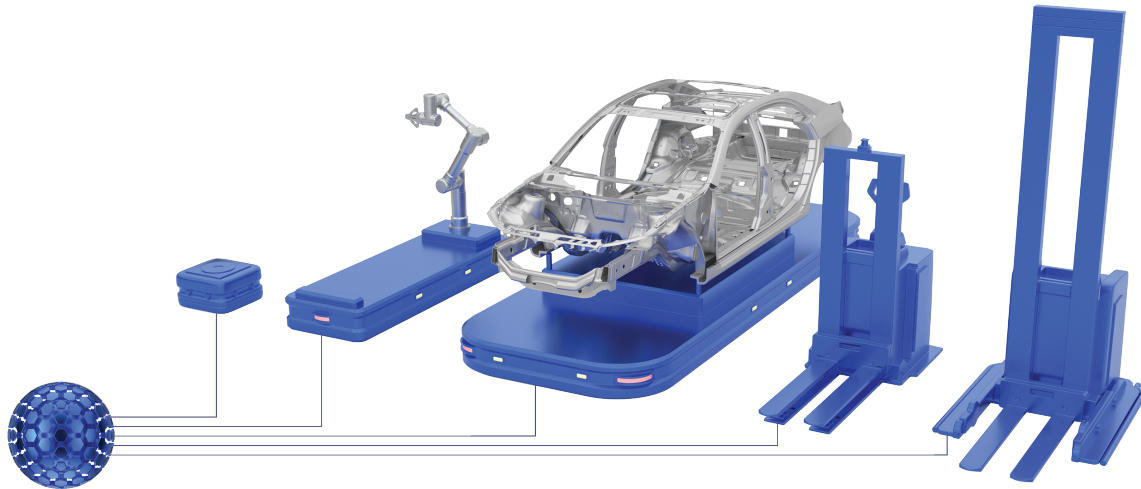




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Environmental Impact from an AGV System

**Assessing GHG emissions from Kollmorgen's products during  
operation and identifying reduction possibilities**

Master's Thesis in Industrial Ecology and Sustainable Energy Systems

OLINE HAGGREN  
WERA NILSSON

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS  
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

---

Chalmers University of Technology  
Gothenburg, Sweden 2023  
www.chalmers.se  
Report No. E2023:112



REPORT NO. E2023:112

## **Environmental impact from an AGV system**

Assessing GHG emissions from Kollmorgen's products during operation and identifying reduction possibilities

OLINE HAGGREN

WERA NILSSON

Department of Technology Management and Economics

Division of Environmental Systems Analysis

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023

Environmental impact from an AGV system

A study about the GHG emissions from Kollmorgen's products during operation and the identified reduction possibilities

OLINE HAGGREN

WERA NILSSON

© OLINE HAGGREN, 2023.

© WERA NILSSON, 2023.

Supervisor: Tomas Ekvall, Technology Management and Economics

Examiner: Gregory Peters, Technology Management and Economics

Report no. E2023:112

Department of Technology Management and Economics

Division of Environmental Systems Analysis

Chalmers University of Technology

SE-413 96 Gothenburg

Sweden

Telephone +46 (0)31-772 1000

Cover: Different types of AGVs in an AGV system.

Gothenburg, Sweden 2023

## **Preface**

This master thesis was conducted at Chalmers University of Technology in collaboration with Kollmorgen Automation AB during the spring term of 2023. It was executed at the Department of Technology Management and Economics, in the Division of Environmental Systems Analysis. The thesis derives from Kollmorgen's interest in assessing the environmental impacts of their products during operation. The project was carried out with the help of two supervisors, Tomas Ekvall from the institution of Technology Management and Economics as well as Cecilia Boström at Kollmorgen Automation AB. Also, a special thanks to Tomas Angervall at Kollmorgen Automation AB for all the help with conducting this thesis. Furthermore, a big thanks to all the other colleagues at Kollmorgen Automation AB for all the helpful insights throughout this master thesis.

Environmental Impact from an AGV System

Assessing GHG emissions from Kollmorgen's products during operation and identifying reduction possibilities

OLINE HAGGREN

WERA NILSSON

Department of Technology Management and Economics

Chalmers University of Technology

## **Abstract**

This thesis was conducted at Kollmorgen Automation AB to investigate the greenhouse gas (GHG) emissions from their products during operation, find the most important factors contributing to the emissions, and finally define possible improvement measures for reducing them. Kollmorgen's products are used in automated guided vehicle (AGV) systems at their end-users' applications.

The method for calculating the emissions was mainly the Greenhouse Gas Protocol (GHG Protocol) which was used throughout the report. Various assumptions were used to calculate GHG emissions from Kollmorgen's products during operations since they are used worldwide. Furthermore, three case studies were executed to investigate the emissions from their products during operation and provide an understanding of AGV systems. Several interviews were held at the case studies and with colleagues at Kollmorgen to identify factors affecting the emissions and find possible improvement measures. Finally, two driving tests were performed to assess the improvement measures' impact on the GHG emissions and validate them.

The results demonstrate that Kollmorgen's products had larger GHG emissions during operation than expected given that their main product is a software. However, Kollmorgen's emissions were also found to only represent 5-10 % of the total AGV system, which indicated the importance of considering AGV systems' emissions. Several factors affecting the GHG emissions were also identified along with improvement measures to reduce the emissions. The results from the driving tests clearly indicated that the driving pattern of an AGV has a significant impact on energy consumption and thereby the GHG emissions. However, one of the factors with the highest impact on the GHG emissions was the energy mix which differs

between regions and is something Kollmorgen's products can not influence.

The discussion covered the significance of assessing the environmental impact of Kollmorgen's products and AGV systems in general. The possible improvement measures were concretized and the implementation of them would lead to an important reduction in GHG emissions. Finally, the reliability of the results was discussed as well as providing suggestions for further investigation.

Keywords: *GHG emissions, CO<sub>2</sub>, AGV systems, GHG Protocol, energy consumption, energy efficiency, environmental impact, climate impact, Kollmorgen*

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Background . . . . .	1
1.1.1	The AGV System . . . . .	1
1.1.2	Kollmorgen Automation AB . . . . .	3
1.1.3	Kollmorgen’s Climate Assessments . . . . .	3
1.2	Purpose and Aim . . . . .	5
1.3	Delimitations . . . . .	5
<b>2</b>	<b>Theory</b>	<b>7</b>
2.1	The Research Questions’ Different Scopes . . . . .	7
2.2	Relevance with Regard to Climate Impact . . . . .	8
2.3	Relevance with Regards to Social Aspects . . . . .	9
<b>3</b>	<b>Specification of Kollmorgen’s Products</b>	<b>11</b>
3.1	Components for the Software . . . . .	11
3.1.1	System Manager . . . . .	11
3.1.2	Operator Interface . . . . .	12
3.1.3	Power Consumption . . . . .	12
3.2	Hardware Components . . . . .	12
3.2.1	Vehicle Controller . . . . .	13
3.2.2	Navigation Sensor . . . . .	13
3.2.3	Drives . . . . .	14
3.2.4	HMI Display . . . . .	14
3.2.5	Power Consumption . . . . .	14
<b>4</b>	<b>Method</b>	<b>15</b>
4.1	Literature Studies and Interviews . . . . .	15
4.2	Flowcharts and System Boundaries . . . . .	15
4.2.1	Life cycle of Kollmorgen’s Hardware . . . . .	15
4.2.2	Flowchart of the Use-Phase . . . . .	16
4.2.3	Life cycle of an AGV System . . . . .	17
4.3	Case Studies . . . . .	18
4.3.1	Case Study 1: DB Schenker . . . . .	19

4.3.2	Case Study 2: Borealis . . . . .	20
4.3.3	Case Study 3: Toyota Material Handling . . . . .	21
4.4	Assumptions for Calculating GHG Emissions . . . . .	22
4.5	Calculation of GHG Emissions . . . . .	25
4.5.1	Case Studies . . . . .	25
4.5.2	Standard System . . . . .	27
4.6	Validation of Improvement Measures . . . . .	28
<b>5</b>	<b>Results</b>	<b>30</b>
5.1	GHG Emissions . . . . .	30
5.1.1	Case studies . . . . .	30
5.1.2	GHG Emissions from Kollmorgen's Products . . . . .	32
5.2	Identified Factors Affecting the GHG Emissions . . . . .	33
5.3	Identified Improvement Measures . . . . .	35
5.4	Results from the Driving Tests . . . . .	36
5.4.1	Speed Management . . . . .	37
5.4.2	Blocking Time Reduction . . . . .	38
<b>6</b>	<b>Discussion</b>	<b>41</b>
6.1	Case Studies . . . . .	41
6.2	GHG Emissions from Kollmorgen's Products . . . . .	42
6.3	Main Factors Affecting the GHG Emissions . . . . .	42
6.4	Improvement Measures . . . . .	43
6.5	Driving Tests . . . . .	45
6.6	Reliability of the Result . . . . .	47
6.6.1	Case Studies . . . . .	47
6.6.2	GHG Emissions from Kollmorgen's Products . . . . .	48
6.6.3	Driving Tests . . . . .	49
<b>7</b>	<b>Conclusion</b>	<b>50</b>
<b>8</b>	<b>Further Investigations</b>	<b>51</b>
<b>A</b>	<b>Case study: DB Schenker</b>	<b>57</b>
<b>B</b>	<b>Case study: Borealis</b>	<b>58</b>

**C Case study: Toyota Material Handling 59**

**D Test 2: Blocking Time Reduction 60**

# 1 Introduction

This master thesis evaluates the environmental impact of an automated guided vehicle (AGV) system during operation and investigates which characteristics of the AGV system can be altered to reduce the environmental impact. The thesis was conducted at Kollmorgen Automation AB during the spring term of 2023. This chapter presents the background and the aim of the project, as well as the delimitations.

## 1.1 Background

This section describes what an AGV system is and gives a presentation of the company Kollmorgen Automation AB, subsequently referred to as Kollmorgen. The section also describes what Kollmorgen has done so far in their climate assessment. As well as this, a background regarding the Greenhouse Gas Protocol (GHG Protocol) is presented, which is used as a tool in this project for calculating the greenhouse gas (GHG) emissions from Kollmorgens products during operations.

### 1.1.1 The AGV System

An AGV is a mobile robot that runs autonomously and operates mostly in factories and warehouses. However, AGVs can be applied and adapted to several areas of application [1]. Furthermore, an AGV system is a fleet of AGVs controlled and navigated by software and navigation technologies. AGV systems improve efficiency and safety compared to manual forklifts. The benefits of using AGV systems are optimized vehicle routes, safety sensors, and smooth start, stop, and driving functions. This is all controlled by smart algorithms in the software which reduces the driving distance, energy consumption and wear on the vehicles and surroundings, which also enables a longer lifetime compared to the use of manual trucks [2]. Another benefit of the use of AGV systems is the increase in workplace safety [3]. The most common types of vehicles used in AGV systems are shown in Figure 1, the systems vary considerably in shape and size depending on their functions and application.

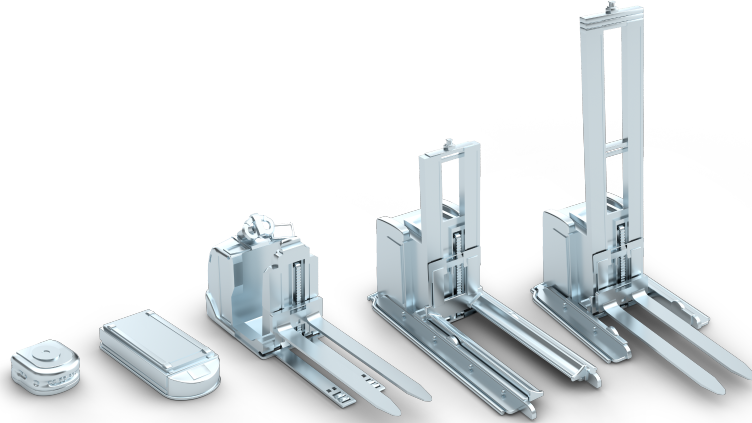


Figure 1: Several types of AGVs [4]

The typical AGV system operates by performing as many tasks in the shortest amount of time possible to maximize performance. This is controlled by the software and typically when the system receives an order, the closest AGV is ordered to execute it as fast as possible [5]. The software controls the whole fleet of AGVs in the system and optimizes routes and speeds for productivity. The AGVs have safety sensors and will stop for obstacles and people and other AGVs. The time when an AGV stops for another AGV is called blocking time. Since the AGVs are programmed to perform every task as fast as possible, some idle time can occur when the AGVs are standing still and waiting for the next order. This is also highly dependent on the number of orders. Furthermore, the AGVs are commonly charged by contact-charging or manually changed batteries. This is also typically controlled by the software to navigate the AGVs to the charging station as needed, which can be optimized by using so-called opportunity charging. Different types of batteries can be used for the AGVs but the most common are lead-acid or lithium-ion. Lithium-ion batteries are the most energy-efficient and have a longer lifetime [6]. Many AGVs and other types of electrical vehicles have a regenerative braking system which means that some of the energy used for the braking is regenerated into the battery [7].

### **1.1.2 Kollmorgen Automation AB**

Kollmorgen provides hardware and software solutions for both navigation and control of AGVs and mobile robots. Kollmorgen sells these hardware and software solutions to their partners who assemble them into a finished AGV system. Their partners in turn sell the AGV systems to the end-users where they are used in warehouses and factories to increase efficiency and agility [8]. However, they also provide their partners with value-adding business services by supporting them with strategic guidance. This strategic guidance is related to how their partners can become better at emerging into new markets and developing material handling solutions. Kollmorgen mostly sells its products in the regions of Europe, North America, China, and the rest of the Asia-Pacific. Kollmorgen Automation AB is part of Kollmorgen Corporation and they are both subsidiaries of Regal Rexnord since 2023. Regal Rexnord is a global manufacturer of machine components [9] and has a sustainability approach focused on energy efficiency and sustainable production [10].

### **1.1.3 Kollmorgen's Climate Assessments**

Kollmorgen's previous climate assessment was based on the GHG Protocol and they have performed calculations concerning their organization, Kollmorgen Automation AB. The GHG Protocol provides a global standardized framework to measure GHG emissions from the private and public sectors [11]. It helps with measuring but also managing GHG emissions by providing standards, guidance, tools, and training for both businesses and the government.

The GHG Protocol includes three different scopes, Scope 1 to 3, and is divided into upstream and downstream activities from the reporting company. Upstream activities refer to suppliers and downstream activities refer to end-users. Scope 1 represents the direct emissions from the company, which includes company vehicles and facilities. Scope 2 represents the indirect emissions from the company's purchased energy, these can be either location- or market-based. The location-based method is based on an average emission factor within a specific geographical boundary and the market-based method is based on the specific emission factor in direct correlation with the electricity supplier for the consumer [12]. The market-based method, therefore, implies that the energy that is purchased might differ from the energy that is generated where the company is located. The emission factor connected to the market-based method is based on an agreement between the two parties involved in the sale and purchase of the energy, which includes energy attributes about the origin of the energy [12]. When the origin of the energy is undetermined, default emission factors could be included in

the agreements, called the residual mix.

