by this part. The fourth part are the discussion related to the analysed data and the result of the work in this thesis. That part is presented in chapter 5. The fifth, and last part, are the conclusion in chapter 6. There are the also recommendations to AutoStore related to possible further work.

2. Theoretical background and literature review chapter

This chapter goes through the necessary theoretical information and relevant literature related to this thesis, and the methods used in the work with this thesis.

2.1 Maintenance theory

Maintenance and different maintenance strategies has developed throughout the years. With having a maintenance management and a maintenance strategy the goal is to have as much uptime as possible and prevent downtime in production. That way it is ensured that all equipment in the facility receives the optimal maintenance in a lifetime. An optimal maintenance strategy is the most cost efficient, ensures the highest production availability and induces lowest risk in HSE [14].

British Standards Institute (BSI) defines maintenance management as "*all activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics*" [15].

There are several approaches to maintenance, and the optimal strategy varies from company to company and from industry to industry. It is important for each company to evaluate and find the correct maintenance strategy that ensures the most efficiency and stability in uptime. Some strategies are visualised below.

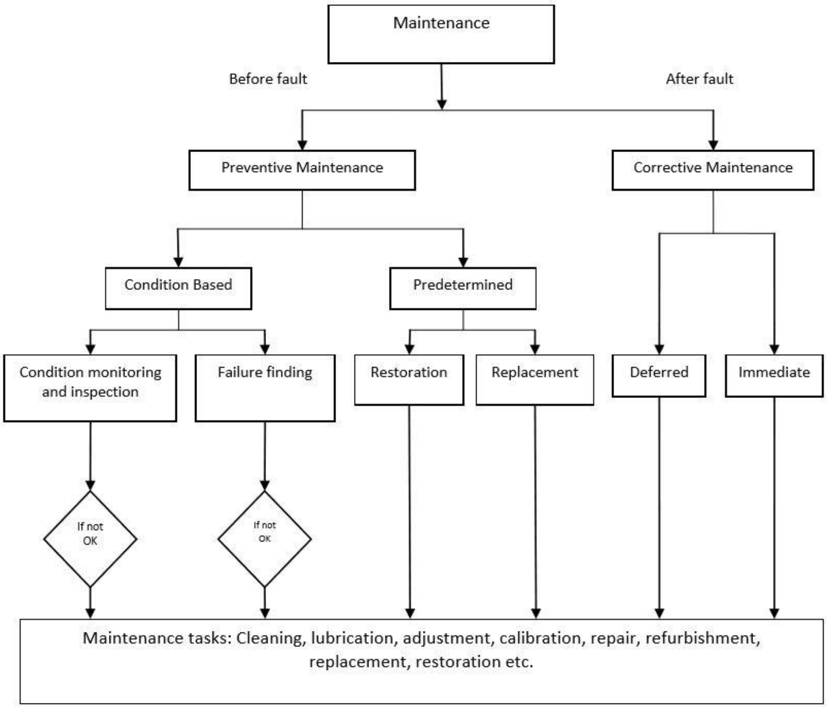


Figure 4 - Different maintenance strategies [16]

The Figure 4 shows some different maintenance strategies, and what the line of action is with the different methods.

Figure 4 shows some common different maintenance strategies, dividing them into proactive - before fault and reactive - after fault. The most common proactive maintenance strategies are preventive, predictive and the more advanced strategy, TPM. Reactive maintenance is known as corrective maintenance or by run-until-failure [17].
Some of the most relevant maintenance strategies for AutoStore are further studied below.

2.1.1 Condition-based maintenance

The condition-based maintenance (CBM) strategy has a basis on that repairs and replacements on assets are based on the condition of the assets. The need for maintenance are determined by monitoring of the equipment, and a change in the assets condition are the reason to perform maintenance. CBM aims to avoid unnecessary maintenance and replacements and only want to perform maintenance when equipment deviates from its normal state. Determination of the condition on the equipment varies from simple visual inspections to more advanced condition monitoring (CM) techniques.

The goal with condition-based maintenance is to minimize total cost of inspection and repairs by using CM data on the equipment. This allows for planned repairs and replacements based on the actual condition of the equipment.

Below is an illustration of the process in a CBM strategy, where data is collected and processed, and the results from those analyses will decide the maintenance decision [18].

Figure 5 - Three steps in CBM program [19]

The Figure 5 shows the CBM process with the three key steps

For the CBM strategy to be successful, the facility must have good CM possibilities and it must be cost effective if the strategy is to pay off. Different CM techniques can be expensive to implement, so cost effectiveness in a lifetime perspective should be considered. Also, it is crucial that the company have a good understanding of failure modes criticality of the different assets, and that they understand the long-term financial aspects of implementing the different maintenance strategies. That way can a justified and correct strategy be implemented [18].

If CBM is successfully implemented, the maintenance costs can be reduced by lowering the number of unnecessary preventive maintenance done on a scheduled, time-driven basis [19].

Diagnostics and prognostics are important aspects in CBM. Diagnostics includes fault detection, fault isolation and fault identification. Those steps include:

- Fault detection can indicate if something is wrong within the monitored system
- Fault isolation can locate the specific defect component
- Fault identification can determine the severity and complexity of the located fault

Prognostics aims to predict errors before they occur. By using estimation, prognostics will try to tell if a failure is likely to occur and when. Prognostics are needed when the facility wants to achieve a close to zero-downtime in the assets and are more efficient to this use than diagnostics. Diagnostics are needed when prognostic estimates fail and failures has occurred. When using CBM can either one or both of the strategies be used [19].

2.1.2 Preventive maintenance

Preventive maintenance has a goal to make repairs and changes on equipment before failure occurs, and therefore have as little corrective maintenance as possible. Preventive maintenance includes both periodic and condition-based maintenance. The preventive maintenance program is time-driven, either in form of running time on equipment or operating cycles.
When operating with a preventive maintenance strategy, repair and maintenance intervals are scheduled either at start-up with recommendations from the manufacturer or along the way with operating experience.

When having a preventive maintenance strategy can data estimations with the basis on the Mean Time To Failure (MTTF) be useful, as preventive maintenance are usually scheduled based on MTTF statistic. MTTF can be illustrated by the bathtub curve [3].

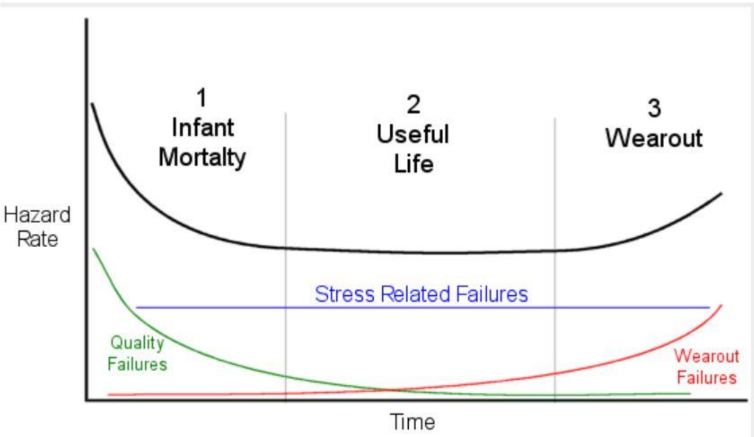


Figure 6 - Bathtub curve [20]

The Figure 6 shows the bathtub curve with the different stages of equipment lifetime

The bathtub curve is a highly used reliability representation of a population of products to estimate expected failures. It consists of three phases; infant mortality, useful lifetime and wear out.
The infant mortality phase represents the start-up of new equipment and has an initially high failure rate with a decreasing slope. Followed by the useful lifetime which is the largest part of a life cycle. Here a more stable uptime can be expected, and it has a low, more constant failure rate. Completed with the wear out phase where failure rate increases, and the equipment starts to wear out [21].

The practical use of preventive maintenance varies, all from a minor implementation with just some lubrication and cleaning, to a more extensive use that includes scheduled repairs, general maintenance procedures and a more extensive equipment maintenance. General for all implementations is the use of scheduled time and actions.
When using MTTF lies the assumption based on statistical life that a certain equipment has a given lifetime, and that preventive actions will take place before this time to prevent breakdown and corrective maintenance. When the equipment is operating, Mean Time Between Failure (MTBF) can also be used to schedule maintenance actions [3].

Preventive maintenance also has some disadvantages. In many cases the tactic using preventive maintenance and MTBF can have a less productive result than desired. It can be difficult to estimate/predict good statistical MTBF. The result can be that many replacements and maintenance are done unnecessary, and the equipment has a longer lifetime than estimated. This will lead to higher maintenance costs than if procedures where done when needed. On the other hand, equipment can fail before the statistical lifetime. That can result in high reactive and corrective maintenance costs. Those cost are estimated three times higher than if the maintenance where done before failure [3].

2.2 The used methods

2.2.1 IDEF for processing flow modelling

IDEF1 is a method used to visual represent the influencing forces by establishing the requirements that influences an activity and should be managed by an organization. The IDEF1 have an activity in the centre which is influenced by requirements of inputs, controls and mechanisms, which leads to an output. Knowledge Based Systems, Inc. defines that IDEF1 is used to "1) identify what information is currently managed in the organization, 2) determine which of the problems identified during the needs analysis are caused by lack of management of appropriate information, and 3) specify what information will be managed in the TO-BE implementation" [22].

By using IDEF1 can organizations easily visually express and analyse the information necessary to manage needs and requirements.

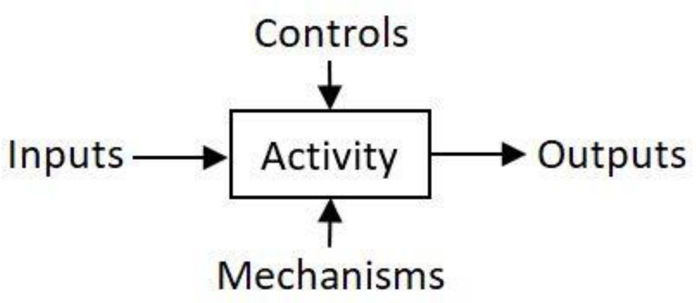


Figure 7 - Build-up of an IDEF1 [22]

The Figure 7 shows how and IDEF1 are built-up, and what resources that influences the activity

2.2.2 CORE9 for system description and modelling

CORE 9 is a system engineering software created by Vitech. The CORE 9 software can create relationships between different elements, and breakdown the structure.

CORE 9 can help visualise the behavioural relationships, and by the help of parameters, identify the key values in a system.

CORE 9 can be used to create hierarchy and make the relationships between different components in a system, and to understand the function of each component. CORE 9 can also help understand the interfaces between the system and its components and help identifying the critical parts [23].

2.2.3 Cost benefit model

The cost benefit model looks at an investment or a cost decision with the aim to evaluate if the investment can be profitable. The cost benefit model looks at the costs of a project or investment and compare this to the benefit of taking on that cost. The cost benefit analysis will evaluate if the revenues will be larger than the cost.

In maintenance strategy, the cost benefit model can be used to evaluate the cost benefits of a current and a possible new maintenance strategy. This can help conclude if the new proposed strategy should be implemented [24].

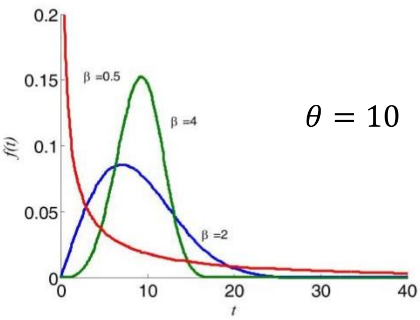
2.2.4 Weibull for time between failure estimation

The Weibull distribution is one of the most used lifetime distribution in reliability and maintenance engineering. It can be used to model failure behaviour in real life systems. This is due to the value of the shape parameter β with a failure rate function that can decrease, increase or have a constant value. The MTTF function is given below:

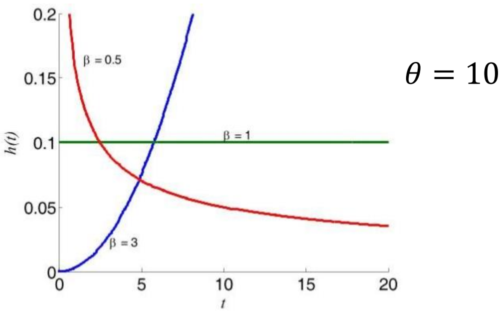
MTTF = $\theta\Gamma(1+\frac{1}{\beta})$, where $\Gamma(\,) \rightarrow \ \Gamma(n) = \ \int_0^\infty e^{-x}x^{n-1}dx$

The corresponding failure rate function is as follows; h(t) = $\frac{\beta}{\theta}(\frac{t}{\theta})^{\beta-1}$

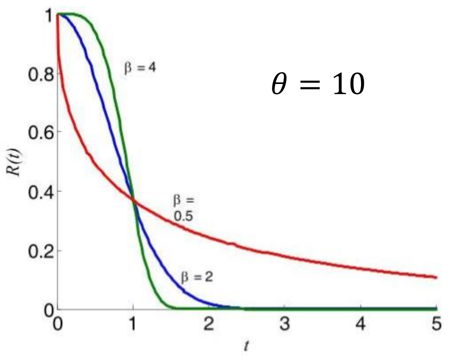
Below are some different Weibull functions for various values of the shape parameter. [25]



Graph of probability density function of Weibull distr. [25]



Graph of Weibull hazard function [25]



The Weibull reliability function is;

$$R(t) = \ e^{-(\frac{t}{\theta})^\beta}$$

Graph of Weibull reliability function [25]

2.2.5 Root cause analysis

Paul G. Preuss defines root cause as:
"the deepest underlying cause, or causes, of positive or negative symptoms within any process that, if dissolved, would result in elimination, or substantial reduction, of the symptom" [26].

Root cause analysis (RCA) allows for reflection and focus on the causation of the error or identified problem. The correct solution of the problem must be aimed on the causation and not at the symptoms. To verify the perception of the cause(s) of the error is it essential to use actual data. RCA provides a structured problem-solving process to identify the root causes of an identified problem, and by dissolving the causes of an error will the symptoms dissipate [26].

RCA can often be made visual by using a root cause tree were the identified problem are on the top with the underlying causes branching out from that problem. A root cause tree can have several levels, depending on how many causes and root causes that analysed problem has [27].

2.3 Smart warehousing systems

Customer shopping process and experience have changed in the resent years. Omni-channel and e-commerce customers now have more shopping selections with several price options and delivery methods. Business success and customer satisfaction now greatly depends on fulfilling the demands and capabilities [28].

For business to meet those demand rises new demands for them related to efficiency and material-handling costs. The key to reduce material-handling costs is to put the right material where, when and how it's needed. By controlling and reducing material-handling costs can productivity be increased and help reduce the costs, ultimately increasing company profit [29].

The use of material handling robots in warehousing can be an efficient way to address those problems and help increase efficiency. The use of robotics in warehousing will increase in the years to come as online retail is estimated to have a rather rapid growth in the next years. Using robots in warehousing can reduce the need for warehouse space, reduce the handling and service time, and increase quality. Qualified labour availability in the Western World is also an issue for many businesses. Using warehousing robots in collaboration with logistic workers can help solve the many described problems in modern material handling [1].

The use of warehouse robots has several advantages. The first, and most obvious advantage is the reduction in the need for human workers. This is cost beneficial, both as a reduction of salaries to workers and that the robots can work 24/7, so the warehouse can run constantly. It also reduces the safety hazard. The need for heavy machinery like forklifts and the use of human interaction will be reduced, and it can therefor help to reduce accidents in the warehouse. Another benefit of using warehousing robots is the amount of space needed. Forklifts need much more space than robots, and area between shelves can be reduced and thereby also increasing warehousing storage [30].

Some disadvantages are also present when using robots in warehousing. Robots have limited possibility to adapt to changing situations. If an error occurs or a robot is having problem with performing a task it will need human assistance. They have no ability to go beyond what they are programmed for. Another disadvantage is adapting the warehouse to the robots. Robots can’t simply go in and replace the logistic workers, they need the warehouse adapting to the robots which often means rebuilding the whole warehouse and warehousing systems. This is often associated with high costs. The robots also need maintenance and replacements of parts. This often requires a dedicated maintenance personnel that usually required higher salaries due to their specialised competence.
When investing in a modern robotics warehouse both the advantages and disadvantages must be considered [30].

3. AutoStore system

This chapter covers all the information about the AutoStore system, the business model and information about the facility DHL-TI Singapore.

