Measuring Product Dimensions during Assembly

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Preface

This master thesis work concludes our education in materials and production engineering at Lund University, Faculty of Engineering (LTH). The master thesis was conducted in collaboration with Volvo Group Trucks Operations in Gothenburg, Sweden during spring 2021.

The workload has been shared and divided equally and both members have shown and taken initiative in all areas during the thesis.

We would like to thank our industrial supervisors, Henrik Paulsson, Briitta Ojala and Bas De Craene, for your guidance and support during our time at Volvo GTO. We appreciate all your effort, time and patience that we got from you throughout the master thesis project.

We would also like to thank our supervisor at LTH, Tekn. Dr. Christina Windmark and PhD. Andrii Hrechuk for providing your experience and support in academic writing and for your valuable input during the master thesis project.

Last, but not least, we want to thank our families for supporting us through our engineering studies, now, we finally have a Master of Science in Engineering!

Lund 2021-05-31

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Sammanfattning

Under vårterminen 2021 genomfördes en avhandling på Volvo GTO. Volvo Lastvagnar är en av de största aktörerna inom fordonsindustrin och levererar lastbilar över hela världen. Företaget erbjuder lastbilar som kan anpassas och modiferas efter kundens önskemål.

Att erbjuda lastbilar med hög anpassnings- och förändringsgrad innebär en hel del påfrestningar på systemet vilket kräver att CAD-ritningar, komponentdokumentation och alla databaser synkroniseras och uppdateras enligt de ändringar som gjorts på lastbilen. Det har observerats inom företaget att lastbilarnas faktiska dimensioner inte alltid sammanfaller med systemdimensionerna. Avvikelserna i lastbilens dimensioner orsakar problem vid transporter eftersom lastbilarna antingen överskrider eller faller under systemdimensionerna.

Målet, med ovanstående i åtanke, har varit att uppnå en bättre förståelse för hur olika mättekniker kan användas vid ett automatiserat system för industriell inspektion. Med hjälp av systemet var syftet att samla in data för att möjliggöra en rotorsaksanalys av avvikelserna.

I projektet har olika sensorer testats för att kunna användas i ett framtida automatiskt system för inspektion. Under projektets gång blev det uppenbart att målet att använda sensorn för insamling av data inte var möjlig. Det fanns flera faktorer som ledde till denna slutsats. Främst berodde det på tidsbrist, men också på de svårigheter som uppstod vid kalibrering och programmering av sensorerna för att uppnå tillförlitliga och exakta mätresultat. Strävan att försöka använda sensorerna gav dock mycket kunskap och data som ansågs vara av stort värde för Volvo. Trots problemen och hindren så genomfördes datainsamling och analys med hjälp av en manuell linjalsticka som fungerade bättre än förväntat.

Vissa, på förhand givna faktorer och orsaker, och konsekvenser bekräftades av mätningarna och analysen av data, medan andra avvisades. En rekommendation för den som kommer tar över projektet är att fortsätta samla in data, både från mätningen vid Tuve och rapporterna från transportörerna. Dessa rapporter bör också förbättras och dokumenteras mer noggrant för att säkerställa att viktig information inte förloras.

Abstract

During the spring term of 2021 a thesis was carried out at Volvo Trucks GTO. Volvo Trucks is one of the largest and most successful actors in the automotive industry and delivers trucks all over the world. The company offers trucks that can be customized and adapted according to the customer wishes.

Offering highly customizable trucks puts a lot of stresses on the system which requires that CAD-drawings, component documentation and all databases are synchronized and updated according to the changes done on the truck. It has been observed within the company that the actual dimensions of the trucks do not always coincide with the system dimensions. The deviations in dimensions of the truck causes problems during transports as the trucks either exceeds or fall under the system dimensions.

The objective, having the above in mind, has been to achieve a better understanding of how different measurement techniques can be used as an automated system for industrial inspection. Using the system, the aim was to collect data to enable a root-cause analysis on the deviations.

In the project, different sensors have been tested in order to identify a capable sensor for a future automated system. During the project it became apparent that the objective of using the sensor for collecting data could not be achieved. There were several factors that led to this conclusion. But mainly it was due to the lack of time, but also due to the difficulties faced when calibrating and programming the sensor to achieve reliable and accurate measurements. However, the struggle of trying to use the sensor provided a lot of knowledge and data which was considered to be of great value for Volvo. The collection of data and analysis was still accomplished, using a manual ruler stick which worked better than expected.

Some pre stated factors and causes, and consequences were justified by the measurements and analyzation of data, while others were rejected. A recommendation for the one who will continue in the footsteps of this project, is that they should continue collecting data, both from measuring in Tuve and reports from carriers. The reports should also be improved and documented more carefully to make sure that important information is not being lost.

Table of Contents

1. Introduction

The following chapter gives an introduction to the master thesis study which includes a background and problem description followed by the objective, research questions and limitations of the study.

1.1. Background

In a global company within the automotive industry that delivers trucks all over the world, the planning for transports and logistics is a key factor to stay competitive. The truck industry delivers products that are highly customized which means that the trucks fluctuate in dimensions and specifications with a high frequency.

Volvo Trucks uses several different databases for documenting and tracking the trucks to enable for control and communication within the Volvo Group and external stakeholders. The databases are used in different fields and for different applications. There are databases used by the sales-department and the dealers to provide necessary information such as tender and lead time to customer. Other databases are being used by the production to provide necessary information for the planning and by the logistics for the outbound transports. Even though the databases are being used for different applications they are interconnected and changes regarding the truck information in one database will most likely affect the information in another database used for another application.

Here, information on the truck dimensions is used for planning and estimating the costs of the outbound and order transports. This requires that information regarding the truck, such as the dimensions are correct.

1.2. Problem description

Volvo offers both variants (standard) and customer adapted trucks (CA), which means that each truck is unique in its dimensions. It has been observed within the company that the actual dimensions of the trucks do not always coincide with the theoretical dimensions.

The deviations in dimensions of the truck causes problems during transports as the trucks either exceeds or fall under the system dimensions. These deviations causes problems such as increased material and immaterial damages, longer transportation lead times, freight costs and impact on the relation with the carriers. There are also aspects around the liability for both Volvo and carrier connected to the dimensions of the load or cargo.

1.3. Objective & research questions

The objective is to achieve a better understanding of how different measurement techniques can improve automated industrial inspection and enable a more solid foundation for root-cause analysis.

The aim is to evaluate and present an optimal vision technique for automated industrial inspection by using literature study and testing analysis. With this scope in mind, the following research questions has been raised:

- What are the economic consequences and how does the current situation affect the relation to the stakeholders, internal- and external customers, transport partners and competitors?
- What kind of measuring techniques exist and how well do they perform related to the set requirements?
- What are the root causes of these deviations?
- What aspects should be considered when integrating a future measuring solution to the production process?

1.4. Limitations

This study will investigate and evaluate different measurement techniques and will not include installation and configuration of a complete measurement system. Furthermore, the study will focus mainly on the transport overseas from the harbor Wallhamn and thus not include all trucks manufactured in Tuve, Gothenburg.

1.5. Disposition

The master thesis is divided into seven chapters which are presented in the following order:

Introduction – *This chapter gives an introduction to the master thesis study which includes a background and problem description followed by the objective, research questions and limitations of the study.*

Method - *This chapter presents the methods used for data collection and the different ways in how data was collected. Initially, the study started with a pre study including a literature study of measurement techniques and a market research. The pre study was followed by experimental work alongside qualitative interviews with employees in the organization. The chapter ends with a discussion regarding validity and reliability in the study.*

Theory - *This chapter presents the major theoretical areas touched during the study. Initially the theory section provides a description of possible measuring solutions in machine vision. Early in the project a machine vision based solution was considered most suitable, considering that the objective was to develop an automated system. Due to this it was decided to focus more on machine vision as a measuring solution. The next part provides facts on fundamental techniques and theory applied to machine vision. The chapter ends with theory regarding transport logistics, buyer-supplier relationship which connect to the problems the company experience because of the dimensional deviations.*

Experimental methods - *This chapter includes a description of the experimental work conducted in the study, how different techniques have been evaluated and then tested to conclude which is the best suitable solution for the objective of the study.*

Results - *This chapter presents the results for each research question. Starting with consequences due to the current situation. The second research question presents the results from testing the sensors in the controlled and demanding environment. The third research question presents the observed factors and causes for the deviation. Finally, the last research question provides a review of aspects that should be considered for a future automated measuring system.*

Discussion - *This chapter discuss the results and findings of the study and the research questions in correlation to the theories presented in chapter 2. The chapter gives a deeper analysis of the findings, conclusions and* *learnings from the master thesis project. Furthermore, the chapter includes a discussion regarding the validity and reliability in the study.*

Conclusions – *This chapter includes final conclusions of the master thesis and presents recommendations for future work*.

2. Method

This chapter presents the methods used for data collection and the different ways in how data was collected. Initially, the study started with a pre study including a literature study of measurement techniques and a market research. The pre study was followed by experimental work alongside qualitative interviews with employees in the organization. The chapter ends with a discussion regarding validity and reliability in the study.

2.1. Methods of data collection

2.1.1. Interviews

Interviews were carried out to get a general insight to the company, understand the causes and consequences of the deviations and identify important aspects for the future implementation of an automated system. The interviews were carried out with employees at Volvo, suppliers of measuring equipment, external integrators, competitor for benchmarking and carriers for outbound transports.

When data is collected in terms of interviews, the method of the interview must be considered. The interview can be either structured, unstructured, or semi structured, usually the interviews are carried out in a more structured way. This means that questions that will be raised during the interview are clear, structured, and predetermined. For the case of an unstructured interview, the approach is the opposite, leaving more room for flexibility in the interview. Unstructured interviews put greater demands on the interviewer and requires deep understanding of the subject. To achieve successful interviews in a study, the interviewers should be trained and selected carefully. The interviews needs to be clear, well-prepared and unbiased to reach desired outcome [1].

In this study, both structured and unstructured interviews were conducted depending on the situation and the aim of the interview. The table below shows all interview conducted during the study.

Table 1. Interviews.

Department	Role	Position
Outbound Transports	Manager Transport Overseas	Volvo Employee
	Controller	Volvo Employee
	Transport Planner	Volvo Employee
	Transport Planner	Volvo Employee
	Transport Planner	Volvo Employee
	Invoice Manager	Volvo Employee
	Risk Manager	Volvo Employee
External	Supplier 1	Sales Engineer
		Sales Engineer
		Key Account Manager
	Supplier 2	Sales Engineer
		Technical Engineer
	Integrator 1	Sales Engineer
	Integrator 2	Sales Engineer
	Competitor	Project Manager
Production	Process Engineer	Volvo Employee
	Production Planning Manager	Volvo Employee
	Customer Adaption Responsible	Volvo Employee
IT	Database Expert	Volvo Employee
	Database Expert	Volvo Employee
	Database Expert	Volvo Employee
	Database Expert	Volvo Employee

2.2. Evaluation and experimental work

The selection and evaluation of measuring techniques was done based on requirements stated by the company and theory from the literature study. The objective of the evaluation was to exclude equipment that did not satisfy the specified requirements and demands. The experimental work included different measuring setups which will be further explained in the chapter experimental methods.

2.3. Measuring

The measuring was done in two separate ways, one was performed in a controlled environment, while the other test was performed in a more demanding environment. The controlled environment test was carried out to investigate the measurement accuracy and to identify strengths and weaknesses of the sensors that showed best performance. The demanding environment test was performed for the statistical analysis where a hypothesis test was performed with a stated null and alternative hypothesis. The demanding environment test was also performed to discover obstacles and other aspects in regard to mounting the equipment for optimal performance.

2.4. Validity and reliability

The validity in a study is ensured by the truthiness of the results and that the right thing is studied, and reliability is ensured that it is studied in the right way.

Validity can be achieved in a study by including a relevant literature study, theory section and using these in the results and discussion and ensuring that the research questions are answered correctly. The validity in a study can then be divided into internal- and external validity. Internal validity ensures that the measurement instrument really measures what it intends to measure and how well-grounded the conclusions are from the measurements.

Another factor that is important in measurements is consistency, by repeating the measurements the values need to be stable over time. If this is achieved, then reliability has been reached. Measurements from instruments can have a high reliability, i.e. measuring consistently the same value, but if the measured value of the instrument is far from the actual value, then the validity is low [2].

For the case of this study the validity can be observed in the evaluation of techniques in terms of measurement accuracy but also when drawing conclusions regarding the deviations.

In this study internal validity is reached and stated by the statistical model presented in chapter 4.4 and the method used is hypothesis testing. For this study it is about reaching a high measurement accuracy of the instruments that are evaluated. Not only does the measurement accuracy needs to be precise but also the resulting accuracy of what is intended to be measured.

The precision of the measurement accuracy can be good and give repetitive values, but it also needs to give measurements that is accurate to the target value. To be able to reach this, the measurement instruments need to be calibrated correctly.

To be able to determine whether the internal validity is secured and measurement accuracy is high, an acceptable measurement error is determined. Reaching accuracy and precision of an experiment put high demands on the researcher and needs to be considered seriously.

3. Theory

This chapter presents the major theoretical areas touched during the study. Initially the theory section provides a description of possible measuring solutions in machine vision. Early in the project a machine vision based solution was considered most suitable, considering that the objective was to develop an automated system. Due to this it was decided to focus more on machine vision as a measuring solution. The next part provides facts on fundamental techniques and theory applied to machine vision. The chapter ends with theory regarding transport logistics, buyer-supplier relationship which connect to the problems the company experience because of the dimensional deviations.