Scope 3 is divided into emissions from upstream respective downstream activities and represents all other indirect emissions. Upstream activities are for example all purchased goods, business travels, transportation and distribution, etc., and downstream activities are processing, use, and end-of-life treatment of sold products, franchises, and investments. The GHG emissions included in the Protocol are CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, and SF<sub>6</sub>. However, this report will only focus on CO<sub>2</sub> emissions. An overview of the different scopes and emissions can be seen in Figure 2 below.

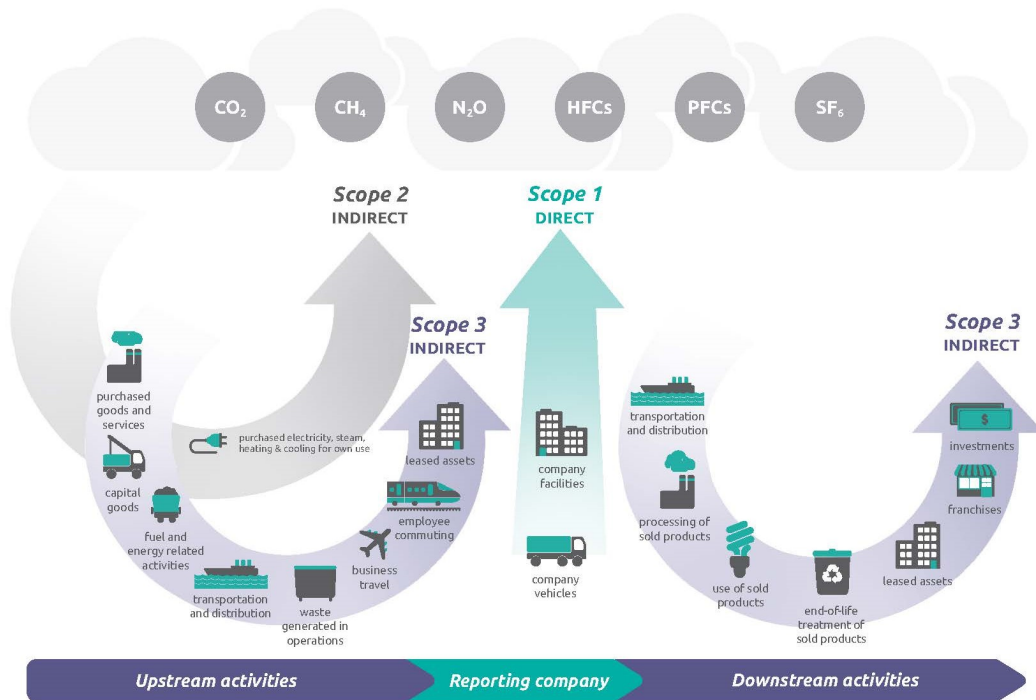


Figure 2: GHG Protocol Scopes [13]

Kollmorgen’s climate assessments have so far accounted for their Scope 1, 2, and Scope 3 upstream activities. Kollmorgen’s Scope 1 has insignificant emissions since they do not have any hardware production of their own or any company vehicles, however, they have suppliers who produce the hardware products that Kollmorgen then sells. Their Scope 2 includes purchases of renewable electricity and district heating where they have calculated their emissions based on local emission factors. The major part of Kollmorgen’s emissions is located in the value chain, which is Scope 3, both upstream and downstream. The Scope 3 upstream activities previously assessed with significant emissions are *purchased goods and services*, *transportation and distribution*, *business travel*, and *employee commuting*. For this

scope, they have calculated their emissions for every part except *purchased goods and services* since there is currently no data available from their suppliers. GHG emissions allocated to *capital goods, fuel, and energy-related activities, waste generated in operation* as well as *leased assets* are regarded as insignificant. Kollmorgen has not fully assessed their emissions for Scope 3 downstream yet, where the main factor is *use of sold products*. One of the aims of this report is to investigate these emissions. This is necessary to complement Kollmorgen's previous climate assessment based on the GHG Protocol. Kollmorgen sells their products to their partners, who assemble the AGV systems and sell them to the end users. This implies that Kollmorgen's Scope 3 *use of sold products* corresponds to the end-users Scope 2 due to the product only consuming electricity during operation.

## 1.2 Purpose and Aim

The purpose of this master thesis was to investigate the climate impact of Kollmorgen's products in the AGV system during operation and find possible improvement measures for the software to reduce GHG emissions. Kollmorgen has not assessed the use of their sold products from an environmental perspective previously which is necessary to complement their earlier assessment according to the GHG Protocol. Furthermore, the identification of possible improvement measures is important since Kollmorgen wants to reduce their environmental impact. A part of this is to identify the main factors that contribute to GHG emissions and which factors can be altered by making changes in Kollmorgen's software solutions to lower the emissions. To answer this, three research questions were formulated and the thesis was based on the following questions:

*RQ1: How large are the GHG emissions from Kollmorgen's products in an AGV system during operation for a year?*

*RQ2: What are the main factors that affect the GHG emissions of the AGV system during operation?*

*RQ3: How can Kollmorgen's software solutions be improved to reduce GHG emissions and prolong the lifetime of the AGV systems?*

## 1.3 Delimitations

The assessment of the environmental impact was limited to climate impact and the GHG calculations were done with regard to CO<sub>2</sub> emissions. This means that other types of en-

vironmental impacts were not investigated in the scope of this master thesis. Furthermore, the main factor contributing to GHG emissions was the electricity use for the AGV systems during operation. Therefore the calculations were based on the electricity used by Kollmorgen's products. External factors like facility lighting, temperature, damage to goods, etc. were not taken into consideration for the calculations of GHG emissions. As well as this, various assumptions were made to calculate the GHG emissions from Kollmorgen's products during operation. The assumptions imply limitations which are explained throughout the thesis. The identification of improvement measures was limited to only include factors that Kollmorgen's software solutions can affect. Thereby, factors like energy mix, battery type, load weight, etc. were not accounted for.

## 2 Theory

This section provides a further explanation of the research questions as well as their relevance and gives a wider perspective regarding the climate and society.

### 2.1 The Research Questions' Different Scopes

The investigation for the first and second research questions, about calculating GHG emissions and identifying factors affecting these, was only performed with regard to the product's use phase. The third research question about improvement measures covered a bigger scope concerning factors and components that are affected by Kollmorgen's software. The first research question was answered with a quantitative method whilst the second and third research question was answered with a qualitative method. This resulted in the whole report using a combination of quantitative and qualitative methods to answer all the research questions.

The quantitative method used for answering the first research question was the calculation of climate impacts based on the GHG Protocol, which affects the result. The main factors that affect the result when using the GHG Protocol are the choice of a location-based or market-based method, and thereby also the emission factor. The result could also differ if another method was used as guidance for the calculations, for example, the use of a life cycle assessment (LCA). LCA is a method where you assess the product or service life cycle whereas the GHG Protocol assesses an organization's climate impact [14]. However, they are both methods that investigate the environmental impact and that are used for calculating emissions.

Various assumptions also affected the results. Assumptions were needed to base the calculations on because Kollmorgen's products are used all over the world by multiple end-users and every application is customized. The number of sold products also varies between year and region. The years investigated in this report are the same as in Kollmorgen's previous climate assessments, and the regions are where most of Kollmorgen's partners are operating. The emission factor for electricity varies between regions which is also a reason for analyzing different regions when performing the calculations for the standard system.

The two other research questions were answered by mainly a qualitative method, based

on interviews with colleagues at Kollmorgen as well as case studies at various end-users. However, some quantitative results for the third research question have been obtained by measuring some of the possible improvements.

## **2.2 Relevance with Regard to Climate Impact**

These research questions are relevant to climate change since it is important for companies to report their climate impacts for both transparency and the possibility to find improvements for minimizing their impact. The GHG emissions from the AGV systems are only a small part of the total climate impact of society. However, it is still important that companies report and try to reduce their emissions as much as possible. Climate change is an important issue and it has both negative environmental as well as social consequences [15]. Some of the environmental consequences are higher temperatures which cause droughts and wildfires. Another consequence is the availability of freshwater since the increased temperature leads to changes in rainfall patterns and increased droughts, which will reduce the quality of freshwater resources. Climate change also has a negative effect on biodiversity, since it is hard for plants and animals to adapt to the changing environment. This will lead to changes in the ecosystem and in turn, affect the ability to provide essential ecosystem services. Examples of these services are climate regulation, provisioning of food, clean air and water, as well as control of floods and erosion. These changes therefore pose both environmental as well as social threats.

Some of the social consequences related to climate change concerns health issues. Because of more extreme weather conditions, diseases connected to lower freshwater quality, decrease in food production, etc. will increase. Regions will also be affected differently, where less developed countries will have a harder time facing the impacts that come with climate change because of poor infrastructure and economy. Climate change is expected to be responsible for around 250 000 additional deaths per year between the years 2030 and 2050 [16]. This is due to factors like malnutrition, malaria, diarrhea, and heat stress, all of which have a direct relation to climate change. Because of all these factors stated above, every company needs to try to minimize their emissions as much as possible, to try to delay the negative effects of climate change. This is especially important for the people living in low-developed countries since they are affected at a higher rate than developed countries.

### 2.3 Relevance with Regards to Social Aspects

Because of increased pressure to minimize GHG emissions around the world, many companies want to achieve more sustainable production [17] and AGV systems could be a solution. This is because of their increased efficiency compared to manual trucks as well as their higher safety. The increased safety with AGV systems compared to manual trucks is partly because they can operate without humans, which is one of the main reasons behind accidents. AGVs have built-in safety sensors that prevent them from colliding with other vehicles, goods, or people [8]. For manual forklifts, the human factor has a great impact, and accidents, in some form, are unavoidable. Another reason for the increased safety is that the AGV systems can perform tasks that are not suited for human workers, for example handling hazardous substances, handling heavy loads, and extreme temperatures. In the United States, accidents related to manual forklifts account for around 10 % of the injuries that occur in warehouses and factories [18]. The main reason behind this is the lack of training and safety measures for the truck drivers and around 70 % of these accidents could be removed with proper training. However, by replacing manual trucks with AGV systems, these numbers could be reduced significantly. This is important both from a social as well as an ethical aspect since the introduction of AGV systems could increase the safety of the workers and minimize accidents. This is positive from a work environment perspective. The manual forklifts also need fair working conditions since they are operated by humans but since the AGV systems can be operated without humans, this factor does not need to be taken into consideration when implementing an AGV system.

Another aspect of this is that it is argued whether people's jobs will be replaced by AGVs and affect social welfare by reducing job opportunities. This can be an issue in many different sectors and historically, job opportunities in for example manufacturing, production, and agriculture have decreased significantly with the implementation of automation. However, others argue that AGVs, and automation overall, do not necessarily mean that jobs are replaced but instead create new types of jobs. Examples of new types of job opportunities are management, programming, as well as supervision of the AGV system [19]. This implies that the reduction of job opportunities might not be the case, instead, it could mean that the displacement of jobs reduces the heavier manual labour for the operators. This can be seen as a positive aspect since work injuries, as mentioned above, are high in these types of environments. A challenge with the displacement of jobs is the need for people with other types of knowledge and skills. This could mean that some people might have a harder time

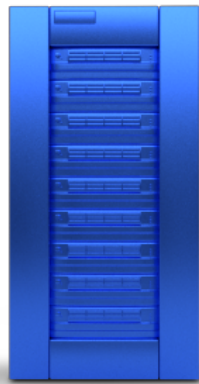
obtaining a job which would have a negative social impact. Nevertheless, the implementation of AGV systems and automation overall are increasing and because of this, it is important to analyze their sustainability.

### 3 Specification of Kollmorgen’s Products

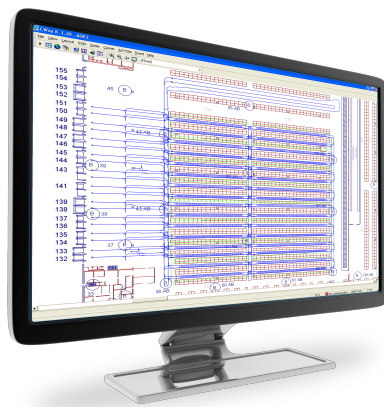
This section presents Kollmorgen’s core hardware and software components that are used today, and these components were also used when calculating the GHG emissions for Kollmorgen’s products.

#### 3.1 Components for the Software

The components needed to run the software system are servers for the system manager and one or several operator interfaces to display the system [20]. The system manager and operator interface is further explained below. The servers and operator interfaces are not delivered by Kollmorgen but are needed for the software, so in order to calculate the environmental impact of the software, the energy consumption for these components needed to be investigated. A graphical illustration of the server and operator interface can be seen in Figure 3 and the power consumption for the components for the software can be seen in Table 1.



(a) Server for the system manager [4]



(b) Operator interface [4]

Figure 3: Components for the software

##### 3.1.1 System Manager

The system manager is Kollmorgen’s software solution package and is used for transport flow control, traffic management, and fleet management for the AGV systems [4]. A server is needed for the system manager, either virtual or physical. According to [21] there were approximately 55,6 % physical servers in 2019 and the rest were virtual servers. The energy

consumption for a typical physical server is assumed to be 218 W [22]. However, the energy consumption for a virtual server is lower than for a physical server and according to [23] it is 51,7 % more efficient, from a power usage perspective, compared to a physical server.

### 3.1.2 Operator Interface

Operator interfaces are used to display and monitor the AGV systems digitally on screens [24]. Ordinary computers with screens are used for this and one application can have one or several operator interfaces. These are also used to get an overview of the system at the specific location and be able to detect errors in the system. The standard operator interface that will be assumed is a 17" LED monitor with an average power consumption of 18 W per hour [27].

### 3.1.3 Power Consumption

In this section, a specification is shown in Table 1 regarding the maximum power consumption for the different components for the software. The power consumption were used in the calculations for the GHG emissions.

Table 1: Power Consumption for the Components for the Software

<b>Component</b>	<b>Power Output [W]</b>
Operator interface	18
Physical Server	218
Virtual Server	105

## 3.2 Hardware Components

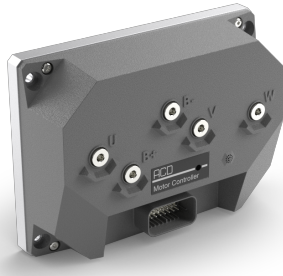
Kollmorgen provides four types of hardware components which are a vehicle controller, a navigation sensor, two drives, and an human-machine interface (HMI) display [20]. The vehicle controller and some type of navigation sensor are sold together with their software solutions to Kollmorgen's partners, whilst their partners sometimes have a different supplier for drives and HMI display when assembling the AGV system. A graphical illustration of the four hardware components can be seen in Figure 4 and the power consumption for each one of the hardware components can be seen in Table 2.



(a) Vehicle Controller [28]



(b) Navigation Sensor [24]



(c) Drive [24]



(d) HMI Display [4]

Figure 4: Hardware components

### 3.2.1 Vehicle Controller

The vehicle controller is the product that manages the steering and navigation of an AGV [28]. This means that it is the product that receives the signals from the system manager and navigates the AGV accordingly. Kollmorgen's latest vehicle controller, CVC700, was used when performing the climate assessment. This vehicle controller is based on a standard technology that allows it to be used for any navigation technology. It can also be used for any type of vehicle and wheel configurations. The vehicle controller can be seen in Figure 4a.