3.1 History of AutoStore

Autostore was started in 1997 by Ingvar Hognaland and Jacob Hatteland, but the idea about AutoStore was founded in 1996. Ingvar Hognaland realised that even with a full warehouse it was still plenty of empty space in the air. Then was the idea about taking advantage of the air space born, and the first system started to develop [31]. The AutoStore system is an automated warehouse solution, by the use of robots on top of a grid. By stacking bins next to each other and on top of each other, a much-increased inventory capacity will be achieved. The complete system is energy efficient, space saving and with high accuracy [32].
It took some time to develop a functional and effective system, and the most part of 2000 and 2001 was used for testing of the AutoStore system. The system was developed through several generations, from generation 1 to the Robot 5 that is used today. The system had some room for improvement in its first years and was used internally in the first years of operation.
The idea about distributing AutoStore was started growing in the early 2000, but the first AutoStore system was delivered in 2005 [31].
Since then the AutoStore system has continued to grow, and today they have delivered 200 systems worldwide, and are continuing to expand. The Robot5 was first delivered on May 1th 2011 and is used in 190 systems to this date [5].

AutoStore offers a complete solution for modern warehouse management.
With an AutoStore system up to 400% more goods can be stored in the same amount of space and with an effective automated system the customer will receive high storage efficiency and inventory accuracy compared to traditional warehousing.

By using automated warehousing provided by AutoStore can the performance be drastically be improved. The AutoStore system can be customized for every customer, so it can be made in any size and design.
AutoStore has about 200 employees in 5 countries. The main office is located in Nedre Vats, Norway and the fabric are located in Poland [33].

3.2 The AutoStore System

The Autostore system consists of a grid, robot(s), port(s) and bins. The Autostore system comes with standard modules, but no standard system design. The grids can be made in any size with a custom setup for each customer. The grids will be adapted to the customers environment and made to fit the current building or warehouse.

The robots are running on top of the grid, in a time interval set by the customers. The robots can run in a 24/7 sequence if desired. The robot receives a command from the "controller" through an access point. The Robot gets a command to locate and pick up a bin. To do that it is also given a "move-command" and will move in the direction commanded while it simultaneously sends commands back to driver. When bin is located it will collect the bin at a given height and drop it off at a port. The robot will then collect the bin again when commanded to do so.

The robot has four engines, one for movement in x direction, one for movement in y direction, one for lift and one for track shift. In the top front of the robot a gripper is located. It is used to lift and grab bins with.

The bins are located on top of each other in the grid. The Autostore system can be made in almost any size possible, as small or as large as desired. The robots will collect the bins on a wireless command from the control system. The bins will be organized automatically, so that the high-running products will stay in the upper layer of the grid, and the less used bins will be placed on the bottom, making high-running products easily available.

Radios, or access points, are located in the ceiling. These communicate with the robots, and both sends out and receives information. After the controller is giving a command to the robot, the robot will respond to the command. It is a 2-ways communication with the controller through access point and the robot can hold up to two commands internally at a time. The robot will at a given constant sequence give feedback to the driver in the controller about its location. This way the completed pathway can be feed for passage of other robots, and the robot can be located if the communication should be lost. The robot will also give confirmations on all commands and report status changes, so that the last movements of the robot can be traced, and it will be reported as a notification and written to a logfile. The AutoStore system also has something called 'X-handler' which can automatically try to correct errors that robots are experiencing. If an error occurs and the robot needs to correct its self through the X-handler this will also be written as a notification. If, for example, a robot has several unprecise movements or fails at the first attempt to perform a command, the X-handler will take over and try to correct the error. All these actions are reported in as a notification, and the staff has access to these notifications if desired, and they will be written to a logfile.

The logfile is a file from the driver where all the information comes in and out. All information comes in and out from the driver, which then writes a logfile. The logfile is a file where all system information can be found, and both succeeded tasks and failure will be written as a logfile. This way the Autostore operators and other personnel can analyse the system status and easily identify failures [32] [5].

Figure 8 – The AutoStore Robot5 [34]

The Figure 8 shows the Robot5 that are analysed in this thesis

3.2.1 Robot recovery time

MTTRc:

AutoStore have set a Mean Time To Recover (MTTRc), which is the time it takes from the system stops until it is running again. The number was set with a basis from the average uptime of 99,6%. From there they found the number of minutes in a week and found how long time a

facility is down per week. Then they took the average of how many times a facility stops. From there they then got the MTTRc, 3-5 minutes. That means that from a facility stops it takes 3 to 5 minutes in average to take out the defect robot and recover the operation.
A.S. run this number by several customers, and they concurred with the estimate.

MTTR:

Mean Time To Repair (MTTR) is the average time it takes to repair a robot after different failures has occurred, and components needs replacement. A.S. have set the MTTR for the different components and have this available in their database 'AutoStore Service Portal'. Customers and distributors have access to this database, and they can easily estimate cost and time used on replacements.

3.3 Typical errors

Table 3 - Typical errors on the Robot5 [35]

Error name	Explanation
Trackshift at stop	Robot is unable to put wheels properly into the track. When Robot approaching to the last drive command cell and trying to put down all eight wheels, it's expecting to have all four Tracksensors covered - inside tracks. If two, the same direction Tracksensors are still uncovered - not in track, most likely wheels miss the expected track by few milimeters and were placed on the edge of the toptrack.
Unstable move Y	The robot has detected that it’s speed deviates too much from the reference speed, and has emergency stopped to ensure that it does not drive too far. Most cases would have led to a [165] Trackshift at stop error if the robot had continued. It should be noted that there will be some false positives as well, in particular when the robot drives slowly.
Unstable move X	The robot has detected that it’s speed deviates too much from the reference speed, and has emergency stopped to ensure that it does not drive too far. Most cases would have led to a [165] Trackshift at stop error if the robot had continued. It should be noted that there will be some false positives as well, in particular when the robot drives slowly.
Missing motor power	Robot lost the radio contact with the system. A safety function activated - hardware cuts the power to all motors.
Moving stopped	Robot is unable to move further. There is power on the motor but no motion.
Commandpos mismatch	X and/or Y start position of next command does not match with the position the robot has or will have when finished current command.

3.3.1 Typical errors related to user failure

Source of claim: Grid overview failure.xlsx document and A.S. Service personnel

Table 4 - Typical errors related to user failure

Error name	Explanation
Wire failure	One or more of the steel strips are loose (The Slacksensor has been activated).
No bottom detected	Robot tries to put or get the Bin at a certain depth and is not able to find anything there. Even after searching for up to 10cm below the expected Bin. Malfunction in the Gripper bin sensors (bottom side of the Gripper).
Bottom too early	Robot tries to put or get the Bin at a certain depth and crash into the bottom before designated depth.

The three failures listed above are usually linked to user failure by the customers, and not a direct robot failure. By analysing the 'grid overview' from the same logfiles that formed the basis for Robot Error Analyses the location of the failures can be identified. From there it is clear to see that the errors linked to "Wire failure", "No bottom detected" and "Bottom to early" usually are located in ports, and not in the bin cells. If the failures where spread all over the bin cells it is more likely that one or more robots had an error, but with errors located in ports the failure is most likely linked to faulty and inaccurate packing of bins.

3.4 The business model

3.4.1 Stakeholders and their needs

The stakeholders are AutoStore AS, their distributors and the customers.

AutoStore aims to provide a complete system for an automated warehouse material handling, with the highest possible uptime. The AutoStore system is a redundant system, where the robots can be taken out for repair without affecting the other functioning robots. They wish to provide a system where the customers can be as self-reliant as possible, with as much maintenance done by the distributor or the customer themselves that is practicable possible. The AutoStore have the second line support personnel. They will provide the necessary service and support when distributor cannot solve the problem themselves, but their long-run goal is to make the distributors as independent as possible.

The distributors are the intermediary between the customers and AutoStore. They distribute the AutoStore system to the customers and have all first-line support and customer contact. They provide the daily operational support for the customers and have the maintenance and service which the customer does not conduct themselves. They design and sell the AutoStore product and is dependent on a reliable system with high uptime where the system is well known. They have access to AutoStore's support system.

The customer needs a reliable system with highest possible uptime, that has a low maintenance and low operating cost. They also need access to support, and other services that are set in the contract with the distributor.

3.4.2 Maintenance arrangements

The AutoStore system comes with a range of solutions, both on facility designs and the contractual agreement between customer and distributor. The distributor constructs a deal with the customer where spare parts, operation and service agreement, maintenance and maintenance cost are agreed on.

Arrangements on maintenance can be that the customer wants to do most maintenance themselves, and they have their own maintenance personnel. Then they can also want to buy spare parts on their own cost and have full responsibility for the spare part procurement. The opposite arrangement can be that the customer is disclaiming all responsibility for maintenance and spare parts and leave the full responsibility on the distributor. The distributor will then do all maintenance, have the necessary maintenance personnel and take on the cost for spare-parts, both expected and unexpected. The customer can also request on-site personnel from the distributor. The customer can desire different arrangements depending on experience, capital and cultural differences, among other.

The cultural differences can clearly be seen from country to country, with The United States and Japan being the extremities. Japan is a country that typically wants an "all inclusive" arrangement, whereas USA wants to do most of the work and maintenance themselves. DHL-TI Singapore has also made an arrangement with their distributor, Swisslog Logistics Singapore. They have signed an all-inclusive agreement with Swisslog. They pay a yearly fixed price to Swisslog, and then Swisslog takes on all cost and responsibility for maintenance, designated maintenance personnel and spare parts. Inspection cost are also included in this price. Swisslog therefor performs both small and large maintenance operations on the DHL-TI facility. DHL-TI Singapore have also set a demand to Swisslog Singapore. Originating in the all-inclusive agreement are an agreement that Swisslog will take action to all stops and errors that occurs. They want a solution or action so the error will not happen again.

Below the line of maintenance agreement between DHL-TI Singapore, Swisslog Singapore and AutoStore be seen. This agreement is one of the possible solutions to a maintenance strategy between AutoStore, distributors and customers.

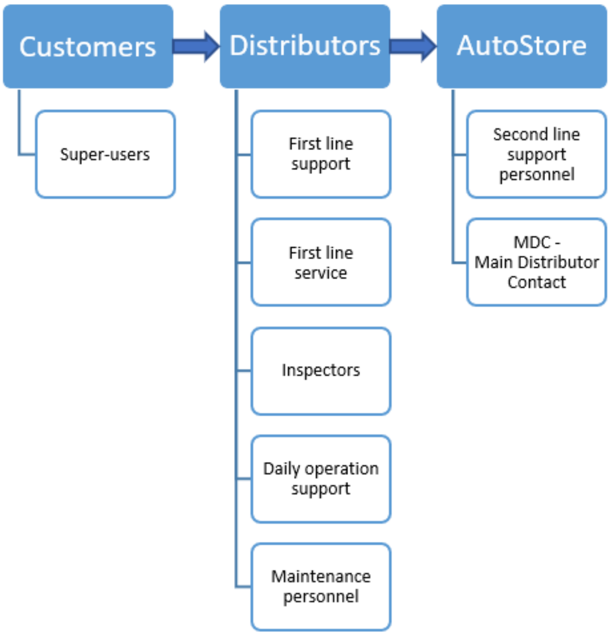


Figure 9 - Maintenance personnel in the different segments

The Figure 9 shows one commonly used service and maintenance agreement of the AutoStore product at DHL-TI Singapore

3.5 DHL-TI Singapore facility

The Singapore DHL-TI facility selected for analyses in this thesis is run by Texas Instruments (TI) and owned by the logistic partner DHL Supply Chain. Texas Instruments are one of the largest semi-conductor companies in the world, and the Singapore facility is the major distribution base for Asia Pacific. The facility upgraded to an AutoStore system in 2013, and with that they increased their capacity from storing 500 million semiconductor units up to two billion units.

The system consists of 36 robots and a grid of 65m x 18m x 5,4m. The two billion semi-conductor chips can be stored in the 63 000 bins in the system that is 108 rows wide, 38 rows deep and 16 bins in height. The investment in an AutoStore system has resulted in 40% increase in productivity.

The DHL-TI Singapore facility was the first AutoStore system in Asia, and they invested in a further system upgrade in 2015-2016 [36].

4. Data analysis

This chapter will give a description of the selected system, show the process with selecting a facility for analysis and conduct error data analyses of the selected facility. Cost analyses and a timeline are done in the end of this chapter, followed by a classification of the most critical errors.

4.1 Description of selected system

The AutoStore system consists of several parts and components, and representations of the build-up of the system are shown in different segments below. From an overview of the whole AutoStore system and component structure to different robot scenarios.

4.1.1 SOS - System of systems of AutoStore system

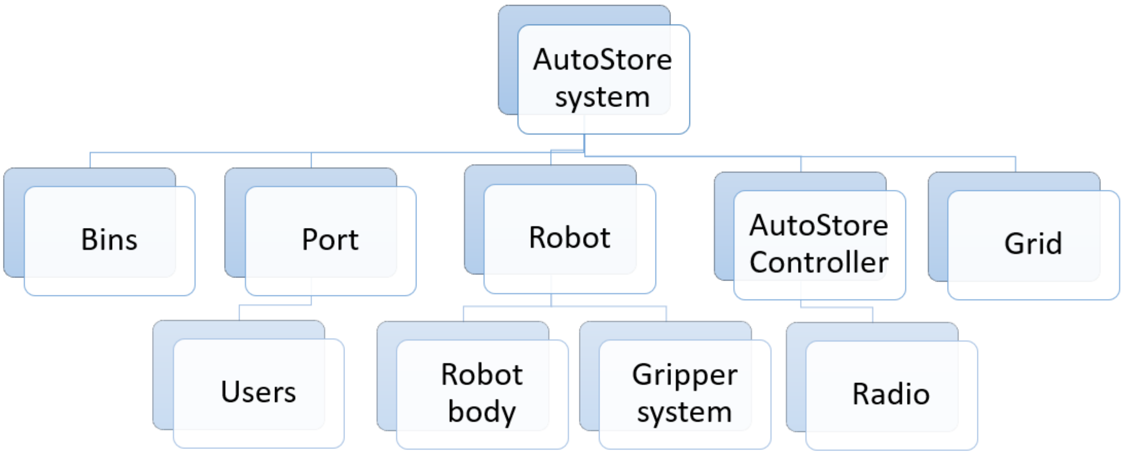


Figure 10 - System of systems (SOS) of AutoStore system

The Figure 10 shows how the AutoStore system is built-up and all relations in the system.

4.1.2 Robot component structure

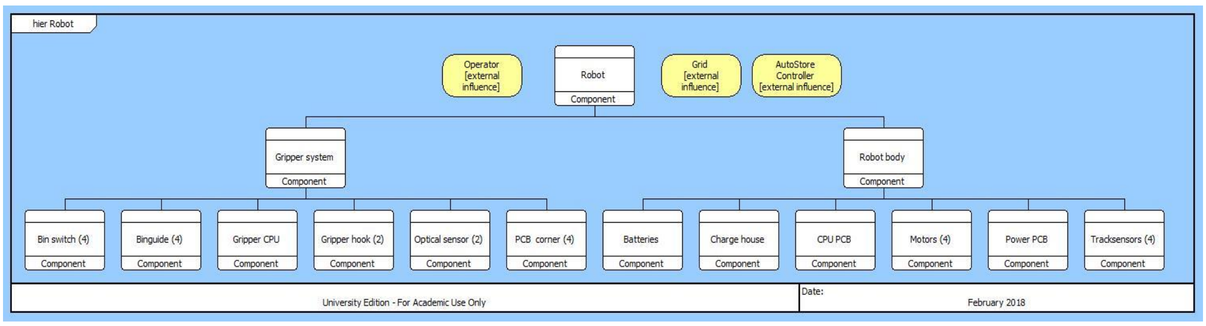


Figure 11 - The robot5 hierarchy

Figure 11 above shows the robot component hierarchy divided into the two largest segments of the robot and its respective components

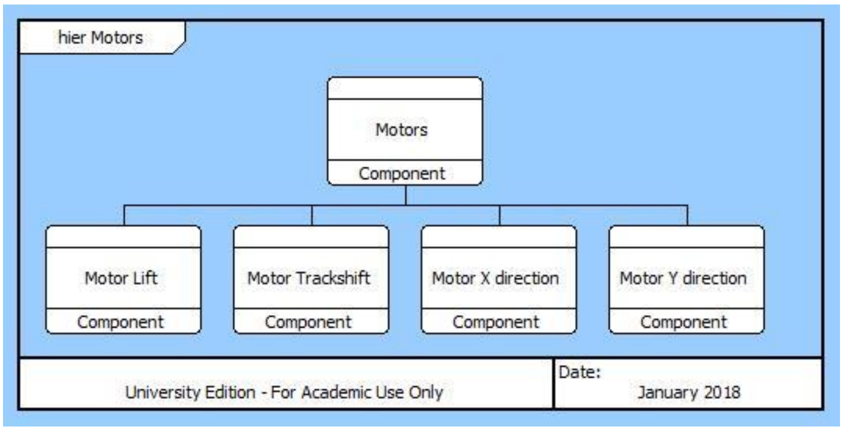


Figure 12 - Robot5 motors

Figure 12 shows the representation of the four different motors found in robot5

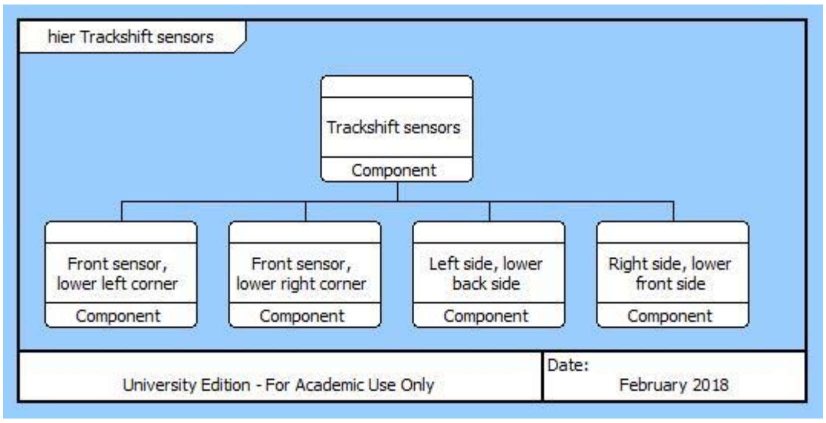


Figure 13 - Trackshift sensors

Figure 13 presents the different trackshift sensors and its location on the robot body

4.1.3 Operating scenario of Robot5

Figure 14 describes the operating scenario of the Robot 5. It shows what influences the Robot when operating, and how activities and information is being managed.