3.1. Machine Vision

Modern machine vision systems can be categorized in PC-based vision systems, embedded vision systems and smart cameras, with varying application range, performance and complexity degree as seen in Figure 1. Smart cameras are a complete solution with embedded lenses, sensors, processors, camera-to-computer interface and software, enabling for control and calibration directly on the device itself, lowering the complexity. The compact design of smart cameras and easy functions enables for a wider application range. However, smart cameras are also limited to the memory-size and software interface and its capabilities, lowering the performance level. PC-based systems usually consists of several devices interacting with each other to provide the required vision system. This enables for high customization and performance level, but also requires advanced programming and hardware knowledge. The embedded system as seen in Figure 1 is a hybrid of the smart camera and PC-based system. An embedded microprocessor, enables to be directly connected to an external PC that can be used for programming, controlling and calibration of the sensor [3].

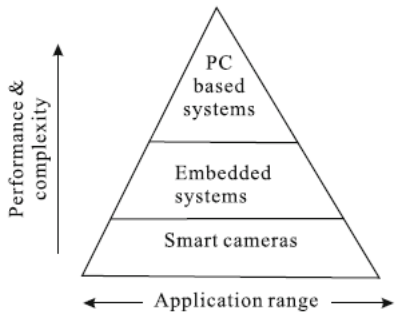

Figure 1 Overview of three machine vision techniques [3].

3.2. Machine Vision Techniques

Machine vision systems are implemented in various processes with different requirements and conditions. The requirements and conditions can differ with the application, hardware and techniques.

3.2.1. Hardware set-up

Camera vision is achieved by combining different components such as, lightning, lens, image sensor and vision processing seen in Figure 2. The lightning is required for illuminating the part to be inspected allowing its features to stand out clearly while the lens (optics) captures the image and presents it to the sensor in the form of light. Image sensors captures the light from the lens and converts it to pixels, producing a digital image [4]. There are two main types of image sensors, charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS) [5]. As in the case of PC-based systems, some vision solution requires a frame-grabber which is the interface between the camera to the computer (PC). The frame-grabber takes the data (analog or digital) provided by the image sensor and converts it into information for image analysis in the PC [4]. During image analysis the information is processed by first correcting any distortions due to imperfect lenses and then extracts the information through different algorithms which highlights the edges and contours, motion, color, size and other attributes. There are several, both commercial and open-source software tools and libraries available for image analysis. One such library is OpenCV which have more than five hundred functions that cover several areas such as camera inception, calibration and robotics. OpenCV is usually written either in python or C [3].

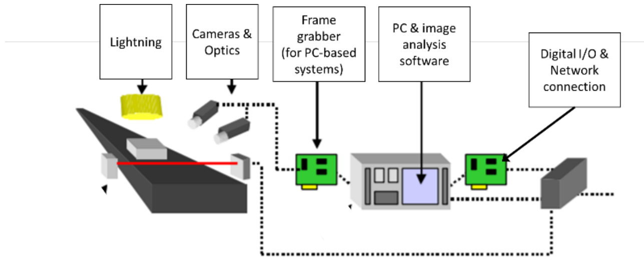

Figure 2 Main components in a typical vision system [4].

3.2.2. LiDAR

LiDAR, an acronym for light detection and ranging is a technology that is well-known and can be used for different measurements equipment. The LiDAR technology can be used for both 2D- and 3D sensors and are being used in a wide range in industrial applications but also in other areas. These sensors make it possible to generate a 3D point cloud of the studied object and the point cloud can be generated in a software. The technology is used widely in the automotive industry for self-driving cars where the demands are high on the techniques, as it requires high resolution, long-range and real time performance and a tolerance to disturbances such as environmental conditions. LiDAR is one of the technologies that can meet these requirements and is therefore used in these kinds of applications.

The LiDAR working principle is based on counting the time between the events when a beam of infrared light is emitted and then the backscattered energy from the pulsed beam is measured. From these time measurements, the speed of light in air is used for computing the distances. This is referred as the time-of-flight (TOF) principle [6].

3.2.3. Time-of-Flight

There are different techniques in how TOF works, but in this study the pulsed approach will be considered. One of the measurement principles that are used in the lidar sensor is called pulsed TOF, where the measurement distance is obtained by counting the time delays from sending and receiving the pulse and is used for determining the distance [7].

The optical signal in LiDAR is projected into the analyzed object, which is also referred to as the target, then the backscattered signal is detected and is processed to measure the distance to the object. The distance to the target is *R* and is obtained by:

$$R = \frac{c}{2} t_{0F}$$

Where *R* is the range to the target, *c* is the speed of light ($c = 3 \times 10^8$ m/s) in free space and t_{0F} is the time it takes for the pulse of energy to travel from the emitter to the observed object and then back to the receiver. Figure 3 shows in an illustrative way how this principle works [6].

One crucial factor that can reduce the accuracy of the sensor is the signal-to-noise ratio, where the laser can lose energy during travel if the distance *R* becomes large and especially if the targets are diffusing. Although this might be a critical factor, the high energy laser pulses make it possible to use this simple measurement principle in cases of long distance and its limited influence of background illumination. This enables possibilities for using this pulse based technique in outdoor applications.

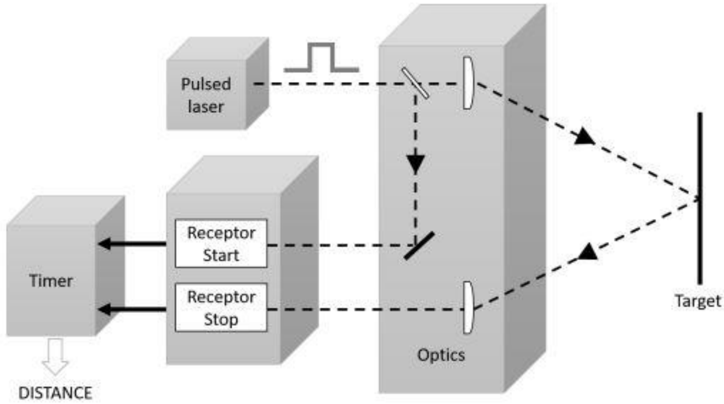

Figure 3 Time-of-flight measurement principle [6].

One critical issue with the TOF principle is the disturbances that can occur due to weather conditions such as snow, rain, or fog. These disturbances can result in false alarms from the backscattered intensity, thus reducing the reliability of the sensor [6].

3.2.4. Triangulation

Triangulation is based on the fundamental concept of measuring the distance to a point by having two known points with a known distance between them. This is shown in Figure 4 were angle a and b, and distance C are known. Machine vision systems based on triangulation uses a combination of an emitter which projects the light and a sensitive receiver that captures the light with the help of a lens. The reflected light is captured at a certain angle relative to the to the projected light which can be used to estimate the object position, Figure 4. Triangulation is more accurate at short distances than TOF and is commonly used for vision systems with high precision demands, such as electronics, pharma and cosmetics and machine tools. The technique is commonly used in industrial application where it can measure from 200 mm up to 10 m with a reduction in accuracy as the distance increases. Besides its limitation for distances over 10 m, triangulation techniques are also prone to angular errors i.e. the angle of the receiver relative to the laser [8].

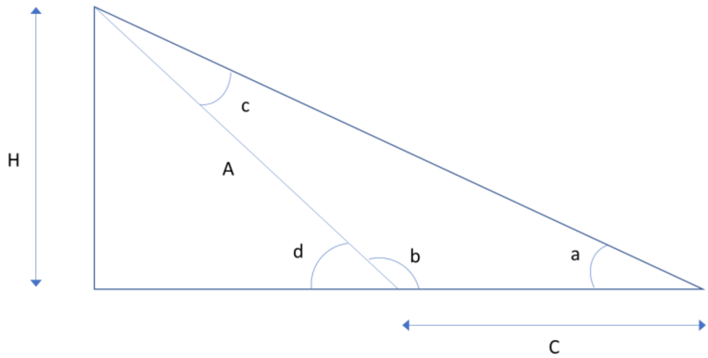

Figure 4 The fundamental concept of triangulation, angle a and b and distance c are assumed to be known.

3.3. Buyer-Supplier Relationship

3.3.1. Collaborative relationship

Relationship and trust in the supply chain becomes a more important factor when it comes to the buying- and selling organization and their partnership. Introducing a more collaborative relationship can strengthen both the buyer and seller and thus making them more competitive in regard to cost, quality, and customer satisfaction. In order to achieve this, clear communication, clarification of needs and expectations and consistency in performance is required. To be able for both parties to maintain a long-term relationship, an ongoing commitment from both sides are required to continuously improve.

The relationship between the parties can be threatened by certain events such as late or missed deliveries or if one of the parties is placed in an uneconomical position. Trust and reliability between the partners put high demands on the communication, but there are several aspects that can affect the relationship, these can be seen below.

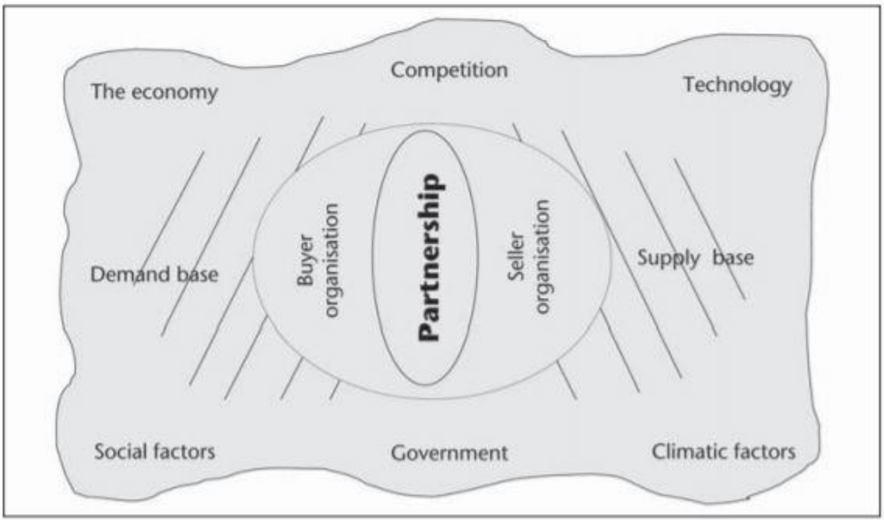

Figure 5 Buyer-supplier relationship [9].

Not only the internal aspects such as cost, quality can affect the relationship but also external factors which includes climatic factors or new technology, regulations and legislations. A successful buyer-seller relationship can be achieved by meeting the expectations that are anticipated from one another. One of the reasons why collaborative relationships fail is due to poor communication, lack of shared objectives and lack in planning [9].

E. Stuart and B. Crocker [9] presents an approach to a successful collaborative relationship by the five stages below:

- Stage 1: Buyer's expectations
- Stage 2: Seller's perceptions
- Stage 3: Mutual understanding and commitment
- Stage 4: Performance activity
- Stage 5: Corrective action

First, the expectations from the buyer's perspective and the perceptions from the seller, needs to be developed and a mutual understanding and commitment between both parties must be developed. The requirements from one another needs to be clear and consistent and both needs to be willing to work towards continuous improvements to stay competitive. If the expectations are not clear and well communicated, there is a high risk of misperceptions from one of the parties, this could threaten the collaborative relationship. Throughout the collaboration there will be events that can ruin the supplier-buyer relationship which can reduce the stability, therefore corrective actions are needed to stabilize the performance activity, which corresponds to stage 5. The five stages are shown in Figure 6.

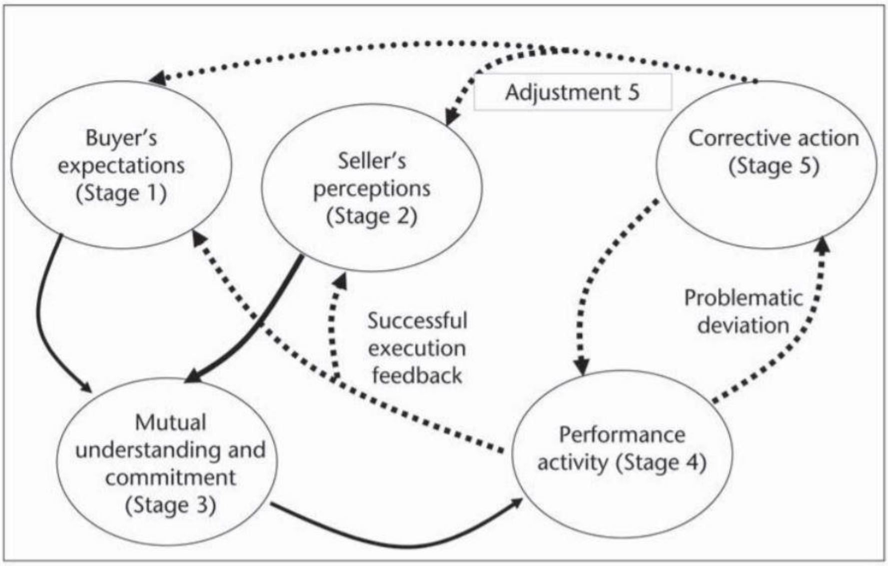

Figure 6 Buyer-supplier collaborative relationship model [9].