### 3.2.2 Navigation Sensor

Kollmorgen has various types of navigation sensors. However, the navigation sensor LS2000 is Kollmorgen's latest navigation sensor that is used for detecting and analyzing the surroundings, which is done by laser scanning [24]. This is the type of navigation sensor that was used for the climate assessment. The navigation sensor can be seen in Figure 4b.

### 3.2.3 Drives

The drives provide current for the electric motors in the truck, there are two drives where one is for steering and the other one is for driving the vehicle [24]. The energy consumption in a technical specification of a drive is the maximum power output possible for the drive to deliver to the motor, i.e. not what the drive consumes itself. The drives energy consumption depends instead on its efficiency and power output. The drives that were used for the climate assessment are ACD4805-W4 (175A) for driving and ACD4805-W4 (70A) for steering. The ACD drive can be seen in Figure 4c.

### 3.2.4 HMI Display

The HMI display that was used for calculations was OPT100, which is a small instrument panel display that is placed on the AGV. It could also be suited for other electrical vehicles [24]. The function of this display is to show the status of the AGV system, and display warnings, errors, and diagnostic information. It can also be used to change the settings for the vehicle as well as operating modes. The HMI Display can be seen in Figure 4d.

### 3.2.5 Power Consumption

In this section, a specification is shown in Table 2 regarding Kollmorgen’s different hardware component’s maximum power consumption. The power consumption was used in the calculations for the GHG emissions.

Table 2: Power Consumption for the Hardware Components

<b>Component</b>	<b>Product name</b>	<b>Power Output</b>	<b>Unit</b>
Vehicle controller	CVC700	6	[W]
Navigation sensor	LS2000	10	[W]
Drive (steering)	ACD4805-W4 (70A)	3 800	[W] (2 min rating)
Drive (driving)	ACD4805-W4 (175A)	9 600	[W] (2 min rating)
HMI Display	OPT100	7	[W]

## 4 Method

In this section, a presentation of the methodology will be done. The main steps of this master thesis are literature studies and interviews with colleagues from Kollmorgen, case studies at various end-users, calculations of the GHG emissions, as well as identification of improvement measures. Relevant flowcharts with system boundaries are also presented in this section, as well as a driving test for validation of some identified improvement measures.

### 4.1 Literature Studies and Interviews

The work process began with literature studies, as well as interviews with colleagues from different departments and roles at Kollmorgen to get a better understanding of the product and company overall. Thereafter, factors and components that affect the electricity use and thereby the environmental impact of the AGV system during operation were identified. This was done by analyzing various items of literature as well as gathering information from the interviews. Even external factors that Kollmorgen's software solutions or the AGVs can not affect directly, but are connected to the AGV systems, were considered. For example facility lighting in the warehouse [25].

### 4.2 Flowcharts and System Boundaries

This section shows flowcharts for the life cycle of an AGV system in total and Kollmorgen's hardware components as well as an illustration of the use phase in detail. The flowcharts over the life cycles both have a system boundary around the use phase to illustrate that this is the main focus. The flowcharts are general and are used to illustrate an overview of the life cycles. It includes the main flows that are relevant to this thesis.

#### 4.2.1 Life cycle of Kollmorgen's Hardware

The first flowchart illustrates the life cycle of Kollmorgen's hardware components, which is represented in Figure 5. It begins with *Raw material extraction* where *Energy*, in the form of fuels, is an inflow that is needed for the extraction. The outflow is *GHG emissions* which is created in the process. The materials extracted are then used for *Manufacturing and production* where they are used for the production of the components. These steps require energy and the manufacturing and production release *GHG emissions*, represented as an outflow.

The resulting product is then used in the next step, the *Use-phase*, where the hardware components operate in an AGV system. This step is also illustrated with a system boundary over the *Use-phase* since this part was analyzed for research question 1, namely calculating the GHG emissions. The inflow for the *Use-phase* is only *Electricity* since the hardware components consume electricity when in operation. The last step of the life cycle is the *End of life*-stage, which occurs when the components are worn out and cannot be used anymore. The AGV systems, and thereby Kollmorgen’s hardware, are used all over the world which means that the waste handling can differ a lot. Waste handling normally consists of recycling, incineration, or landfill [26].

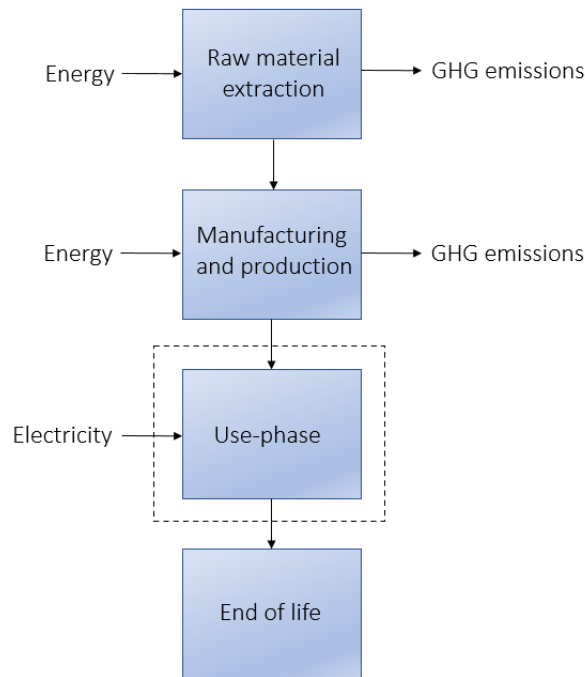


Figure 5: Flowchart over the life cycle of Kollmorgen’s hardware

#### 4.2.2 Flowchart of the Use-Phase

Connected to the previous flowchart over Kollmorgen’s hardware life cycle, a more detailed illustration of only the use phase is shown in Figure 6 below. It illustrates which of Kollmorgen’s hardware components as well as which components for the software are used during the use phase. All of these components, both the hardware components as well as the components for the software require energy in the form of electricity, and therefore is *Electricity* shown as an inflow to the use phase. As mentioned before, electricity is the main factor to consider when calculating the climate impact. This is because the amount and type of

electricity will define how much GHG emissions that are emitted during the use phase. This flowchart is connected to the first research question, which is regarding calculations of the GHG emissions from Kollmorgen’s products during operation.

Before the use phase, Kollmorgen’s products need to be manufactured, which is illustrated by the inflow of *Kollmorgen’s manufactured products*. The outflow from the use phase is *Kollmorgen’s waste products* for when the products are damaged or worn out.

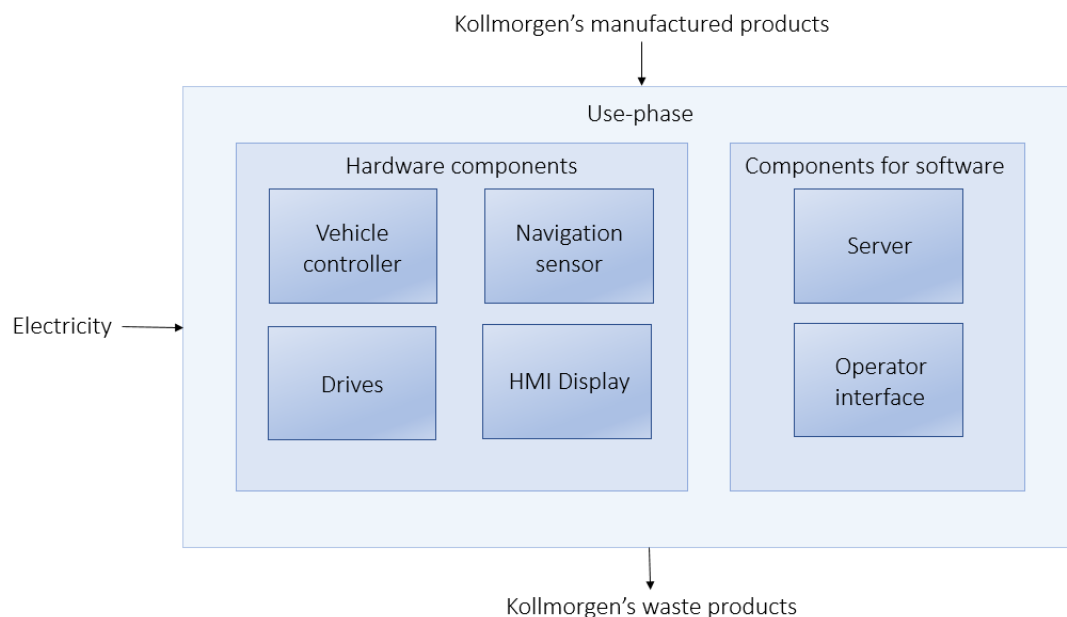


Figure 6: Flowchart over the use-phase

### 4.2.3 Life cycle of an AGV System

The third flowchart can be seen in Figure 7 and represents the whole life cycle of an AGV system. It follows a similar life cycle as for Kollmorgen’s hardware components, which is shown in Figure 5 above, and includes almost the same steps. However, in this flowchart, the *Raw material extraction* and the *Manufacturing and production* include all materials and components from various suppliers that are used in an AGV system, not just Kollmorgen’s. Another difference in this flowchart is that it includes a box covering *Kollmorgen’s software* representing the process of creating Kollmorgen’s software solutions which is an inflow to the *Manufacturing and production*. During this step, the components are assembled into a finished AGV system.

The finished AGV system then operates in the next step, which is the *Use-phase*. This step also differs from the first flowchart since the inflow *Spare parts* and the outflow *Damaged parts* are included since some parts are exchanged during the AGVs' life cycle. These flows are important for the third research question of this report regarding how Kollmorgen's software solutions can be improved to reduce GHG emissions and prolong the lifetime of the AGV systems. By identifying which factors Kollmorgen's software solutions can affect to accomplish this, the number of spare parts and damaged parts could be reduced as well as a decrease in electricity use.

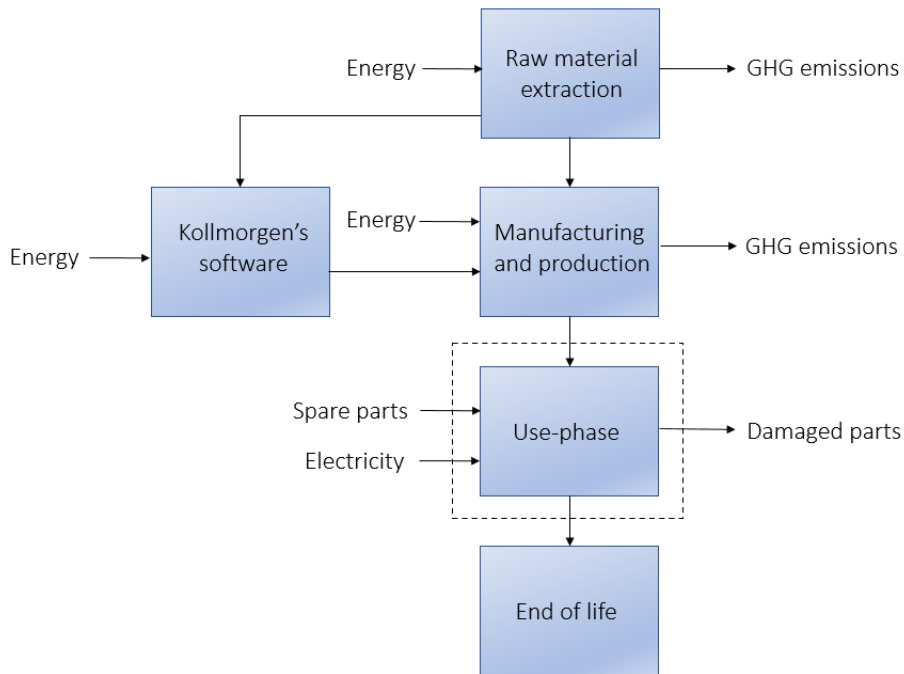


Figure 7: Flowchart over an AGV system's lifecycle

### 4.3 Case Studies

After finishing the literature studies and interviews, three case studies were performed to study the respective end users' AGV systems during operation. The case studies included a study visit to the end-user's facilities and interviews with people who work with the AGV systems. This was done both for the identification of what factors affect electricity consumption and for understanding what factors Kollmorgen's software solutions could affect to minimize the electricity use and thereby also the GHG emissions. Furthermore, this was also done to

be able to calculate the GHG emissions for Kollmorgen's products during operation, for the specific system. To be able to calculate the GHG emissions the electricity use for Kollmorgen's products was calculated. This was then set in comparison to the total AGV system to be able to get a better understanding of how much emissions are allocated to Kollmorgen's products in relation to the total system.

The three case studies were performed in Sweden and the location-based emission factor for Sweden was therefore used. The emission factor for Sweden has been 10 grams of CO<sub>2</sub> per kWh in the last decade [29] and therefore this factor was used for the calculations. The location-based emission factor was used due to availability and for comparability between the three case studies.

#### 4.3.1 Case Study 1: DB Schenker

The first case study was at DB Schenker in Borås. DB Schenker provides logistic solutions and supply chain management, and transports goods and packages all over the world [30]. The location in Borås is one of their biggest warehouses in Sweden and the AGVs are used to transport parcels in boxes from one point to another based on orders. Their 6 AGVs have been operating since 2021. Some of the AGVs at DB Schenker can be seen in Figure 8.



Figure 8: AGVs at DB Schenker

They had a hybrid system of both manual and automatic trucks in the warehouse. The trucks were in operation 20 h a day in total but actively running 8 of these hours, and every weekday of the year [31]. They had lead-acid batteries for the trucks with a capacity of 375 Ah and 24 V and the charger had a capacity of 60 A and 24 V. They had two batteries for every truck, where one was used in the truck all day while the other one was charging and then changed manually after every day. The batteries were fully charged after 6-7 h. The questions that were asked during the case study, as well as the answers to these questions can be found in Appendix A. The questions were regarding the AGVs' operating hours, driving and charging patterns, lifetime, load, etc.

According to [31], the main difference between AGVs and manual trucks is visibly more wear on the manual trucks after a short period. The manual trucks also had a shorter life expectancy than the AGVs, only 5 years instead of 10. As well as this, the batteries for the manual trucks were changed three times a day instead of one and the AGVs were almost twice as productive, 0.6 AGVs per 1 manual truck.

#### **4.3.2 Case Study 2: Borealis**

The second case study was done at Borealis in Stenungsund. Borealis produce polyolefins, base chemicals, and fertilizers [32], however, at Stenungsund they only produce polythene. They had 14 AGVs in their warehouse and they had been running since around the year 2000 [33], a picture of one of the AGVs at Borealis can be seen in Figure 9. The AGVs had a speed of 1.1 m/s and transports a load of about 1.1 tonnes where the type of load was packed polyethylene. The AGVs were running every day of the year and around 9 to 24 hours a day. They had NiCd batteries and the trucks used opportunity charging when the batteries were below 70 %, and they also had one spare battery for each AGV. The batteries had a capacity of 104 Ah/5h with 24 V, and the charger had a capacity of 100 A and 48 V.