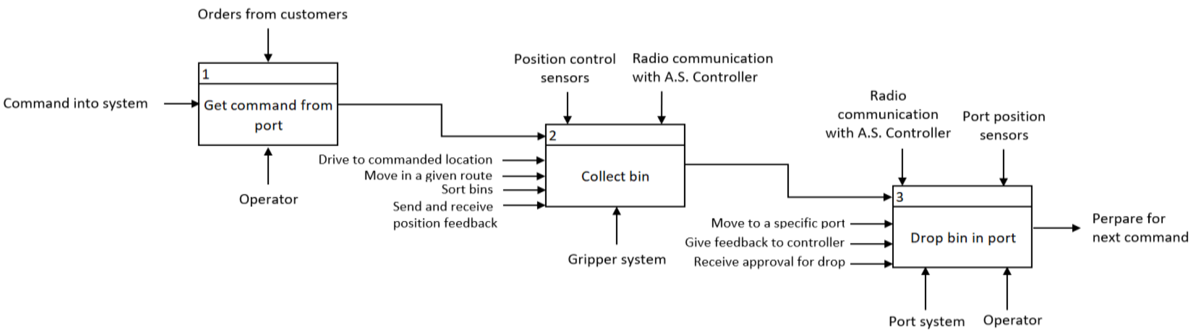


Figure 14 - Operating scenario of robot

4.1.4 Unscheduled maintenance scenario of Robot5

Figure 15 describes the unscheduled maintenance procedure of Robot5. It shows how failures are being managed, and what are the important influences when an error occurs on a robot.

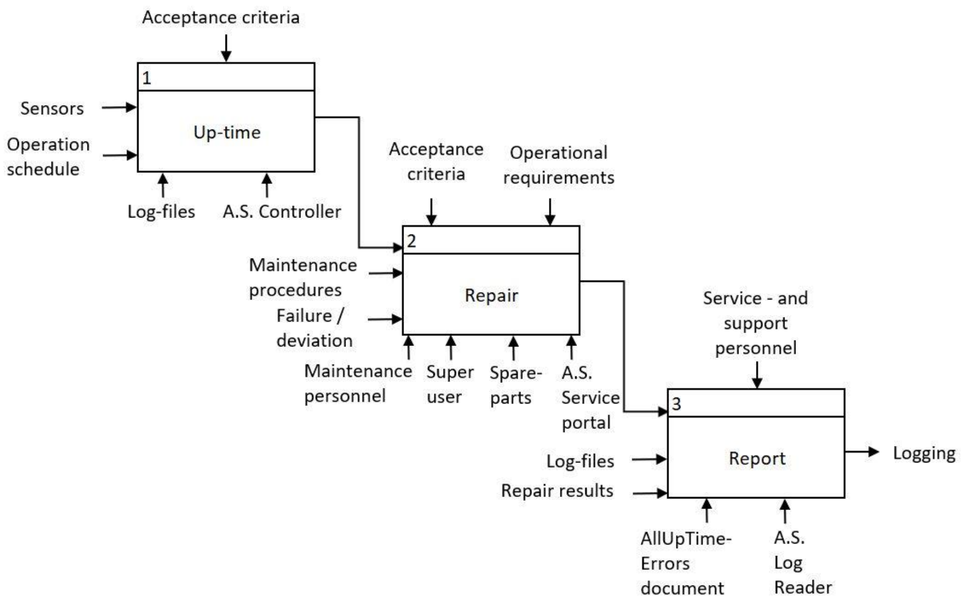


Figure 15 - Unscheduled maintenance scenario of Robot

4.2 Description of the analysed data

The basis for the analyses in this thesis will be created from the available logfile data in AutoStores different existing systems. This is gathered from AutoStores database, and as a delimitation a specific system have been chosen as a basis for the gathering of the system information necessary to create the analyses. The AutoStore system is a standard module, and because of this a methodology can be created and be used and implemented at all AutoStore systems. The focus of the analyses will therefore be to go more in depth in the selected system and identify failure patterns on the Robot5 and try to get a good basis for a methodology.

AutoStore have data available from 130 systems to date, and these are categorised by the weekly operating hours.

The different categories are defined as follows:

Category 1: 0 - 40 hours per week

Category 2: 40 - 80 hours per week

Category 3: 80 - 120 hours per week

Category 4: 120 - 168 hours per week

To be able to make good analyses sufficient amount of data is necessary so that failure patterns and problems can be identified. That way generalizations can be made, and the possible new procedures be implemented on other existing and future AutoStore systems.

After some consideration, categories 3 and 4 was evaluated to be the best systems that had enough data available. To delimit the scope further, the following analyses has been created from a category 4 system. With a category 4 system the amount of data is considered enough to make good estimations, and to analyse failures on the Robot5. Since those systems are running in a high interval, errors on the robot are more likely to occur in the time interval of a year, than on a facility in a lower running category.

This analysis will, as stated, focus on the Robot5, and the first official order on a system with Robot5 was done on May 1th 2011. All data collected is therefore set to be after this date. To eliminate any form of "infant mortality" on the systems the first year will not be considered. The amount of available logfile data is extensive, so a further delimitation that was done was to only consider year 2016 for a first evaluation and as background for choosing a facility.
When a facility is set will the years 2015, 2016 and 2017 be basis for the analyses. The logdata from 2015 to 2017 on a category 4 system is considered enough to get a sufficient basis for a thorough analysis.

4.3 Facility selection

A category 4 system is classified by how much the facility are running during a week. To be able to choose a category 4 facility some different sites needed to be analysed, and from there pick out the sites that reached a classification as a category 4. After inputs from the AutoStore personnel, five facilities where chosen for further analyses. These specific sites where chosen on background of experience and estimations about running times and previous failures that was evaluated to be relevant for this thesis.
The sites that were chosen for site activity and robot error analyses where DHL-TI Singapore, Varner, Competec, Medline and TennisPoint. The first step was to request logfiles from the different databases linked to the sites and downloaded these to the AutoStore database. Next step was to run the analyses in AsLogReader, first for robot errors and then for site activity. The site activity could reveal what category the site was based on the active and inactive times

of the robots. After the analysis was run in AsLogReader the data were transferred to Microsoft Excel for a more accessible analysis. The Figure 16 below shows the robot errors notifications on the DHL-TI Singapore facility on January 2018. With the use of conditional formatting in Excel the highest error rates where easily identified. This methodology was used on all five sites.

Names>	BATTERY_TOO_LOW	TRACKSHIFT_AT_STOP	PARITY	NO_BOTTOM_DETECTED	BOTTOM_TOO_EARLY	WIRE_FAILURE	GRIPPER_FAILURE	
Column1	Column3	Column7	Column8	Column11	Column12	Column13	Column14	Column16
Names>	BATTERY_TOO_LOW	TRACKSHIFT_AT_STOP	PARITY	NO_BOTTOM_DETECTED	BOTTOM_TOO_EARLY	WIRE_FAILURE	GRIPPER_FAILURE	
Robno\Error	124	165	200	215	216	218	219	Sum
ROB017	0	6	0	0	0	3	0	9
ROB029	0	0	0	2	0	11	1	14
ROB015	0	0	0	0	0	7	0	7
ROB025	0	0	2	1	0	5	0	9
ROB019	0	0	0	1	2	5	0	8
ROB010	1	0	0	1	1	0	0	3
ROB024	0	1	0	0	0	10	0	11
ROB014	0	0	0	1	0	5	0	7
ROB007	0	0	0	0	0	7	0	7
ROB031	0	0	0	1	0	1	0	2
ROB005	0	4	0	5	0	0	0	9
ROB002	0	23	0	0	3	2	0	29
ROB023	11	0	0	0	0	2	0	17
ROB018	2	0	0	0	0	3	0	5
ROB032	0	0	0	0	0	3	0	3
ROB035	0	0	0	0	0	0	0	1
ROB008	0	0	0	0	0	4	0	4
ROB016	0	11	0	0	0	0	0	11
ROB033	0	11	0	0	0	0	0	11
ROB006	0	0	0	0	0	3	0	3
ROB027	5	0	0	0	0	1	0	7
ROB030	0	0	0	0	2	1	0	3
ROB020	0	0	0	0	0	1	0	1
ROB026	0	0	0	0	0	1	0	1
ROB028	0	0	0	0	0	4	0	4
ROB021	0	0	0	1	0	2	0	4
ROB003	0	0	0	0	0	2	0	2
ROB011	0	0	0	0	0	0	0	1
ROB001	0	0	0	2	0	2	0	4
ROB004	0	0	0	0	0	2	0	2
ROB012	2	0	0	0	0	0	0	5
ROB013	0	0	0	0	0	1	0	1
ROB009	0	0	0	0	0	1	0	1
Sum	21	56	2	15	8	89	1	
	Robots Total	36			User failure			
	Robots Active	35						
	Robots Charging	4						

Figure 16 - Robot errors at DHL Singapore 1. - 31- January 2018

The Figure 16 above shows the robot error analysis that where done in Excel. The use of conditional formatting makes the high running errors easily identifiable, and the sum is done for both all errors on the different robots and on the different error codes. Marked in grey can the typical user failures be seen.

After the robot errors was analysed, the same procedure was done for the site activity. It was run in AsLogReader and analysed in Excel. The result for DHL-TI Singapore is presented below. Site activity analyses was done for all five facilities and followed the same procedure as for DHL-TI Singapore.

Counts any minute with at least 1 bin update as active.						
Rest is inactivity, then sums this up in selected period						
Date	Activity	Inactivity				
01.01.2018	778	662				
02.01.2018	926	514				
03.01.2018	1245	195				
04.01.2018	1148	292				
05.01.2018	1133	307				
06.01.2018	1246	194				
07.01.2018	1296	144				
08.01.2018	1266	174				
09.01.2018	1266	174				
10.01.2018	1243	197				
11.01.2018	1242	198				
12.01.2018	1188	252				
13.01.2018	1141	299				
14.01.2018	973	467				
15.01.2018	867	573				
16.01.2018	1272	168				
17.01.2018	1233	207				
18.01.2018	1031	409				
19.01.2018	984	456				
20.01.2018	1197	243				
21.01.2018	969	471				
22.01.2018	867	573				
23.01.2018	1253	187		Category 1: 0 - 40 hours per week		
24.01.2018	1239	201		Category 2: 40 - 80 hours per week		
25.01.2018	1218	222		Category 3: 80 - 120 hours per week		
26.01.2018	1213	227		Category 4: 120 - 168 hours per week		
27.01.2018	871	569				
28.01.2018	922	518				
29.01.2018	913	527				
30.01.2018	1222	218		Min. pr day	Min. pr month	
31.01.2018	1294	146		1440	44640	
Total minuts	34656	9984	44640			
34656/44640 =	0,78					
Hours	18,63					
Minuts	37,94					
Category based on running hours	18 hours and 37 min.			Site Category:	130,4258065	**CATEGORY 4**

Figure 17 - Site activity at DHL Singapore 1. - 31. January 2018

The Figure 17 above shows the analysed site category for DHL-TI Singapore in January 2018. By looking at the activity in relation with the total minutes used in a month the weekly active hours can be found. By comparing the result with the defined categories, it came clear that DHL-TI Singapore was a category 4 facility.

By analysing all the five facilities the site activity classification came out as follows:

Table 5 - Site categories of analysed facilities

Site	Category
DHL Singapore	4
Competec	2
MedLine	3
TennisPoint	3
Varner	3

The Table 5 presents the different site categories based on the analyses done in AsLogReader and Excel.

As the Table 5 above shows, only DHL-TI Singapore came out as a category 4 facility. This result formed the basis for further analyses on DHL-TI Singapore with the intent to see if DHL-TI Singapore could be a suitable candidate for this thesis.

4.4 DHL-TI Singapore analyses

4.4.1 DHL-TI Singapore selection

First were the logs from December 2016 obtained. Analyses for the site activity in December was done to confirm the results from the first analyse that the DHL-TI Singapore is a category 4 facility. After that analyses were done on the notifications on robot errors. This was done to roughly see what errors that occurred the most, and that it was a large enough amount of errors on the facility so that it could be reasonable to do more analyses on DHL-TI.

The results from these analyses gave support to conduct further analyses on DHL-TI, and the logfiles from 2016 was requested from DHL-TI Singapore.

The logfiles from all of 2016 was run in a single sequence on AsLogReader, and from there in Excel. The results from the 2016 analyses are summarized below:

Table 6 - Robot errors on DHL Singapore in 2016

Robot errors	Number of errors
Trackshift at stop	751
Unstable move X	145
Unstable move Y	140
Battery too low	24
Gripper failure	23
Brake is on	21
Commandpos mismatch	11

The Table 6 shows the notifications on the most occurring errors on the facility during 2016. All errors with an occurrence below 10 was not considered in this table.

As can be seen in Table 6, 'trackshift at stop', 'unstable move X' and 'unstable move Y' are the highest occurring errors on DHL-TI Singapore in 2016.

After studying the results of the analysed logfiles, the DHL-TI Singapore seemed like a reasonable facility this thesis could choose to focus on. DHL-TI Singapore was chosen as the main facility and the basis for the analyses further in the thesis.

4.4.2 Error notification analyses for 2015 and 2017

With the same procedure as for 2016 was the logfiles from 2015 and 2017 then requested from the DHL-TI Singapore server. The logfiles from the whole year was run in a single sequence in AsLogReader and afterwards in Excel. The results from 2015 and 2017 can be seen in its respective tables below.

2015:

Table 7 - Robot errors on DHL Singapore in 2015

Robot errors	Number of errors
Trackshift at stop	724
Gripper failure	43
Brake is on	35
Position error at stop	23
Hook shift bottom	16
Stop to chargepos	14
Moving stopped	14
Battery too low	12

The Table 7 shows the notifications on the most occurring errors on the facility during 2015. All errors with an occurrence below 10 was not considered in this table.

2017:

Table 8 - Robot errors on DHL Singapore in 2017

Robot errors	Number of errors
Trackshift at stop	1338
Brake is on	253
Hook shift failure	232
Unstable move Y	195
Unstable move X	184
Battery too low	69
Hook shift bottom	50
Gripper failure	44
Brake release 3	35

Missing gap	30
Parity	27
Brake release 1	13

The Table 8 shows the notifications on the most occurring errors on the facility during 2017. All errors with an occurrence below 10 was not considered in this table.

When the errors from 2015 were analysed, it had some deviations from 2016 and 2017. There is no occurring ‘Unstable move X’ or ‘Unstable move Y’ errors. It became clear after a discussion with AutoStore service personnel that the reason for the missing unstable move - errors was a software update on the robot that was implemented in early 2016. The ‘trackshift at stop’ error accounted for such a large proportion of the errors that a further classification was needed. It was then decided to split the ‘trackshift at stop’ error into three errors, ‘trackshift at stop’, ‘unstable move X’ and ‘unstable move Y’. This way a better understanding and evaluation of the error could be achieved. Because of this will only the ‘trackshift at stop’ error show in the analyses for 2015, but an assumption that unstable move X/Y had occurred and are also relevant for 2015 can therefore be made.