3.3.2. Strategic trust and reliability

Trust will be one of the most important factors but will also be a barrier, trust can be achieved through meeting expectations of one another. First and foremost, trust is built between individuals within the companies, common trust will follow when trust between several employees is built up. Although individuals will build trust in a company, it is of high importance that the top management is actively involved in terms of shared long-term objectives for both companies.

Trust includes being honest even with mistakes and not cover them, it includes being transparent and honest. Honest communication, patience and accepting and admitting mistakes is some of the factors that can build trust between individuals in companies. Although the listed factors can achieve trust and a collaborative relationship, trust can also be very individual, as some people can trust right away and some needs to see consistency of a certain behaviour over time. Strategic trust can be presence in the way of shared cost information and shared forecasts, these can also contribute to a more improved and competitive supply chain for both parties [9].

3.4. Transport Logistics

In transport logistics, sea freight is a way of transportation that provides relatively less price than other way of transports and sea freight can also carry large sizes and weights, this is advantageous when it comes to transportation of automobiles. The pollution due to transport overseas is also another advantage compared to other way of transporting goods. One drawback is the long transportation times, the transportation can take up to several months depending on destination. Transport overseas do not usually go from one point to another, it will also include several transhipment points. The planning for the loading on the vessel is therefore an important point in the sea freight, due to several destinations. Due to long transportation times and several transhipment points, the drawbacks that comes along is low flexibility and slow transports. Some plusses and minuses are seen in Figure 7 below.

Transportation Modality	Plusses	Minuses
Parcel and express	Very fast, very reliable, very high trackability and traceability, very high availability, very safe, door to door, relatively flexible, useful for long distances	Very high costs per m^3, high pollution, sensitive for adverse weather conditions, not useful for: heavyweights, oversized dimensions, DGs, and pallets
Airfreight	Relatively fast, relatively reliable, relatively high trackability and traceability, relatively high availability, very safe, relatively flexible, useful for long distances	Relatively high costs per m^3, high pollution, not useful for bulky goods, relatively limited DGs capabilities, sensitive for adverse weather conditions
Road transportation	Fast on short distances, reliable, high availability, high flexibility, low costs per m^3, relatively safe, door to door	Relatively low trackability and traceability, relatively high pollution, sensitive for adverse weather conditions and traffic, limited load capacity, not useful for long distances
Sea freight	Can handle all type of goods and bulky volumes, low pollution, very low costs per m^3, safe, door to door, useful for long distances	Slow, less reliable, low flexibility, sensitive for adverse weather conditions, low trackability and traceability
Train	Can handle all type of goods and bulky volumes, relatively low pollution, relatively reliable, relatively low costs per m^3, safe, useful for long distances	Relatively slow, relatively low availability, relatively low flexibility, no door to door service, low trackability and traceability
Intermodal	Relatively fast, relatively reliable, relatively low costs per m^3, relatively safe	Relatively low trackability and traceability, relatively high pollution, relatively low flexibility

Figure 7 Plusses and Minuses for different transportations modalities [10].

The freight cost for transport overseas may vary depending on the carrier and destination. Another cost that carriers can add for transport overseas is the Bunker Adjustment Factor (BAF), this is a cost for the fluctuating fuel price. BAF can either be an added cost or a removed cost, depending on the fuel price. However, if one carrier starts adding additional costs, the rest of the carriers will usually follow [10].

4. Experimental methods

This chapter includes a description of the experimental work conducted in the study, how different techniques have been evaluated and then tested to conclude which is best suitable for the objective of the study.

4.1. Evaluation of measuring technique

4.1.1. Evaluation matrix

In addition to the literature, several techniques will be evaluated in an evaluation matrix based on criteria stated from the company. These criteria will be assigned with a weighting factor from 1 to 5, based on their importance for the company and the situation. The following criteria have been developed:

1. Installation price: the complete price for the installation of the measurement technique, includes purchase price for equipment and its related accessories, cost for installation and maintenance.
2. Future use: how can the measurement technique be used in the future? Can it only be used for measure height and length or is it able to use it in further applications?
3. Configuration and installation: how much time and work does the measurement technique requires? Does it require maintenance?
4. Usability: how easy is it for a user with no experience with the equipment to understand and use it?
5. Space requirements: the amount of space needed for the technique.
6. Testing possibility: is it possible to rent the equipment for testing?
7. Outdoor use: is it possible to use the equipment outside and how sensitive is it for environmental conditions such as fog, rain, and snow?

Except from the weighting factor the different criteria are assigned a value of 1 to 5, where a value of 5 meets the defined criteria fully and a value of 1 does not meet it at all. The weighting- and criteria values are summarized into a total value where <80 will be assigned red, 80<90 will be yellow and 90> will be green. The candidates assigned a red value will not be considered to order for testing, for the yellow and green candidates both will be considered for testing, but the green ones will be prioritized.

Table 2 Evaluation Matrix.

		SICK						IFM
Criterias	Weightning	LMS4111R-13000	LMS111-10100	LMS511-10100	LMS1000	MRS1000	VPS PRO	O3D302
Installation price	5	3	3	4	3	3	1	5
Future use	2	1	3	3	3	3	5	3
Configuration and installation	4	3	3	3	3	3	5	3
Usability	5	2	2	4	4	4	5	3
Space requirements	2	4	4	4	4	4	2	4
Testing possibility	4	1	1	2	5	5	1	5
Outdoor use	3	2	3	5	4	5	5	2
Total		57	64	89	93	96	83	92

4.2. Measuring techniques

The sensors performing the best in the evaluation process are ordered from the supplier to be tested in two different setup conditions, controlled environment and demanding environment. This section provides a technical overview of these sensors.

4.2.1. MRS1000

The device is an opto-electronic LIDAR sensor that works in the optical wavelength spectra, in the infrared range, around 0.7-2.0 µm. Infrared laser beams are emitted to scan a surrounding from 0° – 275°. The sensor has the ability to adjust the opening angle, enabling for either reducing or increasing the opening angle according to the purpose. The scanning frequency is 50 Hz, while the angular resolution is 0.25°. As the distance from the device increases, the laser beam expands, enlarging the diameter of the light spot on the object surface. Mounting multiple sensors is possible and interference is not an issue, however for best measuring accuracy the sensors should be arranged so that the beams are not received by another device [11] [12].

The sensor can be configured and calibrated through the interface software SOPAS Engineering Tool. Further communication with the sensor is done through telegram-communication, in which a document with telegram commands is supplied by the supplier [11].

When a laser beam strikes an object the laser is reflected and received by a sensor and the position of the object is determined based on the distance and angle using HDDM+ (High Definition Distance Measurement Plus) which is based on the TOF technology. In contrast to the common TOF technology which evaluates each induvial laser pulse, HDDM+ distinguish itself by evaluating and comparing the echoes of several laser pulses simultaneously to calculate a distance value. This enables for excluding echoes of non-interest (e.g. raindrops, snowflakes, fog and small animals) and to select the relevant echo for the distance measurement, also illustrated in Figure 8 [7].

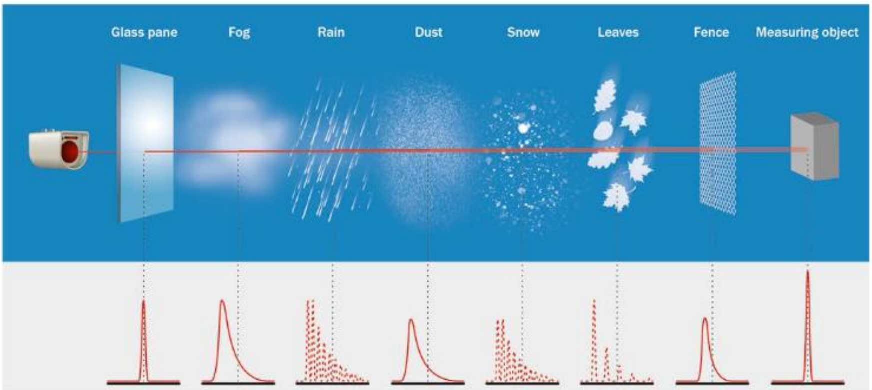

Figure 8 A image illustrating the multi-echo system used in HDDM for accurate distance measurement [7].

4.2.2. O3D302

O3D302 uses a 3D camera and measures the distance value for each single pixel with TOF technology. The camera uses infrared light to calculate the distance. The O3D302 generates 23 232 pixels which creates a real-time three-dimensional point cloud, based on the PMD-technology, a patented technology by IFM based on the TOF technology. A CMOS semiconductor is incorporated to all camera with PMD-technology [13].

In contrast to laser beams, based on the TOF technology, where each single laser beam is transmitted and the target distance is measured by determining the turn-around time, PMD devices illuminates the whole image, using each individual pixel to measure the turn-around time of the pixel light. The difference between TOF for single laser beam and PMD is shown in Figure 9.

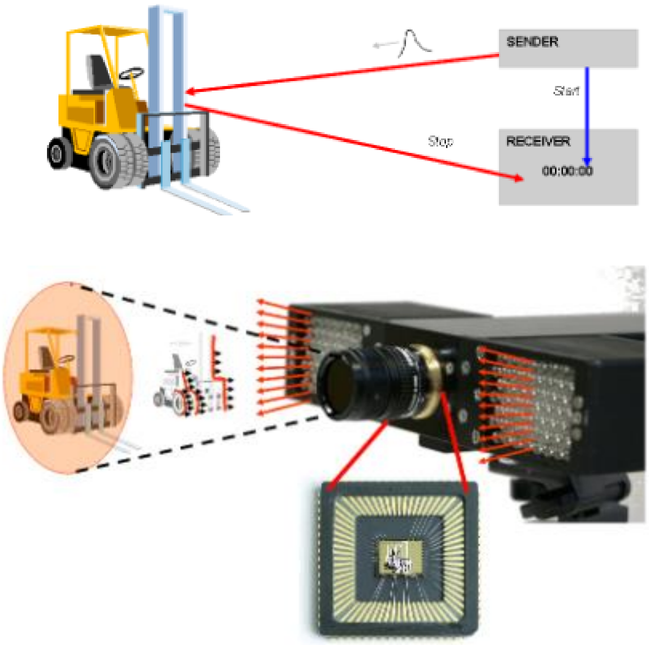

Figure 9 Time-of-Flight principle with single pulsed light (above) 3D imaging principle based on PMD on Time-of-Flight camera [14].

The number of pixels provides the lateral resolution of the camera and also with depth information. Lateral resolution is affected by the width of the pixel and the depth of the imaging. As the depth increases, pixel width also increases thus reducing the resolution and accuracy. Depth accuracy is defined by the amount of active light which arrives from the pixel and is affected by the optics, illumination, fill factor, spectral sensitivity, modulation contrast and also by the active area of the pixel [14] [15].

4.2.3. Extracting and collecting data

Each sensor was connected to a PC via an ethernet cable, enabling for communication between the PC and sensor. Via the ethernet cable the data stream from the sensor can be received, the sensor can be configured and calibrated with either the software interfaces or with commands (telegram commands in the case of the SICK sensors).

The data stream was extracted with python, using TCP/IP library functions and was afterwards converted and refined, leaving only the wanted information.

In the case of the SICK sensors the data stream had to go through some further trigonometrical equation due to how the sensor measured the distance to the object, depicted in Figure 10. As depicted by the figure, object 1 have a shorter measured distance MD, placed perpendicular to the sensor, however Figure 10 shows that object 2 have a shorter wanted distance WD which is the desired distance for this application.

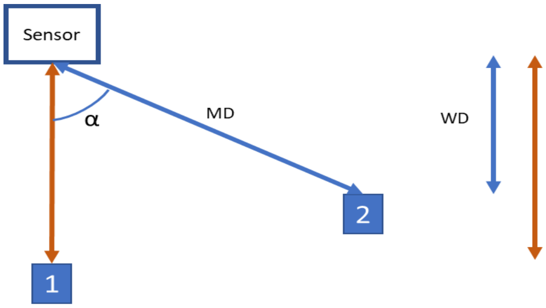

Figure 10 An illustration of the measured distance (MD) and the wanted distance (WD).

4.3. Testing approach

The testing procedure will take place in a controlled environment as well as in a more environmental demanding environment. The testing in the controlled environment will be carried out in an office environment and the testing in the demanding environment will be carried out in a washing hall at the truck factory in Tuve, Gothenburg.

4.3.1. Controlled environment

The controlled environment tests were performed for analyzing the accuracy as a function of different conditions. Two different objects were used during the testing to analyze how well the sensor performed with regards to the object size, shape, contour and color. An image of the objects is provided in Figure 11. Object 1 has a length of 250 mm and object 2 has a length of 220 mm. Object 1 was selected for a first overview and to get a reference value of the performance, hence the basic shape and relatively large dimension. Object 2 was selected to be as similar to an antenna as possible. Object 2 had a smaller dimension than object 1 and had a varying shape and contour, increasing the demands on the sensors. Three different tests were performed, each test had different conditions.

Figure 11 Object 1 (left) and object 2 (right).

A module of all possible setup is illustrated in Figure 12 and an overview of the real setup is seen in Figure 13. The setup conditions were changed based on angle α, distance D and offset M, 1, 2. The angle-condition was only applied to the SICK sensors as they had the ability to change the opening angle that could influence the accuracy. The IFM sensor uses an optical camera where the pixels create a focus area, enabling for defining a region of interest (ROI) through the interface software (IFM vision assistant).