In the warehouse, where the AGVs are operating there were no personnel except some persons who monitor the system and are available if something needs to be fixed manually. There were also no manual trucks inside the warehouse where the AGVs are running. The AGVs were using reflector navigation to navigate through the warehouse and the AGVs were using Kollmorgen's vehicle controller, navigation sensor as well as their HMI display. However, they were not using Kollmorgen's drives. Moreover, they had three operator interfaces and one physical server that was used only for the AGV system.



Figure 9: An AGV at Borealis

For this case study, the same questions as for the previous case study were asked and the answers to these questions can be found in Appendix B.

### 4.3.3 Case Study 3: Toyota Material Handling

The third case study was done at Toyota Material Handling in Mjölby. They produce trucks and other types of equipment for material handling [34]. They had different types of AGV systems in their factory, whereas two types of AGV systems were using Kollmorgen's products, 10 stackers and 5 tow trucks [35]. These can be seen in Figures 10a and 10b. They were using Kollmorgen's vehicle controller and their navigation sensor, but not their HMI display or drives. The most common parts that were being replaced for the AGV systems were the scanner glass for the safety scanners. This is due to the dusty environment where they were operating, the safety scanners need to be cleaned, and because of this scratching occurs.

Toyota had both AGVs and manual trucks in their factory, where the tow trucks were operating over a large part of the factory and therefore running together with the manual trucks. However, the stackers operated in a closed area with no manual trucks. The stackers were operating 12-24 h a day every day of the year and tow trucks 18 h a day on weekdays. The

stackers had a speed of 1.8 m/s and transported a load of 600 kg whereas the tow trucks had a speed of 1.2 m/s and a load of up to 5 000 kg. The current version of stackers had been running since 2022 and the tow trucks since 2016 but were replaced in March 2023.



(a) Stackers [36]

(b) Tow trucks [37]

Figure 10: AGV types at Toyota

The main difference according to [35] between manual trucks and AGV systems was safety, they had close to zero safety issues with the AGV systems but incidents with the manual trucks happen occasionally. Another difference was regarding the wear, the AGVs had much less outer damage compared to the manual trucks. The lifetime was also different: manual forklifts were normally rented for 5 years at a time and the AGV systems were normally rented for 3 years because of the fast development in this field. Lastly, there was a big difference regarding the cost, when using AGV systems the personnel costs decrease considerably and therefore from an economic perspective it was cheaper to have AGV systems even though the investment costs were significantly higher.

#### 4.4 Assumptions for Calculating GHG Emissions

The most important questions in order to calculate the GHG emissions for Kollmorgen's products, and thereby answer research question one, are to find out how many AGV systems

they are using, how long time the systems are operating, how often they operate in a year, which types and how many of Kollmorgen's products they are using as well as their lifetime. However, since Kollmorgen sells their products to various end-users, the answer to these factors can differ and therefore a standard system was assumed for the calculations. The standard system represents a modeled AGV system with assumptions regarding the number of Kollmorgen's products, operator interfaces and servers. These assumptions were developed together with colleagues at Kollmorgen as well as interviews with end-users.

The years analyzed were 2019 to 2022 and the investigated regions were Europe, North America, China, and Asia-Pacific. Furthermore, each AGV was assumed to operate 20 hours a day and was actively running 8 hours per day. The standard system was assumed to operate every working day per year which corresponds to around 253 days per year. These assumptions are shown in Table 3 and were based on the case studies as well as interviews with colleges at Kollmorgen. Further assumptions were regarding the power output. The maximum power output can be seen in Tables 1 and 2, but this is rarely used since the AGVs drive at a low speed and acceleration. A more realistic estimate is 50% for the vehicle controller, navigation sensor, and HMI Display. For the drives, however, the power output seen in Table 2 is the maximum power output to the electric motor from the drives. A more realistic assumption for the operating power of the motor is 25 % of the maximum power [38]. Moreover, the drives have an efficiency of 97.5 % where the operating power for the drives then can be seen in Table 3 [38] [39]. The operator interface was assumed to operate at maximum power, however, the servers were assumed to have a capacity of 50% since they rarely operate at full capacity. These assumptions were verified with colleagues at Kollmorgen and are shown in Table 3.

Table 3: Assumptions for operating time and power for each component

	<b>Operating time [h]</b>	<b>Operating power [W]</b>
Vehicle controller	20	3
Navigation sensor	20	5
Drive (steering)	8	23.8
Drive (driving)	8	60
HMI Display	20	3.5
Operator interface	20	18
Physical Server	24	109
Virtual Server	24	53

Another assumption was regarding the number of Kollmorgen’s hardware components in an AGV system. The number of components was calculated in relation to the amount of sold vehicle controllers in the specific year and region, since Kollmorgen always sells one vehicle controller per AGV. The number of hardware components was based on sales statistics from Kollmorgen which also includes spare parts. However, due to secrecy reasons, the sales statistics are not presented in this report. Explanation and pictures of the components can be seen in Section 3. The standard system was assumed to have one server, and the server used was assumed to be a hybrid based on the share of physical and virtual servers, also presented in Section 3. This was done since the power consumption differs between physical and virtual servers and therefore it is important to include both for the standard system. It is always one system manager per AGV system since it is handling the total system which usually requires one server, hence the assumption. It was also assumed that the standard system has two operator interfaces per system. The number of operator interfaces can vary between end-users and the assumption of two per system is based on interviews with colleagues at Kollmorgen. All these assumptions are assumed to be the same for every year and region.

The calculations of emissions for the standard system have been performed with regard to the location-based method according to the GHG Protocol. This method was chosen since entire regions have been investigated and no specific data from end-users were available. The emission factors are different for the regions, and the regions investigated are as mentioned before, Europe, North America, China, and Asia-Pacific excluding China. China is separated from Asia-Pacific because a lot of Kollmorgen’s partners are located in China and therefore a majority of the sales from Kollmorgen to Asia-Pacific are allocated to China. Therefore

to get a more accurate value for the emission factors, China is investigated separately from the other countries in Asia-Pacific. When calculating the emission factor for Asia-Pacific an average value regarding the countries Australia, Japan, South Korea, Vietnam, and Taiwan is used since these are the other countries in Asia-Pacific that Kollmorgen’s partners are located in. Furthermore, since the years investigated are 2019-2022, an assumption was made that the emission factors are the same for these years and the numbers used are obtained for the year 2020. The emission factors for the different regions are presented in Table 4 below [40] [41].

Table 4: Emission factors

<b>Emission factors</b>	
<b>Region</b>	<b>g CO<sub>2</sub>/kWh</b>
Europe	239
North America	322
China	550
Asia-Pacific	517

## 4.5 Calculation of GHG Emissions

In this section, the calculations for both the case studies and the standard system will be presented. It will specify which parameters that have been investigated and the calculations performed. The GHG Protocol’s *Scope 2 Guidance* [12] and *Scope 3 Calculation Guidance* [42] were used when calculating the emissions.

### 4.5.1 Case Studies

For each case study, the GHG emissions for only Kollmorgen’s products at the specific location were calculated as well as the GHG emissions for the total AGV system, and per AGV. The factors needed to calculate the GHG emissions for Kollmorgen’s products were which types of hardware components that were used in the specific system, the number of operator interfaces and servers, operating hours, and the number of AGV systems. This can be seen in the section for each case study and which components from Kollmorgen that are used are compiled in Table 5.

Table 5: Number of Kollmorgen’s components for each case study

	<b>DB Schenker</b>	<b>Borealis</b>	<b>Toyota</b>
Vehicle controller	1	1	1
Navigation sensor	1	1	1
Drive (steering)	0	0	0
Drive (driving)	0	0	0
HMI Display	1	1	0
Operator interface	3	3	5
Physical server	0	1	0
Virtual server	4	0	2

For calculating the energy consumption for each of Kollmorgen’s components,  $i$ , the energy consumed per day was calculated by multiplying operating power,  $P_i$ , with operating hours,  $t_{operating,i}$ . This was then summarized over all components,  $m$ , and multiplied with the number of AGVs,  $n_{AGV}$ , and operating days per year,  $n_{operating}$ , to get the energy consumption for Kollmorgen’s products during a year at each case study, according to Equation 1. The same calculations are performed for the software components which can be seen in Equation 2. However, for these calculations  $n_{software}$  represents the number of software components,  $k$  represents the total number of components and  $j$  represents each of Kollmorgen’s software products. The energy consumption for the components and software for a year was then multiplied with the emission factor,  $E_f$  for the location of the case study according to Equation 3.

$$E_{components} = \sum_{i=1}^m P_i \cdot t_{operating,i} \cdot n_{AGV} \cdot n_{operating} \quad [kWh/year] \quad (1)$$

$$E_{software} = \sum_{j=1}^k P_j \cdot t_{operating,j} \cdot n_{software} \cdot n_{operating} \quad [kWh/year] \quad (2)$$

$$GHG \text{ emissions} = E_f \cdot (E_{components} + E_{software}) \quad [kgCO_2/year] \quad (3)$$

For the calculations for the total AGV system for each case study the factors needed were the battery’s capacity, the charger’s capacity, and charging time and frequency. To calculate the energy consumption the charger’s capacity,  $P_{charger}$ , was multiplied by charging time,  $t_{charging}$ , and charger efficiency,  $\eta$ . Then with how often the AGV was charged,  $n_{charging}$ ,

and how many AGVs in the system,  $n_{AGV}$ , see Equation 4. The energy consumption for the software was then added to get the total energy consumption for the AGV system, which was then multiplied with the emission factor according to Equation 5.

$$E_{AGV} = P_{charger} \cdot t_{charging} \cdot \eta \cdot n_{charging} n_{AGV} \quad [kWh/year] \quad (4)$$

$$GHG \text{ emissions} = E_f \cdot (E_{AGV} + E_{software}) \quad [kgCO_2/year] \quad (5)$$

The total AGV system's energy consumption was calculated to get an indication of the total AGV system's energy consumption and relate that to Kollmorgen's products for validation.

#### 4.5.2 Standard System

For the standard system, the energy consumption,  $E$ , was calculated for each of Kollmorgen's products,  $i$ , for each year,  $y$ , and region,  $r$ . This is based on their operating power,  $P_{operating,i}$ , number of units per AGV,  $n_{units,i,y,r}$ , and their operating time,  $t_{operating,i}$ , see Equation 6.  $P_{operating,i}$  and  $t_{operating,i}$  are shown in Table 3. This is summarized for all of Kollmorgen's products per year and region where  $m$  is the total number of components. The summarized energy consumption is per AGV and it is then multiplied by the total number of AGVs in the standard system,  $n_{AGV}$  as well as the assumed number of operating days per year,  $n_{operating}$ , see Equation 7.

The same calculations were performed for calculating the energy consumption for the software, however, for these calculations,  $k$  represents the total number of components and  $j$  represents each of Kollmorgen's software products. This is then multiplied by the number of software components,  $n_{software}$ , according to Equation 8. The total energy consumption from Kollmorgen's products was calculated by adding the energy consumption for the components with the software, see Equation 9. This value was then multiplied by the emissions factors for each region and the expected lifetime for the AGV system, see Equation 10. The last step was done for every region since the emission factor, as well as the sales statistics differ between regions.

$$E_{i,y,r} = P_{operating,i} \cdot n_{units,i} \cdot t_{operating,i} \quad [kWh/unit/region] \quad (6)$$

$$E_{components,y,r} = \sum_{i=1}^m E_{i,y,r} \cdot n_{AGV} \cdot n_{operating} \quad [kWh/year/region] \quad (7)$$

$$E_{software,y,r} = \sum_{j=1}^k E_{j,y,r} \cdot n_{software} \cdot n_{operating} \quad [kWh/year/region] \quad (8)$$

$$E_{total} = E_{components,y,r} + E_{software,y,r} \quad [kWh/year/region] \quad (9)$$

$$GHG\ emission_{y,r} = E_{f,r} \cdot E_{total,y,r} \cdot L_t \quad [kgCO_2/year/region] \quad (10)$$

## 4.6 Validation of Improvement Measures

After the literature studies, interviews, and case studies, several possible improvement measures were identified. To test some of the improvement measures, two driving tests were executed from the available conditions and carried out in a testing facility at Kollmorgen. Some of the identified improvement measures were not possible to test and also more evident than others, but two tests were made to validate and further analyze the results. The first driving test was executed to examine how the speed of the AGV affects energy consumption. The other was carried out to test how blockings affect energy consumption. Both driving tests included acceleration and deceleration for each case. The AGV that was used was a relatively small AGV with the dimensions 70x105x60 cm and a battery voltage of 24V. The current that was measured was from the two drives, one for driving and one for steering. This AGV had a regenerative braking system which means, as mentioned before, that some of the energy used when braking is regenerated in the AGV's battery. In this case, the estimate is that 60% of the energy used for the braking is regenerated in the AGV's battery, based on [7] as well as confirmed with colleagues at Kollmorgen. This means that 40% of the energy used when braking results in heat losses which is taken into account in the calculations for the driving tests.

In the first driving test the AGV was driving at full speed, 0.7 m/s in this case, following a path, then it drove the same path at 50% of the full speed, 0.35 m/s. This was tested to examine if the energy consumption of the AGV would be lower with a lower speed. This was measured by examining the torque current [dA] output, it was then visualized in a diagram where the average torque current could be calculated for the AGV when driving at both full

speed and half speed.

In the second driving test, the AGV was running in a path with zero blockings and then the same path with several blockings, where the AGV had to stop and accelerate again after every blocking. This was tested to examine if the energy consumption would increase with increased blockings. Several attempts were measured, including one blocking, three blockings, and six blockings. The torque current [dA] was measured and visualized in a diagram where the average current could be calculated for both the AGV driving with and without blockings.

The paths for the two tests can be seen in Figure 11, where the first test was executed on the left path and the second test on the right path. The red dots in the left path represents the start and stop of the AGV. In the right path, the red dots also includes the amounts of blockings, in this case, six number of blockings. The length of each test was around 15 meters. The stars visualized in the figure down below represent the navigation points of the AGV.

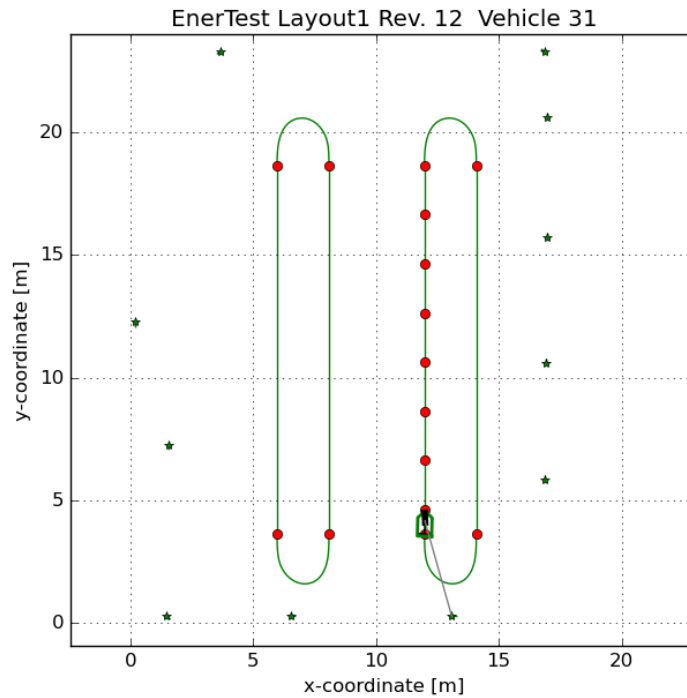


Figure 11: Visualisation of the paths

## 5 Results

In this section, the results from the research questions investigated are presented. It includes the results from the literature studies and interviews, the case studies, calculations for the standard system, possible improvement measures from an environmental perspective and lastly, the results from the driving tests.