When the top 5 errors from 2017 are analysed, two errors stand out when comparing it to the years 2015 and 2016. ‘Brake is on’ and ‘Hook shift failure’ are errors that are occurring with high frequency but is not present in 2016 and are occurring in 2015 with a much lower frequency. By studying the excel document "AllErrors2017" it can easily be seen that there are two robots that are experiencing high occurrences of the different errors, but the errors in general are much lower. This can express that there is a lower problem with the errors in general and is not something that all robots are experiencing on a high frequency basis. Single robot failure can occur, without it being a problem with the robot’s maintenance program or the general lifetime of components. Due to redundancy in the AutoStore system will not the single robot errors affect the operational state of the system in the same way as general high frequent errors.

Names>	BRAKE_IS_ON	HOOK_SHIFT_FAILURE
Robno\Error	214	222
ROB003	0	221
ROB021	1	0
ROB027	0	0
ROB017	0	0
ROB013	0	0
ROB023	1	0
ROB005	0	0
ROB002	2	0
ROB010	1	1
ROB032	219	0
ROB011	7	0
ROB031	0	0
ROB029	0	0
ROB024	1	0
ROB007	0	0
ROB025	8	0
ROB030	0	1
ROB009	1	1
ROB019	0	1
ROB022	1	0
ROB026	4	0
ROB020	2	0
ROB004	2	0
ROB018	0	0
ROB014	1	0
ROB015	0	0
ROB012	0	0
ROB016	1	6
ROB034	0	0
ROB006	0	0
ROB028	1	0
ROB008	0	0
ROB001	0	1
ROB033	0	0
ROB035	0	0
ROB036	0	0
Sum	253	232

Figure 18 - Clip of 'All Errors 2017'

The Figure 18 shows a clip of the Brake is on' and 'Hook shift failure' errors, and two robots have a high error rate, but the appearance of the errors is much lower in general.

When looking at a clip of errors 'Trackshift at stop', 'Unstable move X' and 'Unstable move Y' from the same year it can be seen a much more uniform distribution of the errors between the robots.

Names>	TRACKSHIFT_AT_STOP	UNSTABLE_MOVE_X	UNSTABLE_MOVE_Y
Robno\Error	165	172	173
ROB003	5	0	22
ROB021	54	0	8
ROB027	5	7	6
ROB017	21	11	0
ROB013	1	0	0
ROB023	186	6	8
ROB005	43	0	42
ROB002	133	8	18
ROB010	2	2	0
ROB032	172	15	1
ROB011	1	5	0
ROB031	0	0	0
ROB029	5	1	2
ROB024	12	0	2
ROB007	48	12	34
ROB025	0	0	0
ROB030	13	0	0
ROB009	20	16	10
ROB019	61	7	2
ROB022	2	0	0
ROB026	44	8	1
ROB020	52	1	2
ROB004	16	4	2
ROB018	10	0	1
ROB014	61	25	0
ROB015	0	0	0
ROB012	0	3	1
ROB016	12	26	0
ROB034	14	14	0
ROB006	126	0	6
ROB028	4	0	1
ROB008	70	0	23
ROB001	0	0	0
ROB033	135	13	0
ROB035	9	0	3
ROB036	1	0	0
Sum	1338	184	195

Figure 19 - Clip of top three occurring errors in 2017

The Figure 19 shows that even though some robots have a higher error rate than other robots, the errors are much more uniformly distributed, and are occurring in a greater number of robots.

This even distribution of errors can indicate deficiency in the robot components or with maintenance of the robots in general. The further work and analyses done in this thesis is going to focus on these type of errors, and not so much on single occurring errors.

4.4.3 Robot error classification

A robot error written as logfiles may not lead to stop on the facility, and the system have a software called X-handler. This will, when an error occurs, try to take action and correct the robot from the occurring error, so that it can proceed as planned. If the X-handler is unsuccessful to do so, the facility will stop, and a manual correction or repair is needed. To analyse the errors that lead to a stop on the facility, a document created by AutoStore called "AllUptimeErrors" was provided for analysis.

In the time interval for 2015 the results are presented below

Table 9 - Robot errors that lead to stop in 2015

Robot errors that lead to stops	Number of errors
Trackshift at stop	43
Stop to chargepos	9
Moving stopped	9
Battery too low	8

The Table 9 shows number of stops in the system related to the different errors. These are cases where the X-handler did not manage to rectify the occurring errors.

By comparing the results from Table 9 with ‘Table 7 - Robot errors on DHL Singapore in 2015’ can it be seen that ‘trackshift at stop’ as the error that lead to most stops complies with the most occurring error notification in 2015. Neither of error notifications 'Gripper failure', 'Brake is on', 'Position error at stop' or 'Hook shift bottom' lead to stops, and this can indicate that those are less critical error notifications.

'Stop to chargepos', 'Moving stopped' and 'Battery too low' had a low number of occurrences in 2015, respectively 14, 14 and 12 total error notifications. If this is compared to errors that lead to stop, it can be seen that a large percentage of the errors resulted in stops in the system. This can give an indication of the criticality of those errors, and that they are likely to cause a stop in the system. Especially moving stopped are a critical error. When the error occurs, a robot can either stop or move to far, and then other moving robots can crash into it. This can have a critical outcome, and the facility will then stop. If the crash occurred with high speed can both robots take damage and must be put out of operation until repaired.

In the time interval for 2016 the results are presented below

Table 10 - Robot errors that lead to stop in 2016

Robot errors that lead to stops	Number of errors
Trackshift at stop	10
Missing motor power	6
Commandpos mismatch	3

The Table 10 shows number of stops in the system related to the different errors. These are cases where the X-handler did not manage to rectify the occurring errors.

As presented in Table 10 the errors occurring with highest frequency in 2016 are 'trackshift at stop', 'missing motor power' and 'commandpos mismatch'. When compared to 'Table 6 - Robot errors on DHL Singapore in 2016' can it be seen that the top error leading to stop, 'trackshift at stop', compiles with the all robot errors in 2016. 'Missing motor power' are not an error with notifications over 10, but the significance of the error can be further analysed.

1	MISSING_MOTOR_POWER
2	125
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0
26	0
27	0
28	0
29	0
30	0
31	0
32	0
33	1
34	5
35	0
36	0
37	0
38	0
39	6

Figure 20 - Clip of missing motor power notifications 2016

The Figure 20 shows total number of 'Missing motor power' error notifications in 2016.

Figure 20 shows that the total number 'missing motor power' errors notifications in 2016 are six. Compared to robot errors that lead to stop in 2016, Table 10, it can be seen that all error notifications on this error lead to a stop in the facility. This can illustrate that a notification of this error can have a high impact on system and when 'missing motor power' occurs the whole system will always stop. This is because when 'missing motor power' occurs, a robot has lost contact with the Controller and will no longer be able to receive or send commands. Then the robot will stop, and a stagnant robot can be a hazard to the other moving robots since it can no longer communicate with the Controller, and the facility will therefore stop.
Commandpos mismatch are on the list of robot errors in 2016 that occurs ≥ 10 times, with eleven recorded notifications. This means that 27% of all error notifications on this error lead to stop in the facility.

In the time interval for 2017 the results are presented below

Table 11 - Robot errors that lead to stop in 2017

Robot errors that lead to stops	Number of errors
Trackshift at stop	24
Unstable move X	7
Unstable move Y	9

The Table 11 shows number of stops in the system related to the different errors. These are cases where the X-handler did not manage to rectify the occurring errors.

As presented in Table 11, the errors occurring with highest frequency in 2017 are ‘trackshift at stop’, ‘unstable move X’ and ‘unstable move Y’.
When comparing the values in Table 11 to the discussed event regarding single robot errors in section ‘4.4.2 Error notification analyses for 2015 and 2017’, it can be seen that the values here concurs with this presumption about those errors having a lower impact on the system. Neither of the errors ‘Hook shift failure’ or ‘Brake is on’ did lead to a stop in the facility.
If the single robot occurring errors for 2017 are ruled out, the table consists with the three most occurring errors in 2017. The results from the tables above can be used to identify the top three all over critical errors on the DHL-TI facility.

4.5 Cost analysis

4.5.1 Estimated cost vs actual cost

In evaluation of errors and critical errors, and how they affected DHL-TI Singapore it is an important aspect to look at cost in the year for the analyses. AutoStore have set up a cost estimation for the customers in a 10-year perspective. That way can customers have a cost reference and a base when constructing and maintaining a budget. This Excel document have been provided as a reference when evaluating the costs in this thesis.

After every year are all spare parts used and replacements made reported in to AutoStore. This is compiled in the Excel documents "All Systems" and shows date of replacement, robot number, spare part, total replacements done and costs.

	A	B	C	D	E	F	G
13	11.feb.16	Robot 8	1	AS-35031	Motor lift assembly	kr 6 930,00	6
14	22.mar.16	Robot 28	1	AS-35031	Motor lift assembly	kr 6 930,00	
15	14.apr.16	Robot 29	1	AS-35031	Motor lift assembly	kr 6 930,00	
16	12-May-16	Robot 7	1	AS-35031	Motor lift assembly	kr 6 930,00	
17	10-Oct-16	Robot 36	1	AS-35031	Motor lift assembly	kr 6 930,00	
18	29.nov.16	Robot 25	1	AS-35031	Motor lift assembly	kr 6 930,00	
19	20.jan.16	Robot 23	1	AS-35033	Move-X motor assembly	kr 7 064,00	9
20	22.mar.16	Robot 22	1	AS-35033	Move-X motor assembly	kr 7 064,00	
21	22.mar.16	Robot 8	1	AS-35033	Move-X motor assembly	kr 7 064,00	
22	07.jun.16	Robot 33	1	AS-35033	Move-X motor assembly	kr 7 064,00	
23	28.jun.16	Robot 31	1	AS-35033	Move-X motor assembly	kr 7 064,00	
24	6-Oct-16	Robot 36	1	AS-35033	Move-X motor assembly	kr 7 064,00	
25	11-Oct-16	Robot 32	1	AS-35033	Move-X motor assembly	kr 7 064,00	
26	18-Oct-16	Robot 8	1	AS-35033	Move-X motor assembly	kr 7 064,00	
27	27-Dec-16	Robot 32	1	AS-35033	Move-X motor assembly	kr 7 064,00	
28	08.mar.16	Robot 34	1	AS-35065	Move-Y motor assembly	kr 6 940,00	13
29	26.apr.16	Robot 16	1	AS-35065	Move-Y motor assembly	kr 6 940,00	
30	15.jun.16	Robot 26	1	AS-35065	Move-Y motor assembly	kr 6 940,00	
31	15.jun.16	Robot 1	1	AS-35065	Move-Y motor assembly	kr 6 940,00	
32	28.jun.16	Robot 31	1	AS-35065	Move-Y motor assembly	kr 6 940,00	
33	28.jun.16	Robot 18	1	AS-35065	Move-Y motor assembly	kr 6 940,00	

Figure 21 - Clip of Excel spreadsheet of All Systems 2017

The Figure 21 shows a clip of the necessary details related to replacements made on the robots in 2016. (The document is made in 2017).

This is useful to see how many replacements that where actually done, and when.

By analysing this document can it be seen if there are any deviations between estimated replacements and actual replacements done, and that way also the deviations in costs.

First step in this process is to compare the total spare parts used of the different types and compare this to estimated spare part use.

ROBOT PARTS - ESTIMATED CHANGE OUT OVER 10 YEAR PERIOD			ESTIMATED NUMBER OF CHANGES OVER A 10 YEAR PERIOD				Rev 1.4		04.01.2017
Article:	Part text:	piece pr modul	Based on category 1	Based on category 2	Based on category 3	Based on category 4	Estimated number of parts to be replaced	Price/part DBP	Total cost DBP
AS-35046	Motor Trackshift assembly	1	0	0	1	1	36	6 120,00	220320,00
AS-35028	Lift gear assembly	2	0	0	1	2	144	1 225,00	176400,00
AS-35007	Gripper motor	2	0	0	1	1	72	560,00	40320,00
AS-35195	Robot 4, Belt GT3 5MR 700 25	2	0	0	1	1	72	280,00	20160,00
AS-35197	Robot 4, Belt Twin HTD 5M 670 15	1	0	0	1	1	36	766,00	27576,00
AS-35199	Robot 4, Belt GT3 5MR 650 15	2	0	0	1	1	72	202,50	14580,00
AS-35201	Robot 4, Belt GT3 5MR 400 9	2	0	0	1	1	72	135,00	9720,00
AS-35219	Belt HTD3 1420 5M 15	1	0	0	1	1	36	460,00	16560,00
AS-35052	Brush kit	2	0	0	2	2	144	959,00	138096,00
AS-35031	Motor lift assembly	1	0	0	1	1	36	6 930,00	249480,00
AS-35065	Move-y motor assembly	1	0	0	1	1	36	6 940,00	249840,00
AS-35033	Move-x motor assembly	1	0	0	1	1	36	7 064,00	254304,00
AS-35024	Brake assembly	1	0	1	1	2	72	2 380,00	171360,00
AS-35019	Wheel & rim assembly	8	0	0	1	1	288	1 312,50	378000,00
AS-35047	Chargehouse assembly	1	1	1	2	2	72	940,00	67680,00
AS-35210	Robot, Battery Assembly2x Batteries with connectors	1	1	2	3	4	144	4 995,50	719352,00
AS-35149	Robot strip kit	1	1	1	2	3	108	875,00	94500,00
AS-35023	Tracksensor	4	0	1	2	2	288	869,00	250272,00
AS-35005	Gripper guides	1	1	1	2	3	108	1 140,00	123120,00
	Time inspection	1	15	20	30	40	1440	850,00	1224000,00
	Time service	1	2,4	3,7	22,5	26,3	945	850,00	803250,00
Total:							1872		5248890,00

Figure 22 - Estimated spare part cost for customer over a 10-year period

A cut of the Excel spreadsheet in Figure 22 shows estimated use for both the number of parts and the total cost in a 10-year period. The cost related to time used on inspection and service where not considered in this cost analyses.

By dividing the number "Estimated number of parts to be replaced" in Figure 22 (column J) with 10, the estimated yearly number of spare parts can be found. With comparing this to Figure 23 below can estimated vs actual use be compared.

	A	B	C	D	E	F	G	H	I
1	Date	Robot	Quantity	AS-no	Description	Price 2015	Total used	Robots:	36
2	11.aug.15	Robot 2	1	AS-35201	Robot 4, Belt GT3 5MR 400 9	kr 135,00	1		
4	04.nov.15	Robot 25	1	AS-35194	Robot Gripper	kr 17 700,00	1		
29	02.jan.15	Various robots	1	AS-35006	Gripper CPU	kr 3 080,00	2		
30	04.aug.15	Robot 5	2	AS-35046	Motor trackshift assembly	kr 12 240,00	2		
31	13.aug.15	Various robots	1	AS-35149	Robot strip kit	kr 875,00	2		
33	11.nov.15	Various robots	1	AS-35031	Motor lift assembly	kr 6 930,00	6		
43	08.sep.15	Various robots	1	AS-35018	CPU Board	kr 5 600,00	9		
51	17.aug.15	Various robots	2	AS-35210	Robot, Battery Assembly 2x Batteries with connectors	kr 9 246,60	14		
52	16.jan.15	Various robots	1	AS-35065	Move-Y motor assembly	kr 6 940,00	27		
57						**kr 382 071,20**		Pr robot	kr 10 613,09

Figure 23 - Spare part use for DHL Singapore in 2015

The Figure 23 presents the various robot spare parts replaced in 2015, that are reported in from DHL-TI Singapore.

When analysing this for 2015 and comparing estimated numbers with the actual numbers, did two spare parts deviates from the estimated use. The two parts that have a higher usage than estimated are "Motor lift assembly" and "Move-Y motor assembly", and the cost results are presented in the Table 12 below.

The CPU Board are not presented in the- Estimated spare part cost for customer over a 10-year period" and cannot be compared to actual use. It will therefore not be analysed in this part of the thesis.

Table 12 - Estimated vs actual spare part use for DHL Singapore 2015

Spare part	Estimated	Actual	Difference
Motor lift assembly	1 per robot per 10 years ≈ 3,6 per year, 6930 NOK/unit ≈ 24948 NOK/year	6 units used, 6930 NOK/unit = 41 580 NOK	(41 580 - 24 948)NOK = - 16 632 NOK
Move-Y motor assembly	1 per robot per 10 years ≈ 3,6 per year, 6940 NOK/unit ≈ 24984 NOK/year	27 units used, 6940 NOK/unit = 187 380 NOK	(187 380 - 24 984)NOK = - 162 396 NOK

The Table 12 shows the deviation in expected and actual cost of the two spare parts DHL-TI Singapore replaced more than expected in 2015

As can be seen in the Table 12, DHL-TI replaced the Move-Y motor a lot more than estimated. 27 units where replaced in 2015, and it lead to a substantial higher cost than estimated.
The reason for the high number of replacement will be analysed further in chapter '4.6 Timeline DHL-TI Singapore'.