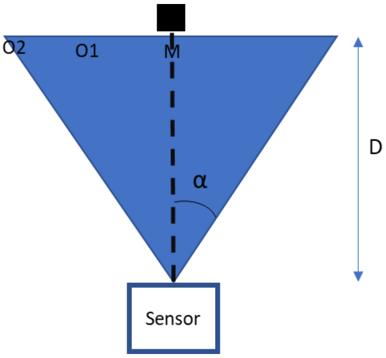

Figure 12 Setup for the controlled environment testing where α = angle, D = distance, M = middle, O1 = offset 1 and O2 = offset 2.

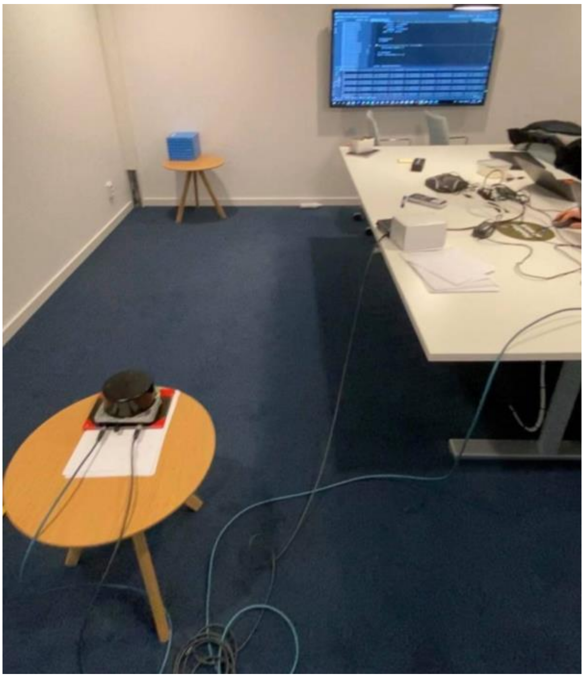

Figure 13 An overview of the controlled environment testing.

The different test setups had the following combination of conditions illustrated in Figure 14. Each combination was performed 3 times, in the case of test 1 this means that the total number of measurements was 52.

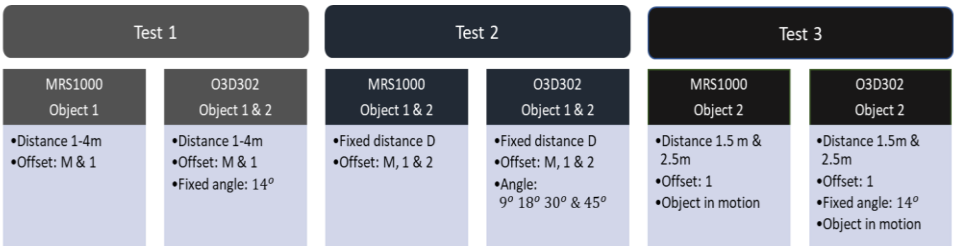

Figure 14 The three tests with their respective conditions.

4.3.2. Demanding environment

The demanding environment test was performed to obtain data for the hypothesis testing and to identify the optimal mounting position of the sensors. The measurement conditions were the same for the two sensors, that is identical, distance, opening angle (14°) and object (a white Volvo S90).

4.4. Statistical model

To be able to evaluate the different measurement techniques that are chosen, a hypothesis testing will be performed. The null hypothesis will be based on criteria from the company and the margins that are critical for the organization. The statistical model will be used to strengthen the results and will correspond to a quarterly production of trucks. The approach to the hypothesis testing will be in terms of a z-test, that is assumed to follow a normal distribution with a set confidence level of 95%. The number of tests, i.e., the sample size, will depend on how long it takes to reach a stationary mean value. Since the total deviation are considered, an upper tailed test will be performed.

The approach to the hypothesis testing will be in the way of a test statistic. A test statistic is formulated to see how large the mean deviation is, for the case of the master thesis, the actual deviation from the height. Therefore, the test statistic will be based on an acceptable deviation range and the sample mean deviation [7].

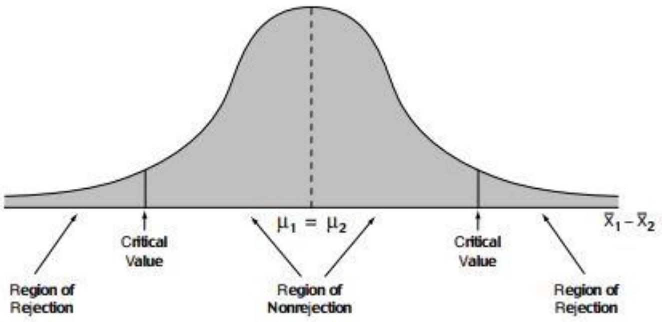

Figure 15 Regions of rejection and non-rejection [16].

The distribution of the values of the tests will be separated into two regions, one region where the null hypothesis is not rejected and one region where it is rejected. As the range of deviation is studied, only the right side of curve will be considered, i.e. an upper tailed test. The margins for the acceptable range of deviation will be divided into two:

- One margin of error based on requirements from the carriers, which is set to 30 mm. Trucks that deviates less than 30 mm in height is usually not a problem when the carriers do the control measurements in Wallhamn. The 30 mm margin of error will also consider factors such as air suspension in wheels and bumps/irregularities in the ground.
- One margin of error that is used for the hypothesis testing, which is set to 15 mm. This margin of error is set to 15 mm due to that high measurement accuracy of the sensors will be required if they will be used for further implementation of a capable measurement process.

Based on the above, the following hypothesis has been stated:

- **Null hypothesis (H_0):** $x \leq 15$mm
- **Alternative hypothesis (H_1):** $x \geq 15$mm

Where *x* is the maximum acceptable mean range of deviation. The following formula is then used to obtain the test statistic:

$$Z = \frac{X - \bar{x}}{\frac{\sigma}{\sqrt{n}}}$$

Where X is the acceptable deviation in millimetres, $\bar{x}$ the sample mean deviation, σ is the standard deviation and n is the sample size. With the chosen confidence interval, the test statistic for 95% confidence interval will give a z-score of 1.96. By calculating the z-score for the sample size, the obtained result will conclude how accurate the measurements are from the equipment. If the z-score is below 1.96, the null hypothesis is not rejected, but if the z-score is larger than 1.96, it will fall within the region of rejection which means that the null hypothesis is rejected. The z-test is used for this project as it is best suitable for cases when the average value from a sample will be compared to a target value, i.e., the actual height. When the z-score is calculated, a p-value can be obtained from tables, where the z-score represents a percentage which decides the level of significance for the result, the p-value is given its closest level of significance, for example 1%, 5% etc. [17]

The number of tests will depend upon when a stationary mean value is reached. The results from the hypothesis testing can be seen in the performance matrix in chapter 5.2.3.

5. Results

This chapter presents the results for each research question. Starting with consequences due to the current situation. The second research question presents the results from testing the sensors in the controlled and demanding environment. The third research question presents the observed factors and causes for the deviation. Finally, the last research question provides a review of aspects that should be considered for a future automated measuring system.

5.1. Research question 1

This section treats research question 1. The section starts by presenting how the outbound transports are being affected by the deviations, it goes through the risk for damages, regulatory issues, costs and short shipping. The following sections presents how the administrative work and supplier-buyer relationship are affected. The last section, economics losses, provides an overview for how the outbound transports, administrative work and supplier-buyer relationship increase costs due to the deviations.

5.1.1. Outbound transports

The underlying problem to the deviations and the upcoming of the thesis from the company's point of view is partly due to the consequences that the dimensional deviations is causing for the organization. The outbound transports are included in this and is one of the most crucial consequences of the deviations, this includes mainly the transport overseas. For the transport overseas, Volvo currently base their planning on the truck dimensions that are in the systems and as there are deviations, it has created problems in many ways where some of them will be listed down below.

5.1.1.1. Damage and regulatory issues

According to the risk manager, as the dimensions are deviating, there are situations where this can be crucial for the trucks and there have been accidents where damage has occurred to the trucks. First, if the truck is too high, accidents on the road can occur when the truck drives under a bridge that has a maximum height of 4 meters for example. If the dimensions are not correct, there is risk for collision between truck and bridge and the consequences can be very crucial, both in regard to damage of truck but also to humans. Second, if the truck is too high during loading on the vessel, there can also be damage to the trucks. When the carriers are planning their loading process on the vessel, the margins for the height of the vehicles are small, so basically there is no room for deviations. The decks on the vessels are flexible, meaning that it is possible to adjust the height of the deck and the carriers wants to maximize the space on the vessel, which means that it is of high importance that Volvo state correct measurement data. The accidents that can occur in regard to this, is collision between the deck on the vessel and the roof of the truck.

According to the competitor the main reason for implementing a system for measuring truck dimensions was among others, the risk for accidents and damages during transportation. The competitors mentioned the benefits of being able to prove they had the correct dimensions, especially with regards to land transports in Europe where regulations on vehicle height and weight can differ. In most countries they have specific height limits and vehicles are forbidden to exceed them. There are issues regarding responsibilities for violating the laws. According to the competitor the responsibility of providing correct dimension can vary depending on country. In some countries, the transport company is responsible for providing the correct dimensions, while in other countries it is the manufacturer who are responsible for providing the correct dimensions. Furthermore, in some countries the truck driver is also regarded as responsible and will face consequences.

5.1.1.2. Freight costs

The company are paying freight costs for transport overseas in volume prices. One of the carriers are performing control measurement of the truck in the harbor, right before loading and if there is deviations, the carriers will send new updates of the invoice, which in turn result in a higher freight cost. If the truck is too high, this is obvious but for the case of when the truck is too low, the carriers are assumed to not update the invoice which means Volvo will pay more than needed and also be unaware of this kind of deviation.

The result from testing the hypothesis of weather the carriers reported when trucks were too low is based on interviews with a transport planner and a report from Wallhamn that covers all trucks that was reported during the period from Oct 2020 – April 2021 due to too large deviation (see Figure 16). The report was cross-checked with measurements done in Tuve (see Figure 17) to see if the Wallhamn report and measurements in Tuve had the same ratio for the two different types of deviations.

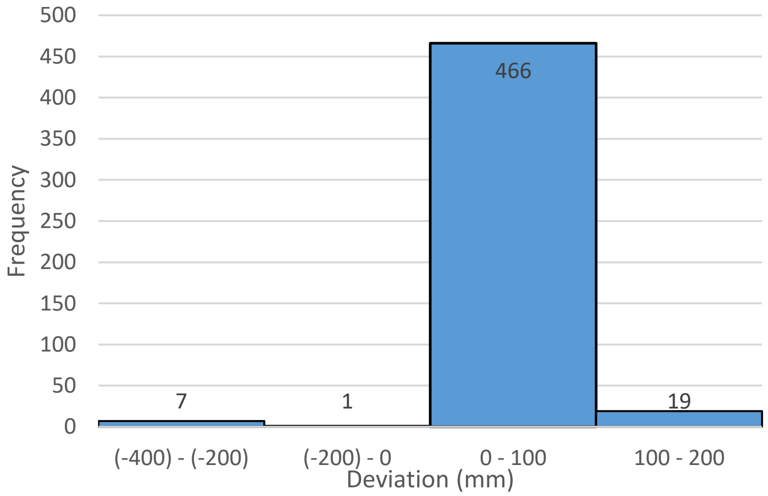

Figure 16 Distribution of the report from Wallhamn (deviations<0 corresponds to system dimension lower than measured height).

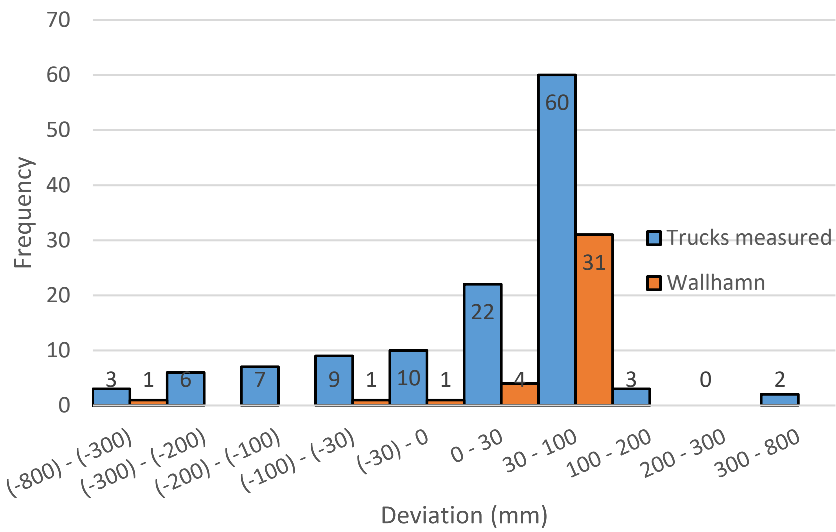

Figure 17 Distribution of deviation for trucks measured in Tuve and number of trucks that are transported overseas from Wallhamn (deviations<0 corresponds to system dimension lower than measured height).

From Figure 16 the total number of trucks can be counted to 493 trucks out of which 8 trucks had a system dimension larger than what was measured (MSD), this corresponds to 0.2% for the total number of trucks produced during the same time period covered in the report (3231 trucks). The transport planner mentioned however, that the Wallhamn report is not complete and that some trucks can have been lost as they are not being documented. Comparing with data from Tuve measurement where total measured trucks are 122 (see Figure 17), of which 25 trucks where more than 30 mm too low. However, out of these 25 trucks only 2 was supposed to be transported overseas from Wallhamn. Figure 17 indicates that out of the total 122 trucks, 38 trucks are supposed to be transported to Wallhamn for overseas transportation. This means that out of 38 trucks, 2 trucks were too low, corresponding to 5% of all trucks that were transported to Wallhamn.

5.1.1.3. Short shipping

During one of the interviews, the transport manager mentioned an incident where trucks had been short shipped during transport overseas. Short shipping is the event that occurs when the trucks are left in the port and cannot be loaded on the vessel due to incorrect dimensions, recently the trucks that was short shipped were 4 cm higher than stated. This kind of event is crucial for the company in many aspects. First, Volvo will not be able to deliver the truck to the customer in time as short shipped trucks will have to wait until the next departure. The transport time on the vessels can be long, up to a month and next departure to the destination might be only three or four times per month. Second, the freight costs will increase as they need to book new transports for the trucks.

5.1.2. Administrative work

One of the most time-consuming activities related to the dimensional deviations includes the administrative work that follows. When the trucks arrive to the vessels for loading, the carriers are performing control measurements on the height of the trucks to make sure that they are the same as the dimensions given by Volvo. If the measurements are not correct, the carrier will send an updated list of the correct measurements, If Volvo do the manual system update of the measurements in time, which in turn takes a lot of time, the invoice will be updated and correct according to the new correct dimensions, i.e. an updated freight cost. The invoice management at Volvo is handled by employees located in India, if the invoicing is correct and the updates are done in time, everything will be alright. If Volvo does not make the manual system updates in time, the invoice will be locked and thus not updated according to the correct dimensions. This is followed by crucial consequences, if the invoicing is not correct the employees in India will start to call employees at Volvo and question why there are deviations in the invoicing, thus creating a lot of extra administrative work.

An invoice manager from India was contacted to get an understanding of the administrative work and the number of locked invoices. The invoice manager mentioned that they were receiving invoices from all Volvo business areas but did not differentiate the invoices according to respective business area such as Volvo Busses, Trucks and Penta. The invoices are instead categorized according to the departments seen in Figure 18 which shows invoices from April 21 2021. The No-FTP corresponds to locked invoices and a total number of No-FTP is 6196 of which 347 are transport products. According to the invoice manager the different departments corresponded to different aspects, as an example transport parts corresponds to components and separate parts, delivered by the different business areas, while transport products correspond to the product itself such as trucks, buses and marine engines.

Department	FTP	No-FTP	Total	FTP%	No-FTP
Transport Matrerials	14895	5714	20609	72%	28%
Transport Products	2533	347	2880	88%	12%
Transport Parts	74	135	209	35%	65%
Services Non Transp	3		3	100%	0%
Grand Total	**17505**	**6196**	**23701**	**74%**	**26%**

Figure 18 Data on invoices from 21 April 2021. Categorization of invoices seen at the column to the far left. No-FTP stands for locked invoices.

Focusing on transport products, the invoices could be further filtered according to pre-defined reasons, such as price/quantity deviation, manual PO creation/correction, internal correction, atlas PO creation/correction and other. In this case the reason, price/quantity deviation where of interest. The data could be further filtered according to which carriers have reported the invoice.

Cross-checking data from the invoice manager with the Wallhamn data a possible correlation between number of invoices (filtering on transport products with price/quantity deviation and specific carriers) and number of reported trucks from Wallhamn (See Figure 16) during the same time period (Oct 2020 – April 2021) could be detected. Seen in Figure 19 the sum of locked invoices is 565, comparing that with the Wallhamn report which had 493 trucks.

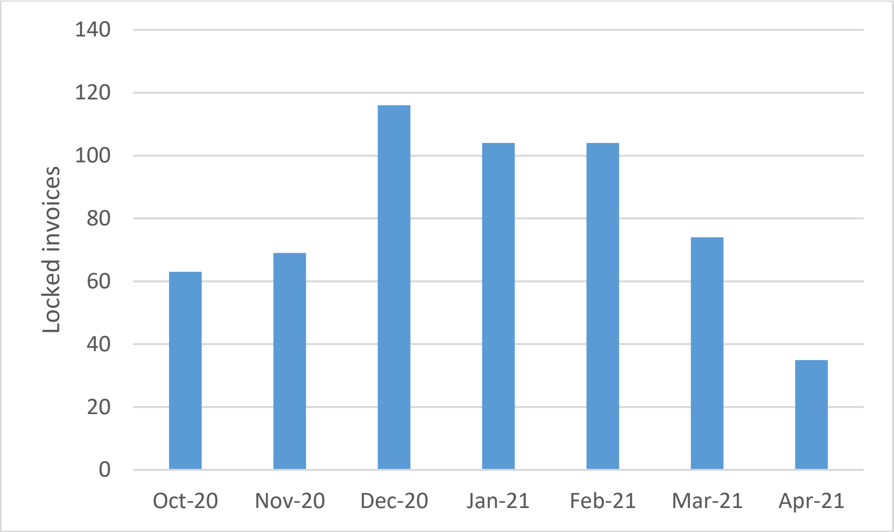

Figure 19 Locked invoices (No-FTP) for transport products with price/quantity deviation, reported by STL and Wallenius Wilhelmsen, covering the time period Oct 2020 - April 2021.

5.1.3. Supplier-Buyer relationship

One problem that does not has a direct effect on the organizational consequences but that is rather a summary of all the consequences previously stated is the relationship to the carriers. The control measurement process done by the carriers is seen below, if Volvo would be able to provide 100% accuracy in the stated measurement data, this process might be excluded. For the freight costs, the carriers will take into consideration that they need to perform control measurements as well as the given dimensions might deviate, which in turn lead to extra hours of work and therefore higher freight costs as well.

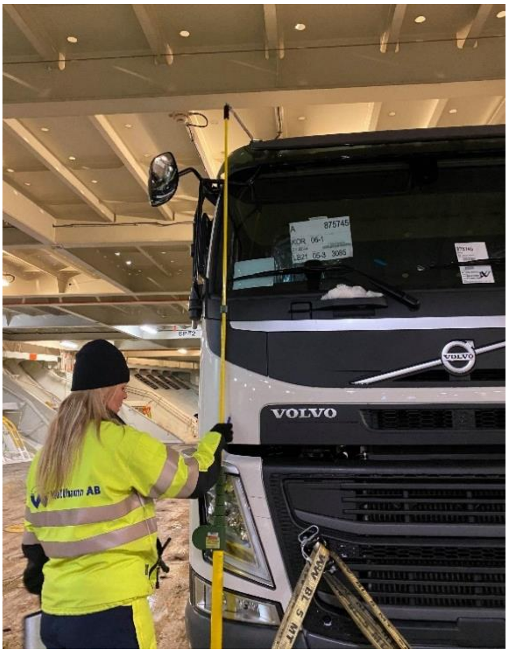

Figure 20 Control measurement in Wallhamn.

5.1.4. Economical losses

The economic losses are based on data from truck height measurements and interviews with a transport planner, a manager for transports overseas and with responsible for the invoice management. The different costs are labeled as either Tuve related or global costs. This is being done because administrative costs and costs that occur abroad during transportation is difficult to trace directly back to Tuve.

5.1.4.1. Costs for short shipping

If the short shipping has occurred abroad in a separate country the short shipping costs will be labeled as global. Trucks goes through several harbors and can go through a change in dimensions during the transportation which makes it difficult to directly connect Tuve to an eventual short shipping abroad. According to the transport planner the frequency of events related to short shipping is approximately once a year. The manager for transport overseas mentioned a short shipping incident which occurred during 2021 where 40 trucks got stuck at the harbor located in Antwerpen, Belgium for seven days due to too high deviations. The cost per truck for each day was approximately 600 SEK/day according to the manager. As the harbor is located in a separate country the cost is being labeled as a global cost.

5.1.4.2. Costs for the administrative work

The administrative work can be divided into costs due to manual system updates based on the Wallhamn reports and costs due to administrative work that occurs for managing the locked invoices. The costs due to manual system updates are directly connected to Tuve as these reports, according to the transport planner are only sent from the harbor in Wallhamn. The costs due to locked invoices are regarded as global costs. During the interview with the invoice manager, it was apparent that they receive invoices from all Volvo business areas, but do not differentiate the invoices according to business area such as Volvo Buses, Trucks and Penta.

However, from the interviews it was also apparent that the task performed by the transport planner and invoice manager was interlinked. When the invoice manager receives a locked invoice he has to contact the transport planner to verify the mismatch (the locked invoice) and the transport planner have to investigate if the mismatch is valid and if that’s the case, manually update the system and give the invoice manager the approval for updating the invoice. The transport planner stated that he is in average setting one hour every week for correcting the deviations. The invoice manager mentioned that the handling of all invoices requires almost a full time job for one person.

5.1.4.3. Freight costs for deviations

The freight costs due to deviations is based on the reports received by the transport planner and from the truck height measurement data. Only deviations where the system had provided a too large value to the carriers than the actual dimension were considered. The costs were estimated by calculating the trucks, transported overseas, with a deviation exceeding more than 30 mm as a percentage of the total number of trucks for the corresponding period.

Based on the report from Wallhamn the percentage of trucks that would be transported overseas, trucks with a deviation more than 30 mm below the system dimensions estimated to be 0.2% of the total number of trucks for the corresponding period. This value was then cross-checked with the Tuve measurement data were the percentage of trucks, transported overseas, with a deviation more than 30 mm below the system dimensions estimated to be 5%. Based on the two estimations the percentage of trucks, transported overseas, with a deviation greater than 30 mm should be between 0.2% - 5%.

5.1.4.1. Costs due to damages and regulatory issues

Besides the administrative costs for responding to damages and accidents during transportation, fixed costs, such as paying for damages to the carriers or trailers and damages to the infrastructure such as bridges will be included. Furthermore, Volvo will have to repair the damaged truck if possible or produce a new truck. Violating regulations can lead to lawsuit and fines, further increasing the costs.

5.2. Research question 2

This section treats research question two. It provides the testing results from the defined testing methods (see section 4.3 – 4.4) and the chosen measuring techniques (see section 4.2). The result from testing in controlled environment is first being presented and afterwards the result from the demanding environment test is presented, followed by results from the hypothesis testing and performance matrix.

5.2.1. Controlled environment

5.2.1.1. Test 1 – MRS1000

From Figure 21 it is possible to observe that all offsets can provide a constant value with increased opening angle. Offset 1 and 2 are providing values that are almost equal for each opening angle, providing values around 263 mm, while offset M provides values around 287 mm.

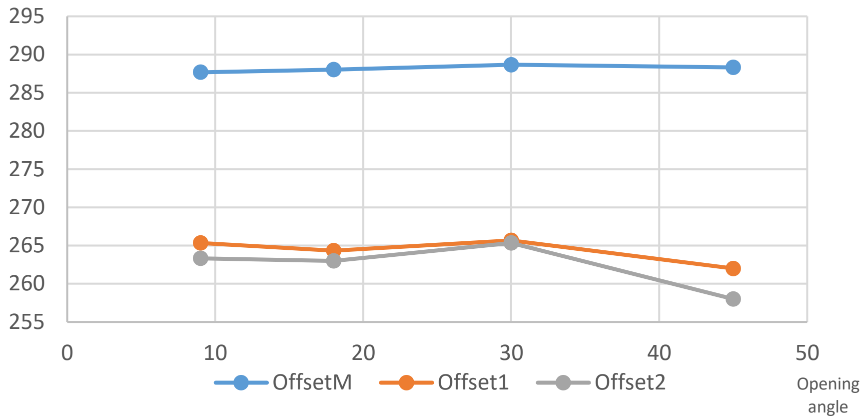

Figure 21 Test 1 for object 1 with actual dimension of 250 mm.

5.2.1.2. Test 1 – O3D302

Figure 22 illustrates a small deviation for both offset M and 1, where offset 1 is measuring just below the actual value and offset M measure just above the actual value. In the case of Figure 23 it is possible to observe a larger deviation for both offset M and 1. Once again offset M provides with a little higher value than offset 1, but they are both measuring noticeably lower values than the actual value.

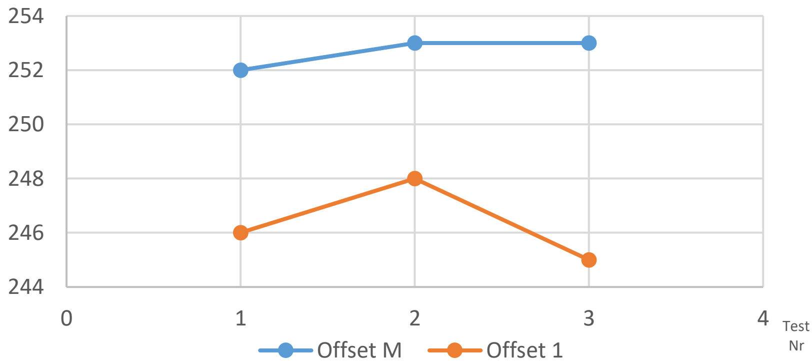

Figure 22 Test 1 for object 1 with actual dimension of 250 mm.

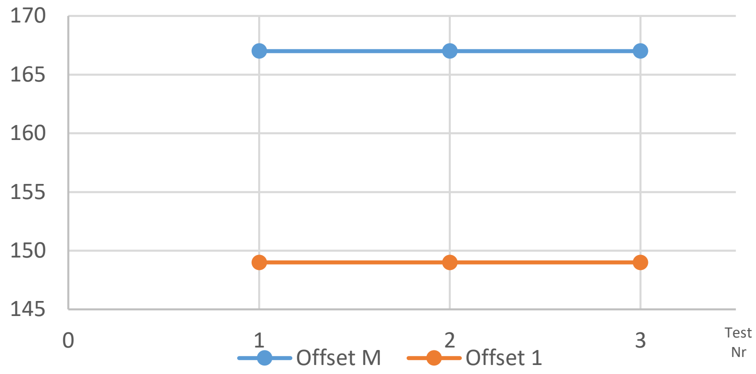

Figure 23 Test 1 object 2 with actual dimension of 220 mm.

5.2.1.3. Test 2 – MRS1000

From Figure 24 it is possible to observe that offset 1 is more accurate at a distance of 1 m, however it starts to deviate more with increased distance. Offset M is less accurate at a distance of 1 m, with a noticeably larger value than the actual value, however the deviation decreases with increased distance. From Figure 25 it is possible to observe that both offset M and 1 have difficulties to measure the object throughout the different distances.

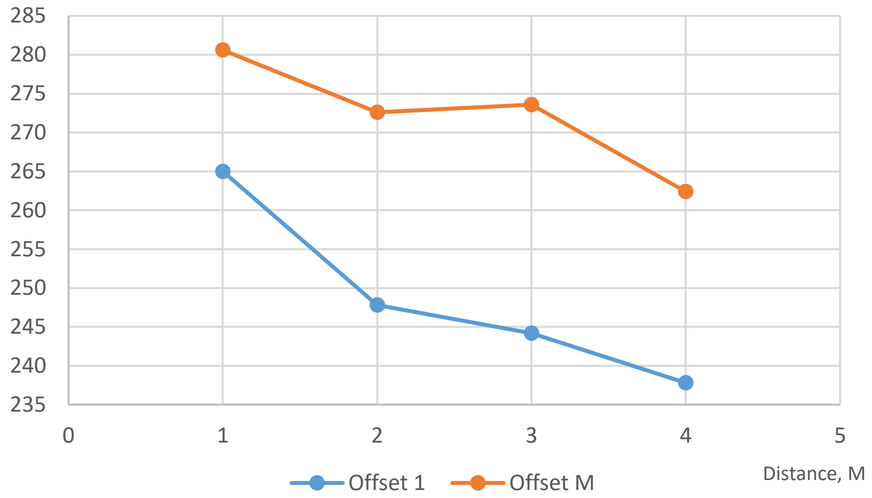

Figure 24 Test 2 for object 1 with actual dimension of 250 mm.

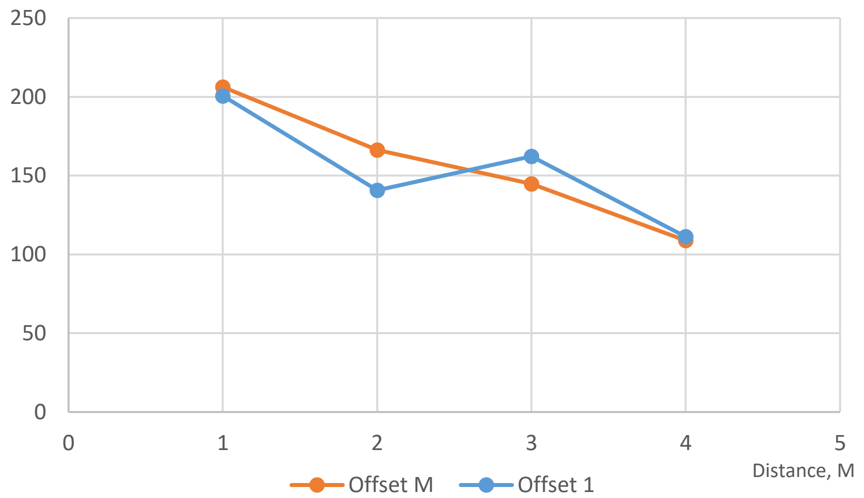

Figure 25 Test 2 object 2 with actual dimension of 220 mm.

5.2.1.4. Test 2 – O3D302

From Figure 26 it is possible to observe that offset M and 1 have a noticeably large deviation throughout the different distances. However, while offset M appear to increase the deviation with increased distance from the measured object, offset 1 appear to become more stable at distance of 3 m where it keeps a constant deviation. The measurement accuracy is poor as well in Figure 27 for both offset M and 1. Both offsets vary and appear to fluctuate back and forth.

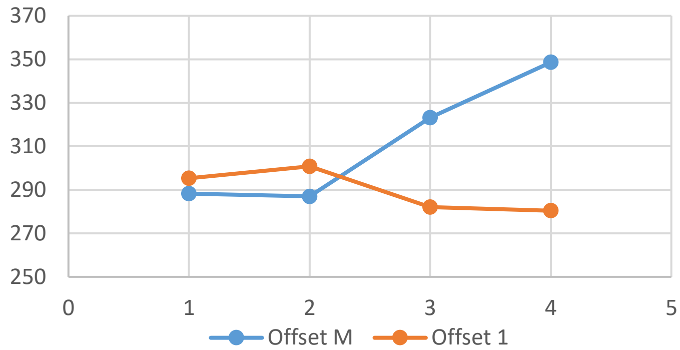

Figure 26 Test 2 object 1 with actual dimension of 250 mm.

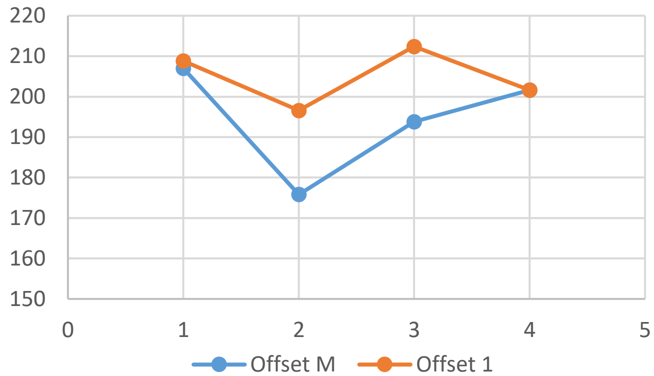

Figure 27 Test 2 object 2 with actual dimension of 220 mm.

5.2.1.5. Test 3 – MRS1000

From Figure 28 it is possible to observe that both offset M and 1 are deviating from the actual value, however for both offsets the deviation is under 2 cm except for a small number of extreme outliers.

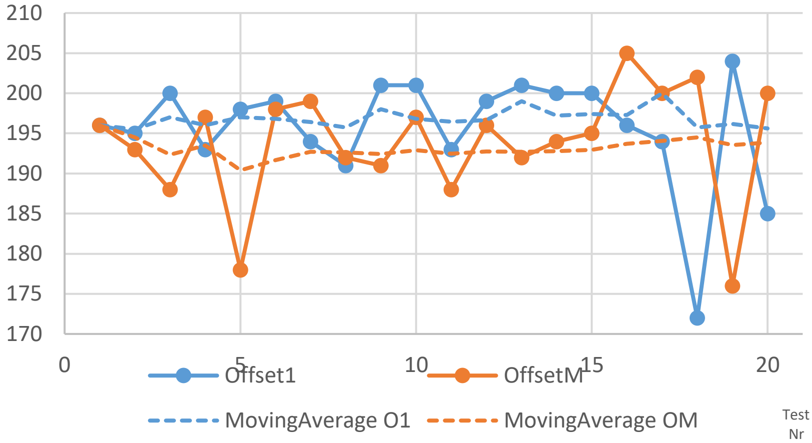

Figure 28 Test 3 object 2 with actual dimension of 205 mm.

5.2.1.6. Test 3 – O3D302

From Figure 29 it is possible to observe that distance 2.5 m is more accurate than distance 1.5 m. However, distance 1.5 m appears to reduce the deviation from test 7 and forward, while distance 2.5 m keeps fluctuate around the actual value of 220 mm.

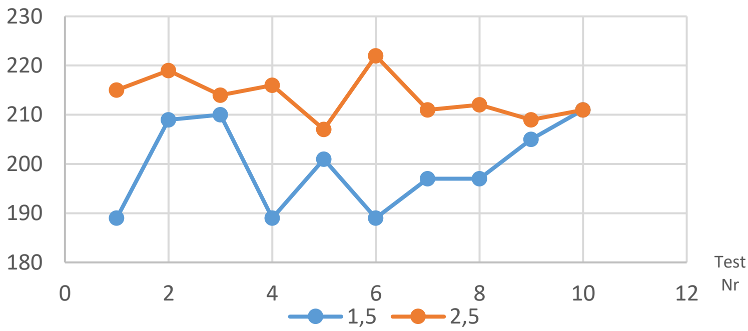

Figure 29 Test 3 object 2 with actual dimension of 220 mm.

5.2.2. Demanding environment

From Figure 31 it is possible to observe that the moving average is lying around the actual height of the car, 1440 mm, however the number of outliers and the fluctuation is also clearly noticeable. Comparing Figure 31 with Figure 32 it is clear that MRS1000 measures more accurately than O3D302 which has both more extreme outliers and a moving average that has a noticeable deviation from the actual value. The distribution in the histogram is also greater for O3D302 compared to MRS1000. The histogram shows that MRS100 has a higher frequency within the interval ±30 mm (1410-1470 mm) compared O3D302. The frequency is 62 for MRS1000, while 17 for O3D302.

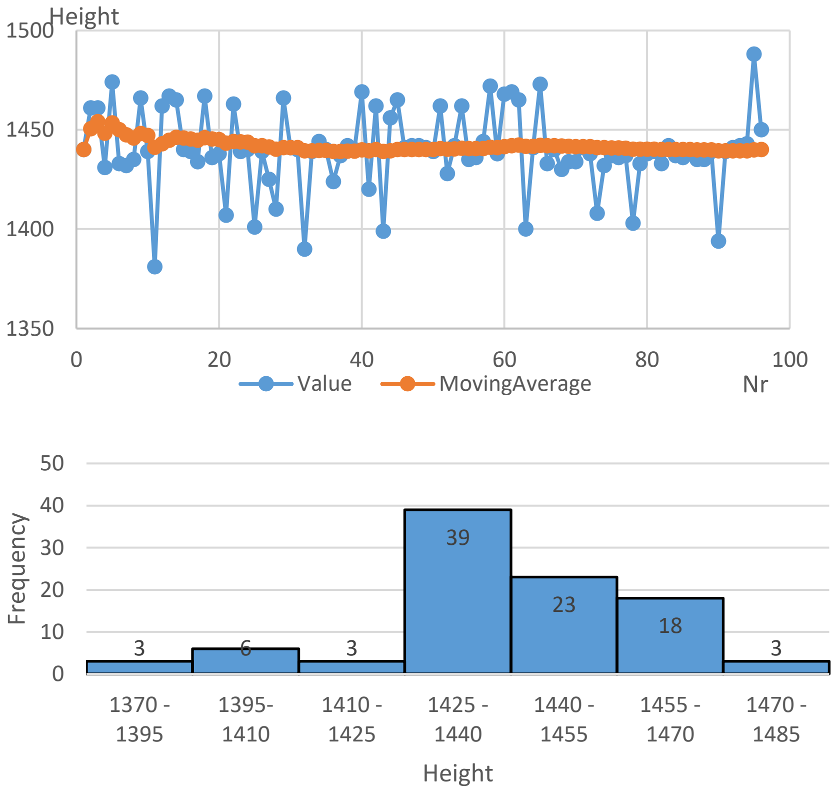

Figure 30 Raw data (above) and histogram distribution (below) from the testing result with MRS1000 on a white Volvo S90 as measured object (height 1440 mm).

Figure 31 Raw data (above) and histogram distribution (below) from the testing result with MRS1000 on a white Volvo S90 as measured object (height 1440 mm).

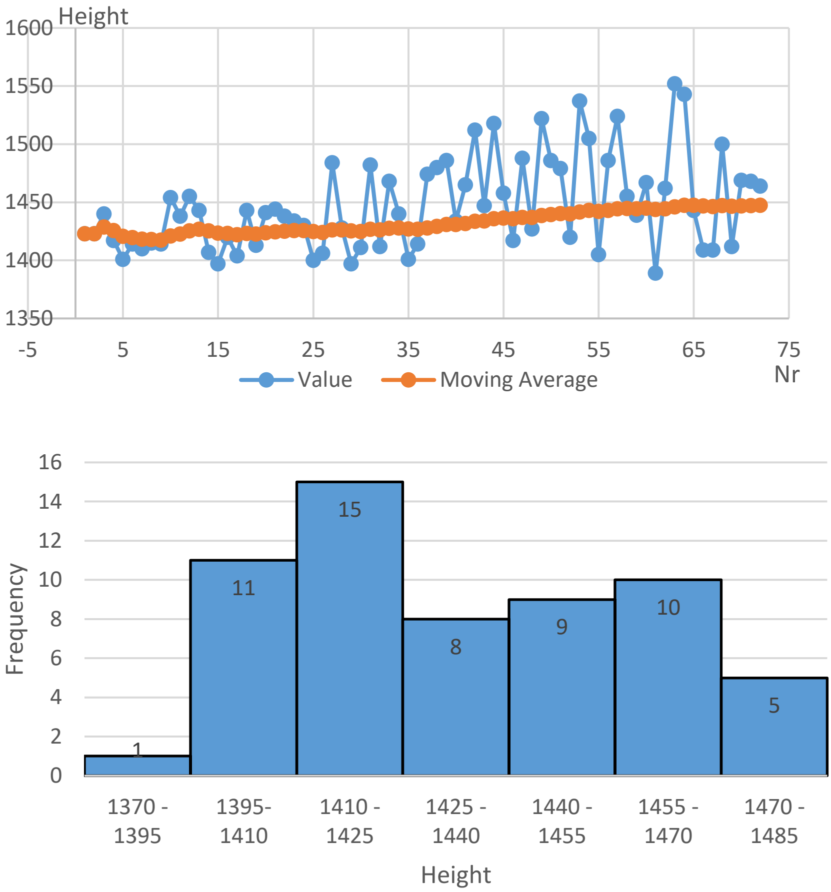

Figure 32 Raw data (above) and histogram distribution (below) from the testing result with O3D302 on a white Volvo S90 as measured object (height 1440 mm).