### 5.1 GHG Emissions

In this section, the results from the calculations for both the case studies and from Kollmorgen's products are presented regarding the GHG emissions. The results present both the energy consumption and GHG emissions in the form of CO<sub>2</sub> from respective case studies as well as for Kollmorgen's products globally for the investigated years.

#### 5.1.1 Case studies

The results from the case studies will be presented in this section. Three case studies have been done, one at DB Schenker in Borås, one at Borealis in Stenungsund, and one at Toyota Material Handling in Mjölby. The results show the energy consumption and GHG emissions for both only Kollmorgen products in the specific case study as well as from the total AGV system. It also shows the energy consumption and GHG emissions for one AGV, both with respect to Kollmorgen's products as well as the total AGV system.

#### DB Schenker

The results for the first case study at DB Schenker can be seen below in Table 6. The energy consumption for Kollmorgen's products and the total AGV system can be seen in Table 6a. The results for the GHG emissions for Kollmorgen's products and the total AGV system can be seen in Table 6b. As can be interpreted from these results, Kollmorgen's products stands for approximately 9.3 % of the emissions from the total AGV system.

Table 6: Results for DB Schenker

(a) Energy consumption		(b) GHG emissions	
<b>Energy consumption [MWh/year]</b>		<b>GHG emissions [tonne CO<sub>2</sub>/year]</b>	
Kollmorgen's products	1.1	Kollmorgen's products	0.011
Kollmorgen's products per AGV	0.18	Kollmorgen's products per AGV	0.0018
Total AGV system	12	Total AGV system	0.12
One AGV	1.9	One AGV	0.019

### Borealis

The results from the second case study at Borealis are presented in Table 7. The energy consumption and GHG emission are presented both solely for Kollmorgen's products as well as for the total AGV system. For this case study, it can be seen that Kollmorgen's products stands for approximately 5.6 % of the emissions for the total AGV system.

Table 7: Results for Borealis

(a) Energy consumption		(b) GHG emissions	
<b>Energy consumption [MWh/year]</b>		<b>GHG emissions [tonne CO<sub>2</sub>/year]</b>	
Kollmorgen's products	2.8	Kollmorgen's products	0.028
Kollmorgen's products per AGV	0.2	Kollmorgen's products per AGV	0.002
Total AGV system	50	Total AGV system	0.5
One AGV	3.6	One AGV	0.036

### Toyota Material Handling

The results from the third case study at Toyota Material Handling can be seen in Table 8a. The energy consumption and the GHG emissions include the combined consumption and emissions for both the stackers and the tow trucks. Kollmorgen's products corresponds to 8 % of the emissions from the total AGV system in this case study.

Table 8: Results for Toyota Material Handling

(a) Energy consumption		(b) GHG emissions	
<b>Energy consumption [MWh/year]</b>		<b>GHG emissions [tonne CO<sub>2</sub>/year]</b>	
Kollmorgen’s products	2.6	Kollmorgen’s products	0.026
Kollmorgen’s products per AGV	0.17	Kollmorgen’s products per AGV	0.0017
Total AGV system	32	Total AGV system	0.32
One AGV	2.1	One AGV	0.021

### 5.1.2 GHG Emissions from Kollmorgen’s Products

In this section, the results from the calculations based on the standard system are presented. The answers to Equations 6 - 10 presented in Section 4 can be seen in Table 9 below. The tables present the energy consumption in MWh per component in the standard system for every investigated year as well as the total energy consumption for Kollmorgen’s products per year. The results depend on the sales statistics from every year and region. The number of sold hardware components is in relation to the number of sold vehicle controllers, mentioned earlier, while the number of sold software components depends on the number of AGV systems.

Table 9: Energy Consumption [MWh/year]

<b>Component</b>	<b>2019</b>	<b>2020</b>	<b>2021</b>	<b>2022</b>
Vehicle controller	40	42	45	55
Navigation sensor	64	62	76	74
Drive (steering)	63	62	67	57
Drive (driving)	140	110	71	89
HMI Display	20	18	14	16
Operator interface	76	81	76	85
System manager/server	210	230	210	240
<b>Total [MWh/year]</b>	<b>610</b>	<b>600</b>	<b>560</b>	<b>610</b>

The energy consumption for each year was then used to calculate the GHG emissions in the form of  $CO_2$  according to Equation 10. This is presented both per year and for the whole

lifetime which is assumed to be 10 years on average. The results are presented in Table 10. The calculations of these results have been according to the GHG Protocol and the result are used to represent Kollmorgen’s *Use of sold products* in the GHG Protocol as well as answering research question 1.

Table 10: GHG Emissions [tonne CO<sub>2</sub>]

	2019	2020	2021	2022
<b>Total per year</b>	240	250	210	250
<b>Total per lifetime</b>	2400	2500	2100	2500

## 5.2 Identified Factors Affecting the GHG Emissions

The results gathered from the literature studies and interviews are presented in Table 11. It is divided into three parts, with one column representing the external factors that affect the GHG emissions. Another column represents the factors that the software affects and lastly, a column represents components that the software affects.

Table 11: Identified components and factors

<b>External factors affecting GHG emissions</b>	<b>Factors impacted by the software</b>	<b>Components affected by the software</b>
Energy mix	Acceleration	Battery
Room temperature	Routes	Electric motor
Facility lighting	Speed	Drives
Battery type	Charging time	Vehicle controller
Charger type	Lifetime	Wheels
Battery capacity	Battery lifetime	Wheel bearings
Load weight		
Truck weight		
Motor type		
Hardware energy efficiency		

As can be seen above the *External factors affecting GHG emissions* are external factors affecting the emission from the total AGV system. These are factors that can not be affected by Kollmorgen's products but are relevant to consider since it implicates the *Use of sold products* for Kollmorgen, and thereby the scope of this report. These factors can instead be affected by Kollmorgen's end-users to some extent. The *Energy mix* has a direct impact on the GHG emissions since this determines the emission factor. The GHG emissions can decrease by having a high share of renewable energy in the energy mix. *Room temperature* and *Facility lighting* are external factors in the warehouse or facility the AGV system is operating. Both factors consume electricity and thereby generate GHG emissions, but are not necessarily needed for the AGVs since they do not need the same working conditions as humans. For example, facility lightning in warehouses represents 17 % of the total electricity consumed in the US, which makes it an important area to investigate in order to reduce the overall energy consumption [25]. Furthermore, all factors linked to the AGVs' batteries, like *Battery type*, *Charger type*, and *Battery capacity* can be optimized and utilized to minimize the energy consumption for each AGV. Both the *Load weight* and *Truck weight* affect the emissions in the way that more electricity is required to transport more weight. Lastly, *Motor type* and general *Hardware energy efficiency* are factors important to optimize in order to decrease energy consumption.

Following this, the *Factors impacted by the software* are factors that Kollmorgen's software can affect to minimize the GHG emissions. The system manager has the possibility to optimize the fleet in order to decrease *Acceleration*, shorten the *Routes* and lower the *Speed* to minimize energy consumption and thereby lower the GHG emissions accordingly. The software can also manage the *Charging time* by optimizing the charging with regards to the specific battery type which can prolong the *Battery lifetime*. Providing these measures even the *Lifetime* of the AGV can be prolonged which indirectly affects the emissions due to less need for new production of AGVs.

In the last column *Components affected by the software* are indirect impacts from the software on hardware components. For example, if the software decides to make the AGV system drive more smoothly with fewer stops, it can decrease the wear on the wheels which prolongs its lifetime. This applies to all components in the table.

### 5.3 Identified Improvement Measures

Based on the case studies, the identified improvement measures that Kollmorgen's software solutions can achieve are presented in the bullet list below, along with a short explanation of the specific improvement measure.

- **Improved route planning** - This implies optimization of both distance and time when the AGV is in use. More specifically, minimizing the distance traveled for each AGV for the executed task, as well as minimizing the required time for each task.
- **Blocking time reduction** - The energy consumption could be reduced by minimizing the blocking time. Kollmorgen's software solutions could be used to optimize the route planning of the AGV systems in order to minimize the number of unnecessary stops for the AGVs and be able to reroute the AGVs to avoid obstacles.
- **Idle time reduction** - By minimizing the idle time for the AGV system the energy consumption could reduce. The software could be customized to track and monitor the idle time and adjust the scheduling and the routes for the AGVs to reduce the idle time as much as possible.
- **Minimize empty driving** - Empty driving refers to when an AGV is driving without load, these drives do not produce any value, and minimizing them will also reduce energy consumption. Kollmorgen's software could for example monitor the empty driving of the AGVs and adjust the scheduling of the AGVs in order to always choose the shortest distance and the AGV that is closest to the task that should be performed.
- **Speed management** - By adapting the speed for the AGV during operation it could minimize the energy consumption. Kollmorgen's software solutions could be customized to select the most energy-efficient speed based on the task that is being performed, as well as which type of AGV that is being used. By doing this the speed will always be adapted to be as energy efficient as possible.
- **Optimized battery charging** - Since the energy consumption of the total AGV system is in direct correlation with its battery, the energy consumption could be reduced by optimizing the battery charging. By implementing opportunity charging of the AGVs without manual interference, Kollmorgen's software solutions could be customized to optimize the charging of the battery by analyzing the battery level and charging patterns based on the battery type. The battery could thereby be charged in a way that

reduces the wear on the battery and thereby increase the battery life.

- **Switch off the AGV when not in operation** - Another way of reducing the energy consumption is to turn off the AGV completely when it is not needed if possible. Some applications have "peak hours" when all AGVs are running actively, but the rest of the time includes more idle periods due to fewer orders. For these applications, it could be possible to switch off some of the AGVs during these periods to reduce energy consumption.

The time the AGV is actively driving is the the main cause of higher energy consumption. This implicates that the first improvement measure, *Improved route planning*, is the most important one to optimize since this also covers several of the other improvement measures. To optimize the route planning to only drive the AGVs when necessary and shorten the distances, as well as driving in an energy-efficient way will have a great impact on the energy consumption. This, as well as the other improvement measures, is discussed in Section 6.4.

## 5.4 Results from the Driving Tests

Two driving tests were made in order to validate some of the identified improvement measures, namely *Speed management* and *Blocking time reduction*. The paths were previously presented in Figure 11, where the first test was executed in the left path, and the second test in the right path in the figure. A velocity curve illustrating the acceleration and deceleration for the AGV in the tests can be seen in Figure 12. When calculating the results for the driving tests the absolute value for the steering was used in order to calculate the total current demand for steering. The same goes for the driving, but with regards to the regenerative braking system. 40 % of the energy needed for braking was included in order to calculate the total current demand, and the rest is regenerated back into the battery.

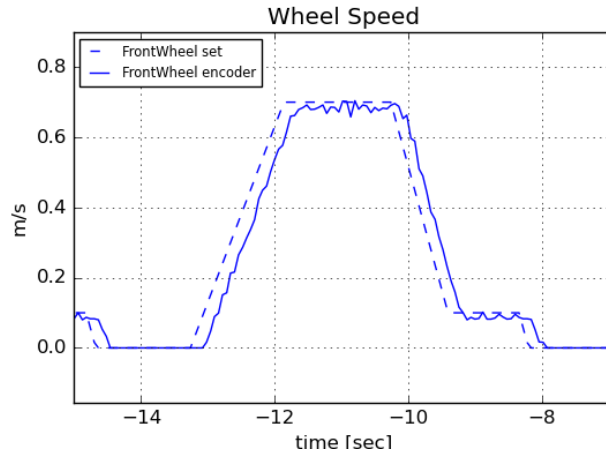


Figure 12: Example of a velocity curve

### 5.4.1 Speed Management

The results from the first test of letting the AGV drive the same path at full speed and 50 % of full speed can be seen in Figure 13 and 14. The graphs illustrate the power output from each drive in the AGV, the blue curve represents driving and the orange represents steering. The negative output in the graphs represents the deceleration of the AGV which also consumes current. This was included in the results by using the absolute value and with regard to the regenerative braking system, as previously explained. As can be seen in the graphs, both cases look quite similar but it is also evident that it takes more power to drive the AGV at full speed than half the speed.

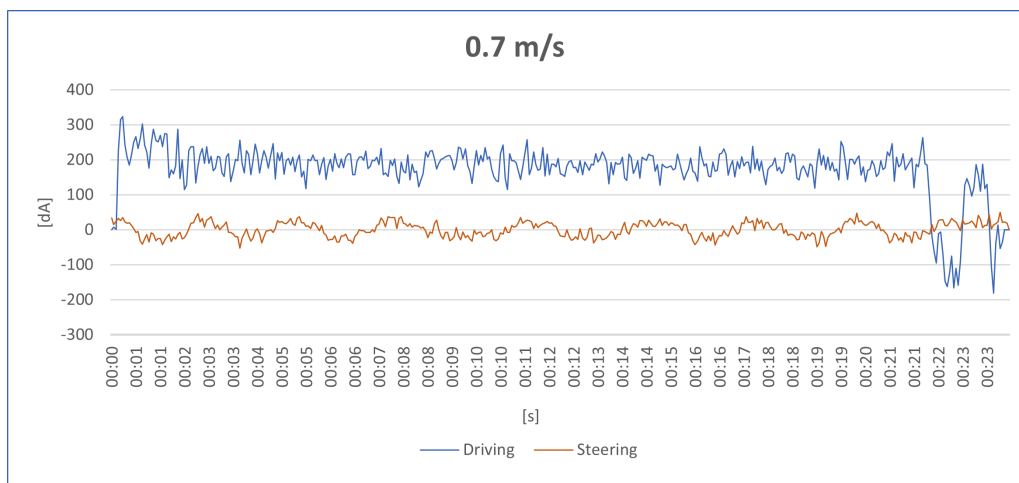


Figure 13: Full speed

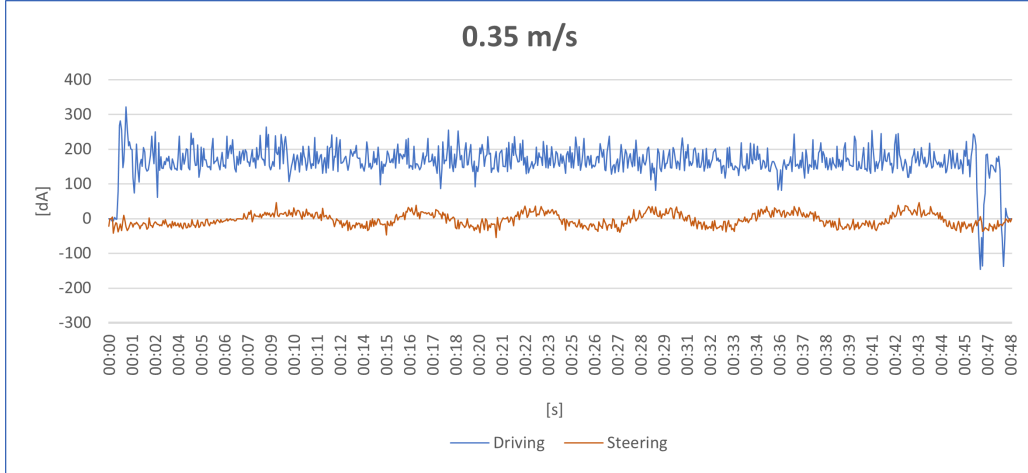


Figure 14: 50% of full speed

The average current for driving at full speed was 195 dA and for 50 % of full speed, the average was 181 dA. This included both driving and steering. However, when taking the time for the AGV to drive the same distance at different speeds to calculate the consumption, the results were different. It took 24 s for the AGV to run the path at full speed and 48 s at half-full speed, which indicated a total consumption of 1.30 dAh and 2.41 dAh respectively for the same path. The hypothesis was that it would require less energy to drive at a lower speed but that was not the case. This is due to the average power for the second case was not sufficiently lower to compensate for the longer amount of time needed. The results from the first test are compiled in Table 12 below.