The same procedure is done for 2016. Divide the number "Estimated number of parts to be replaced" in Figure 22 (column J) with 10, the estimated yearly number of spare parts can be found. With comparing this to Figure 24 below for 2016 can estimated vs actual use be compared.

	A	B	C	D	E	F	G
1	Date	Robot	Quantity	AS-no	Description	Price 2016	Total used
2	20.sep.16	Robot 9	1	AS-35006	Gripper CPU	kr 3 080,00	1
3	25.aug.16	Robot 28	2	AS-35007	Gripper motor	kr 1 120,00	2
4	13-Oct-16	Robot 36	1	AS-35017	Power board	kr 6 965,00	2
6	13.jan.16	Various robots	1	AS-35018	CPU Board	kr 5 600,00	2
8	19-Oct-16	Various robots	1	AS-35020	Robot radio 433Mhz	kr 5 477,50	2
10	28.jun.16	Robot 18	1	AS-35023	Tracksensor	kr 869,00	1
11	06.apr.16	Various robots	1	AS-35026	Strip Reel Kit	kr 7 588,00	2
13	11.feb.16	Robot 8	1	AS-35031	Motor lift assembly	kr 6 930,00	6
19	20.jan.16	Various robots	1	AS-35033	Move-X motor assembly	kr 7 064,00	9
28	08.mar.16	Various robots	1	AS-35065	Move-Y motor assembly	kr 6 940,00	13
48	10.aug.16	Robot 6	1	AS-35199	Robot 4, Belt GT3 5MR 650 15	kr 202,50	2
50	28.jun.16	Various robots	1	AS-35201	Robot 4, Belt GT3 5MR 400 9	kr 135,00	3
53	30.mar.16	Various robots	1	AS-35210	Robot, Battery Assembly 2x Batteries with connectors	kr 4 995,50	9
61						**kr 368 511,00**	

Figure 24 - Spare part use for DHL Singapore in 2016

The Figure 24 presents the various robot spare parts replaced in 2016, that are reported in from DHL-TI Singapore.

When analysing this for 2016 and comparing estimated numbers with the actual numbers, did three spare parts deviates from the estimated use. The three parts that have a higher usage than estimated are "Motor lift assembly", "Move-X motor assembly" and "Move-Y motor assembly", and the cost results are presented in the Table 13 below.

Table 13 - Estimated vs actual spare part use for DHL Singapore 2016

Spare part	Estimated	Actual	Difference
Motor lift assembly	1 per robot per 10 years ≈ 3,6 per year, 6930 NOK/unit ≈ 24948 NOK/year	6 units used, 6930 NOK/unit = 41 580 NOK	(41 580 - 24 948)NOK = - 16 632 NOK
Move-Y motor assembly	1 per robot per 10 years ≈ 3,6 per year, 6940 NOK/unit ≈ 24984 NOK/year	13 units used, 6940 NOK/unit = 90 220 NOK	(90 220 - 24 984)NOK = - 65 236 NOK
Move-X motor assembly	1 per robot per 10 years ≈ 3,6 per year, 7064 NOK/unit ≈ 25430 NOK/year	9 units used, 7064 NOK/unit = 63 576 NOK	(63 576 - 25 430)NOK = - 38 146 NOK

The Table 13 shows the deviation in expected and actual cost of the three spare parts DHL-TI Singapore replaced more than expected in 2016

The Table 13 above shows that both motors for lift, move-Y and move-X has been changed more than estimated, but especially move X and Y motors has been changed vastly more which gave a negative economical outcome.

The same procedure is also done for 2017. Divide the number "Estimated number of parts to be replaced" in Figure 22 (column J) with 10, the estimated yearly number of spare parts can be found. With comparing this to Figure 25 below for 2017 can estimated vs actual use be compared.

	A	B	C	D	E	F	G
1	Date	Robot	Quantity	AS-no	Description	Price 2017	Total used
2	18.jul.17	Various robots	1	AS-35006	Gripper CPU	kr 3 080,00	2
4	11.jul.17	Various robots	1	AS-35007	Gripper motor	kr 560,00	4
8	06.mar.17	Various robots	1	AS-35017	Power board	kr 6 965,00	7
15	04.jul.17	Robot 16	1	AS-35018	CPU Board	kr 5 600,00	1
16	17.aug.17	Various robots	1	AS-35020	Robot radio 433Mhz	kr 5 477,50	2
18	05.jun.17	Various robots	1	AS-35023	Tracksensor	kr 869,00	6
21	24.aug.17	Various robots	1	AS-35024	Brake assembly	kr 2 380,00	2
23	28.nov.17	Various robots	1	AS-35026	Strip Reel Kit	kr 7 588,00	2
25	04.jan.17	Various robots	1	AS-35031	Motor lift assembly	kr 6 930,00	9
34	15.mar.17	Various robots	1	AS-35033	Move-X motor assembly	kr 7 064,00	13
47	15.aug.17	Robot 4	1	AS-35052	Brush kit	kr 959,00	1
48	21.feb.17	Various robots	1	AS-35065	Move-Y motor assembly	kr 6 940,00	13
62	19-Oct-17	Robot 36	1	AS-35199	Robot 4, Belt GT3 5MR 650 15	kr 202,50	1
63	28.feb.17	Various robots	1	AS-35201	Robot 4, Belt GT3 5MR 400 9	kr 135,00	45
108	14.feb.17	Various robots	1	AS-35210	Robot, Battery Assembly 2x Batteries with connectors	kr 4 995,50	16
118						**kr 436 151,50**	**124**

Figure 25 - Spare part use for DHL Singapore in 2017

The Figure 25 presents the various robot spare parts replaced in 2017, that are reported in from DHL-TI Singapore.

Five parts have a higher spare-part usage than expected for 2017 and are represented in the Table 14 below.

Table 14 - Estimated vs actual spare part use for DHL Singapore 2017

Spare part	Estimated	Actual	Difference
Robot Belt GT3 5MR 400 9	2 per robot per 10 years ≈ 7,2 per year, 135 NOK/unit ≈ 972 NOK/year	45 units used, 135 NOK/unit = 6075 NOK	(6075 - 972)NOK = - 5103 NOK
Move-Y motor assembly	1 per robot per 10 years ≈ 3,6 per year, 6940 NOK/unit ≈ 24984 NOK/year	13 units used, 6940 NOK/unit = 90 220 NOK	(90 220 - 24 984)NOK = - 65 236 NOK
Move-X motor assembly	1 per robot per 10 years ≈ 3,6 per year, 7064 NOK/unit ≈ 25430 NOK/year	13 units used, 7064 NOK/unit = 91 832 NOK	(91 832 - 25 430)NOK = - 66 402 NOK
Motor lift assembly	1 per robot per 10 years ≈ 3,6 per year, 6930 NOK/unit ≈ 24948 NOK/year	9 units used, 6930 NOK/unit = 62 370 NOK	(62 370 - 24 948)NOK = - 37 422 NOK
Robot batteries	4 per robot per 10 years ≈ 14,4 per year, 4995,50 NOK/unit ≈ 71935 NOK/year	16 units used, 4995,50 NOK/unit = 79 928 NOK	(79 928 - 71 935)NOK = - 7993 NOK

The Table 14 shows the deviation in expected and actual cost of the three spare parts DHL-TI Singapore replaced more than expected in 2017

When studying the Table 14 for 2017 can it be seen that “Move-Y motor assembly”, “Move-X motor assembly” and “Motor lift assembly” have the highest deviations in cost. Even though the “Robot belt GT3 5MR 400 9” did have the highest deviation in estimated vs actual spare part use, did it not have a large economic impact. The same can be seen for “Robot batteries”, they did not deviate largely from estimated, neither did it have a large impact economically.

The remaining three components did DHL-TI Singapore change quite a bit more than estimated and had a much higher deviation in cost. Therefore does “Move-Y motor assembly”, “Move-X motor assembly” and “Motor lift assembly” stand out as the high-impact components.

The “CPU Board”, “Power board”, “Robot radio” and “Gripper CPU” are not presented in the "Estimated spare part cost for customer over a 10-year period” and cannot be compared to actual use. It will therefore not be analysed further for 2017.

4.6 Timeline DHL-TI Singapore

The DHL-TI Singapore facility started up in 2013 and have since then undergone some maintenance operations and replacements of different parts in the robot. To clarify which performed maintenance that was in accordance with the scheduled maintenance program and which maintenance that deviated from this, a timeline is made to make a visual representation of the maintenance history. The timeline will account for previous errors and stops on the facility that was so distinctive that action beyond expected maintenance procedures was required.

Through identifying errors and the actions that were done can this be put in perspective with new and expected errors. By doing so can it form a basis for predicting errors than can happen in the future beyond the expected time and use. This cannot only be used on this facility but since the AutoStore system is a standard module system it can be used in other existing and future AutoStore facilities. The timeline can also be used to evaluate and reaffirm the most critical errors (from the analysed data).

At AutoStore the main distributor contact (MDC) have the main contact and responsibility with the respective distributor and does therefore inherent some profound knowledge about the DHL-TI Singapore facility. To make the timeline it will be used historical robot failure data and the costs related to repairs and change of parts, in addition to interviews and information from the MDC and AutoStore service personnel.

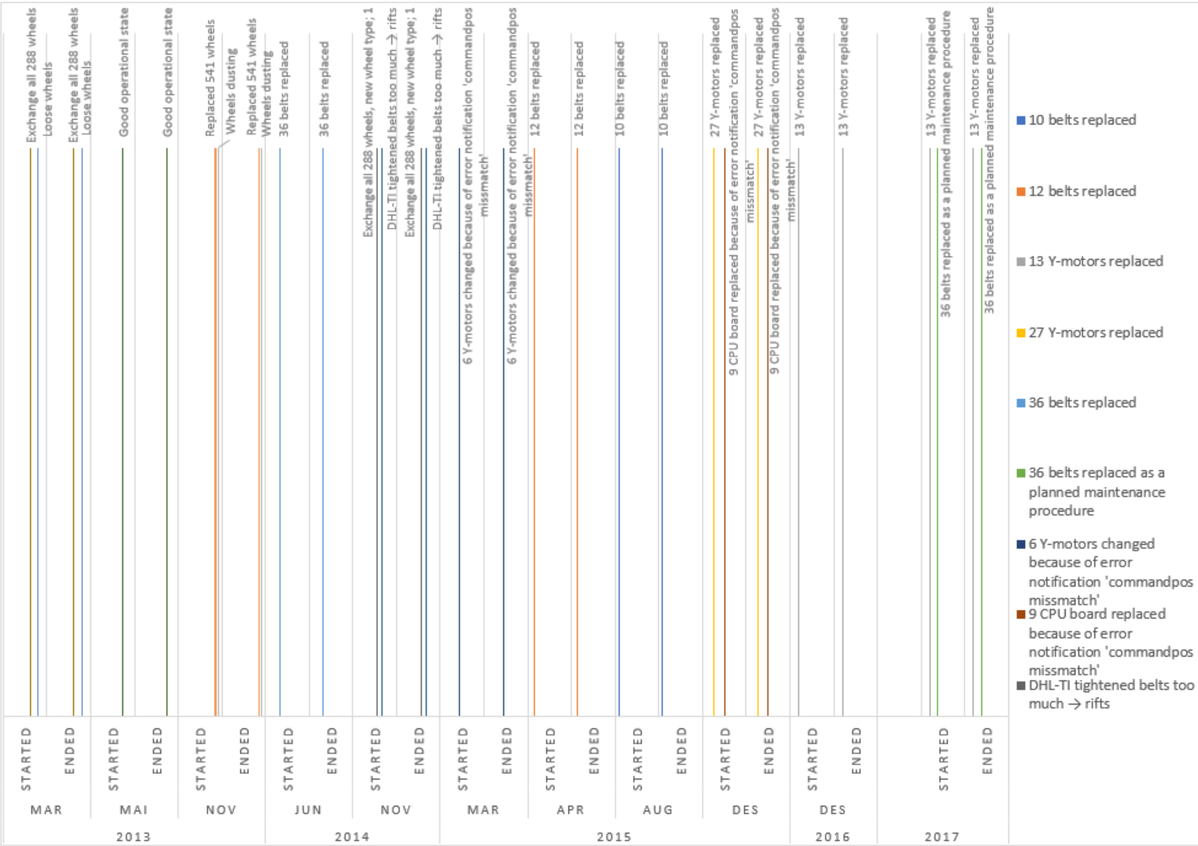


Figure 26 - Timeline DHL-TI Singapore

The Figure 26 shows the timeline from the years 2013 to 2017 at DHL-TI Singapore. It includes replacements done and when, and other information about the operational state at DHL-TI. The graph illustrated when the different activities was started and ended.

There have been several firmware updates since the start-up at DHL-TI in 2013. The Table 15 below shows some important firmware updates, and when they were implemented.

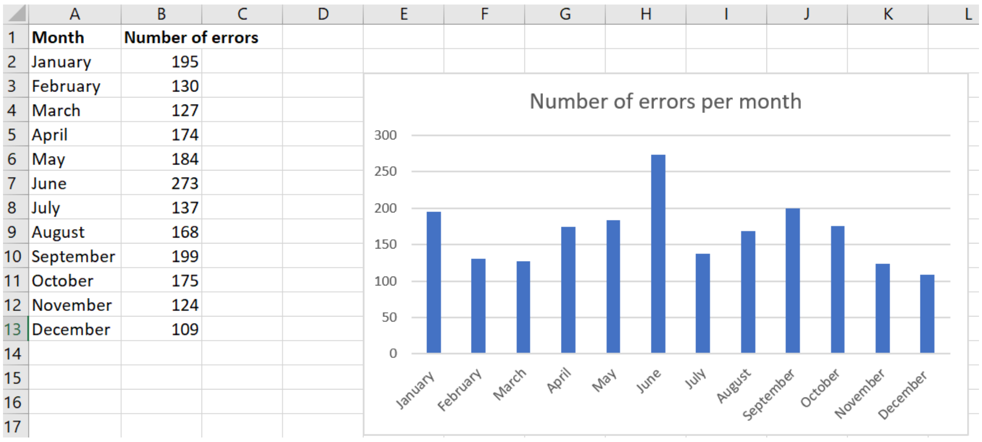
Table 15 - Important firmware updates [37]

Firmware updates	Comment
18.12.2013	*No comment*
17.02.2016	- Improved Robot-XHandler communication to make more error cases easily solvable - Adjustments to TRACKSHIFT_AT_STOP behaviour to reduce the risk of collisions if the robot has moved too far

27.07.2016	Smoothened the move-controller during extension of move commands, making it more robust against mechanical looseness.
11.10.2016	*No comment*
09.05.2017	- Reworked acceleration phase to better handle motors that are borderline specification wise - Several adjustments and improvements to the move controller to reduce the number of UNSTABLE_MOVE errors
03.07.2017	Corrected move controller issue causing robots with borderline specifications to get a significant number of Trackshift_at_stop errors
15.02.2018	*No comment*

4.6.1 Robot error notification by month

All robot error notifications from each year, 2015 to 2017 was divided into months. The files where run in AsLogReader for each month and gathered in Excel. The results from each year are presented below.



Month	Number of errors
January	195
February	130
March	127
April	174
May	184
June	273
July	137
August	168
September	199
October	175
November	124
December	109

Figure 27 - Monthly overview 2015

Figure 27 shows the error notifications in 2015 divided by a monthly basis

Month	Number of errors per month
January	177
February	90
March	140
April	171
May	92
June	214
Juli	247
August	186
September	122
October	323
November	127
December	228

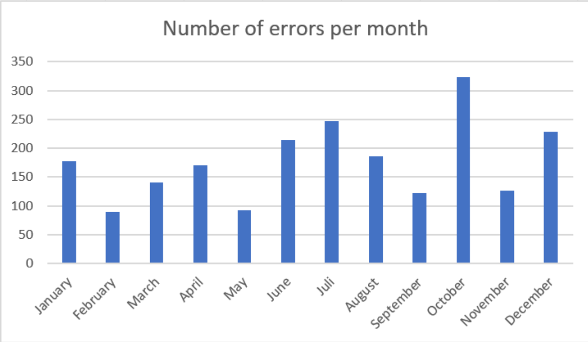


Figure 28 - Monthly overview 2016

Figure 28 shows the error notifications in 2016 divided by a monthly basis

Month	Number of errors
January	249
February	204
March	394
April	312
May	503
June	391
July	231
August	165
Septembe	463
October	194
Novembei	314
December	254

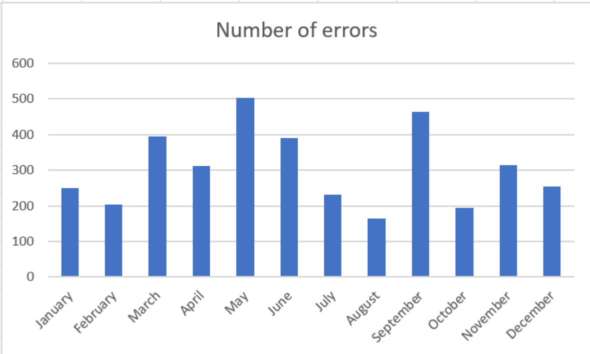


Figure 29 - Monthly overview 2017

Figure 29 shows the error notifications in 2017 divided by a monthly basis

4.6.2 Robot stop errors by month

Robot errors that lead to stop can be divided into months for each analysed year, and that way get an easy overview over the occurring errors. From the document "AllUptimeErrors" was the errors collected by month and are represented below in Excel.

	A	B	C	D	E
1			2015		
2		**Trackshift at stop**	**Stop to chargepos**	**Moving stopped**	**Battery too low**
3	January	3	0	1	0
4	February	3	0	1	0
5	March	2	0	0	0
6	April	4	0	0	0
7	May	5	1	1	0
8	June	3	0	0	0
9	July	0	0	1	1
10	August	9	0	1	3
11	September	3	2	1	2
12	October	5	5	3	0
13	November	5	1	0	1
14	December	1	0	0	1
15	**Sum**	**43**	**9**	**9**	**8**
16					

Figure 30 - Robot stops monthly 2015

Figure 30 shows the robot errors for 2015, presented in section 4.4.3 Robot error classification, on a monthly basis

	A	F	G	H	I
1				2016	
2			**Trackshift at stop**	**Missing motor power**	**Commandpos missmatch**
3	January		0	0	0
4	February		2	0	0
5	March		1	0	0
6	April		0	0	0
7	May		0	0	1
8	June		2	1	0
9	July		1	0	0
10	August		0	0	0
11	September		0	0	2
12	October		2	3	0
13	November		0	2	0
14	December		2	0	0
15	**Sum**		**10**	**6**	**3**

Figure 31 - Robot stops monthly 2016

Figure 31 shows the robot errors for 2016, presented in section 4.4.3 Robot error classification, on a monthly basis

	A	K	L	M
1			2017	
2		**Trackshift at stop**	**Unstable move X**	**Unstable move Y**
3	January	0	0	0
4	February	1	0	1
5	March	2	0	0
6	April	3	1	0
7	May	9	2	0
8	June	3	1	0
9	July	1	1	0
10	August	1	1	1
11	September	2	0	1
12	October	0	1	2
13	November	0	0	1
14	December	2	0	3
15	**Sum**	**24**	**7**	**9**

Figure 32 - Robot stops monthly 2017

Figure 32 shows the robot errors for 2017, presented in section 4.4.3 Robot error classification, on a monthly basis

4.7 Error criticality

To classify the most critical errors, several factors must be considered. Both stops on facility, spare parts used, and cost related to this are important factors to account for. To do this the errors that lead to stop must be compared to replacements done and analysed in relation to the timeline made for DHL-TI Singapore.

4.7.1 Trackshift at stop

The most occurring error 'Trackshift at stop' have most error notifications and the error that resulted in most stops in the facility for both 2015, 2016 and 2017. The significance of this error makes this the most critical error in the AutoStore system. This error has a high occurrence and the complexity related to the error due to the number of underlying causes makes this a critical error.

The errors 'Unstable move X' and 'Unstable move Y' are also errors related to robot driving. These where a part of 'trackshift at stop', but where separated as independent errors after a firmware update in early 2016. Since these errors are related to many of the same problems as with 'trackshift at stop' are these errors also considered critical.

An underlying cause that can lead to 'trackshift at stop' error is lack of general maintenance. Both sensors and belts with all appurtenant bolts and nuts need frequent maintenance and cleaning. If this is not done can the parts become loose and dirty and lead to inaccurate driving of robot.

If lacking maintenance is not the problem, worn-out sensors or belts can be the problem. They have a limited lifetime and is estimated to need replacements during a lifetime. Defect motors can also cause stops and errors. Both Y-motor, X-motor and Trackshift-motor can cause error 'Trackshift at stop' and 'Unstable move X/Y'. Replacements of these should be a last resort but are estimated to need replacement during a lifetime. Good established procedures are therefore necessary to prevent both the 'Trackshift at stop' and 'Unstable move X/Y' error.

The driving of the robot must also be calibrated from time to time. An automatic solution to this was provided in the last six months of 2017, but in the vast majority of the analysed time interval was this calibration done manually by DHL-TI Singapore. This calibration is needed to ensure correct driving of the robot and could typically be done if some 'trackshift at stop' errors emerged.

4.7.2 Moving stopped

Another critical error is the 'Moving stopped' error. This error can, as explained in section '4.4.3 Robot error classification' lead to crashes with other robots and give stops on the facility. The crashes can have critical outcomes and is therefore a highly unwanted error. The possible critical outcome of this error makes this error one of the most critical errors.

This error can arise if the Y-belts in the robot become worn. The robot can then move to far due to lack of ability to have a precise movement and brake when required. This lead to 9 stops in the facility in 2015 but have improved in the last years. Better firmware and stronger belts are a reason for this improvement. It is still an issue that can arise, so awareness and prevention of this is important.

4.7.3 Commandpos mismatch

'Commandpos mismatch' are an error that is not necessarily so critical when it occurs. Due to a firmware update that gave the X-handler the possibility to correct the error when it occurred without it having to stop or be manually corrected lead to that is it not the most critical error. 'Commandpos mismatch' can appear even though it is not visible at the error notification analyses, and DHL-TI Singapore themselves can analyse how many times X-handler needs to correct the error.

However, 'commandpos mismatch' will be further considered as a critical error in this thesis due to the effect this error has on DHL-TI Singapore. The 'commandpos mismatch' will sometimes occur when the X-handler are not able to correct the error by itself, and the maintainer responsible at Swisslog Singapore will act to every error that occurs. This action has often been to replace the Y-motors and CPU-boards, and the error will therefore result in high replacement costs. They do this as a reaction to the error and are experiencing improvement when it's done, but it is not established that the Y-motor or CPU board are the reason for the occurring error.

4.8 Root cause tree

A root cause tree was done for the critical error 'trackshift at stop' to make visible all possible root causes of the error, and the extent of the error as it is developed today.

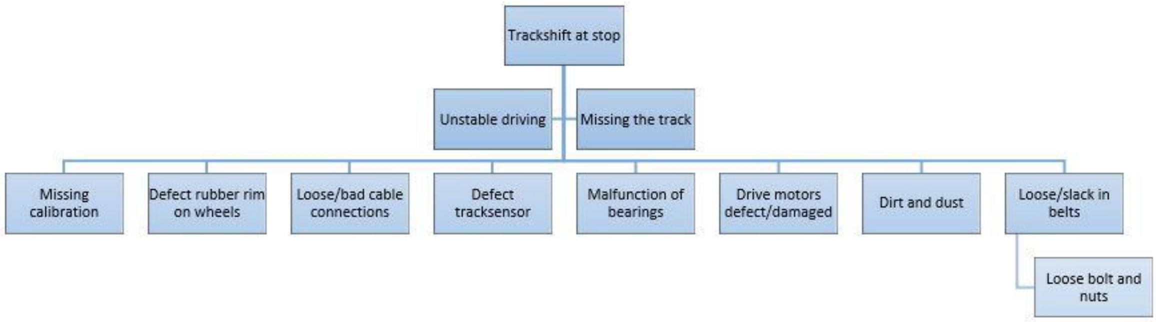


Figure 33 - Root cause tree - Trackshift at stop error

The Figure 33 shows the two symptoms of the error, and all the possible root causes to the 'trackshift at stop' error

4.9 Learn how to maintain robots by historical error data

By using the historical data from the analyses done earlier in chapter 4 it can be proposed replacement intervals on some spare parts that are linked to a critical error or have several replacements done during the analysed interval.

In estimating replacements intervals Weibull can be a useful tool. Weibull can be used to analyse lifetime data and model an assets failure times [38].

A spare part that has proven to be critical are the robot belts. Worn and defect belts can cause not only 'trackshift at stop', but also the critical error 'moving stopped'. As can be seen in chapter '4.5 Cost analysis' and in chapter '4.6 Timeline DHL-TI Singapore' are belts replaced several times, both as planned and unscheduled maintenance procedures. With using the Weibull distribution for the robot belts (named Belt GT3 5MR 400 9) can a replacement interval be estimated.

A Weibull calculator was provided for the analyses.

There were some larger replacements between July 15 and October 17 that is visual on the DHL-TI Timeline, but those where done as a corrective action to rifts in the belts that occurred when DHL-TI tightened the belts too much. They went on the guarantee and are not logged in the overview of spare parts usage. The planned maintenance procedures where the belts on all 36 robots were replaced happened in June 2014 and in November 2017. That is 40 months between the planned replacements. As can be seen in the cost analyses were a total of 13 belts replaced beyond the planned events, with the number increasing every year. 1 replacement done in 2015, 3 in 2016 and 9 in 2017. This substantial increase in 2017 can indicate that the belts are starting to exceed its lifetime.

In 2015 there were 9 stops in the system because of the error 'Moving stopped', and that error can occur if the belts become worn. By inserting the value from the 9 stops and enter the number of cycles the system is desired to achieve, how large percentage of the robots that is desired to survive the number of cycles, these results will emerge from the Weibull calculator:

40 months:

Enter the minimum number of cycles you desire the product to achieve:	40
Enter the percentage of product you wish to survive the desired number of cycles:	90 %
Shape Parameter, Beta: Infant life failures (< 1), wearing out (> 1), or constant failure rate (= 1)	19,01
Characteristic Life, Alpha: The number of cycles at which 63.2% of the product will fail	36
Reliability at 40 cycles	0,04 %

Conclusions:

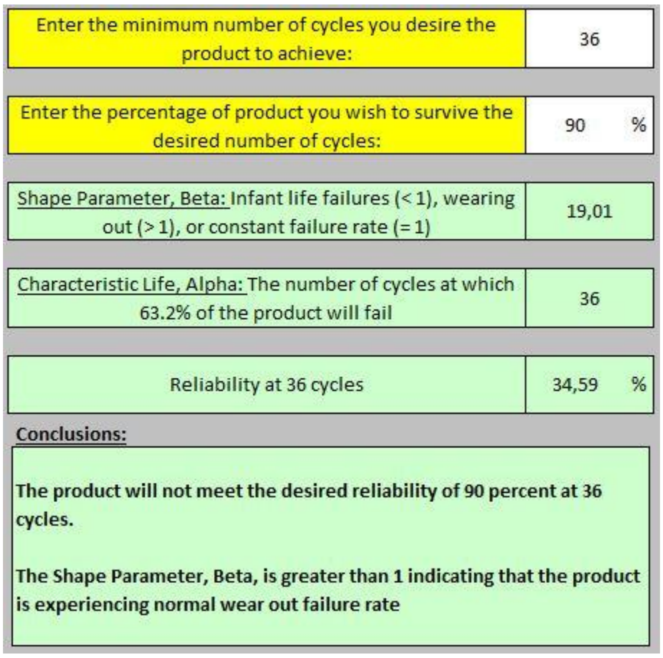
The product will not meet the desired reliability of 90 percent at 40 cycles.

The Shape Parameter, Beta, is greater than 1 indicating that the product is experiencing normal wear out failure rate

Figure 34 - Weibull calculator with 40 months running time on the belts

As can be seen in Figure 34 will the belts not meet the desired reliability of 90% at 40 months. The replacement interval should be shorter than 40 months. The reliability is only at 0,04%. This can support the assumption made above that the belts are starting to exceed their lifetime in 2017.

36 months:



Enter the minimum number of cycles you desire the product to achieve:	36
Enter the percentage of product you wish to survive the desired number of cycles:	90 %
Shape Parameter, Beta: Infant life failures (< 1), wearing out (> 1), or constant failure rate (= 1)	19,01
Characteristic Life, Alpha: The number of cycles at which 63.2% of the product will fail	36
Reliability at 36 cycles	34,59 %

Conclusions:

The product will not meet the desired reliability of 90 percent at 36 cycles.

The Shape Parameter, Beta, is greater than 1 indicating that the product is experiencing normal wear out failure rate

Figure 35 - Weibull calculator with 36 months running time on the belts

The Figure 35 shows the reliability with a running time of 36 months. The conclusion here will be the same as for the 40 months interval, that the desired reliability of 90 percent cannot be met with running time of 36 months. The reliability at 36 months is only 34,6% and will not meet the desired demand for stable uptime. The belts should therefore be replaced before a 3-year interval.

31 months:

Enter the minimum number of cycles you desire the product to achieve:	31
Enter the percentage of product you wish to survive the desired number of cycles:	90 %
Shape Parameter, Beta: Infant life failures (< 1), wearing out (> 1), or constant failure rate (= 1)	19,01
Characteristic Life, Alpha: The number of cycles at which 63.2% of the product will fail	36
Reliability at 31 cycles	94,01 %

Conclusions:

The product will meet or exceed the desired reliability of 90 percent at 31 cycles.

The Shape Parameter, Beta, is greater than 1 indicating that the product is experiencing normal wear out failure rate

Figure 36 - Weibull calculator with 31 months running time on the belts

The Figure 36 shows the reliability with a running time of 31 months. With that replacement interval will the 90 percent reliability demand be met, and the reliability at 31 cycles is 94%. This ensures a high uptime in the system, and a low probability of worn out belts before this time. The belts should therefore be replaced then reached 31 months of operation.

Source of the Weibull calculator: Dean Christolear, 2009

If the Weibull estimated and the scheduled time interval for replacements of belts are compared to ‘Figure 22 - Estimated spare part cost for customer over a 10-year period’, it can be seen that this deviate from the Weibull estimates and practise that they are performing today.
This result shows that the spare part cost estimate for customers should be revised and updated when they obtain more data that are better understood, so that the cost estimations become more accurate and realistic.

The Weibull estimation above is an example of what can be done if data collection and analyses are continued in a longer lifetime perspective. When deeper knowledge about failures and uptime are present, more accurate and useful estimated can be attained. This will help AutoStore with their goal to achieve world-class maintenance.

4.10 Learn how to maintain robots by real-time learning i.e. condition monitoring

By using condition monitoring (CM) can more detailed information about the errors be achieved. As will be discussed in chapter '5.1 Discussion of analysed data'; have 'trackshift at stop' many possible root causes without it being clear which exact cause was the reason behind the occurring error at the time. This is problematic when trying to improve the reliability of the system. By using different CM techniques can real time data and the actual status of a component become known.
Bolts need regularly tightening in a lifetime to ensure they don't become loose and affect the operational state of other components. Loose bolts can cause slack and vibration and give inaccuracy of the equipment. The AutoStore system is an accurate system that rely on precise movements and stability. To monitor the tightness of bolts can potential looseness be detected before it has an effect on the system.

Guangming Dong, Fagang Zhao and Xiaoke Zhang [39] describes how using vibration-based monitoring can be a good and economical alternative for loosening detection of bolts. Loosening of bolts can be measured by frequency and can be detected by the deviation in frequency from the normal state. This happens by following the natural frequency, so it can be seen when bolts need to be tightened since the reduction of stiffness changes the natural frequency. Using vibration monitoring can be a CM alternative for AutoStore to detect at real-time when bolts become loose and reduce the need to take robots out of operation to check and tighten bolts unnecessary. This can reduce the time used on unnecessary maintenance and the manhour cost.

Another alternative for monitoring tightness of bolts can be a 'smart washer', a piezoceramic based transducer that can monitor looseness of a bolted connection [40].
This can provide a status of the health condition of the bolts in real time. The smart washer will be placed between the bolt and the system to monitor the torque. This can then measure when the looseness increases.

Both with the smart washer and vibration monitoring can the system give indications in an early stage when bolts are becoming loose. This can give the opportunity to take condition-based maintenance decisions, either by schedule basis or by operational basis. With schedule basis can maintenance take place in groups, with e.g. 15 robots that has over a given time provided feedback that bolts are becoming loose, and they can be maintained in a planned operation to reduce the total time spent on maintenance. The other option is to use the operational based status where robots are repaired separately after the CM gives feedback that bolt(s) in the robot are loose. The robot is then almost immediately taken out of operation for maintenance.

5. Results and discussion

This chapter shall cover the discussion of the analysed data and the results, and the advantages and disadvantages of the various solutions are discussed.

5.1 Discussion of analysed data

To gain a good understanding of the selected system and create a basis for understanding the Robot5 better, a visual representation and description of the system was presented in section '4.1 Description of selected system'. Here the build-up of the AutoStore system and the robot was shown. The unscheduled maintenance and operation scenario of Robot5 was also covered. The IDEF1 of unscheduled maintenance scenario shows the process when unexpected maintenance occurs. There are logging of the unplanned maintenance incident but no processing of that logging. AutoStore have a database for storage of the logs, but after the error has been corrected there are little to no learning outcomes of the unscheduled incident. There is no failure cause description, and the corrective action performed are not described and stored to learn what was done to fix the error. It is low overall benefits in a holistic learning process of errors that has occurred for AutoStore as a whole, but more individual learning of the employees who handled the error. This will affect the long-term learning and limit the process of AutoStore achieving world-class maintenance and gain the full benefit of service-dominant logic theory, and the more short-term goal with having a more preventive approach [41].
The AutoStore system has also undergone some design changes and modifications since the start-up at DHL-TI Singapore in 2013. The different changes that have influenced the system function makes it difficult to have a historical learning perspective, especially in the previous years when quite a few changes took place.

In order to systematise my discussion, I will like to discuss each step of my methodology and the related work.

First, to develop a methodology for the analyses was the facility selection criteria discussed in relation to running time and number of occurring errors. The selected facility needed to be in a high running category and have enough errors to get a sufficient basis for the analyses. After an evaluation was DHL-TI Singapore selected, and the methodology for the analyses was set.

The selected methodology comprises of 5 stages:

1. Analyses of failure data
2. Classify critical failure modes
3. Analyse errors that lead to stops
4. Identify the most critical error(s)
5. Evaluate cost effectiveness of current used strategy in relation to replacements, and then compare current strategy with new solution.

There were a lot of errors at DHL-TI in 2015 to 2017 which gave a sufficient basis for doing the error analyses. The first years from start-up, 2013 and 2014, where neglected as of infant mortalities and the available amount of data from year 2015 to 2017. The results from both error notifications and errors that lead to stops deviated from each year. There was little overall context between the years, and the link between error notifications and error stops for each year also have some incoherence. Year 2016 had great variations between error notifications and stopping errors. An error notification can therefore occur without it having much effect in the system, and criticality of an error can only to a very small extent be linked to number of error notifications. Criticality of error have in this thesis been connected to number of stops in the system. The only error that are occurring with highest frequency in all years 2015, 2016 and 2017, and that have a clear correlation between highest occurrence in both error notifications and error stops are 'Trackshift at stop'. Trackshift are also occurring in a much higher frequency relative to the other errors.

The maintenance arrangement DHL-TI Singapore has with Swisslog Singapore affects the results of the analysed cost in section ‘4.5 Cost analysis’. Swisslog will take action to every occurring error and some errors may have several root causes and is therefore difficult to treat. Many replacements have been done, without it necessarily being needed. The cost may have been affected by this, and replacement cost are possibly much higher than estimated because of this. A decision to replace vital parts should be thoughtfully considered and justified, and not just done as an automatic corrective response to an occurring error.

The timeline in chapter ‘4.6 Timeline DHL-TI Singapore’ visually represents all important replacements and events that has taken place since the start-up in 2013. There were several cases of replacements and improvement that where done throughout the years. Most of these went on the warranty from AutoStore and will therefore not necessarily be represented in the cost analyses and replacements logged there. It is therefore a representation of the learning process that has happened at AutoStore, both in a general perspective and at DHL-TI Singapore. Several measures have been done, and an example of this is the robot wheels. At first, they were loose before they started dusting which gave a lot of 'trackshift at stop' errors among more because of the dust in the tracks. AutoStore changed wheel producers and replaced a total of 1117 wheels in the years 2013 to 2014, taken on the warranty. It is therefore important to evaluate the whole process with replacements done and improvements made to create a clear picture of the current maintenance process and use this in the composing of a new maintenance strategy.

In chapter ‘4.7 Error criticality’ error criticality is discussed, and the complexity of the 'trackshift at stop' error was explained, along with the many possible root causes. The possible causes are also visually presented in the root cause tree. Because of all the potential causes for the occurrence of 'trackshift at stop' and the high frequency, the 'trackshift at stop' are the most critical error.

5.2 Expansion and development of current system's condition monitoring

Based on the data AutoStore have today and their goal to improve maintenance, some measures are needed in order to achieve their goal. The analysed data in the selected years are not supportive towards recommending a specific maintenance program, and AutoStore should initiate some measures to ensure more detailed data and understanding of the robot errors. As a result of the analysed data are one main solution proposed in this thesis.

The solution expresses the need for a better understanding of error root causes, establishing new procedures for error data analyses and performing root cause analyses. Fault tree analysis are a good method to gain such an understanding, and AutoStore could highly benefit from an automatic error cause registration. Good understanding of root causes is the basis for enhancing the learning outcomes and obtaining a better maintenance performance.

The current AutoStore system today allows for development of condition monitoring. The robots send notifications about every status update, and this information can be obtained if desired. The information can tell if a robot is experiencing difficulties and can indicate faults in the robot system. If a robot is constantly being corrected by the X-handler this will indicate that the robot should be taken out for inspection and possibly undergo maintenance. However today this information is only available if it is intentionally acquired by individuals and analysed further. This is a cumbersome process where one must deliberately investigate the system with the purpose of finding errors. Many service personnel internationally do not know how to easily benefit from this information and are today also more used correctively than preventive. If this system is developed further and made easily obtainable it can be an alternative condition monitoring. Then it can give direct information about the state of the system and its robots without the personnel having to personally acquire the information from several links in the system. If developed in a fulfilling manner can it deliver direct, real-time information about the system to the operating personnel on site or at the distributor.

6. Conclusion

The research question in this thesis was formulated *"How can the maintenance program for the critical system of the smart warehousing system be improved in a cost-effective manner?"*. To be able to provide a solution to this question, two approaches were investigated. First solution was based on the analysed historical data, followed by a solution using real time data. The thesis first analysed the historical data of Robot5 at DHL-TI Singapore to generate recommendations for improvement of the existing maintenance program. By using the historical data related to the robot belts, it could roughly be suggested a new replacement schedule with the use of Weibull.

The performed analyses in this thesis could also provide a basis for better understanding the general maintenance related to Robot5. It presented some suggestions with implementing condition monitoring techniques, in this case a smart washer that measures torque and a loosening detection using natural frequency, both used to measure the real-time health of bolts. These suggestions could potentially support upon the condition-based maintenance program.

By using the project methodology this thesis was able to relatively effectively provide an answer to the research question, but there were several challenging issues that emerged throughout the process. By analysing the robot errors, the aim was to reveal some structures in the failures and stops to see if a preventive maintenance program could be a cost effective and reliability improving maintenance program for AutoStore. The analysed robot error data is, however, considered to be inconclusive. This is due to several reasons: a relative short period (3 years) that are too early in the life cycle of the system, incomplete information about maintenance issues in regards of error causes and why something was fixed, and the system design enhancements. Due to a lot of replacements, firmware updates and improvements is it difficult to base a possible new strategy on the errors and stops that have occurred at DHL-TI Singapore. The AutoStore system with Robot5 is a relative new system and they are still in a learning process in relation to doing cost-effective maintenance, and the analysed data bear touch of this. Hence, concluding in a specific maintenance program would not be a prudent solution.

All these aspects influence the reliability of using historical data to learn, foreseen and make future decisions. Therefore, this approach will be more effective over the time as more data are collected and error causes become more known. The thesis suggests using fault tree analysis to analyse the collected data in an automatic manner. The manual error and cause analyses in this thesis was time consuming but will have large improvement potential and an advantage of being automated in the future. With an automated process will the procedure with documentation become much easier, and the associated service personnel will see the benefit of documenting and sharing their experiences about error causes and how to mitigate or monitor such errors.

The learning process based on historical error data has one limitation in regard to future learning. The future design changes and system enhancements will affect the learning process of historical errors and failure patterns. For example, if the belts undergo a major design change or the types of belts are changed, the previous 3 years of data collection will have limited value to the future learning process. System updates and design modifications is however necessary in a lifetime perspective to ensure business growth and be competitive in a constantly changing and evolving market.

A second learning approach was therefore suggested. The use of condition monitoring can provide real-time status of health condition of components and equipment. The learning of how to maintain the robot system will be based on the actual condition of the equipment using real-time data. Any design changes can more easily be compared. With more concrete failure data can more specific analyses be done and help reduce cost consuming, unnecessary replacements. One of the reasons DHL-TI and Swisslog are doing so many replacements today is that they don't know the underlying root cause for the various errors. The error analyses performed in this thesis is a starting point for such an intelligent learning approach, which can enable condition-based maintenance. Effective monitoring solutions need a clear determination of the critical error modes and causes to decide if it can be monitored or not. AutoStore is an online system and they have made several enhancements in the last years to become better at information handling and monitoring. The X-handler is an example of this. They have a good potential to develop and become more sophisticated in planning and performing maintenance. Clarification of the critical error modes and causes is, however, crucial for a successful maintenance strategy at AutoStore.

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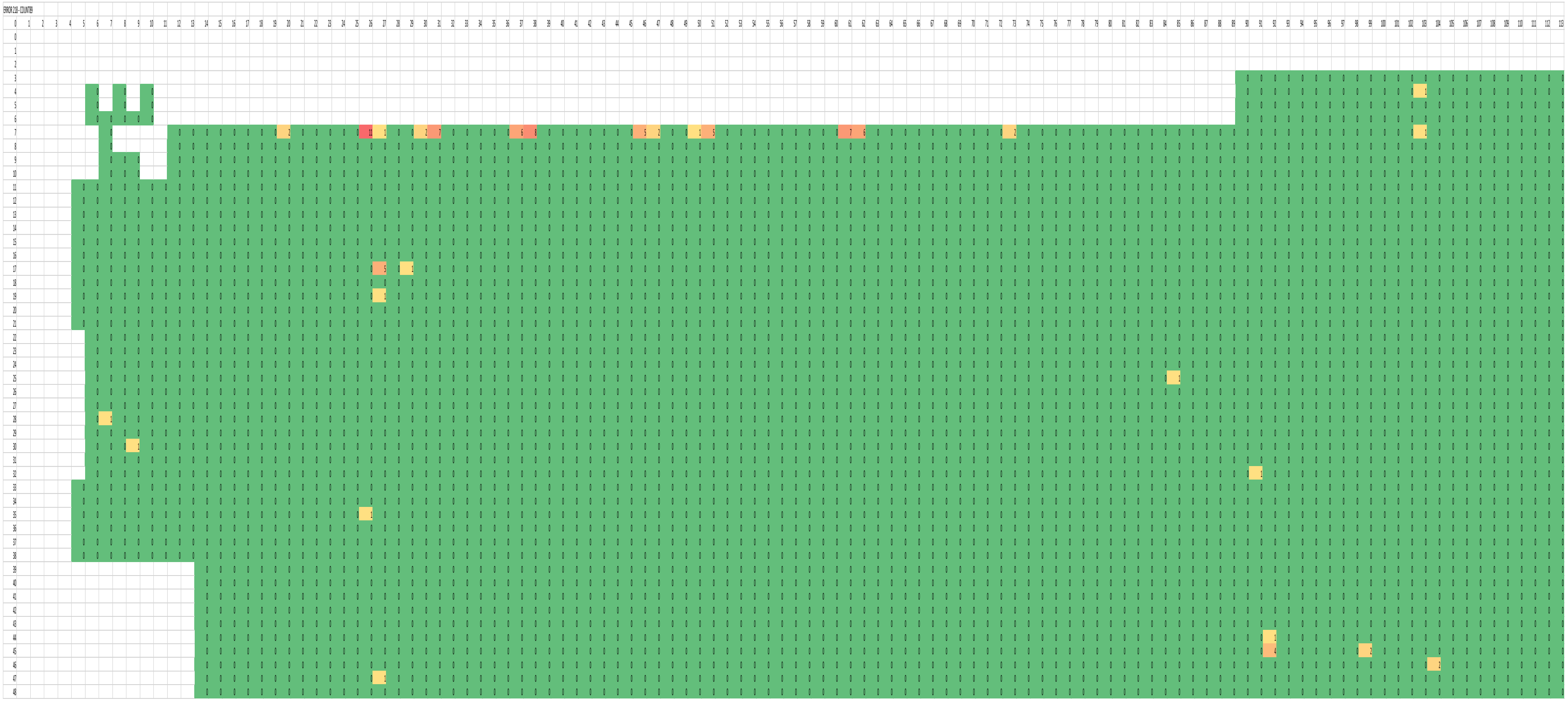
Appendix

Attachment 1: Technical model of Robot5

Attachment 2: Clipping of Grid overview failure.xlsx over error '218 – Wire Failure'. Green indicates normal state with no errors



Attachment 3: All errors at DHL-TI Singapore in 2016

Names>	MOTOR_C	TRANSIST(	BATTERY_	MISSING_	COMMAN	TRACKSHI	MISSING_	GAP_SIZE	STOP_POS	STOP_TO_	MOVING_	TRACKSHI	POSITION_	UNSTABLE	UNSTABLE	PARITY	MISSING_	BRAKE_FA	BRAKE_IS_	NO_BOTT(	BOTTOM_	WIRE_FAI	GRIPPER_I	HOOK_ON	HOOK_SH	TOPSW_T(	UNKNOWI	OVERLOAI	OVERLOAD_3_1	
Robno\Err	122	123	124	125	151	157	158	160	161	162	164	165	169	172	173	200	201	209	214	215	216	218	219	223	225	226	231	235	236	Sum
ROB034	0	0	0	0	0	0	0	0	0	1	2	7	0	0	0	0	0	0	0	0	62	0	0	0	0	0	0	0	0	72
ROB025	0	0	0	0	0	0	0	1	0	0	0	3	0	0	5	0	0	0	0	15	3	34	0	0	0	0	0	0	1	62
ROB022	0	0	0	0	0	0	0	0	1	0	0	23	0	0	0	0	0	0	0	5	0	3	0	0	0	0	1	0	0	33
ROB024	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	6	1	24	1	1	0	1	0	0	0	36
ROB011	0	0	0	0	1	0	0	0	0	0	0	9	0	5	0	0	0	0	9	21	2	0	1	1	0	0	0	0	1	50
ROB035	0	0	0	0	0	0	0	0	0	0	0	16	1	2	2	0	0	0	0	0	1	2	0	0	0	0	0	0	0	24
ROB023	0	0	0	0	0	0	0	0	0	0	0	7	4	0	4	0	0	0	0	4	0	14	0	0	0	0	0	0	0	33
ROB003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	9	0	23	6	0	0	0	0	0	0	39
ROB018	0	0	0	0	1	0	0	1	0	0	0	32	0	0	22	0	0	0	0	3	0	6	0	0	0	0	0	0	0	65
ROB006	0	0	0	0	0	0	0	0	0	0	1	12	0	0	21	0	0	0	0	8	2	24	0	0	0	0	0	0	0	68
ROB008	0	0	1	0	1	1	0	0	0	0	1	87	0	40	0	0	0	0	0	5	0	17	0	0	0	0	0	0	1	154
ROB030	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	1	30	9	0	0	0	0	0	0	54
ROB014	0	0	0	0	0	0	0	0	0	0	0	21	0	0	25	0	0	0	1	22	0	17	0	0	0	0	0	0	0	86
ROB004	0	0	0	0	1	0	0	0	0	0	0	25	0	9	1	0	0	0	1	12	1	15	0	1	1	0	0	0	0	67
ROB015	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	3	0	3	10	1	21	1	0	0	0	0	0	0	41
ROB005	0	0	0	0	0	0	0	0	0	0	0	3	0	6	0	0	0	0	0	4	2	8	0	0	0	0	0	0	0	23
ROB028	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	0	1	13	1	5	0	0	0	0	0	0	1	25
ROB009	0	0	5	0	0	2	1	0	0	0	0	1	0	1	0	1	0	0	0	39	0	38	2	0	1	0	0	0	0	91
ROB002	0	0	0	0	0	0	1	0	1	0	0	23	0	8	3	0	0	0	0	6	3	21	0	0	0	0	0	0	0	66
ROB016	1	0	0	0	1	0	0	0	0	0	0	87	0	5	5	0	0	0	0	6	0	24	0	0	0	0	0	0	0	129
ROB001	0	0	0	0	0	0	2	0	0	0	1	2	1	0	0	0	0	0	1	9	0	25	0	0	0	0	0	0	0	41
ROB010	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	14	5	0	1	0	0	0	0	0	0	22
ROB032	0	0	0	0	0	0	0	0	0	0	0	107	0	23	0	0	0	0	0	3	3	10	0	0	0	0	0	0	0	146
ROB031	0	0	4	0	0	0	0	0	0	0	0	12	0	8	0	0	0	0	1	6	3	20	1	0	0	0	0	0	0	55
ROB019	0	0	0	0	0	0	0	0	0	0	0	2	0	10	0	0	0	0	0	0	1	16	0	1	0	0	0	1	0	31
ROB013	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	8	1	33	1	1	0	0	0	0	0	46
ROB029	0	0	1	0	1	0	0	0	0	0	0	4	0	0	14	0	0	0	0	28	0	62	0	1	0	0	0	0	1	112
ROB020	0	0	1	0	0	0	0	0	0	0	0	15	0	2	12	0	0	0	0	18	6	25	0	0	0	0	0	0	0	79
ROB033	0	0	9	0	1	0	0	0	1	1	0	85	0	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	103
ROB007	0	0	0	0	0	0	0	0	0	0	0	8	0	2	12	0	0	0	0	3	0	25	0	0	2	0	0	0	2	54
ROB017	0	0	0	1	1	0	0	0	0	0	1	0	0	10	0	0	0	0	0	2	0	9	0	0	0	0	0	0	0	24
ROB036	0	2	0	5	1	0	0	0	0	0	0	1	0	0	2	0	3	0	0	0	0	0	0	2	0	0	0	0	0	16
ROB021	0	0	3	0	0	0	1	0	0	0	1	109	0	0	8	0	0	0	0	5	0	12	0	0	0	0	0	0	0	139
ROB012	0	0	0	0	0	0	0	0	0	0	0	2	0	5	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	11
ROB027	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1	0	4	1	11	0	0	0	0	0	0	0	20
ROB026	0	0	0	0	0	0	0	0	0	0	0	44	0	1	0	0	0	0	0	6	0	7	0	0	0	0	0	0	0	58
Sum	1	2	24	6	11	3	5	3	3	2	7	751	6	145	140	1	6	1	21	311	100	581	23	8	4	1	1	1	7	2175
																														Totalt feil

Attachment 4: All errors at DHL-TI Singapore in 2017 ("AllErrors2017")

Colum	Colum	Colum	Colum	Column4	Column5	Column6	Colum	Colum	Colum	Column	Colum	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column	Column
Names>	MOTOR_C	TRANSIST	BATTERY_1	MISSING_MOTOR	TRACKSHIF	MISSING_I	GAP_OVEI	GAP_SIZE	STOP_POS	STOP_TO_	MOVING_S	TRACKSHI	UNSTABLE	UNSTABLE	PARITY	BRAKE_RE	BRAKE_RE	BRAKE_RE	LIFT_OVERL	BRAKE_IS	NO_BOTTO	BOTTOM_T	WIRE_FAIL	GRIPPER_F	HOOK_ILLE	HOOK_SHIF	HOOK_ON_I	HOOK_SHIF	MISSING_T	UNKNOWN	OVERLOAD	OVERLOAD_3_1	
RobnoiErr	122	123	124	125	157	158	159	160	161	162	164	165	172	173	200	206	207	208	212	214	215	216	218	219	221	222	223	225	228	231	235	236	Sum
ROB003	0	0	2	0	0	0	0	0	0	0	0	5	0	22	0	0	0	0	0	0	12	0	20	0	0	221	0	0	0	0	0	0	282
ROB021	0	0	0	0	0	2	0	0	0	0	0	54	0	8	0	0	0	0	0	1	7	2	14	0	0	0	0	0	0	0	0	0	88
ROB027	0	0	0	0	0	0	0	0	0	0	0	5	7	6	0	0	1	0	1	0	10	1	11	0	0	0	0	25	0	0	0	0	67
ROB017	0	0	3	0	0	2	0	0	0	0	0	21	11	0	0	0	0	0	0	0	9	0	18	1	0	0	0	0	0	0	0	0	65
ROB013	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	3	57	0	0	0	0	0	0	0	0	0	63
ROB023	0	0	0	0	0	9	0	0	1	0	1	186	6	8	0	0	0	0	0	1	11	3	33	0	0	0	0	1	0	0	1	0	261
ROB005	0	0	8	0	0	5	0	0	0	0	0	43	0	42	0	0	0	0	0	0	3	0	21	1	0	0	0	0	0	0	0	0	123
ROB002	4	0	4	0	0	0	0	0	1	0	0	133	8	18	0	0	0	0	0	2	16	6	31	0	0	0	0	0	0	0	0	0	223
ROB010	0	0	0	1	0	1	0	0	0	0	1	2	2	0	0	13	2	33	0	1	3	13	0	1	0	1	0	6	0	0	1	0	81
ROB032	1	0	9	0	0	1	0	1	0	0	1	172	15	1	0	0	0	0	0	219	1	0	9	7	0	0	0	0	0	0	0	0	437
ROB011	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0	7	26	4	0	2	0	0	0	0	0	0	0	0	45
ROB031	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	8	0	24	3	0	0	0	0	0	0	0	0	36
ROB029	1	0	0	0	0	0	0	0	0	0	0	5	1	2	3	0	0	0	0	0	29	0	142	5	0	0	0	0	0	1	0	0	189
ROB024	0	0	21	0	0	1	0	0	0	0	0	12	0	2	0	0	0	0	0	1	5	1	25	1	0	0	0	0	0	0	0	0	69
ROB007	0	2	0	0	0	0	0	0	0	0	0	48	12	34	0	0	0	0	0	0	6	3	27	0	0	0	0	2	0	0	0	0	134
ROB025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	8	13	0	105	2	0	0	0	0	0	0	0	0	141
ROB030	0	0	0	0	0	1	0	0	0	0	0	13	0	0	0	0	0	0	0	0	8	3	28	0	0	1	0	0	0	0	0	0	54
ROB009	0	1	0	0	1	0	0	1	0	1	0	20	16	10	5	0	0	0	0	1	14	0	59	10	0	1	0	0	0	0	0	0	140
ROB019	0	0	0	0	0	0	0	0	0	0	0	61	7	2	1	0	0	0	0	0	0	17	21	2	1	1	0	1	0	0	0	0	114
ROB022	0	0	6	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	1	4	3	20	0	0	0	1	0	0	0	0	0	38
ROB026	0	0	1	0	0	0	0	0	1	0	0	44	8	1	0	0	0	0	0	4	4	2	23	1	0	0	0	0	1	0	0	0	90
ROB020	0	0	0	0	0	2	0	0	1	0	0	52	1	2	0	0	0	0	0	2	5	0	30	1	0	0	0	11	0	1	0	0	108
ROB004	0	0	2	0	0	0	0	0	0	0	0	16	4	2	0	0	0	0	0	2	9	2	16	0	0	0	0	0	0	0	0	0	53
ROB018	0	0	0	0	0	0	0	0	2	0	0	10	0	1	0	0	0	0	0	0	2	1	9	0	0	0	0	1	0	0	0	0	26
ROB014	0	0	0	1	0	1	0	0	0	0	1	61	25	0	0	0	0	0	0	1	5	0	12	0	0	0	0	0	0	0	0	0	107
ROB015	0	0	10	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	4	1	19	2	0	0	0	0	0	0	0	0	38
ROB012	0	0	0	0	0	1	0	0	0	0	0	0	3	1	0	0	0	0	0	0	6	6	0	2	0	0	0	0	0	0	0	0	19
ROB016	0	0	1	1	0	4	0	0	0	0	0	12	26	0	0	0	2	2	0	1	4	0	25	0	0	6	0	0	0	0	1	0	85
ROB034	0	0	0	0	0	0	0	0	0	0	2	14	14	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	32
ROB006	0	0	0	0	0	0	0	0	0	0	0	126	0	6	0	0	0	0	2	0	10	0	27	0	0	0	0	2	0	0	0	0	173
ROB028	0	0	0	0	0	0	0	0	0	0	0	4	0	1	2	0	0	0	0	1	2	13	13	2	0	0	2	0	0	1	0	0	41
ROB008	0	0	0	0	0	0	0	0	0	0	0	70	0	23	0	0	0	0	0	0	3	1	5	0	0	0	0	0	0	0	0	0	102
ROB001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	5	28	0	0	1	0	0	0	0	0	0	41
ROB033	0	0	0	0	0	0	0	1	0	0	0	135	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	149
ROB035	0	0	2	0	0	0	0	0	0	0	0	9	0	3	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	16
ROB036	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5
Sum	6	3	69	3	1	30	1	4	6	2	7	1338	184	195	27	13	6	35	3	253	248	90	873	44	1	232	3	50	1	3	3	1	

Attachment 5: All errors at DHL-TI Singapore in 2015

Names>	MOTOR_O	BATTERY_	MISSING_I	COMMANDPOS_MIS	EARLY_ST	ILLEGAL_1	TRACKSHI	MISSING_(	GAP_OVER	GAP_SIZE	STOP_POS	STOP_TO_I	MOVING_S	TRACKSHIF	POSITION_E	PARITY	MISSING_TI	BRAKE_REI	BRAKE_REI	BRAKE_IS_	NO_BOTTO	BOTTOM_T	WIRE_FAILL	GRIPPER_F	HOOK_SHIF	HOOK_ON_	HOOK_SHIF	OVERLOAD	OVERLOAD_3_1	
Robno\Errc	122	124	125	151	155	156	157	158	159	160	161	162	164	165	169	200	201	206	208	214	215	216	218	219	222	223	225	235	236	Sum
ROB015	0	0	0	2	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	3	1	9	0	0	0	0	0	0	24
ROB020	0	0	0	0	0	1	0	0	1	0	0	0	0	30	4	1	1	0	0	0	58	0	27	4	0	0	0	1	0	128
ROB035	0	0	0	0	0	0	0	0	0	1	0	0	3	31	4	0	0	0	0	0	1	0	0	0	0	0	0	0	1	41
ROB014	0	0	0	0	0	0	0	0	0	0	0	0	0	19	2	0	0	0	0	2	46	2	8	0	0	0	0	0	0	79
ROB025	0	0	0	0	0	0	0	0	0	0	0	0	2	39	0	0	0	0	0	0	32	4	52	12	0	0	0	0	0	141
ROB018	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	1	5	0	2	0	0	0	0	0	0	20
ROB004	1	0	0	1	0	0	0	0	0	0	0	1	0	88	1	0	0	0	0	0	23	4	12	0	0	0	0	0	0	131
ROB008	0	0	0	1	0	0	0	1	0	0	0	3	0	39	0	0	0	0	0	1	20	0	8	0	0	0	0	0	0	73
ROB003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	16	1	13	2	0	0	0	0	0	36
ROB013	0	0	0	0	0	0	1	0	1	0	0	0	1	1	1	0	0	0	0	0	22	1	22	0	0	0	0	0	0	50
ROB002	0	1	0	0	0	0	0	0	0	0	0	0	1	61	0	0	0	0	0	0	3	0	3	18	0	0	0	0	0	87
ROB026	0	0	0	0	0	0	0	0	0	1	0	2	0	10	3	0	0	0	1	0	8	2	5	0	0	0	0	0	0	32
ROB005	0	1	0	0	0	0	0	0	0	1	0	1	3	53	0	0	0	0	0	0	14	0	18	0	0	1	0	0	1	93
ROB028	0	1	1	0	0	0	0	0	0	0	0	2	0	26	0	0	0	0	0	0	4	2	9	0	0	2	0	0	0	47
ROB030	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	1	15	3	0	0	0	0	0	55
ROB007	0	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	5	1	21	1	0	0	0	0	0	34
ROB016	0	0	0	0	0	0	0	0	0	0	0	1	0	17	0	0	0	0	0	0	43	1	10	0	0	1	0	0	0	73
ROB029	0	0	0	0	0	0	0	0	0	0	0	0	1	31	0	0	0	0	0	0	51	2	36	0	0	0	0	0	0	121
ROB001	0	0	0	2	0	0	0	0	0	0	0	0	0	4	0	0	1	0	0	0	24	0	9	1	0	1	0	0	0	42
ROB009	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	136	1	31	1	0	0	1	0	0	172
ROB036	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
ROB011	0	0	0	0	0	0	0	0	0	0	0	1	0	30	0	0	1	0	0	6	31	0	0	0	0	1	0	0	0	70
ROB019	0	3	0	0	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	1	0	1	5	0	0	0	1	0	0	16
ROB010	0	0	2	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	6	3	0	0	3	1	0	0	0	19
ROB006	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	26	0	8	0	0	1	0	0	0	40
ROB012	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	12	14	2	0	0	0	0	0	0	0	30
ROB031	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	3	0	6	0	0	0	14	0	1	26
ROB024	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	12	0	16	0	0	0	0	0	0	41
ROB027	0	2	0	0	0	0	0	1	0	0	0	1	1	6	0	0	0	0	0	0	8	0	24	0	0	0	0	0	0	43
ROB022	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	2	3	0	0	0	0	0	1	9
ROB033	0	0	0	1	0	0	0	0	0	0	0	0	1	47	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	50
ROB021	0	1	0	0	0	2	0	2	0	0	0	0	0	40	0	0	0	0	0	0	5	1	4	0	0	0	0	0	0	55
ROB017	0	0	0	0	0	0	0	0	0	0	0	0	0	21	1	0	0	0	0	12	6	1	7	0	0	0	0	0	0	48
ROB034	0	1	0	0	0	0	0	1	0	0	0	0	1	6	2	0	0	0	0	0	2	21	4	1	0	0	0	0	0	39
ROB023	0	0	0	0	1	0	0	0	0	1	0	1	0	3	0	0	0	0	0	0	7	0	12	0	0	0	0	0	0	25
ROB032	0	0	0	0	0	0	0	1	0	0	0	0	0	63	3	0	0	0	0	0	3	1	4	0	0	0	0	0	0	75
Sum	1	12	4	9	1	3	1	7	2	4	1	14	14	724	23	5	3	1	1	35	675	55	403	43	3	8	16	1	4	2073

Attachment 6: Large scale clipping of 'Estimated spare part cost for customer over a 10-year period'.xlsx

				ESTIMATED NUMBER OF CHANGES OVER A 10 YEAR PERIOD						
2	ROBOT PARTS - ESTIMATED CHANGE OUT OVER 10 YEAR PERIOD							Rev 1.4		04.01.2017
3	Article:	Part text:	piece pr modul	Based on category 1	Based on category 2	Based on category 3	Based on category 4	Estimated number of parts to be replaced	Price/part DBP	Total cost DBP
4	AS-35046	Motor Trackshift assembly	1	0	0	1	1	36	6 120,00	220320,00
5	AS-35028	Lift gear assembly	2	0	0	1	2	144	1 225,00	176400,00
6	AS-35007	Gripper motor	2	0	0	1	1	72	560,00	40320,00
7	AS-35195	Robot 4, Belt GT3 5MR 700 25	2	0	0	1	1	72	280,00	20160,00
8	AS-35197	Robot 4, Belt Twin HTD 5M 670 15	1	0	0	1	1	36	766,00	27576,00
9	AS-35199	Robot 4, Belt GT3 5MR 650 15	2	0	0	1	1	72	202,50	14580,00
10	AS-35201	Robot 4, Belt GT3 5MR 400 9	2	0	0	1	1	72	135,00	9720,00
11	AS-35219	Belt HTD3 1420 5M 15	1	0	0	1	1	36	460,00	16560,00
12	AS-35052	Brush kit	2	0	0	2	2	144	959,00	138096,00
13	AS-35031	Motor lift assembly	1	0	0	1	1	36	6 930,00	249480,00
14	AS-35065	Move-y motor assembly	1	0	0	1	1	36	6 940,00	249840,00
15	AS-35033	Move-x motor assembly	1	0	0	1	1	36	7 064,00	254304,00
16	AS-35024	Brake assembly	1	0	1	1	2	72	2 380,00	171360,00
17	AS-35019	Wheel & rim assembly	8	0	0	1	1	288	1 312,50	378000,00
18	AS-35047	Chargehouse assembly	1	1	1	2	2	72	940,00	67680,00
19	AS-35210	Robot, Battery Assembly2x Batteries with connectors	1	1	2	3	4	144	4 995,50	719352,00
20	AS-35149	Robot strip kit	1	1	1	2	3	108	875,00	94500,00
21	AS-35023	Tracksensor	4	0	1	2	2	288	869,00	250272,00
22	AS-35005	Gripper guides	1	1	1	2	3	108	1 140,00	123120,00
23		Time inspection	1	15	20	30	40	1440	850,00	1224000,00
24		Time service	1	2,4	3,7	22,5	26,3	945	850,00	803250,00
25										
26	Total:							1872		5248890,00

Attachment 7: Large scale 'Timeline DHL-TI Singapore'