5.2.3. Hypothesis testing & performance matrix

The hypothesis testing will be performed in the washing hall with a car to be able to resemble the real conditions to the largest possible extent. Two different sensors are used for the testing, resulting in two different hypothesis tests where the results are seen in a performance matrix in table 3. Based on these results, conclusions can be drawn about the measurement accuracy performance for the equipment.

Table 3 Performance Matrix.

	SICK	IFM
	MRS1000	**O3D302**
Mean deviation	12,90625	31,61
Standard deviation	14,38	24,68
Z-score measurements	-1,426	5,71
Z-score hypothesis	1,96	1,96
Null hypothesis	Not rejected	Rejected

The results from the hypothesis testing will be used for determining which of the sensors that is recommended to use in the future automatic measuring solution.

5.3. Research question 3

The factors to the deviations and their root causes are presented in this section. The factors are listed in Figure 33 and are based on collected data from measurements and interviews with personnel, responsible of risk management for outbound transport and responsible for production planning. The factors can be divided into two categories, insufficient synchronization and error.

Insufficient synchronization is related to the dimensions in company databases and are derived from CAD drawings where all component dimensions are added, providing a total dimension of the truck. Two different causes for insufficient synchronization have been identified. In some cases, the system dimensions are not updated according to customer adaptions (CA), changes that can have an noticeable effect on the dimensions. In other cases the system dimensions have not been updated for trucks, modified prior to handover to the carriers, modifications that can have noticeable effect on the dimension.

Two different errors affecting the dimensions were identified. The dimensions in the system assumes that the boggy-axle is in its lowest position. A deviation can occur if the boggy-axle is not lowered down during the measuring moment. The dimension in the system assumes that the spoiler is installed in the lowest level. The measuring dimension will deviate from the system deviation if the spoiler has a different installation level at the measuring moment.

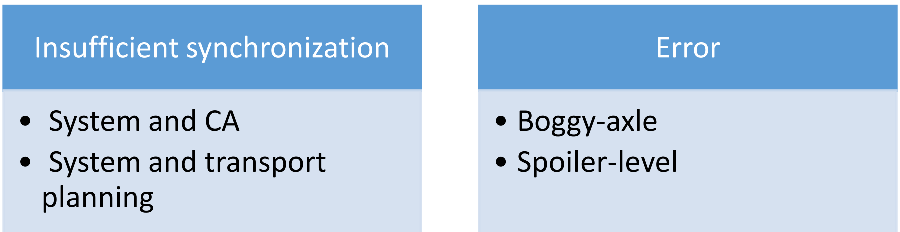

Figure 33 Possible factors for deviations on trucks.

The factors have been further proven by data collected from measuring the truck height manually on the parking yard. A total of 122 trucks were measured, the result is provided in Table 4 and includes observations which were made in regard to the factors listed.

Table 4 Compilation from Tuve parking yard measuring data (SDM = System Dimension > Measured, MSD = Measured > System Dimension).

	Number	Comment
Total measured trucks	122	87 trucks had a deviation exceeding 30 mm.
MSD (deviation > 30mm)	62	Corresponds to the majority of the 87 trucks (71%).
SDM (deviation > 30mm)	25	29% out of all 87 had a small dimension. 10 (40%) trucks had the roof spoiler mounted on the chassis.

5.3.1. Root causes

From the interviews it was possible to identify different root causes for the factors listed in Figure 33. The root causes have been illustrated in a fishbone-diagram, see Figure 34. The root causes are divided into four groups. Equipment and systems describe possible causes related to CAD-engineering and the databases, legislation describes possible causes due to laws and regulations related to transport dimension in Sweden, management describes the possible causes due to the leadership and company culture and transportation describes the number of modifications made on the truck in the activities after production to handover to the carriers.

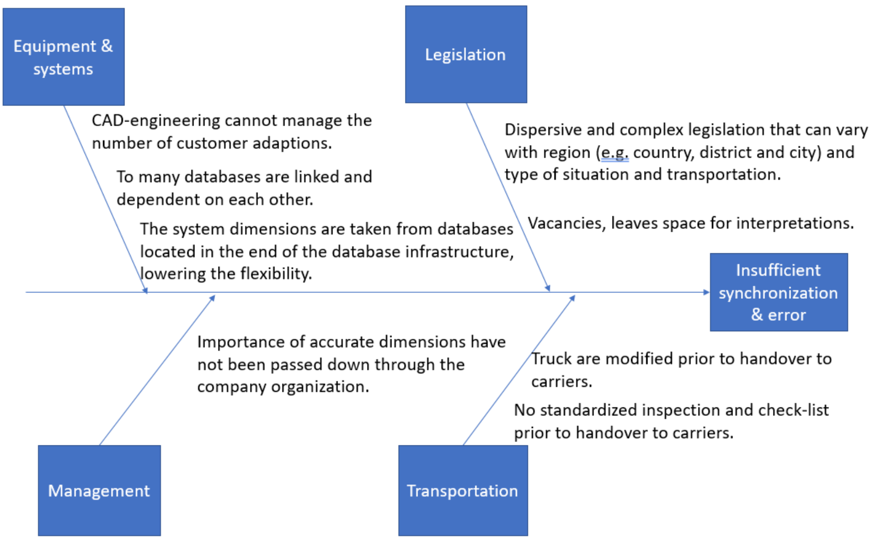

Figure 34 Fishbone-diagram, root causes for the possible factors.

5.4. Research question 4

Aspects that are to be considered when integrating a future measuring solution to the production process is presented in this section. The majority of the aspects are based on interviews.

5.4.1. Traceability

Traceability relates to the task of determining which trucks are to be measured, how to track the trucks and how to determine which time the trucks are to be measured.

5.4.1.1. Truck variants

The company offers several different variants that can be further customized according to customer demands. Based on the degree of customization the trucks are labeled as CA-trucks (customer adaption). CA-trucks requires further activities which are either done internally within the company or externally at another company, so called bodybuilders. Bodybuilders can either be domestic or located in a foreign country. The internal CA-activities are either done as part of the original production process or as a separate process on a different location in the factory, so called CA-docks.

Trucks that are supposed to go through CA-docks are either diverted directly to the docks or in other cases they are first parked in the parking yard, waiting to be picked up and moved to the docks.

In some cases, trucks that are not labeled as CA-trucks will still go through a CA-activity, usually this consists of control activities such as weighing. An overview of the total number of produced trucks, categorized into CA and non-CA-trucks for the production year 2020 is provided in Figure 35. The majority of CA activities consists of add-ons, coating and painting, weighing and washing.

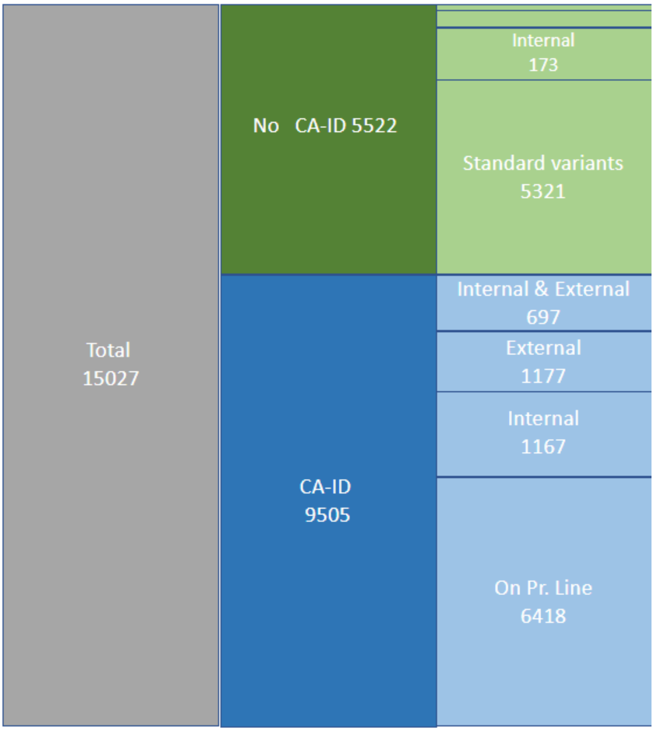

Figure 35 Total number of produced trucks during 2020 and number of CA and non-CA trucks.

According to Figure 35 the total number of trucks that go through some sort of CA-activity, internally, externally, or internally and externally comes up to the following value

$$CA_{internal} + CA_{external} + CA_{internal\&external} + NonCA_{internal} + NonCA_{external}$$

$$\mathbf{1167 + 1177 + 697 + 173 + 25 = 3239}$$

This make up to 22% of the total number of produced trucks for the year 2020.

According to a CA-manager and a production planner they stated that it is preferable to locate the measuring system outside of the production facility to enable measurement of trucks that have deviated from standard production process such as trucks that gone through CA-docks.

5.4.1.2. Production planning system

Volvo uses a system for production planning to follow-up and monitoring activities and sequences from order to the delivery process. The system provides a tree, displayed in Figure 36, which shows a list of all activities to be performed for a certain chassis.

Whether a new activity is going to be added to the system as a separate activity or be included to an existing activity is determined by the operational planning time (OPT) which estimates the time for producing a truck.

Figure 36 Tree example for a certain chassis with both internal and external workshop.

According to the production planner it would be preferable to insert the measuring system to the system right before the factory handover which is where the truck is hand overed to the outbound transportation team. This will ensure that trucks that gone through the CA-docks are measured as well.

5.4.2. Measuring system

This section provides the practical and technical issues in regard to installing, calibrating and maintaining the future measuring system. The result is based on a benchmark interview which was done with a competitor that had implemented a system for measuring trucks. The benchmark provided an insight to why they decided to implement such a system and their experience related to installing, calibrating, and maintaining the system. The next section, supplier and integrators goes through the result from the interviews with integrators and suppliers.

5.4.2.1. Benchmarking

According to the competitor the main reason for implementing a system for measuring truck dimensions was due to similar reasons as Volvo, that is, the great number of deviations in dimensions, increasing costs, the risk for accidents during transportation, and disturbances to their relationship with transport companies and carriers.

Based on what the competitors specified as requirements, they identified a suitable supplier which they believed could develop a system according to their requirements. One main benefit with the certain supplier is that they have local competence, close to the facility of the competitor, enabling for easier collaboration, support and maintenance.

According to the competitor, the measuring system that they have implemented to their production is not fully accurate which has required extended programming and calibration to extract the wanted value from the system. The system is able to filter through the data stream and exclude extreme values and wrong measurements that are generated due to unfavorable object color, surface texture and lightning. The competitor has increased the reliability to the system by integrating a real-time control that compares the measured value with the system dimension. The operators are given a signal if the deviation is too extreme and unreasonable. In such case the truck will go through the measurement system once more until a reasonable value has been provided. The real-time control system was developed as a collaboration between the suppliers and the competitors own IT-personnel.

5.4.2.2. Suppliers and Integrators

There are a number of different suppliers that provides with equipment that enables for measuring the trucks in an automated system, during this project, some have been evaluated and then tested, see the following sections 4.1, 5.2.1 and 5.2.2. Integrating an approved and certified measuring system requires specific competences from the supplier or in other cases from external integrators. The identified competences are displayed in Figure 37.

Figure 37 The required competences for integrating a measuring equipment to an automated system.

Continuous maintenance and calibration

Both during the benchmark with the competitor and the integrators and suppliers, the access to support and maintenance was highlighted as important keys in establishing a well performing and reliable measuring system. This will enable for a better communication between the parties which will benefit both the development and implementation phase.

Programming knowledge

The amount of programming and calibration necessary for increasing the robustness against sensitivities and disturbances is an important and a major part in developing a well performing measuring system. This was realized during the testing phase of the measuring techniques and also something that was stated by the competitors and integrators and suppliers. The position of the sensor in relation to the object had to also be considered to receive the correct value, increasing the complexity of the programming.

Infrastructure for network communication

Further programming will be required if the company, similarly to the competitor desires to integrate a control system to the measuring system. Such a system will require competences in system and database communication to establish the real-time communication.

Certifications and standards

Both the integrators and the suppliers have good knowledge in the field of automation and measuring systems, with a long history of being in the field. They are also certified according to standards and labels that certifies and approves their competence in the field and makes sure that regulatory requirements in regard to meeting the customer requirements, establishing sustainable and effective partnerships and usage of approved equipment and techniques.

6. Discussion

This chapter discuss the results and findings of the study and the research questions in correlation to the theories presented in chapter 2. The chapter gives a deeper analysis of the findings, conclusions and learnings from the master thesis project. Furthermore, the chapter includes a discussion regarding the validity and reliability in the study.

6.1. Measurement results

6.1.1. Selection and evaluation of equipment

Initially in the master thesis, the aim of the work was to implement an automated measurement process in the production plant. With this goal in mind, the objective with the evaluation and selection process of the measurement equipment was to ensure that the equipment could fulfill these requirements. Therefore, the criteria defined in the evaluation, was based on factors that will be important for securing a capable measurement process in Tuve, Gothenburg. The purpose with the evaluation matrix was to investigate which of the techniques that fulfilled the criteria best for securing a capable process.

However, as the thesis work went on, the more we realized we could not implement an automated measuring process during the thesis project. The main reason for this decision was due to the limitation of time but other factors played a part as well, some of them are presented in the result chapter but will be further discussed here. First, implementing an automated process in a production plant will involve several departments and parties in the organization. The production planning needs to be involved as the measurement process needs to be added as a new activity in the production, this includes integrating it as a new activity in the production planning system, but it will also add time to the total production time. The maintenance department needs to be involved in the installation as well as the maintenance required when the process is up and running. It is also fortunate if the maintenance personnel have previous experience of the equipment from the supplier as this will facilitate the maintenance work. During interviews conducted with employees from maintenance, they highlighted the importance of having integrators responsible for processes and that the process and equipment is certified according to international standards. Due to these findings, we concluded that if we were to implement an automated process, these requests from maintenance were not able to be fulfilled. The industrial communication plays an important part in the implementation of an automated measuring process as well, therefore skilled engineers in programming and industrial automation is required, preferable if the competence is available internally in the company. Understanding and learning the IT-structure in the company turned out to be a challenging task for us, mostly due to the complex structure of the databases but also for our lack in knowledge and experience regarding databases, programming and data extraction. Another area where we experienced lack in knowledge was the different aspects that needed to be taken into consideration for the implementation of an automated process in terms of needed equipment for identification of trucks and triggering of the process, due to this it was hard and challenging to provide the necessary equipment for the company that was needed for the process. This problem created issues when it came to the purchasing part as well, as we were not sure which equipment to order.

Based on the conclusions presented above the decision was taken to start performing manual measurements of the trucks on the yard to collect data for the analysis of the dimensional deviations.

6.1.1. Challenges during testing

The results from the testing in controlled- and demanding environment gave us insights in the equipment and their respective strength and weaknesses.

There were three main weaknesses identified for the MRS1000 sensor: the importance of the opening angle, distance to measured object and the difficulties to detect small objects. The results from both the controlled environment and the more demanding one showed that if the opening angle were too wide, the measurement accuracy become worse and were not able to give accurate values relative to the target value. However, if the opening angle was too small, the sensor could not capture the whole width of the truck. This finding resulted in a trade-off between measurement accuracy and the possibility to capture the whole truck, a goal that we were not able to achieve. One solution to this problem was to put two sensors next to each other to make use of two lasers, but this was realized in the end of the project and was therefore not possible to perform. Second, the distance to the measured object and the placement of the sensor relative to the object were shown to be a crucial factor as well. If the sensor was placed too close to the measured object, the color of the object was reflected to the sensor and thus providing inaccurate measurements. If the sensor was placed too far away from the objects, around 4 m, the measurement accuracy also became worse. The conclusions that could be drawn for the testing with different distances is that 2 m seems to be a relevant placement of the sensor. However, the tests with different distances was only taken place in the controlled environment and not in the demanding one. Last, the conclusion could be drawn that the sensor was not capable to detect small objects such as object 2 in the controlled environment tests. This is crucial since the equipment needs to be able to capture this kind of small objects due to antennas on the roof of the trucks for example. The strengths identified from the tests with this sensor was the relative high measurement accuracy and that it performed well with different types of colors.

The conclusions that were drawn from the results with the other sensor, O3D302 were similar to the first one. The weaknesses identified for this sensor was the sensitivity to certain colors such as black or white. This sensor really faced difficulties when measuring objects in the mentioned colors, which could be crucial when measuring trucks with these kinds of colors. The strengths identified for this sensor was the ability to detect small objects and the possibility to even provide high accuracy at large angles. Although the sensor showed good performance in measurements of small objects, the drawbacks with the colors was a too important factor that needed to be considered carefully.

Based on the results from the tests, the MRS100 performed best in terms of the results from the hypothesis testing and the performance matrix. Even though it was not able to reject the null hypothesis, the MRS1000 could not be used for measuring trucks and for the statistical analysis due to too many extreme measurement values in terms of outliers in the measurements.

6.2. Conclusions regarding the validity & reliability

The testing procedure was a requirement for securing the internal validity in the study and to draw conclusions whether the measurement equipment could be used to secure a capable process. Conclusions could be drawn during the tests that the equipment selected was not able to secure a good internal validity due to some certain outliers in the measurement performed, although quite high measurement accuracy. Due to these found outliers, it was concluded that it could not be seen as a capable process to measure trucks and secure accurate values for the truck height.

6.3. Economics

In this section the economic losses will be discussed. The section will first go through each economic losses, described in section 5.1.4 to discuss and estimate their impact on the total economic losses and to discuss whether there is sufficient data and support for such estimations.

6.3.1. Economic losses

The main issue when estimating the costs due to short shipping is not calculating the costs, rather it is to identify the underlying reason and find the origin that causes the short shipping. The short shipping incident, described in section 5.1.4.1 had a fee of 600 SEK/day for each truck, which is what the harbor normally charges for keeping vehicles on their parking yard. Thus, calculating the cost is not an issue, however this incident did occur in Antwerpen, Belgium, so the question was if it could be linked to the original production factory. Fortunately, in this case all trucks belong to the same batch and could, thanks to their chassis number be linked to the production in Ghent, Belgium. Also, as these trucks had been produced in the same factory and belonged to the same batch it became an easier task to trace back and identify the causing factor for the short shipping.

The main issue is when there is number of short shipped trucks, produced in different factories and countries. In these cases, it is not possible to group all the short shipped trucks, instead, each truck has to be treated separately, complicating the search for the causing factor. In some cases, the causing factor can be traced back to the production factory such as Tuve or Ghent. In other cases, the causing factor can be of different origin, trucks are commonly going through some modification during transportation, the spoiler is mounted on or off and antennas are mounted on or off the cab, just to give some examples. Based on this discussion, if, unlike the case in Antwerpen is not possible to directly link the trucks to a certain factory then the short shipped trucks should be considered and marked as a global cost.

When the thesis started it was assumed that the major costs should be due to trucks that were too high. However, it became apparent afterwards that these trucks would only result in extra administrative work for managing the locked invoices and manually updating the system. Trucks that are too high will only require an update according to the correct height, in other words, Volvo will be charged for the correct volume. However, too high trucks also increases the risk for material and immaterial damages during transportation overseas and on land. It also increases the risk for lawsuits and receiving fines. Thankfully, such incidents are scarce, but they would require a different measure of action to investigate and provide documentation for the causing factors which could increase administrative work and other overhead costs.

During the thesis it become more apparent that too low trucks would result in unnecessary payments as Volvo would be charged for a larger volume than required. It was therefore interesting to investigate how many trucks that were too low to be able to estimate the amount of unnecessary costs Volvo was being charged for. Estimating the number of too low trucks was done by investing the Wallhamn report and cross-check that with the Tuve measurements. Prior to investigating the reports, it was expected and assumed that the number of too high trucks and too low trucks would be almost equal, with perhaps some variations. However, when the Wallhamn report was investigated only 8 of a total 493 trucks were too low, while the rest were too high. This made us suspect that only trucks that were too high were reported and trucks that were too low were avoided as reporting them would result in a lower volume and thus a lower charge. This hypothesis was eventually tested by cross-checking with the Tuve measurement. At a first glance the Tuve measurement had 25 trucks that were too low out of the 122 trucks that had been measured. This was a greater ratio than what was seen in the Wallhamn report, but when investigating further the data it was revealed that not all 25 trucks were supposed to be sent to Wallhamn for overseas transportation. Some trucks were domestic, and some trucks were transported on land. Out of the 25 trucks it was concluded that only 2 were going to be transported to Wallhamn for overseas transportation. When looking at the statistics, from Oct 2020 to April 2021, 8 trucks had been reported from Wallhamn due to too low dimensions and as mentioned in section 5.1.1.2 this was 0.2% of the total number of trucks sent to Wallhamn for the same time period. In the same section it was also revealed that the 2 trucks in the Tuve measurement made up to 5% of the total number (38 trucks) that were sent to Wallhamn.

This observation went against the hypothesis as it showed that the number of too low trucks were noticeably below the number of too high trucks. Even though 5% is significantly higher than 0.2%, the difference in magnitude of trucks between the two data must be taken into consideration. The Tuve measurements are samples, while the Wallhamn report extends over a seven month period. Furthermore, it should be noted that the Wallhamn report is not fully complete and some trucks can have been lost as they are not being documented.

Considering the administrative work for managing the invoices and manually updating the system, one can link the locked invoices to the Tuve production. As mentioned in section 5.1.2 it was possible to see a correlation between the number of No-FTP, filtered based on departments, reason and carriers and the number of reported trucks from Wallhamn. Thus, estimating the amount of time spent on receiving and correcting locked invoice could be achieved. As mentioned in section 5.1.4.2 the costs due to locked invoices could be divided into costs due to locked invoices and manually updating the system. It was also mentioned that both of these tasks were interlinked and communication between the responsible employees (transport planner and invoice manager) was taking place. Both employees did estimate the amount of time they were spending on receiving the invoices and manually updating the system. However, the invoice manager gave a general estimation for all invoices, but there was a correlation in number of locked invoices and the number of reported trucks from Wallhamn. Their tasks were also interlinked and therefore it could be assumed that the invoice manager is setting aside similar amount of time as the transport planner. Based on this the combined total administrative time for the invoice manager and transport planner due to deviations can be estimated to a few hours every week.

6.4. The factors and causes

The process for identifying the causes can be described as having a reverse approach. The process started by determining the factors that led to the deviations and afterwards identifying what root causes were behind the emergence of this factors. Some factors had been stated and collected from our interviews and some had been identified from analyzing the Tuve measurements. The factors that had been mentioned during the interviews did also match with observations made on the Tuve measurement. As an example, the factor “spoiler” was reflected by the Tuve measurement which showed that 10 out of 25 trucks (40%) that were too low had the roof spoiler mounted on the chassis. In other words, the system assumed that the spoiler was mounted on top of the cab and thus providing greater height than the actual height.

However, this could not be argued for all factors such as the “boggy-axle”. The factor “boggy-axle” had been mentioned as a potential factor that caused deviations. There was also a correlation in number of trucks, deviating more than 30 mm and the number of trucks with the boggy-axle in an upward position. However, when testing the effects of lowering the boggy-axle on a truck that had it on an upward position, no effects in height dimension could be observed. This was done on a small sample of trucks, but they all showed the same result. One reason for this can perhaps be the reliability of the manual ruler-stick used for measuring the trucks, but this risk was reduced by making sure that the ruler was measuring from the same ground point and the same point on the truck prior to and after lowering the boggy-axle, in other words the reference points were the same for the two measuring occasions.

The question that remains is if the other factors, similarly to the “boggy-axle” can be questioned. The factor “spoiler” is an exception and can be easily legitimized by subtracting the spoiler from the system dimensions for those trucks that had the spoiler mounted on the chassis. The other factors such as “System and CA” that is, the system dimensions have not been updated according to the customer adaptions. Even though this factor sounds legitimate which the “boggy-axle” also did until it was proven otherwise, all factors has to be verified. Perhaps the addition of a component on a CA-truck could affect the height, but these would require more measurements in the parking yard and also investigating and comparing the number and type of components documented in the system dimension with the components for a specific truck. In that way no speculations will be left untouched.

6.5. Future implementation process

The objective of implementing a fully automated system to the production was abandoned and reformulated when the need for such a system was questioned and when it became apparent that the time was limited. However, the thesis provided a lot of knowledge and data that was collected while the original objective still was in mind.

The opinion was that this information was of high value and should not go to waste. It was therefore decided to reformulate the objective to instead, provide a foundation for a future implementation process. With such a foundation Volvo would have better knowledge in evaluating their need for such a system, they would have data on techniques that have been tested and use that when specifying their requirements and when negotiating with suppliers and integrators and they will also be aware of the production process and how it should be included and taken into account when implementing the system.

7. Conclusion

This thesis provided a great opportunity to investigate the potentiality of an automated measuring system, to see what benefits, and also what disadvantages such a system would bring. The objective of using the system for measuring the trucks during the root-cause analysis was not achieved. Mainly due to the lack of time, but also due to the difficulties faced when calibrating and programming the sensor to achieve reliable and accurate measurements. It should however be mentioned that the struggle of trying to use the sensor for measuring the trucks provided a lot of knowledge and data which we believe would be of great value for Volvo. The root-cause analysis was still accomplished, using a manual ruler stick which worked better than expected.

Some pre stated factors and causes, and consequences could be justified by the measurements and analyzation of data, while others were rejected. A recommendation for the one who will continue in the footsteps of this project, is that they should continue with collecting data, both from measuring in Tuve and from the Wallhamn reports. The Wallhamn reports should also be improved and documented more carefully to make sure that important information is not being lost.

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