Table 12: Results for Test 1

	<b>Average current [dA]</b>	<b>Total consumption [dAh]</b>	<b>Time [s]</b>
Full speed	195.42	1.30	24
50 % of full speed	180.67	2.41	48

### 5.4.2 Blocking Time Reduction

The results from the second test, namely assessing how the number of blockings affects energy consumption, are presented in Table 13 below. The speed was 0.7 m/s in this test. From the table, it is evident that the average current drawn decreases when the amount of blockings increases. However, the total power consumption is increasing when the number of blockings increases. Since the distance is the same, it shows that when the time to drive the

path is taken into consideration the total consumption is higher when the number of blockings increases. This is mostly because of the longer time it takes for the AGV to complete the path when the number of blockings is increasing but also due to the need for several accelerations.

Table 13: Results for Test 2

<b>Blockings</b>	<b>Average current [dA]</b>	<b>Total consumption [dAh]</b>	<b>Time [s]</b>
0 blockings	188.90	1.31	25
1 blocking	188.53	1.47	28
3 blockings	167.64	1.63	35
6 blockings	158.21	2.07	47

The test was, as stated above, carried out for various numbers of blockings. The result for zero blockings and six blockings are presented in Figures 15 and 16. The figures for all tested blockings can be seen in Appendix D. The figure representing zero blockings is used as a reference and is shown for comparison.

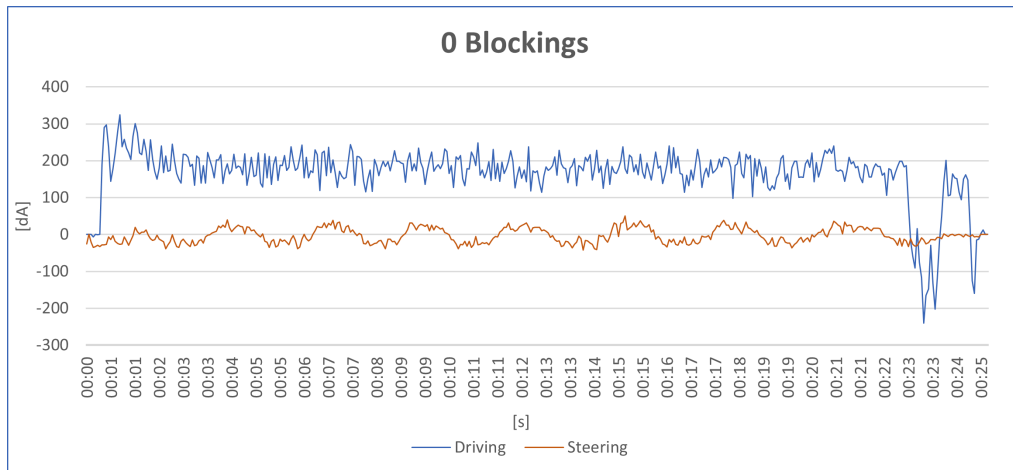


Figure 15: Results for 0 blockings

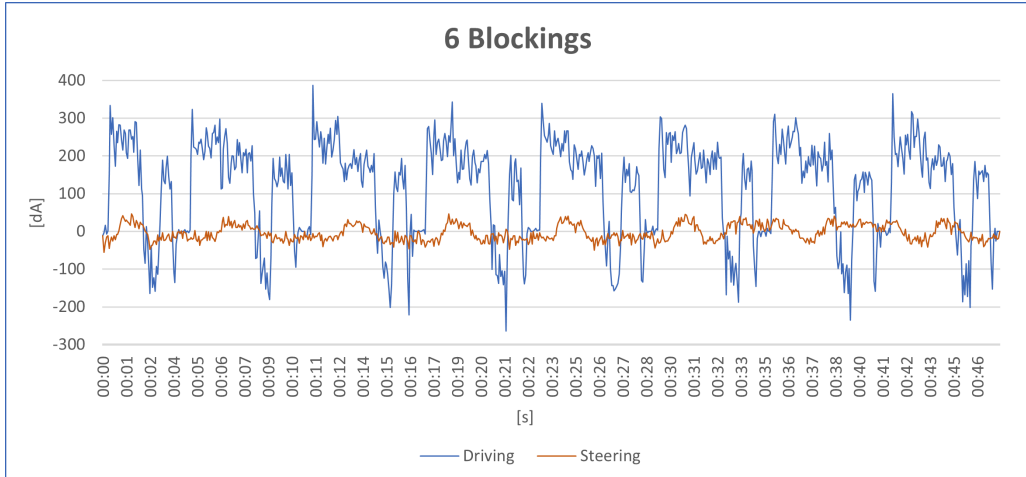


Figure 16: Results for 6 blockings

## 6 Discussion

In this section, a discussion regarding the results is presented, concerning case studies, identified factors contributing to GHG emissions, improvement measures, and driving tests. Furthermore, an analysis of the reliability of the results is presented with regard to the assumptions when calculating the GHG emissions and the driving tests.

### 6.1 Case Studies

The case study was mostly performed in order to get a better understanding of AGV systems in general, to analyze different applications, and to find improvement measures. The results from the case studies regarding that Kollmorgen's share of emissions in the total AGV system was about 5-10 % was an interesting finding to put the emissions in perspective. This shows that the emissions from Kollmorgen's products were a small share of the total system. Moreover, the case studies were valuable in order to make reasonable assumptions for the standard system and validate these results by comparing them with the results from the case studies. To only compare the results for the case studies with each other is not of interest since the applications were different from each other regarding the number of AGVs, operating hours, battery type, load, etc. This is the reason why the results regarding energy consumption and GHG emissions also differ. Nonetheless, analyzing different applications was important for the holistic understanding and for the research question regarding improvement measures. As well as providing adequate assumptions regarding the standard system.

Another finding from the case studies was regarding the use of manual trucks compared to AGV systems. From both a production and environmental perspective it was found that the AGV systems are more effective and can reduce both costs and the environmental footprint. This finding is also supported by other literature [19]. Both DB Schenker and Toyota Material Handling utilized a hybrid system of both manual and automatic trucks, and one main difference found was the wear on the vehicles. The manual vehicles had visibly more wear than the AGVs. It was also found that the manual trucks are running longer distances for the same orders as the AGVs due to the human factor, and they were also charged more often. Another big difference between these two systems was the expected lifetime. The expected lifetime for the AGV systems is about two times longer than for the manual trucks. In addition to this, the AGV systems at DB Schenker were also almost twice as productive. This is beneficial from both an economic perspective and from an environmental point of

view since longer life expectancy implies reduced impacts from manufacturing and end-of-life treatments. Moreover, it also reduces both energy consumption and GHG emissions for the whole lifetime of the trucks. At Toyota Material Handling, however, the AGVs were leased for 3 years and then replaced but they also have an established after-market for the AGVs.

Aside from the environmental benefits, one of the other main factors is safety. This was mentioned in all case studies and as well found in the literature studies which made it evident that AGVs are significantly safer. When manual trucks are used there are occasional accidents happening due to the human factor. However, this is not the case for the AGVs because of their safety sensors.

## **6.2 GHG Emissions from Kollmorgen's Products**

The GHG emissions from Kollmorgen's products during the use phase were calculated based on a standard system assumed for every application where their products are used globally. The calculations of Kollmorgen's *Use of sold products* were performed according to the GHG Protocol. Even though their main product is their software and some hardware products with low power consumption, it was clearly seen in the result that their GHG emissions have a contributing impact. This is highly dependent on the extent their products are used. The differences between emissions for each region are mostly dependent on the emission factor which differs from the regions. Other differences between the years and regions depend on the sales statistics of Kollmorgen's products.

## **6.3 Main Factors Affecting the GHG Emissions**

Several factors affecting the GHG emissions from the AGV system have been identified, to answer research question 2. These have been based on both the literature studies, interviews with colleagues at Kollmorgen, as well as analyses from the case studies. These have been investigated further to get a better understanding of which improvement measures could be made to minimize the energy consumption of the AGV system, and thereby the GHG emissions.

From the results, it is evident that some of the factors that have the high impact on GHG emissions are not factors that Kollmorgen's software solutions can affect. One of the factors that has been identified to have considerably high impact on GHG emissions is the energy mix. This is because the emission factor is taken into account when calculating the GHG

emissions, which depends on the energy mix. The energy mix is the reason why the emission factor is much higher for China and Asia-Pacific than for Europe, due to the share of renewable energy. This is not a factor that Kollmorgen’s software solutions can affect.

Following this, there are several other identified factors that have an impact on the total GHG emissions from the AGV system during operation, but that Kollmorgen’s products can not affect. For instance the surroundings like facility lighting which is not necessary for AGVs, the energy-efficiency of other hardware components, as well as the weight of the truck and the load, etc.

However, the factors seen in Table 11 that the software can affect mostly depend on driving pattern, charging schedule, etc., which is more thoroughly described in the section *Improvement measures* below. It was found during this thesis that the driving pattern of the AGVs has a high impact on the energy consumption and therefore the improvement measure *Improved Route Planning* is one of the most important measures to consider. Changing these factors will also in turn reduce the wear on hardware components and prolong the overall lifetime. This is important to optimize to further reduce the overall GHG emissions during operation.

## 6.4 Improvement Measures

Various factors that Kollmorgen’s software solutions can influence have been identified. One of the most important improvement measures is *Improved route planning* since this covers several of the other improvement measures, where the most affected are *Blocking time reduction*, *Idle time reduction*, and *Minimize empty driving*. The improvement measure *Improved route planning* implies optimization of both distance and the driving time for the AGVs. Kollmorgen’s software could be optimized to always choose the shortest route in order to minimize both distances traveled for the AGV as well as the time it takes to execute the specific task. This can also be seen in other literature where it was found that the distance traveled for an AGV is one of the main factors affecting energy consumption [17], which highlights the importance of optimized route planning.

Another affected improvement measure is *Blocking time reduction*. This means trying to reduce the number of blockings to minimize the time it takes for the AGV to execute the specific task as well as minimize the amounts of accelerations and decelerations. A driving test regarding this was performed, to further analyze how the blocking time affects the energy

consumption. This test showed that an increased number of blockings led to increased total consumption since it took longer for the AGV to complete the same path compared to no blockings. The AGV also had to accelerate and decelerate after each blocking which has an effect on the amount of energy needed. To be able to minimize the number of blockings, an analysis of the system and the routes that the AGVs take could be done. Kollmorgen's software solutions could be optimized to be able to identify new routes for the AGVs in order to avoid each other and therefore reduce the blocking time and make the system more efficient. By making the system more efficient this could also lead to reduced operating time for the AGVs which in turn reduces the energy consumption and therefore also the environmental impact, more specifically the GHG emissions.

The next measure, *Idle time reduction*, means trying to minimize the amount of time that the AGV is turned on but is not required for any tasks. By minimizing the idle time for the AGVs, the system would be more efficient and require less energy. Kollmorgen's software could be modified in order to minimize the amount of idle time for the AGVs. This could be done by monitoring the amount of idle time for the AGVs and then regulating the scheduling and routes to minimize the idling. Another solution to reduce idle time is to charge or turn the AGV off during idle periods. When optimizing the system to reduce idle time, it is a possibility that even fewer AGVs would be needed in the system depending on the application, which will reduce the overall environmental impact. Furthermore, the improvement measure *Minimize empty drive* means reducing the amount of time the AGV drives without a load. By minimizing the amount of empty drive, the system will be more efficient, both regarding energy as well as time. This could also be regulated by the software in the same way as for the improvement measure *Idle time reduction*. The empty drive of the AGVs could be monitored in the same way as the idle time to adjust the scheduling based on this factor. All of these three factors, which have a direct correlation with the first improvement measure *Improved route planning*, are factors that are not of significance for the system and do not produce any value. However, they are somewhat unavoidable for the system to function but minimizing these factors as much as possible will make the system more efficient.

Another factor that Kollmorgen's products could influence is *Speed management*. This improvement measure has also been validated by a test. This test showed that the average current for the AGV traveling at a lower speed was lower than for the AGV traveling at a higher speed. However, as mentioned before, when the time it takes to travel the same path

was included the result differed. This means that it is not always better to travel at a lower speed, therefore it is important to find an optimum regarding speed and time per task that the AGV is supposed to finish. According to [17], the speed is another main factor affecting the energy consumption, which enhances the importance of finding an optimum speed based on the task being performed. Speed management could also enable the possibility to reduce the number of blockings caused by AGVs. This is something that Kollmorgen's software solutions possible could control and therefore regulate depending on the most efficient speed.

Another identified improvement measure is *Optimized battery charging*. This implies controlling the charging of the AGV so that the AGV charges in the most efficient way based on the type of battery and the age of the battery. This can be done by opportunity and contact charging which means that the AGV can be charged when it is convenient without human involvement. This can also decrease idle time by charging the AGV during these times. By optimizing the battery charging the lifetime of the battery could be increased which is positive from an environmental point of view.

The last improvement measure identified is *Switch off the AGV when not in operation*. This measure implies turning off the AGV when it is not needed. Based on the case studies as well as interviews with colleagues at Kollmorgen, it has been noticed that the AGVs rarely are turned off completely. From an environmental point of view, it is unnecessary to have the AGVs active all the time, even though they are not needed. In many of the warehouses where the AGVs are used, they have "peak hours" which means that they have periods of time when all of the AGVs are running actively. However, when these peak hours are over, many of the AGVs are in idle time due to fewer orders. By turning off the AGVs that are not required during these idle periods, energy could be saved which in order would reduce the total energy consumption.

## 6.5 Driving Tests

The two different tests were performed in order to validate and assess two of the improvement measures identified. Of all the improvement measures identified, only two were tested due to the prerequisites available. The test was performed with one small AGV to test the hypotheses generally. The test was performed by measuring the torque current from both drives since this was the parameter available to measure and this is linear with the energy consumption.

In the first test where *Speed management* was tested, the hypothesis was that the energy consumption would decrease accordingly to the speed. However, this was found not to be the case. From what could be seen in the results, the peaks of current were lower when driving at 50 % of full speed but since this test took twice as long to perform, the energy consumption was significantly higher. What can be interpreted from this is that it is not necessarily less energy-consuming for the AGV to drive at a lower speed. This result is probably due to the low driving speed of the AGV, if the speed were higher factors like air resistance will matter and then the results could differ. This applies generally since all AGVs typically drive at low speeds. However, when analyzing this result it is important to consider that the AGV tested was of an older model, which could affect the energy-efficiency. Moreover, many AGVs are larger than the AGV tested which can also affect the energy needed for acceleration and the air resistance which impacts the energy consumption. However, it could be possible to find an optimum of which speed has the least energy consumption and still be able to perform tasks on time. More tests are needed to validate this.

The hypothesis of the second test, *Blocking time reduction*, was that more blockings would be more energy-consuming and the result was found to be consistent. An increasing number of blockings was found to have a significant impact on energy consumption. This is due to the increased acceleration and deceleration needed for every stop together with the longer time needed for the AGV to complete the same path. From the results, it could be seen that the peaks are higher for the test with six blockings but since the AGV was decelerating for every stop, and due to energy recovering from braking, the average current was lower. When taking the time for the AGV to complete the path into consideration, the energy consumption increased.

The overall conclusion from these tests is that the operating time is of high significance for the energy consumption. Because of the low speed an AGV has, the operating power was not of as significant difference which could be seen in the first test and therefore has less impact. The overall hypothesis was that instead of driving at full speed with a lot of stops, it would be less energy-consuming to run the AGVs at a lower speed with fewer stops. This was derived from the fact that many AGV systems are operating with the focus of performing each task as fast as possible without regard to the number of stops. However, it was thought that driving at a lower speed, and thereby taking longer time for the AGV to finish a task but with fewer stops, could reduce energy consumption. With the premise that it was suitable for the application. However, since it was more energy-consuming to drive at 50 % of full

speed it is better to focus on avoiding blockings. It could also be seen that it requires more energy for driving at 50 % of full speed than with full speed and six blockings. The AGV was running the same path in both tests, and up to six blockings could be an accurate assumption on that distance for an AGV in operation at an end-user. However, more tests are needed for different speeds and blockings since an optimum can probably be found regarding its energy consumption. Performing tests with different types of AGVs, and more recent models of AGVs that probably are more energy-efficient, are also needed to further investigate the impact on energy needed for acceleration, etc.

## **6.6 Reliability of the Result**

The assumptions made in this report have a large impact on the result. Assumptions have been made both for the case studies and for the standard system. Also, a validation of the results was made by comparing the results from the case studies and the results from the standard system. A discussion of the reliability of the driving tests is also presented in this section.

### **6.6.1 Case Studies**

The assumptions regarding which types of Kollmorgen's hardware products were used for the calculations are based on the assumed standard system. As well as this, each of the components' operating power was also based on the same assumptions as for the standard system. However, all other factors used in the calculations of the energy consumption and the GHG emissions were based on the information gathered from the visits and the interviews held with people at the specific end-users. Because most of the information used for the calculations was based on facts gathered from the specific companies analyzed, the reliability of the case study results is assumed to be quite high. Therefore, the case study calculations are used to validate the standard system calculations.

Another factor to keep in mind when analyzing the result from the case studies is the emission factor. It was based on the Swedish average energy mix, given that the location for the case studies was in Sweden, which affect the result. Sweden has a high share of renewable energy which generated low emissions from the case studies. However, this does not mean that the emissions are negligible and they would differ if for example the market-based method was used, which would also affect the use of emission factor.

### 6.6.2 GHG Emissions from Kollmorgen's Products

When calculating the GHG emissions based on the standard system, in order to answer research question one, various assumptions were made. The main factor that affects the result for research question one is thus the use of a standard system. Since Kollmorgen sells their products to many different end-users around the world a standard system was needed to be able to obtain a result.

Another assumption was about how many of Kollmorgens products are used generally since the number of products used per system can vary depending on the end-user. However, since one vehicle controller is always sold together with Kollmorgen's software solutions, an estimation of the number of the other hardware products from Kollmorgen was made, based on the sales statistics. The number of components used for the software, operator interfaces and servers, was also assumed since this varies depending on the application.

As well as this, the operating time of the AGV system also varies between applications. However, based on the case studies as well as interviews with colleagues at Kollmorgen, estimations regarding the operating time were done. This impacts the result and is not accurate for every type of AGV system but required to be able to calculate the GHG emissions from Kollmorgen's products.

All assumptions made were not possible to investigate more thoroughly due to time constraints and available information, and altering the assumptions would most probably influence the result. Even though, the result is considered to be of quite high reliability because of the assumptions being justified and confirmed to the extent possible.

Another main factor affecting the result is the use of the GHG Protocol. The results could have differed if another method was used to calculate the result, for example a LCA. The methods have similarities since both assess the environmental impact, but the GHG Protocol are more focused on organizations' emissions [14]. The result is still considered to be reliable due to the GHG Protocol being a well-known framework. Moreover, the use of the location-based method in the GHG Protocol affect the result. This method has similarities with an attributional LCA, since it is based on an average emission factor. If instead, the market-based method was used, the emission factors would differ. However, this method was not possible to use because of the lack of data from end-users. Therefore, the results for the emissions of Kollmorgen's products are considered to be reliable.

### 6.6.3 Driving Tests

The results from the driving tests are influenced by the type and speed of the AGV used, and the testing path. The type of AGV used was a small, older type of AGV, only used for performing tests, with low speed. Hence, the results might have differed if another type, size, or speed of AGV was used, as well as the type of hardware components in the AGV and the use of a regenerative braking system. This would in turn impact air resistance, friction, acceleration, and deceleration. The testing facility was also in a confined environment without interference from obstacles and humans. Another factor that might have affected the result was the measurement value available, namely torque current. Thereby not the exact energy consumption, however, it was sufficient enough to suggest the energy consumption. The AGV used also had an older version of Kollmorgen's software, which is another factor that could have affected the result. Therefore, it is important to take this into account when analyzing the result. The values gathered from these driving tests are therefore not applicable to every type of AGV system. However, they give an indication of how the blocking time and the speed affect the total energy consumption.

## 7 Conclusion

An overall understanding from this thesis is that estimating the GHG emissions from AGV systems is complex since they can be used in various applications and have different sizes and functions. This makes it hard to make an exact estimate of all AGV systems and currently, it is difficult to access data from Kollmorgen's end-users. The software in the AGV systems is another parameter that is hard to assess and make accurate assumptions about, since it does not have as obvious energy consumption as hardware components. Regardless of this, the case studies and driving tests performed have been valuable and important to enable valid assumptions about the advanced AGV systems.

However, a conclusion from this thesis is that the environmental impact in the form of GHG emissions from the AGV systems is to be considered. Kollmorgen's products stand for a smaller amount of the total emissions from the AGV system but given that their main product is a software, the results were higher than expected. Since no assessment regarding this has been made previously, this thesis has been valuable for understanding the environmental impact of AGVs. This enables the possibility to also decrease their environmental impact for a more sustainable application.

Several factors have been identified in order to achieve lower GHG emissions, where the one with the most impact is not possible for Kollmorgen's software solutions to impact. As previously discussed, the biggest factor is the energy mix where changing to renewable energy will significantly reduce the emissions. With that said, several other improvement measures were identified that Kollmorgen's software actually can affect. Furthermore, the driving tests clearly indicated that the driving pattern of an AGV directly correlates with energy consumption. This emphasizes the importance of further investigation and implementation of improvement measures to progress towards more sustainable products. Regarding the factors Kollmorgen can not affect, they still have the opportunity to influence their partners and end-users to make sustainable choices regarding products and electricity suppliers.

To conclude, this thesis has underlined the AGV systems' environmental impact and suggestions for improvement measures for reducing their emissions. The findings highlight the importance of implementing sustainable approaches and Kollmorgen has the potential of leading the way in this area.

## 8 Further Investigations

There are many aspects related to this thesis that would be valuable and of interest to further investigate. One of these aspects is related to the difference between manual trucks and AGV systems. In this thesis, only a qualitative assessment regarding this was made with regard to safety and lifetime, etc. However, this could be further investigated by assessing the environmental difference quantitatively. This is an interesting aspect since many companies are changing from manual trucks to AGVs.

Furthermore, only two driving tests regarding the identified improvement measures were made in this thesis. To further broaden this, validation tests of the other improvement measures would be of interest to assess. To validate this further with a quantitative approach could be of higher credibility. Moreover, to execute validation tests with other types of AGVs to get a better understanding of the different factors' impact. As well as this, it would be interesting to assess the driving tests more thoroughly. By for example testing different speeds in order to find an optimum speed for the AGVs regarding energy efficiency.

The overall climate assessment was based on a standard system, which comes with limitations. To achieve a more precise result a further investigation would be to gather more data from end-users if possible. Then the assessment could be expanded to include the market-based method in order to get an even more complete assessment in accordance with the GHG Protocol. Accessing data from end-users could also be used for evaluating the whole AGV system's environmental impact at every specific application. This could be done by using life cycle assessment, to get an understanding of which state in the life cycle that has the most impact. By finding this, changes could be made to lower the environmental burden for the total AGV system. This also applies generally to all of Kollmorgen's products.

Finally, another investigation that could be made to broaden this matter is to include more environmental aspects, since in this thesis, the evaluation only included the GHG emission CO<sub>2</sub>. However, there are many more environmental aspects that could be of interest to assess. For example, the use of resources, land contamination, and air pollution.

## References

- [1] Kollmorgen, "Bring out the best in your AGVs", 2023. [Online]. Available: <https://www.kollmorgen.com/en-us/solutions/automated-material-handling/automated-guided-vehicles/> (accessed on: 2023-01-23).
- [2] Altra Motion, "Sustainability in Motion," 2021. [Online]. Available: [https://s22.q4cdn.com/325574979/files/doc\\_downloads/2022/Altra-CSR-Report-2021.pdf](https://s22.q4cdn.com/325574979/files/doc_downloads/2022/Altra-CSR-Report-2021.pdf) (accessed on: 2023-01-23).
- [3] C. Benevides, "7 Cost-Saving Benefits of Automated Guided Vehicles (AGVs)," 2022. [Online]. Available: <https://www.conveyco.com/blog/7-cost-saving-benefits-automated-guided-vehicles-agvs/> (accessed on: 2023-02-24).
- [4] Kollmorgen, "Buying AGVs," 2023. [Online]. Available: <https://www.kollmorgen.com/en-us/solutions/automated-guided-vehicles/buying-agvs/> (accessed on: 2023-01-31).
- [5] Kollmorgen, "Building AGVs," 2023. [Online]. Available: <https://www.kollmorgen.com/en-us/solutions/automated-guided-vehicles/building-agvs> (accessed on: 2023-02-31).
- [6] Toyota Material Handling, "Sustainability Report 2021," 2021. [Online]. Available: <https://toyota-forklifts.eu/about-toyota/sustainability/> (accessed on: 2023-02-23).
- [7] Greening Inc., "HOW DOES REGENERATIVE BRAKING BOOST EFFICIENCY?," 2021. [Online]. Available: <http://greeninginc.com/blog/test-equipment/how-does-regenerative-braking-boost-efficiency/> (accessed on: 2023-06-11).
- [8] Kollmorgen. "Our Sustainability Initiative LEADING THE WAY," 2020. [Online]. Available: <https://ndcsolutions.com/media/1427/35200-047a-sustainability-initiative-n.pdf> (accessed on: 2023-01-23).
- [9] Regal Rexnord, "We Create a Better Tomorrow," 2023. [Online]. Available: <https://www.regalrexnord.com/> (accessed on: 2023-04-11).

- [10] Regal Rexnord, "2022 Sustainability Report," 2022. [Online]. Available: [https://s28.q4cdn.com/452460759/files/doc\\_downloads/2022/12/2022-Regal-Rexnord-Sustainability-Report.pdf](https://s28.q4cdn.com/452460759/files/doc_downloads/2022/12/2022-Regal-Rexnord-Sustainability-Report.pdf) (accessed on: 2023-04-11).
- [11] Greenhouse Gas Protocol, "About us," 2023. [Online]. Available: <https://ghgprotocol.org/about-us> (accessed on: 2023-02-02).
- [12] Greenhouse Gas Protocol, "Scope 2 Guidance," 2023. [Online]. Available: <https://ghgprotocol.org/scope-2-guidance> (accessed on: 2023-02-02).
- [13] Greenhouse Gas Protocol, "Corporate Value Chain (Scope 3) Accounting and Reporting Standard," 2023. [Picture]. Available: [https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporting-Standard\\_041613\\_2.pdf](https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporting-Standard_041613_2.pdf), (accessed on: 2023-02-02).
- [14] A. Braunschweig, "The Relation between LCA and GHG Accounting," 2008. [Online]. Available: [https://www.researchgate.net/publication/301765892\\_The\\_Relation\\_between\\_LCA\\_and\\_GHG\\_Accounting](https://www.researchgate.net/publication/301765892_The_Relation_between_LCA_and_GHG_Accounting), (accessed on: 2023-06-01).
- [15] European Commission, "Consequences of climate change," 2023. [Online]. Available: [https://climate.ec.europa.eu/climate-change/consequences-climate-change\\_en#territorial-threats](https://climate.ec.europa.eu/climate-change/consequences-climate-change_en#territorial-threats) (accessed on: 2023-04-18).
- [16] World Health Organization, "Climate change and health," 2023. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health> (accessed on: 2023-04-18).
- [17] S. Riazi, K. Bengtsson, and B. Lennartsson, "Energy Optimization of Large-Scale AGV Systems," *IEEE Transactions on Automation Science and Engineering*, vol. 18, no 2, pp. 638-649, Apr. 2020, doi:10.1109/TASE.2019.2963285.
- [18] BLUEBOTICS, "NATIONAL FORKLIFT SAFETY DAY: FOCUSING ON AUTOMATED FORKLIFT SYSTEMS," 2023. [Online]. Available: <https://bluebotics.com/forklift-safety-day> (accessed on: 2023-04-14).
- [19] R. Stefanini, G. Vignali, "Environmental and economic sustainability assessment of an industry 4.0 application: the AGV implementation in a food industry," *The International Journal of Advanced Manufacturing Technology*, vol. 120, no. 2, pp. 2937-2959, Feb. 2022, doi:10.1007/s00170-022-08950-6

- [20] Kollmorgen, "Building AGVs", 2023. [Online]. Available: <https://www.kollmorgen.com/en-us/solutions/automated-guided-vehicles/building-agvs/> (accessed on: 2023-03-01).
- [21] Statista, "Share of the global server market in the first half of 2018 and 2019, by virtualization type", 2021. [Online]. Available: <https://www-statista-com.eu1.proxy.openathens.net/statistics/915091/global-server-share-physical-virtual/> (accessed on: 2023-04-20).
- [22] J. G. Koomey. "Estimating Total Power Consumption by Servers in the US and the World," Stanford University, USA, 2007. [Online]. Available: [https://www.researchgate.net/publication/228365136\\_Estimating\\_Total\\_Power\\_Consumption\\_by\\_Servers\\_in\\_the\\_US\\_and\\_the\\_World](https://www.researchgate.net/publication/228365136_Estimating_Total_Power_Consumption_by_Servers_in_the_US_and_the_World). (accessed on: 2023-04-20).
- [23] L. Liu. O. Masfary. N. Antonopoulos, "Energy Performance Assessment of Virtualization Technologies Using Small Environmental Monitoring Sensors," Title of journal, vol. 12, no. 4, pp. 6610-6628, May. 2012, doi:10.3390/s120506610
- [24] Kollmorgen, "Bring out the best in your Mobile Robots," 2023. [Online]. Available through: <https://www.ndcsolutions.com> (accessed on: 2023-03-01).
- [25] eia, "Trends in Lighting in Commercial Buildings," 2017. [Online]. Available: <https://www.eia.gov/consumption/commercial/reports/2012/lighting/> (accessed on: 2023-05-30).
- [26] European Commission, "Waste Framework Directive," 2023. [Online]. Available: [https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive\\_en](https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en) (accessed on: 2023-03-13).
- [27] S. Deepanjan, D. R. Chowdhury, "Green Computing : Efficient Practices And Applications," *International Journal of Computer Sciences and Engineering*, vol. 4, no. 1, pp. 38-47, Feb. 2016, doi: 10.5281/zenodo.5226613
- [28] *CVC700 Vehicle Controller - Small Enough to Make a big Difference*, Mölndal, Sweden: Kollmorgen Automation AB, 2020. [Online]. Available: <https://www.kollmorgen.com/en-us/products/vehicle-controls/literature/cvc700-vehicle-controller-brochure>, Accessed on: 2023-03-30.

- [29] Statista, "Carbon intensity of the power sector in Sweden from 2000 to 2021," 2023. [Online]. Available: <https://www-statista-com.eu1.proxy.openathens.net/statistics/1290491/carbon-intensity-power-sector-sweden> (accessed on: 2023-04-13).
- [30] DB Schenker, "About us," 2023. [Online]. Available: <https://www.dbschenker.com/global/about> (accessed on: 2023-03-01).
- [31] R. Karnabi, DB Schenker, 2023. *Interview 2023-02-28*.
- [32] Borealis, "About Borealis," 2023. [Online]. Available: <https://www.borealisgroup.com/about-us> (accessed on: 2023-03-16).
- [33] J. Andersson, Borealis, 2023. *Interview 2023-03-16*.
- [34] Toyota, "Toyota Material Handling," 2023. [Online]. Available: <https://toyota-forklifts.se> (accessed on: 2023-04-13).
- [35] D. Krusell, Toyota, 2023. *Interview 2023-04-12*.
- [36] Toyota Material Handling, "AUTOMATIC GUIDED VEHICLES (AGVS) TOYOTA STAXIO SAE160 AUTOPILOT," 2023. [Picture]. Available: <https://www.toyotamaterialhandling.com.au/products/automatic-guided-vehicles-agvs/toyota-staxio-sae160-autopilot/#case-study> (accessed on: 2023-04-20).
- [37] Toyota Material Handling, "AUTOMATIC GUIDED VEHICLES (AGVS) TOYOTA MOVIT TAE500 AUTOPILOT," 2023. [Picture]. Available: <https://www.toyotamaterialhandling.com.au/products/automatic-guided-vehicles-agvs/toyota-movit-tae500-autopilot/> (accessed on: 2023-04-20).
- [38] B. Forsman, Inmotion, 2023. *Interview: 2023-04-26*.
- [39] ABB, "Efficiency estimation Guide," 2011. Available: [https://library.e.abb.com/public/ab22cf21c367d260c12573e9004d88a4/efficiency\\_calc\\_guide.pdf](https://library.e.abb.com/public/ab22cf21c367d260c12573e9004d88a4/efficiency_calc_guide.pdf) (accessed on: 2023-03-30).
- [40] Statista, "Forecasted CO2 intensity of electricity generation worldwide from 2000 to 2050, by region," 2023. [Online]. Available: <https://www-statista-com.eu1.proxy.openathens.net/statistics/1257765/>

global-emission-intensity-electricity-generation-region (accessed on: 2023-04-13).

[41] Statista, "Carbon intensity of the power sector in the Asia-Pacific region in 2020, by country or territory," 2023. [Online]. Available: <https://www-statista-com.eu1.proxy.openathens.net/statistics/1299708/apac-carbon-intensity-power-sector-by-country> (accessed on: 2023-04-13).

[42] Greenhouse Gas Protocol, "Scope 3 Calculation Guidance," 2023. [Online]. Available: <https://ghgprotocol.org/scope-3-calculation-guidance-2> (accessed on: 2023-02-02).

# Appendix

## A Case study: DB Schenker

Questions	Answers
How many AGVs are in the warehouse?	6 AGVs
How many hours are the AGVs in operation?	20 h
How many of these hours are they active running?	8 h
How many days/year are the AGVs in operation?	Weekdays
What speed and acceleration do the AGVs have?	-
What lifetime to the AGVs have?	At least 10 years
What type of load to the AGVs have?	Packages
What is the weight of the load?	600 kg
What type of batteries do the AGVs have?	Lead-acid
How many batteries are used per AGV?	2
What is the capacity of the batteries?	375 Ah, 24 V
How often and how long time are the batteries charged?	Every other day for 24 h Fully charged after 7 h
What type of hardware products from Kollmorgen are used in the AGV?	Vehicle controller Navigation sensor HMI Display
How many operator interfaces are used?	3
How many virtual servers are used for the AGVs?	4
Where is the electricity that is used in the warehouse from?	Borås Energi och Miljö
How often and what type of spare parts are replaced for the AGVs?	No data due to new system

## B Case study: Borealis

Questions	Answers
How many AGVs are in the warehouse?	14 AGVs
How many hours are the AGVs in operation?	9-24 h
How many of these hours are they active running?	At least 9h
How many days/year are the AGVs in operation?	Every day
How long distance are the AGVs running?	-
What speed and acceleration do the AGVs have?	1,1 m/s
What lifetime do the AGVs have?	20-25 years
What type of load to the AGVs have?	Polyethylene plastic in octagonal packages
What is the weight of the loads?	1,1 tonnes
What type of batteries do the AGVs have?	Nickel-cadmium
How many batteries are used per AGV?	1
What is the capacity of the batteries?	520 Ah/5h
How often and how long time are the batteries charged?	Every 1h and 45min and each charge takes around 10 minutes
What type of hardware products from Kollmorgen are used in the AGV?	Vehicle controller Navigation sensor HMI Display
How many operator interfaces are used?	3
How many servers are used for the AGVs?	1 physical
Where is the electricity that is used in the warehouse from?	Average Swedish energy mix
How often and what type of spare parts are replaced for the AGVs?	Wheels and side bumpers

## C Case study: Toyota Material Handling

Questions	Answers
How many AGVs are in the warehouse?	Stackers: 10, Tow trucks: 5
How many hours are the AGVs in operation?	Stackers: 24 h, Tow trucks: 17.5 h
How many of these hours are they active running?	Stackers: 12h, Tow trucks: 17.5h
How many days/year are the AGVs in operation?	Stackers: 365 days, Tow trucks: 253 days
How long distance are the AGVs running?	Stackers: 50 km per week Tow trucks: 50 km per week
What speed and acceleration do the AGVs have?	Stackers: 1.8 m/s, Tow trucks: 1.2 m/s
What lifetime do the AGVs have?	Stackers: Leased for 3 years Tow trucks: 7 years
What type of load to the AGVs have?	Stackers: EUR standard pallets Tow trucks: 2-5 wagons with EUR pallets
What is the weight of the loads?	Stackers: 600 kg, Tow trucks: 5000 kg
What type of batteries do the AGVs have?	Lithium-ion
How many batteries are used per AGV?	Stackers: 1, Tow trucks: 1
What is the capacity of the batteries?	Stackers: 250 Ah, Tow trucks: 300 Ah
How often and how long time are the batteries charged?	Stackers: 3 times/day for 20 minutes Tow trucks: During lunch breaks and nights
What type of hardware products from Kollmorgen are used in the AGV?	Vehicle controller Navigation sensor
How many operator interfaces are used?	5
How many servers are used for the AGVs?	2 virtual
Where is the electricity that is used in the warehouse from?	Average Swedish energy mix
How often and what type of spare parts are replaced for the AGVs?	The scanner glass for the safety scanners Tires - not so common Electrical parts - if needed

## D Test 2: Blocking Time Reduction

In this appendix, all graphs from the different tests for *Blocking time reductions* is presented.

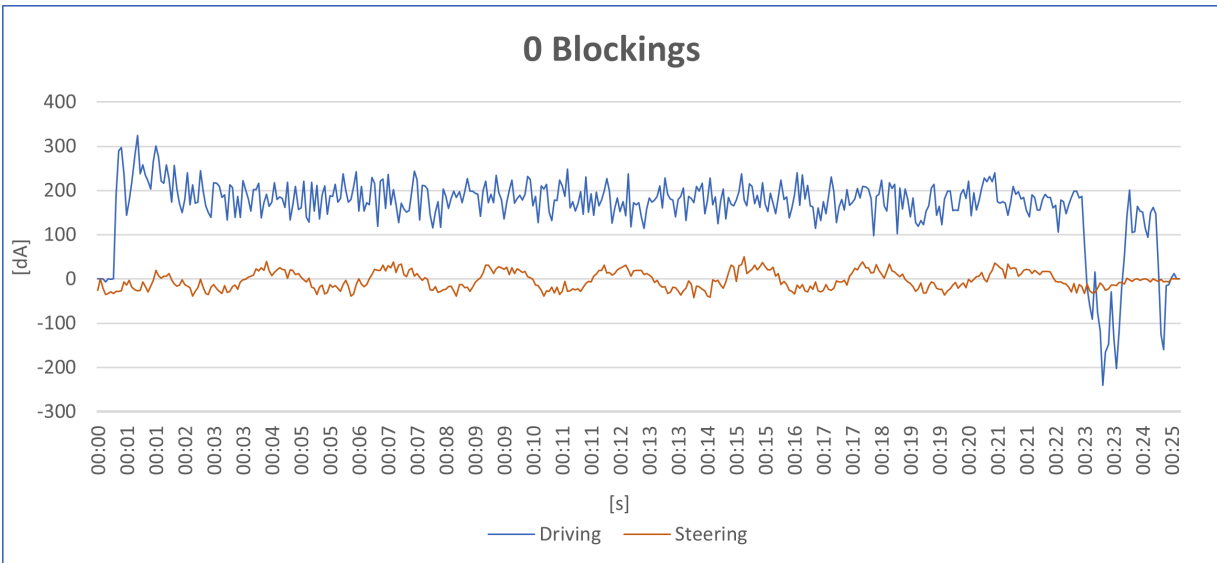


Figure 17: 0 Blockings



Figure 18: 1 Blocking

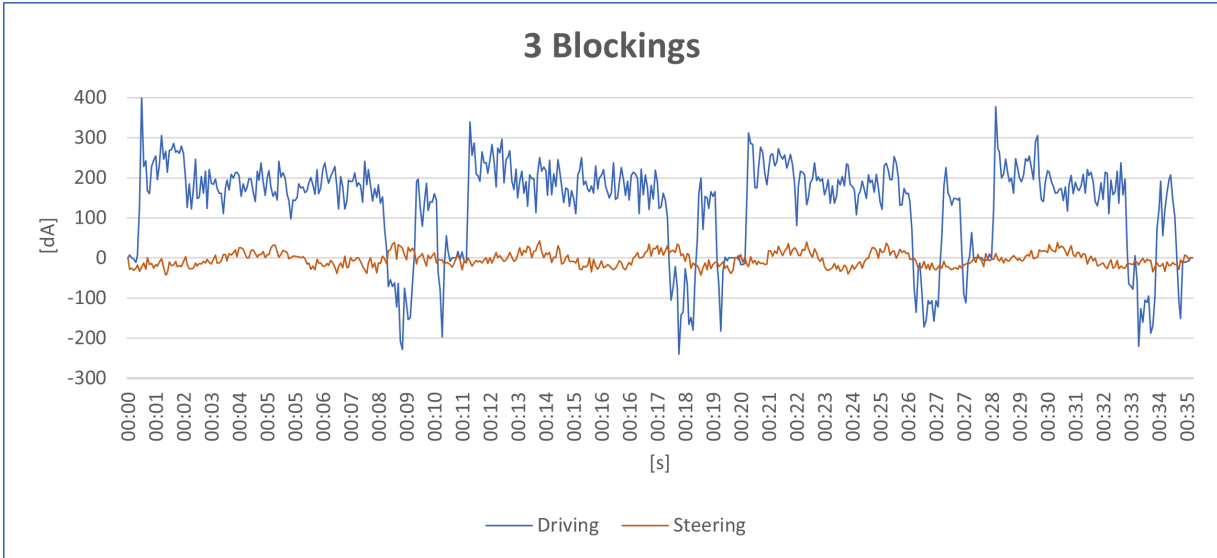


Figure 19: 3 Blockings

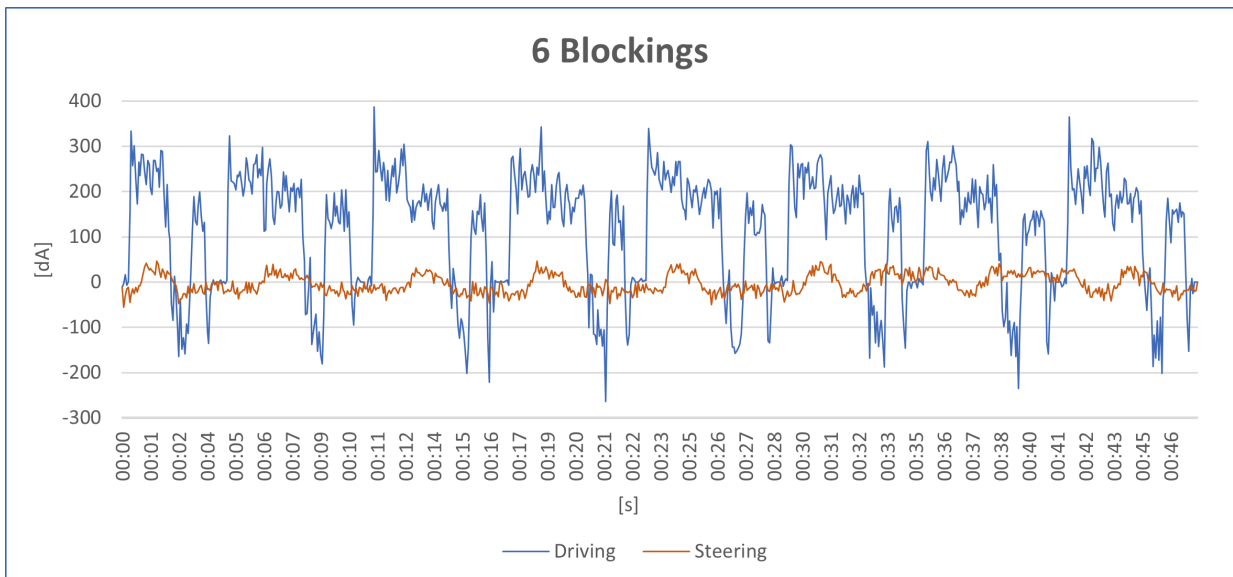


Figure 20: 6 Blockings



DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS  
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS  
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden

[www.chalmers.se](http://www.chalmers.se)



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY