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Sustainability impact of optimizing construction fleet operations

- A case study of productivity services at construction sites

Master's thesis in Product Development

JULIA FERREIRA SANDBERG
INA WOLLMER

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
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JULIA FERREIRA SANDBERG
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Examiner: Johan Malmqvist, Department of Industrial and Materials Science
Industry Supervisor: Erik Roos, CPAC SYSTEMS AB

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Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Abstract

Co-Pilot is an onboard display, supported by sensors and cloud services, that delivers real-time data to construction equipment operators to support their daily work. The purpose of this thesis is to analyze how the changes in performance and user behavior on construction sites guided by Co-Pilot impact the CO_2 emissions of the equipment. The product is developed by CPAC Systems AB, for Volvo CE. It is sold as a productivity service, increasing the efficiency of the site. Furthermore, it is believed that Co-Pilot increases the site sustainability by helping reduce the CO_2 emissions.

The research is focused on understanding how Co-Pilot contributes to sustainability. This is done by comparing user behavior and equipment performance before and after implementation of the product and translating these differences into CO_2 emissions. Three different use cases where Co-Pilot is currently used are analyzed and compared to receive diverse perspectives. The applied user study methodology is a quantitative approach supported by qualitative methods to help explain the findings.

To conclude, the results are considered positive as more is produced per tonne emitted CO_2 at a majority of the studied sites. The fuel consumption and all production category measures included in the study decreased after the implementation of Co-Pilot. To maximize the improvement of sustainability, fuel consumption must be the most decreasing measure out of all production categories, which is the case for two out of three use cases. To improve Co-Pilot and its sustainability impact even further, development should focus on decreasing idling and queuing times, and strive to make Co-Pilot even easier to use and understand to promote full utilization.

Keywords: Co-Pilot, sustainability, CO_2 emissions, construction equipment, CPAC, innovative solutions, productivity, services.

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Julia Ferreira Sandberg, Gothenburg, June 2021
Ina Wollmer, Gothenburg, June 2021

Contents

1

Introduction

This chapter aims to introduce the project, company and industry together with the purpose, research questions, expected results and limitations. Finally, the overall structure of the report is outlined.

1.1 Background

The background seeks to present the context of the project. Hence, company background, introduction to the product and application, and the current status of sustainability within the construction industry are presented.

1.1.1 CPAC Systems AB

CPAC Systems AB is a tech company developing products and system solutions related to the construction, marine and industry sectors. This is mainly done for Volvo Group, more specifically Volvo Penta, Volvo Trucks, Volvo Buses and Volvo CE. CPAC develops innovative technologies that integrate several different functionalities. It can be to develop a driver assistance system that supports the driver in one specific situation or to be part of developing a completely self-driving vehicle (CPAC, 2019b).

The construction segment focuses on development related to construction equipment like bulldozers, dumper trucks, wheel loaders, pavers, excavators and steamrollers. One solution they have developed includes an onboard display connected to different applications and sensors. It delivers real-time data and information of for example loading and vehicle performance to the machine operators. This solution, called the Volvo Co-Pilot, has been on the market only a few years and is still under fast development.

1.1.2 Co-Pilot

Volvo Co-Pilot was developed to support machine operators at construction sites with relevant information during their daily work and is currently sold as a productivity service to Volvo CE's wheel loaders, dumper trucks, excavators and pavers. Co-Pilot is an interactive onboard display supported by sensors, cameras and cloud services, delivering real-time data to machine operators and enabling integration of the different machines on site. It integrates vehicle performance data like fuel efficiency, operating time and safety, and clearly shows the desired information on the display.

The operator can either use the received information as support in the work or solely enter the exact data necessary for the step to be performed. Co-Pilot gives the operator total control over the machine and increases the precision (CPAC, 2019a). In addition, it increases the productivity and sustainability of construction sites. Figure 1 shows the Co-Pilot display in a wheel loader cab.

Figure 1: The Co-Pilot display in a wheel loader cab (Volvo Group, 2019)

Co-Pilot has several different applications used by several different machines, see figure 2. Other than the Co-Pilot display, the applications can be used in mobile devices and order offices. This study will focus solely on one of its applications: Haul Assist.

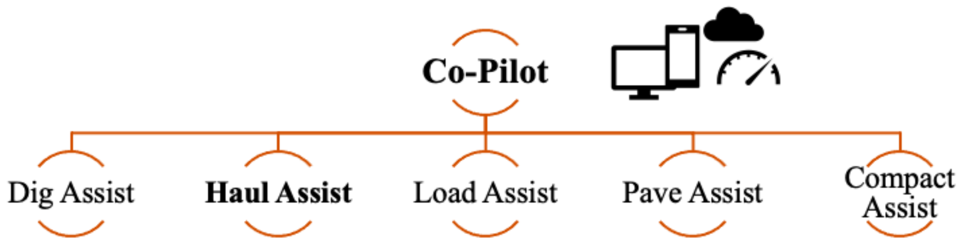


Figure 2: Hierarchy of Co-Pilot and it's applications

1.1.3 Sustainability in the Construction Industry

The construction industry accounts for a large portion of the global carbon dioxide emissions. More precisely, 23% of the global economics emissions (Huang et al., 2017) and 39% of the world's energy-related emissions when grouped together with the building sector (UN Environment & International Energy Agency, 2017). According to UNE and IEA, one of the main reasons is the use of fossil fuels; in 2014, 20% of the emissions due to fuel combustion originated from the manufacturing industry and the construction industry (The World Bank, 2014). Although, the vision of the World Green Building Council (WorldGBC), which is endorsed by Volvo CE, is for the building and construction sector to reach net-zero carbon emissions by 2050 (WorldGBC, 2019). Hence, measuring and aiming to decrease the emissions of construction products is of utmost importance.

Within the construction sector, greenhouse gas emissions are highly connected to productivity; increasing productivity decreases emissions (Kim et al., 2012). Kim et al. (2012) refers to equipment productivity as the rate of output and argues that it is related to greenhouse gas emissions due to for example site conditions and idling time. According to a study performed by McKinsey & Company, one way to improve construction productivity is by infusing digital tools and automation (Barbosa et al., 2017). As Co-Pilot and its applications are productivity services improving the productivity of equipment and sites (Volvo CE, 2021c), the starting point of this project is that these improvements also impact the CO_2 emissions.

1.2 Purpose

The purpose is to analyze how the changes in user behavior implied by Co-Pilot impact the performance and thus CO_2 emissions of the equipment. Hence, it is needed to compare the user behavior and equipment performance before and after the implementation of the product and translate these differences into quantitative CO_2 emissions. This will be done by studying three different use cases where the Haul Assist application is implemented. Investigating three different use cases with different levels of complexity should enable comparison and diverse perspectives.

The overall ambition is to understand how Co-Pilot impacts and contributes to sustainability. Holistically, this project is the first step towards using quantitative sustainability measures as product performances. Hence, the applied method should be scalable and defined to enable similar studies of other products in the future.

1.3 Research Questions

To achieve the purpose, the following research questions will be analyzed and answered:

1. What are the differences in user behavior and equipment performance before and after having implemented Co-Pilot?
2. How large is the quantitative difference in CO_2 emissions implied by the changes in user behavior and equipment performance?
3. How can Co-Pilot be further developed to improve its' impact on sustainability?

1.4 Expected Results

The overall results of this study are expected to help the understanding of how Co-Pilot impacts and contributes to sustainability and more specifically CO_2 emissions. Therefore, the expected results are related to the research questions.

1. A concrete list of differences in user behavior and equipment performance before and after having implemented Co-Pilot.
2. A clear visualization of the difference in CO_2 emissions using charts or other visualization tools.
3. A list with suggestions on how Co-Pilot can be further developed to improve its impact on sustainability.

1.5 Limitations

The study will be performed with respect to the following limitations:

- Only the Haul Assist application is taken into consideration.
- Only three chosen use cases will be evaluated. The results will not be related to other sites, applications or segments of the industry that are not included in the study. This means that there might be other sites, that are not included in the study, where Haul Assist would have provided different results.

- When evaluating CO_2 emissions, only those impacted by the user behavior and equipment performance will be considered. For example, the CO_2 emissions from developing or manufacturing the product itself will not be considered or included in the evaluation.
- When referring to sustainability throughout the project, it refers to environmental sustainability. Social (e.g., equality) and economic (e.g., circular economy) aspects of sustainability are not part of the study.

1.6 Outline of thesis

The report is structured in chronological order, starting with introduction, followed by theory, research approach, results, discussion and finally conclusions. Chapter 2 presents a theoretical framework, different publications of emission data and competitive products. Further, it explains the equipment and the application that is referred to throughout the report. The research approach is presented in chapter 3 and accounts for the entire research process, from the selection of use cases to data analysis. Further, the final results are presented in chapter 4. An important note is that the results chapter includes only the final results. All partial results from certain method steps are presented in the research approach, as they are required to understand the methodology but not part of the thesis results and findings. Moreover, chapter 5 includes discussion of the achieved results, the research approach, and fulfillment of research questions. Conclusions along with recommendations for future development and research are presented in chapter 6.

Lastly, the first two appendices present the questions that were asked during the interviews performed with a transportation manager and operator. The three last appendices present all production data from all use cases that served as the basis of analysis. In general, the appendices are not a necessity to understand the research and results of the thesis but may explain certain matters more in detail.

2

Theory

The theory chapter presents the theoretical framework that is relied on and referred to throughout the project. Firstly, relevant background on construction equipment and the Haul Assist application is presented. Secondly, research and evidence on user studies are explained. Thirdly, the background information and data used to perform the quantitative evaluation of CO_2 emissions is presented. Lastly, a benchmark is performed where Co-Pilot is compared to competitive products.

2.1 Construction Equipment

Dumper trucks are heavy machinery that are used to transport large volumes of different kinds of loose materials across construction sites. This could for example be dirt, sand, gravel or demolition waste. The dumpers are usually filled with material by another machine, for example, a wheel loader. This material is then transported and dumped at a specified location. Due to its possibility to lift the dump, it can easily be emptied. This project will treat articulated dumper trucks, see figure 3a, which work great across rough terrains (iSeekplant, 2019).

Wheel loaders, see figure 3c, are heavy machinery primarily used for lifting and loading loose materials like sand and gravel. This is done with a front-mounted bucket that is raised and lowered by a lift arm (Construction Equipment, 2021b). Often, wheel loaders are used to fill other vehicles. In this project, wheel loaders that fill trucks, like the one shown in figure 3b, and dumper trucks with material from construction sites are treated.

(a) Dumper truck (Volvo CE, 2021a)

(b) Truck (Volvo Trucks, 2021b)

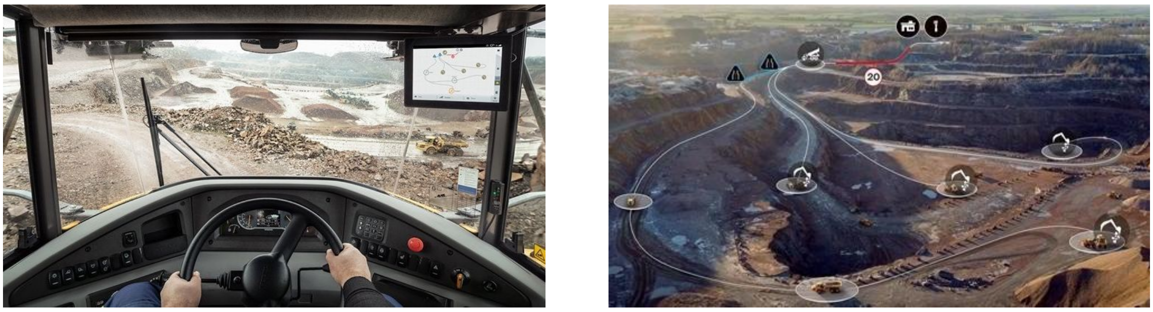
(c) Wheel loader (Volvo CE, 2021d)

Figure 3: Construction vehicles treated in the project

2.2 Co-Pilot Haul Assist

Haul Assist is an application used by dumper trucks to increase the site efficiency. The Co-Pilot displays where other machines are located which makes it easier for the operator to avoid potentially dangerous situations. Further, by being able to monitor the traffic and follow the current transportation flow, it is easier for the operators to optimize the haul cycles and anticipate the best driving decisions, which increases the efficiency. The Haul Assist application is supported by GPS units built in the dumper trucks and used for positioning. Co-Pilot uses these to enable communication between the different machines. If two machines are approaching each other, the operators will receive a notification. In addition, transportation routes are shown on the display to ease the navigation on the site (Volvo CE, 2019).

Moreover, an on-board weighing system (OBW) is integrated in the Co-Pilot Haul Assist, enabling the dumper trucks to load and transport the optimal amount of material. It minimizes the number of to small loads to increase the productivity, but protects against overload to decrease fuel consumption and wear out on the dumpers. An example of the display in the cab and visualization of a construction site map are presented in figure 4.



(a) Co-Pilot in the dumper truck cab (Volvo Group, 2020)

(b) Construction site map (Volvo CE, 2019)

Figure 4: Haul Assist

Hypothetically, utilizing the Haul Assist application will decrease CO_2 emissions, due to improved productivity and efficiency. Firstly, the amount of loaded material (per load) can be increased since it is visualized on the display and can therefore result in fewer required haul cycles. Secondly, it is believed that the number of overloads will decrease which consequently will decrease fuel consumption. Thirdly, since the operators can see other machines on the site, driving can be more effective. For example, the routes can be planned to minimize the number of meetings between two or more dumpers. As a result, the idling time can be decreased and consequently also the CO_2 emissions.

2.3 User Studies

This section presents commonly used user study methodologies and existing evidence related to the project. Hence, a theoretical framework of qualitative versus quantitative approaches and user experience (UX) evaluation is presented.

2.3.1 Qualitative vs. Quantitative Approach

When collecting and analyzing data, the research can be done qualitatively or quantitatively. Qualitative research involves non-numerical data, for example, audio, video or text. It is usually used to gather insights into a problem and to understand concepts or opinions. Quantitative research, on the other hand, is expressed in numbers and graphs. It can be used as a tool to establish generalized facts about a topic and to test or confirm assumptions (Streefkerk, 2019).

The two different approaches have weaknesses that can be compensated for by the strengths of the other. For example, whilst quantitative methods produce factual data the qualitative methods provide a more rich and valid process data with a contextual understanding. Because of this, integration of the two methods can be advantageous. This can be done in one of the following ways (Steckler et al., 1992):

1. The qualitative approach can be used to help explain quantitative findings.
2. The quantitative approach can be used to enhance a qualitative study.
3. The two methods are used equally and in parallel.
4. Qualitative measures are used to develop quantitative measures.

The same is suggested by Driscoll et al. (2007), as they state how the different methods can compensate for each other's weaknesses. In addition, it is mentioned that the utilization of both methods can expand the scope. However, it is further stated that the process of combining the two methods can be time-consuming and expensive if the research question to be answered is of a complex nature.

2.3.2 UX Evaluation

In the field of user experience (UX), product evaluations are often divided into formative and summative (Joyce, 2019). While formative evaluations are carried out to evaluate future steps of development and redesign, summative evaluation assesses the overall performance of a complete design. According to Kirakowski (2005), summative evaluation methods can be used to evaluate the product performance and the potential customer benefits of acquiring it. One method of summative evaluation is UX Benchmarking (Moran, 2020); it is about evaluating product performance and impact by collecting quantitative data on the user experience and comparing it to a reference point. Examples of common reference points are competitive products or an earlier version of the design.

To enable benchmarking, data on key metrics are collected by quantitative research methods (Joyce, 2020). Data can be automatically gathered using analytics and performance tracking or manually gathered through rating surveys. Commonly used metrics are related to the three components of usability: effectiveness, efficiency and satisfaction (Kirakowski, 2005). Moreover, Kirakowski (2005) defines efficiency as the use of resources; time being the most important resource, common metrics are the time to complete a task or recover from an error.

2.4 CO_2 Emissions in the Construction Industry

This section includes data on CO_2 emissions in the construction industry. Firstly, emissions from construction equipment and parameters to quantitatively assess them. Secondly, methods and previous research on how emissions within the construction sector can be reduced.

2.4.1 Emissions from Construction Equipment

The most dominant greenhouse gas emission from construction equipment is the emission of CO_2 (Zhang et al., 2017). Other than greenhouse gases, construction equipment emits pollutants such as nitrogen oxides, carbon monoxide and particulate matter that endanger the environment (Fan, 2017). Zhang et al. (2017) state that the main contributor to CO_2 emissions is the combustion of fossil fuels. At the same time, they argue that emissions are highly dependent on operational and machine parameters such as speed, load, and engine type, age and usage.

As a consequence, there are various ways and multiple parameters used to quantitatively assess emissions from construction equipment. Examples of parameters that impact the fuel consumption of the construction equipment handled in this study are power range and category of usage. The power ranges of wheel loaders and dumper trucks are shown in table 1, while the truck diesel consumption for each category of usage is presented in table 2. For trucks, the categories of usage are urban, regional and long-haul driving (Volvo Trucks, 2021a).

Table 1: Construction equipment power range

Description	Equipment	Unit	Value	Reference
Power range	Wheel loader	kW	56-560	(Volvo CE, 2021b)
	Dumper truck		130-560	

Table 2: Truck diesel consumption per category of usage

Description	Category of usage	Unit	Value	Reference
Fuel consumption	Urban	$\frac{\text{liter}}{100\text{ km}}$	21	Volvo Trucks (2021a)
	Regional		23	
	Long-haul		33	

Moreover, there are several ways to measure how much CO_2 is emitted from the use of diesel fuel. Therefore, different publications suggest different parameters to quantitatively assess the emissions. A selection of these parameters is presented in table 3. Firstly, parameters translating how many kilos of CO_2 are emitted from the combustion of one liter diesel. Secondly, parameters to determine power utilization from diesel.

Table 3: Parameters to quantitatively assess emissions from construction equipment

Description	Unit	Value	Reference
CO_2 emission from diesel consumption	$\frac{kgCO_2}{\text{liter diesel}}$	2.60	Volvo Trucks (2018)
		2.67	Valsecchi et al. (2009)
		2.66	Natural Resources Canada (2014)
		2.62	FleetNews (2020)
		2.69	Miljöfordon (2020)
Energy content from fuel	$\frac{kWh}{\text{liter diesel}}$	9.80	Energigas Sverige (2019)
		9.96	Karlsson and Johansson (2009)

2.4.2 Methods to reduce CO_2 Emissions

As CO_2 emissions are highly related to fuel use, the most apparent measure to reduce emissions is to reduce fuel consumption. According to Lewis et al. (2012), operational efficiency and idling time are fuel measures highly related to emissions; increasing efficiency and reducing idling time reduces the CO_2 of construction equipment. US Environmental Protection Agency (EPA) also suggests reducing idling as an activity to lower CO_2 emissions (EPA, 2009). Among activities related to changing the fuel type and sourcing, they also suggest that improving maintenance and driver training has a large impact on emissions.

Szamocki et al. (2019) performed a case study on how to reduce greenhouse gas emissions at construction sites. Once again, reducing idling was concluded a successful measure. Further, they found that improving task and operation planning would reduce emissions. Task planning, which is the planning of a single vehicle, is about making sure that all tasks are carried out efficiently. An example is optimizing the depth of cut for an excavator. Operation planning, that is the operation planning of all involved equipment, creates a better flow of operations. In one of the studied cases, even adding an additional dumper eased operation planning and decreased CO_2 emissions. As Co-Pilot is a productivity service optimizing not only fuel efficiency but all these factors, it should hypothetically also have a positive impact on emissions.

2.5 Competitive products

The concept of monitoring efficiency at construction sites, using an onboard weighing system or similar technologies has been developed by other companies as well. This section presents three of these companies and their respective technologies.

The first company, Trimble, is a company that develops software solutions for energy, water and public administration industries. One of their developed solutions is the Trimble Earthworks, a grade control application for construction and compact machines. It aims to maximize the control, speed and flexibility of different equipment by eliminating guesswork and rework (Trimble, 2021a). It is an application built on an Android operating system that runs on a touch-screen display inside the operator cab. The application was developed based on feedback from construction operators around the world (Construction Equipment, 2021a).

In addition, Trimble has developed the application Utility To Go. It provides convenient and secure access to utility network data and improves the communication between the field and the office. Further, the application enables decision-making since both the office and field have the most accurate data on the current situation (Trimble, 2021b). This application can be compared to the Co-Pilot map function and cloud service that enables the communication between different machines. However, according to Trimble (2021b), Utility To Go is mainly used for electricity, water and district heating utilities which are not primarily the usage sectors of Co-Pilot.

Another company that has developed an onboard weighing system is Caterpillar Inc, a world-leading manufacturer of construction and mining equipment (Caterpillar, 2021a). The system is called Cat Payload and is described as a technology that delivers real-time feedback and information about the loaded material, keeps track of this information, helps operators get the right load onboard and indicates when the optimum capacity is reached. The technology supports different applications that can be used by wheel loaders, excavators, trucks, off-road haulers and scrapers (Caterpillar, 2021b). The system consists of an on-the-go weighing, an in-cab display and comprehensive reporting. The on-the-go weighing helps the operators hit exact loading targets all the time which can result in fewer loads, saving both time and fuel. In-cab displays, see figure 5, let operators easily see and receive real-time information and thanks to the comprehensive reporting, key performance indicators can be tracked (Caterpillar, 2021c).

Figure 5: Cat Payload in operating cab (Caterpillar, 2021c)

Lastly, the company Komatsu has developed a wireless monitoring system named KOMTRAX. It is a technology that facilitates tracking of the machines, monitoring their performance and provides updates on the status of the equipment. The monitoring can be tracked directly on a computer, phone or tablet. Further, it is factory-fitted on every Komatsu machine and does not cost anything extra (Komatsu, 2021). KOMTRAX can be used in the majority of Komatsu's wheel loaders, dumper trucks, dozers and excavators. Firstly, the system keeps track of the performance, for example, fuel consumption, running hours, idling and productivity. Secondly, it also provides essential information about the machines' condition and potential fault codes or issues that require maintenance. Thirdly, it includes a safety function that prevents unauthorized usage, receives unusual location changes and alerts if the machine works outside of a defined area.

When performing a benchmark with the identified companies and products, see table 4, it can be stated that Earthworks, Cat Payload and KOMTRAX can be compared to Co-Pilot in one way or another. All of them include several different machines and are sold on a global market. However, none of them include a map function to be used by the operator, which is one of the most important functions of Haul Assist. The map function that is included in KOMTRAX is mainly to be used by managers to know where the machines are stationed. Overall KOMTRAX does not focus on the operator, it is according to Komatsu (2021) mainly used for monitoring and fleet management. This can further be highlighted as KOMTRAX does not have an onboard weighing system to support the operators' daily work.

Moreover, the system Earthworks is sold separately by a company that does not sell any machines. Meaning that it is not specifically adapted to one type of machine and neither one specific brand. Caterpillar, however, sells both the system Cat Payload and machines. It can also be seen that the types of machines in question are very similar to the ones that can utilize Co-Pilot. In addition, the main focus with Cat Payload is, similarly to Co-Pilot, to facilitate the work for the operators. Note that no prices are compared, as they depend on site procedures, size and other specific circumstances.

Table 4: Benchmarking with competitive products

	Cpac	**Trimble**		**Caterpillar**	**Komatsu**
Category	Co-Pilot	Earthworks	Utility To Go	Cat Payload	KOMTRAX
Machines that can use the product:	Wheel loaders Dumper trucks Excavators Trucks Dozers Pavers	Wheel loaders Scrapers Excavators Compact machines Dozers	-	Wheel loaders Dumper trucks Excavators Off-highway trucks Scrapers	Wheel loaders Dumper trucks Excavators Graders Dozers Bulldozers Skid-steer loader
Machine manufacturer	Yes (Volvo)	No	No	Yes	Yes
Market	Global	Global	Global	Global	Global
On-board weighting	Yes	Yes	No	Yes	No
Wireless data sync	Yes	Yes	Yes	Yes	Yes
Automatic steering	No	Yes	No	No	No
Map-function to be used by operators	Yes	No	No	No	No
Map-function to be used by managers	Yes	No	Yes	No	Yes
Currently under development	Yes	Slighlty	No	No	No
Customizable	Yes	Yes	Yes	Yes	No
Extra service or included from start	Extra	Extra	Extra	Extra	Included
Mainly supports manager or operator	Operator	Operator	Management	Operator	Management

3

Research Approach

The overall research approach of the project comprised selecting use cases, collecting quantitative and qualitative data through user studies and analyzing the data. The major steps and what was done for each use case is visualized in figure 6. As seen in the figure, the overall methodology is the same for all use cases. The only exception is that interviews were performed only at one site.

Figure 6: Phases of the research approach applied in the study

The applied user study methodology was a quantitative approach supported by qualitative practices to explain the findings. The quantitative study is a summative benchmark, comparing performance and CO_2 emissions before and after having implemented Co-Pilot. Moreover, a qualitative approach was used to complement and understand the quantitative findings. Lastly, the findings were analyzed and visualized separately depending on the characteristics of the data.

This chapter first presents the selection of use cases and the applied criteria. Thereafter, the research approach of one use case is explained. As the methodology was designed to receive results in the same format from all use cases, the research approach of the following two use cases is very similar to the first one. Therefore, the research approach of Use Case 1 serves as a basis and is the only one described in detail. For Use Case 2 and 3, only adaptations to the previously described approach are presented. This means that if nothing else is mentioned, the same methodology as for the first use case was applied for the following two.

3.1 Selection of Use Cases

Analysis of the actual impact of Co-Pilot required study of real sites that have implemented and are utilizing the product. Three sites that use the Haul Assist application were chosen as use cases. The sites remain anonymous throughout the project and report, to ease the collection of honest and accurate data in the user studies. Hence, they are referred to as Use Case 1, Use Case 2 and Use Case 3.

The studied use cases were selected based on the fulfillment of several criteria. Firstly, the site needed to have used Co-Pilot long enough for its full potential to be utilized but had been up and running before implementation too. This enables comparison but also makes sure that potential interview objects have experienced both alternatives. Secondly, enough machines had to be present and working on the sites, as one of the main benefits of the application is collaboration. Thirdly, the bigger the transportation distances, the better. As dumper trucks are continuously moving around the site, effectively managing large transportation routes has a bigger impact on CO_2 emissions. Fourthly, if interviews were to be performed at the site, the possibility to include both managers and operators in the study was required, to allow different perspectives and goals. All selection criteria are presented in table 5.

Table 5: Criteria to select use cases

1	The site has implemented Co-Pilot, but was up and running before implementation too.
2	At least two dumper trucks should be working on the site.
3	The bigger the size of the site and the longer transportation distances, the better.
4	If interviews are performed, it should be possible to include both site operators and managers in the study.

3.2 Use Case 1

The following section presents the research approach applied to Use Case 1. As previously mentioned, this approach serves as a basis for the descriptions of the methodologies applied to the following two use cases. Before describing the research approach itself, this section starts with a description of the use case site.

3.2.1 Description

The first Haul Assist use case is a China clay mine that utilizes dumper trucks to transport the clay. The dumper trucks are full suspension articulated haulers, similar to the one previously shown in figure 3a. They utilize Co-Pilot and the Haul Assist application, which was implemented in 2020, to locate other dumper trucks on the site and measure the weight of the load. Further, Co-Pilot is used to track site operations, for example by reporting haul cycle durations, transportation distances and loading time.

For this use case, it is not the site owner that participated in the study, but the subcontractor providing the machines and operators. The same subcontractor also provides the machines at the second use case site. As both sites are located in the same area, the machines can be moved between the sites depending on the current need. On average, eight dumper trucks are used daily on the site during 2020.

The site is divided into several different zones, see figure 7. Over time, clay is extracted at different zones. Although, the daily work is carried out where it is most needed and at the current extraction point. Therefore, the dumper trucks move around smaller fractions of a single zone daily. However, the biggest zones are the most common extraction points. These are indicated in the figure, as 1 and 2, and the distance between them is approximately 4 kilometers. The total area of the entire site is around 10.6 km^2.

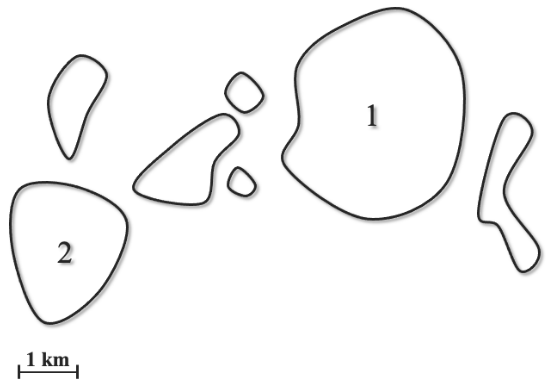


Figure 7: Visualization of the first use case site

3.2.2 Data Collection

The data collected from Use Case 1 was performance and production data gathered by the subcontractor before and after implementation of Co-Pilot at the site. Therefore, the included data and corresponding time periods were not adjustable. Before implementation, four production categories were reported: fuel consumption, machine hours, number of loads and loaded tonnes. Reporting started halfway through 2014 and was performed weekly until August 2015. After that, reporting was done monthly until Co-Pilot was implemented in January 2020.

After implementation, the amount of reported data is more extensive. The time period starts in January 2020 and ends on the day of collection. Other than the four production categories included in the pre-implementation data, the post data includes details of each haul cycle. For example, all transportation distances and durations of each cycle are included. Instead of reporting monthly or weekly, each cycle is reported individually. Even though this decreases the risk of inaccurate data, it requires more processing, which will be described in the forthcoming sections. For example, machine hours are reported for each machine and increases over time, similar to the mileage of other vehicles. As the same categories need to be included in the data both before and after implementation to enable comparison, the cycle details are used only to understand site characteristics and daily procedures. Table 6 shows an overview of the collected data from Use Case 1.

Table 6: Summary of the data that was collected from Use Case 1

	Time period	Categories
Before implementation	Oct 2014 - Dec 2019	Fuel consumption
		Machine hours
		Nr of loads
		Loaded tonnes
After implementation	Jan 2020 - Mar 2021	Fuel consumption
		Machine hours
		Nr of loads
		Loaded tonnes
		Cycle details E.g., durations and distances

3.2.3 Validation of data

To ease the comparison, one year before and one year after implementation were included in the study. To make sure that seasonal differences did not impact the results, full years were included. As the data before implementation contained several different years, the sum of all data categories each year were compared to chose which year to include in the study. Further, the goal was to include as recent data as possible. The yearly sums of the categories are shown in figure 8. Based on this, 2019 was included in the study, as it is the most recent year and does not deviate from the other years in the charts. As the data after implementation only included one full year, 2020 was included in the study.

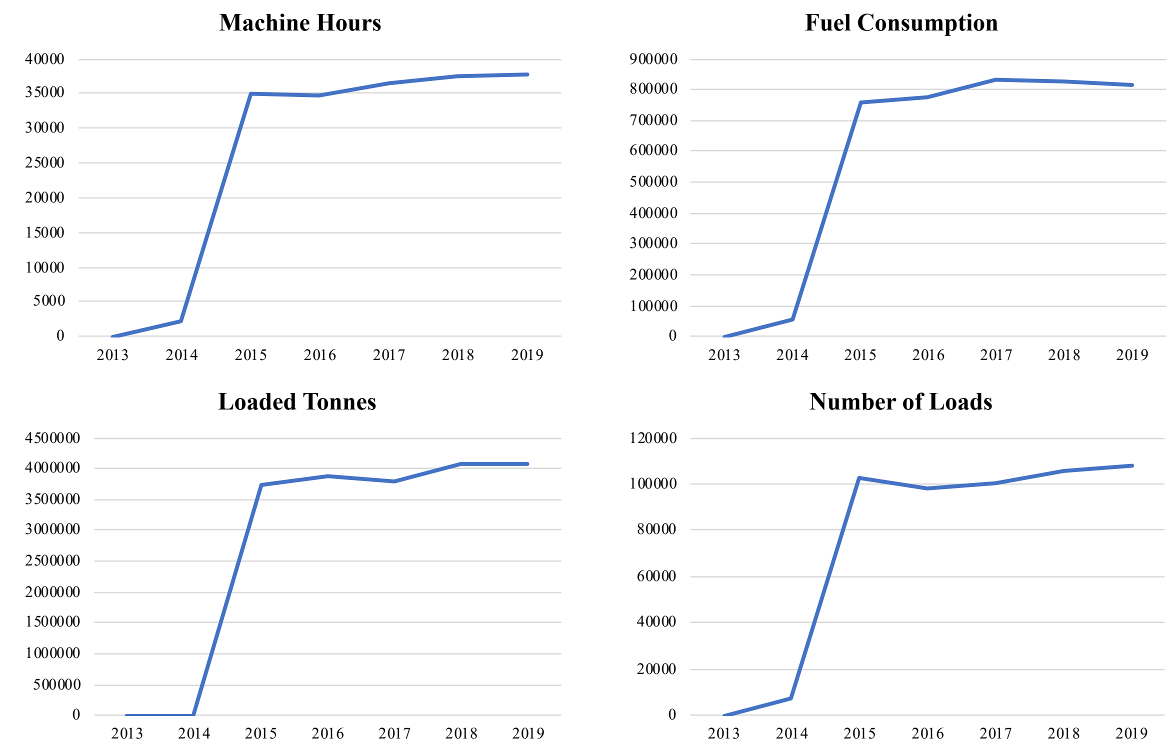


Figure 8: Yearly sums of the categories used to validate the choice of what year before implementation to include in the study

3.2.4 Analysis of Site Operations

As the post-implementation data includes cycle details, this information was used to better understand the daily work procedures on the site. Duration and distance parameters were used to calculate monthly and total averages for each parameter. The aim was first to understand the haul cycles, secondly to see if there are monthly differences. The number of cycles per month and in total was calculated to understand differences in workload. Further, analysis of cycle time stamps during the day showed the working hours of the site and how they changed during the year. Firstly, the earliest and latest time stamps each month were gathered to understand the daily working hours. Secondly, the number of performed haul cycles each hour was also analyzed to understand for example break patterns and busy hours.

Other than understanding the site operations, the parameters were used to compare Use Case 1 to Use Case 2. As they are both China clay mines and the machines are provided by the same subcontractor, the site operation results may help explain differences in the final results. Tables 7 shows all parameters that were used to analyze site operations.

Table 7: Parameters used in the analysis of site operations

Parameter	Area of use
Cycle duration	Calculate monthly and total average
Empty travel duration	
Loaded travel duration	
Empty stop duration	
Loaded stop duration	
Cycle distance	
Empty travel distance	
Loaded travel distance	
Number of cycles	Calculate monthly and yearly total
Time stamp	Understand working hours and daily cycle distribution

3.2.5 Analysis of Differences

To analyze the differences before and after implementation, the data first needed to be processed to make sure that the format was consistent. Firstly, machine hours post-implementation were reported as an increasing total of machine hours per machine, similar to the mileage of other vehicles. However, the desired format was the total machine hours utilized on the site per month. To achieve this, the maximum and minimum reported machine hours for each machine were used to calculate how many hours each machine worked during each month. These numbers were then summarized to achieve the total machine hours on the site each month. The calculation is shown in equation 1. Secondly, the number of loads each month was not directly stated. As each data point corresponds to one haul cycle, the number of loads per month was achieved by counting the number of data points.

$$\begin{gathered}\text{Machine hours}_i = \sum_j \left(\text{Machine hours}_{\text{max},i,j} - \text{Machine hours}_{\text{min},i,j}\right) \\ \text{where } i = \text{months and } j = \text{machine serial numbers}\end{gathered} \tag{1}$$

After ensuring the correct format was used, several different calculations were used to identify differences between the pre and post-implementation years. Firstly, the exact differences were calculated by subtracting the 2019 value each month from the 2020 value for every data category. These differences were then used to calculate percentual change according to equation 2. This was done for all four production categories: machine hours, fuel consumption, number of loads and loaded tonnes. The total differences and percentual changes were also calculated, using the yearly sums of all categories. In addition, yearly averages were calculated to better understand general production differences.

$$\text{Change (\%)} = \frac{\text{Difference}}{\text{Value}_{2019}} = \frac{\text{Value}_{2020} - \text{Value}_{2019}}{\text{Value}_{2019}} \tag{2}$$

Further, the production category values were normalized to compensate for differences in production. For example, rightfully comparing machine hours before and after implementation requires that production remained the same. Therefore, the production categories were normalized based on one category. As loaded tonnes is the production category representing the result of the work conducted at Use Case 1, it served as the basis of normalization.

To normalize the other production categories, they were recalculated to represent the numbers they would have been if loaded tonnes remained the same both before and after implementation. To achieve this, a normalization factor was applied to the 2020 values. The equation applied to calculate the normalized value, Value_n, of the categories machine hours, number of loads and fuel consumption, is presented in equation 3.

$$\text{Value}_n = \text{Normalization factor} \cdot \text{Value}_{2020} = \frac{\text{Loaded tonnes}_{2019}}{\text{Loaded tonnes}_{2020}} \cdot \text{Value}_{2020} \tag{3}$$

Other than analyzing the production categories, three productivity rates based on the collected data were analyzed. The goal was to further understand the procedures and behaviors on the site. These were fuel burn rate, cycle rate and loading rate. The calculations are shown in equations 4, 5 and 6. The rates were analyzed in the same way as the categories, by calculating both monthly and total differences, percentual changes and averages.

$$\text{Fuel burn rate}_i = \frac{\text{Fuel consumption}_i}{\text{Machine hours}_i} \tag{4}$$

$$\text{Cycle rate}_i = \frac{\text{Nr of loads}_i}{\text{Machine hours}_i} \tag{5}$$

$$\text{Loading rate}_i = \frac{\text{Loaded tonnes}_i}{\text{Machine hours}_i} \tag{6}$$

where i = months

3.2.6 Translation to CO_2

Translation to CO_2 was done individually for the different data types. In general, the fuel consumption was translated into emissions but also used to evaluate the site CO_2 productivity quotas. Although, to be able to quantitatively assess the emission impact of other categories of data, they also needed to be translated. This means that increases or decreases in machine hours and number of loads were also translated to CO_2. Averages of the power ranges, categorical diesel consumption and parameters to quantitatively assess emissions from construction equipment presented in section 2.4.1 were used to enable the translation. After translating all data categories, the total emissions of CO_2 were also divided by the daily average number of machines utilized on the site. This eased the comparison of the use case results.

The first step of analyzing the differences in emissions at the site was to translate the fuel consumption into CO_2 emissions. As the fuel is diesel, an average of the CO_2 emissions from diesel consumption presented in 2.4.1 was used. The average (equal to 2.648 $kgCO_2$/liter diesel) was multiplied with the monthly and total fuel consumption before and after implementation of Co-Pilot. It was also divided by 1000 to get the CO_2 emissions in tonnes instead of kg. The applied calculation is shown in equation 7. Further, differences and percentual changes were calculated, as described in the previous section.

$$\Delta tCO_2 = \frac{\Delta \text{Diesel consumption} \cdot 2.648}{1000} \tag{7}$$

Secondly, the difference in machine hours was translated. This was done by multiplying the difference in machine hours with the average power range (equal to 345 kW) and the average emission from diesel fuel (equal to 2.648 $kgCO_2$/liter diesel) and dividing the product by the average power consumption (equal to 9.88 kWh/liter diesel). It was divided by 1000 to get the emissions in tonnes instead of kg. The applied calculation is shown in equation 8.

$$\Delta tCO_2 = \frac{\Delta \text{Machine hours} \cdot 345 \cdot 2.648}{9.88 \cdot 1000} \tag{8}$$

Thirdly, the difference in the number of loads was also translated. This was done by multiplying the difference in number of loads with the average power (equal to 345 kW), the average site cycle duration and average emission from diesel fuel (equal to 2.648 $kgCO_2$/liter diesel) and dividing the product by the average power consumption (equal to 9,88 kWh/liter diesel). Once again, it was also divided by 1000 to get the CO_2 emissions in tonnes instead of kg. The applied calculation is shown in equation 9.

$$\Delta tCO_2 = \frac{\Delta \text{Nr of loads} \cdot \overline{\text{Cycle duration}} \cdot 345 \cdot 2.648}{9.88 \cdot 1000} \tag{9}$$

After translating all data categories, the emissions from fuel consumption were used to analyze the site CO_2 productivity quotas. The following quotas were applied as productivity measures: machine hours, loaded tonnes and number of loads per tCO_2. These quotas represent the production per tCO_2 before and after implementation, independent of yearly differences, changed needs or other external circumstances. Therefore, they are seen as the final result of the data analysis.

3.2.7 Visualization

Several different methods were used to visualize the results. Firstly, the values in all data sheets were colored green or red depending on if they were positive results or not. This was to easily visualize positive and negative trends. What was considered a positive result depended on the data that was analyzed. For example increases in productivity are positive, while increases in fuel consumption are negative.

Secondly, the results were visualized using different charts. Bar, pie and line charts were used depending on the type of data. The same data could also be visualized in several ways to compare the effectiveness and clarity.

3.2.8 Validation with Subcontractor

To further understand the results, they were validated together with the manager from the subcontractor firm who provided the data. The validation objectives are shown in table 8. In general, the purpose was to deepen the understanding of the data and results.

Table 8: Objectives of the result validation

1	Understand how the data was collected and the quality of it.
2	Understand circumstances that may impact the analyzed data categories, such as differences in yearly demand or the material.
3	Understand potential causes of the results that were computed in the study.
4	Validate conclusions regarding site procedures.

The validation was an open discussion centered around result values and charts, to allow dialogue and follow-up questions. During the validation, mainly three different topics were discussed. Firstly, the collection and quality of data. Secondly, deviating results, charts and numbers. Thirdly, general results, charts and conclusions, to understand if they were aligned with the manager's own view of the site or not.

3.3 Use Case 2

Use Case 2 is the second China clay mine that operates machines provided by the previously mentioned subcontractor. As the site characteristics and the collected data are very similar to Use Case 1, the research approach is also very similar. This section presents a description of Use Case 2, along with method adaptations in data collection, data validation and analysis. There are no adaptations in the visualization or validation of results, therefore they are not described for Use Case 2.

3.3.1 Description

Similar to the first use case site, the second is a China clay mine. The machines at the site are provided by the same subcontractor as the first use case. Therefore, the machine types are the same on both sites. According to the subcontractor, Co-Pilot is also implemented and utilized in the same way.

On average, five dumper trucks worked on the site daily during 2020. In comparison to the first use case, the site for Use Case 2 is much smaller. The total area is approximately 4.55 km^2, divided into three main zones, as seen in figure 9, where the site is visualized. As mentioned in the first use case, the machines work in all different zones.

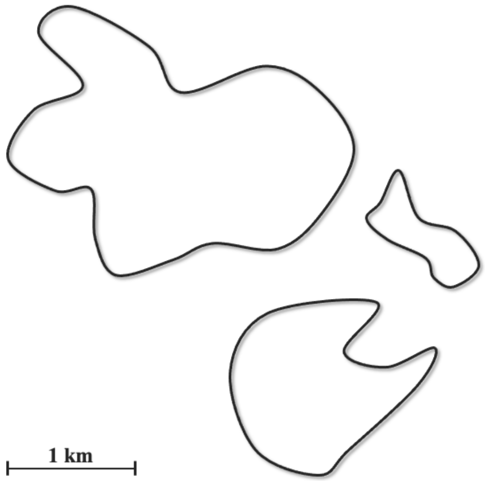


Figure 9: Visualization of the second use case site

3.3.2 Data collection

Compared to the first use case, the first difference is what data categories were reported before the implementation of Co-Pilot. Similar to Use Case 1, fuel consumption and machine hours were reported. Although, loaded tonnes and number of loads are not included. Secondly, the time period is different. Reporting started in December 2013 and was performed weekly until December 2018. After that, reporting was done monthly until Co-Pilot was implemented in January 2020. A summary of the collected data from Use Case 2 is shown in table 9.

Table 9: Summary of the data that was collected from Use Case 2

	Time period	**Categories**
Before implementation	Dec 2013 - Dec 2019	Fuel consumption
		Machine hours
After implementation	Jan 2020 - Mar 2021	Fuel consumption
		Machine hours
		Nr of loads
		Loaded tonnes
		Cycle details E.g., durations and distances

3.3.3 Validation of Data

For Use Case 2, the same full years before and after implementation as for Use Case 1, 2019 and 2020, were included in the study. The yearly sums of data categories are shown in figure 10. Based on this, the choice of analyzing 2019 is motivated in the same way as for Use Case 1; it is the most recent and does not deviate from the other years in the charts.

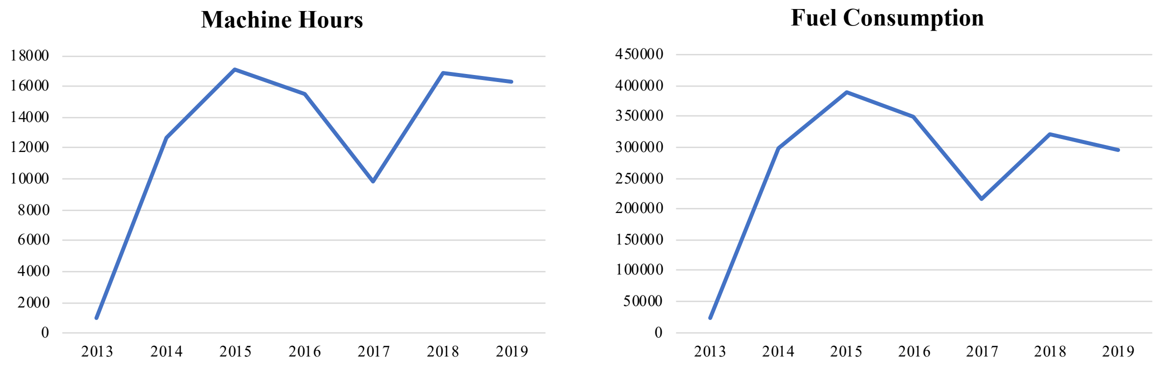


Figure 10: Yearly sums of the categories used to validate the choice of what year before implementation to include in the study

3.3.4 Analysis

Analysis of the data was performed in the same way for Use Case 2 as Use Case 1, with only two exceptions. The first difference is a consequence of the fewer data categories. As mentioned earlier, number of loads and loaded tonnes were not included in the pre-implementation data from Use Case 2. Therefore, these categories could not be analyzed or translated. Consequently, only one of the productivity rates could be analyzed, fuel burn rate.

As neither loaded tonnes nor number of loads were available, the second difference is that the normalization was based on machine hours. As only machine hours and fuel consumption were available, machine hours was chosen as the category primarily representing the work conducted at the site. Hence, the fuel consumption values were normalized according to equation 10.

$$\text{Fuel consumption}_n = \text{Normalization factor} \cdot \text{Fuel consumption}_{2020} = \frac{\text{Machine hours}_{2019}}{\text{Machine hours}_{2020}} \cdot \text{Fuel consumption}_{2020} \tag{10}$$

3.4 Use Case 3

The third use case is very different compared to the first two. Therefore, there are many adaptations in the research approach, mainly in the received data and the required data processing. Moreover, interviews were performed solely on the third use case site. This section first presents a description of the site, followed by adaptations in the data analysis. Lastly, preparation, execution and analysis of interviews are described.

3.4.1 Description

The third Haul Assist use case is a gravel processing site. Geographically, it consists of two separate zones connected by a road. One of the zones is a gravel pit where the gravel is extracted, and the other performs the processing. Hence, the gravel needs to be transported between the zones. The distance between the zones is approximately 3,6 km and the total area is 0.4 km^2. A visualization of the site is presented in figure 11.

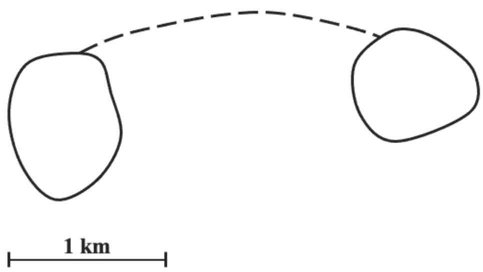


Figure 11: Visualization of the third use case site

Trucks are used to transport the gravel in and between the zones. In total, three trucks, one wheel loader and a spare truck have installed and use Co-Pilot and the Haul Assist application. Even though the typical users of Haul Assist are dumpers, the trucks at the site utilize the functionality in the same way. Therefore, the trucks at the site were considered equal to dumpers in the study and results were evaluated accordingly.

3.4.2 Data Collection

The data that was received from Use Case 3 includes production and fuel consumption data from one year before implementation (2019) and one year after (2020). In comparison to Use Case 1 and 2, the data from Use Case 3 was received directly from the transportation manager of the site and not from a subcontractor. In the production data set, number of loads and hours per week were reported each year. In the fuel consumption data set, the total diesel consumption per month was reported, but also the diesel use allocated to the categories driving, idling and power take-off (PTO). PTO refers to the power it takes to transmit energy from the engine to other systems of the truck, for example the hydraulic system used to dump the material in the bucket. Moreover, the total AdBlue consumption was included. AdBlue is a liquid added to diesel engines to reduce emissions of pollutants, mainly NO_x. Table 10 presents a summary of the received data from Use Case 3.

Table 10: Summary of the recieved data from Use Case 3

<table>
<tr><th>Data set</th><th>Time unit</th><th>Categories</th></tr>
<tr><td rowspan="2">Production</td><td rowspan="2">Weekly data points</td><td>Nr of loads</td></tr>
<tr><td>Machine hours</td></tr>
<tr><td rowspan="5">Fuel consumption</td><td rowspan="5">Monthly data points</td><td>Total diesel consumption</td></tr>
<tr><td>Driving</td></tr>
<tr><td>Idling</td></tr>
<tr><td>PTO</td></tr>
<tr><td>AdBlue</td></tr>
</table>

3.4.3 Validation of Data

As previously mentioned, the fuel consumption data included total diesel consumption as well as categorical consumption. According to the transportation manager, the sum of the categories driving, idling and PTO should correspond to the reported total consumption. Before analyzing the data, it was validated by comparing the reported total to the sum of categories. The percentual deviation was calculated, according to equation 11.

$$\text{Deviation (\%)} = \frac{\text{Total consumption} - (\text{Driving} + \text{Idling} + \text{PTO})}{\text{Total consumption}} \tag{11}$$

Table 11 shows the percentual deviation between the reported total consumption and the sum of categories. In the table, negative percentages mean that the sum of the categories is lower than the total consumption. As seen, some months have a larger deviation than others. As a consequence, deviating values were eliminated from the analysis. This will be further explained in the following section.

Table 11: Percentual deviation between the reported total diesel consumption and the sum of categories

	2019	**2020**
Jan	-0.10%	0.00%
Feb	-0.13%	-33.1%
Mar	-0.20%	-33.1%
Apr	-0.14%	-33.6%
May	-0.15%	-25.8%
Jun	-0.12%	-26.6%
Jul	-0.12%	-42.5%
Aug	-0.13%	167%
Sep	-0.11%	-0.13%
Oct	-0.12%	-0.13%
Nov	-0.12%	-0.11%
Dec	-0.10%	-0.14%

3.4.4 Elimination of Data

In the received production data, several weeks did not contain any values or had values equal to zero, which meant that no work was conducted during these weeks. This applies to both 2019 and 2020. At times, the same weeks were affected both years, most likely during vacations. Including these weeks in the analysis and calculations would result in an unfair comparison as it would benefit one of the two years. Therefore, it was decided to exclude the weeks where no work was conducted. In addition, the corresponding week the other year was also eliminated. Table 12 shows the weeks that were affected.

Table 12: Weeks that were excluded from the weekly production data

Weeks	Reason	Excluded from
1, 29, 30, 31	Vacation weeks. Applies for both years.	2019 and 2020
10, 11, 52	No work conducted during 2019	2019 and 2020
6, 17, 18, 19, 20, 32, 46	No work conducted during 2020	2019 and 2020

Moreover, to secure the quality of the data and make sure that the results represent the actual site performance, unreasonably deviating results were eliminated. Firstly, the categorical fuel consumptions were eliminated for all months that had a deviation higher than 1% any of the years in table 11. According to the transportation manager, these deviations must be caused by a software bug in the reporting system. Figure 12 shows the total consumption and the sum of categories for both years. As seen in the figure, the total consumption values 2020 look accurate, while the sum of categories is clearly deviating. This justifies the choice to keep the total consumption values and eliminate the categories. During 2019 the total consumption is exactly equal to the sum of categories.

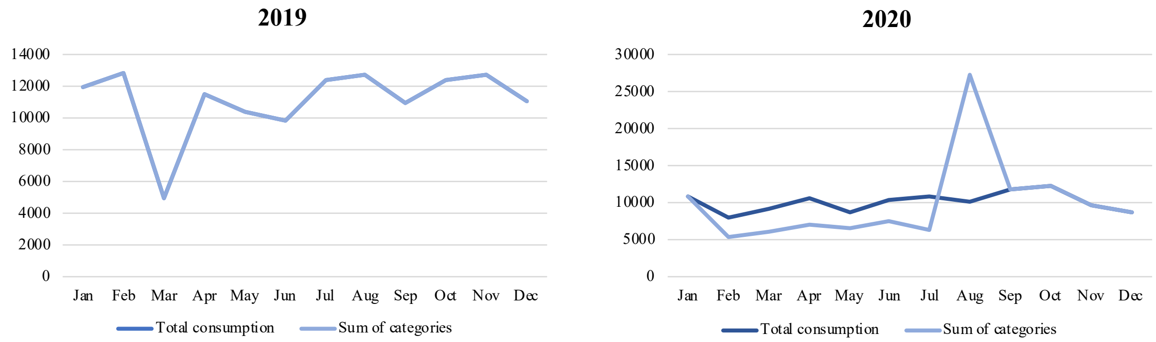


Figure 12: Total fuel consumption compared to the sum of categorical consumption

Secondly, the total fuel consumption in March 2020 was significantly larger than it was in March 2019. As seen in figure 12, March 2019 has an unrealistically low fuel consumption compared to the rest of the year. Therefore, the total consumption values were eliminated for March both years. As the categorical fuel consumption values in March were also eliminated due to the previously described deviation, no March values remained.

After eliminating values, a majority of the total fuel consumption values remained. On the other hand, several categorical values were eliminated. This means that total consumption results are of higher importance than the categorical ones, as they are based on larger amounts of data. Table 13 shows the values remaining after elimination. All values marked with ”x” in the table were kept.

Table 13: Values that remained after elimination and were included in the forthcoming analysis

	Total fuel consumption	**Fuel consumption by category**
Jan	x	x
Feb	x	x
Mar		
Apr	x	
May	x	
Jun	x	
Jul	x	
Aug	x	
Sep	x	x
Oct	x	x
Nov	x	x
Dec	x	x

3.4.5 Compensation Factors

Compensation factors were used to enable comparison of the data sets before and after implementation. As the pre and post-implementation data correspond to different years, there are differences in working days, holidays and active time. Comparing these data sets without compensating the yearly differences would show results that are not implied by the use of Co-Pilot. The first step of compensation was to identify the weeks where there are differences in the number of working days. Secondly, these weeks and their corresponding working days were used to calculate compensation factors. Thirdly, the data sets were compensated by multiplying the affected values in the received data with the compensation factor, according to equation 12.

$$\text{Compensated value} = \text{Received value} \cdot \text{Compensation factor} \tag{12}$$

To compensate the weekly data, the production data was transformed to allow equal comparison of the same week's data from the two different years. The compensation factor, C_W, was based on the maximum and minimum number of worked days during each week any of the two years. The calculation of the factor is shown in equation 13. A compensation factor was calculated for every week with a misaligned number of working days, resulting in the compensation factors presented in table 14. In this way, the values of weeks containing fewer working days during one of the years were transformed to the hypothetical values they should have been if the number of working days was equal. Moreover, since the production data was received in weeks it had to be converted into months to make it possible to use together with the data on fuel consumption.

$$C_W = \frac{\text{Maximum number of working days}}{\text{Minimum number of working days}} \tag{13}$$

Table 14: Compensation factors, C_W, used to compensate the weekly production data

Week	Year	C_W
15	2020	1.67
21	2020	1.67
22	2019	1.67
23	2019	1.25

To compensate the monthly fuel consumption data, the fact that months had different numbers of working days during different years and that different weeks have been inactive or allocated to holidays was taken into consideration. Therefore, the compensation factors, C_M, were calculated based on the average number of working days each month and the actually worked days. The average number of working days is the average of the same months working days during the two years. The calculation of the compensation factors is shown in equation 13 and the used factors in table 15.

$$C_M = \frac{\text{Average working days}}{\text{Worked days}} \tag{14}$$

Table 15: Compensation factors, C_M, used to compensate the monthly fuel consumption data

	2019	2020
Jan	1.13	1.13
Feb	1.33	1.33
Mar	1.34	0.98
Apr	1.00	1.82
May	0.95	2.22
Jun	1.08	0.93
Jul	2.30	2.88
Aug	1.08	1.34
Sep	1.02	0.98
Oct	0.98	1.02
Nov	1.00	1.31
Dec	1.18	0.95

3.4.6 Analysis

As no cycle details were provided in the data from Use Case 3, site operations were not analyzed. Also, all data were reported monthly, after converting the weekly production data, which meant that no data processing was needed. Therefore, differences and percentual changes could be calculated directly. Regarding categories of data, loaded tonnes could not be analyzed as it was not included in the data that was received from Use Case 3. As a consequence, only two of the productivity rates were analyzed: fuel burn rate and cycle rate.

Further, as loaded tonnes were not available, the normalization was based on the number of loads. Compared to machine hours and fuel consumption, it was considered the category primarily representing the work conducted at the site. Hence, machine hours and fuel consumption values were normalized according to equation 15.

$$\text{Value}_n = \text{Normalization factor} \cdot \text{Value}_{2020} = \frac{\text{Nr of loads}_{2019}}{\text{Nr of loads}_{2020}} \cdot \text{Value}_{2020} \tag{15}$$

3.4.7 Translation to CO_2

Translation to CO_2 was performed in the same way for Use Case 3 as for Use Case 1. The only exception is the quota loaded tonnes per tCO_2 that could not be calculated, as there was no data on loaded tonnes. Further, the translation of the number of loads was calculated differently. As the transportation distance is known and constant at the site, it was used in the translation. Therefore, the difference in number of loads was multiplied with the transportation distance, the average value for categorical diesel consumption (equal to 0.22 liter/km) and the average emission from diesel fuel (equal to 2.648 $kgCO_2$/liter diesel). The product was also divided by 1000 to get the emissions in tonnes instead of kg. The applied calculation is shown in equation 16.

$$\Delta tCO_2 = \frac{\Delta \text{Nr of loads} \cdot \text{Transportation distance} \cdot 0.22 \cdot 2.648}{1000} \tag{16}$$

3.4.8 Validation with Transportation Manager

Similar to for Use Case 1 and 2, the results were validated in order to further understand them. In comparison to the first two cases, this one was done with the transportation manager of the site and not with a subcontractor. Otherwise, the same objectives were applied and the validation was performed in the same way.

3.4.9 Preparation and Execution of Interviews

Interviews were conducted solely for Use Case 3, in addition to compiling the received data. As explained in section 2.3.1, qualitative approaches can help explain quantitative findings (Steckler et al., 1992). The interviewees were the transportation manager and one operator of the site. The site is relatively small with just a few operators working daily and therefore solely these two interviews were performed. However, the interviews were only meant to be used as a complement to the quantitative analysis and were not seen as a separate study. Therefore, only a few interviewees were obtainable. Interview questions were prepared in advance and differed depending on the intended interview target. Two different interview guides were created and the time frame of each interview was 30 minutes.

Three different categories of questions were asked. Firstly, an introduction that included a short description of the purpose and goal of the interview. This was followed by two questions that clarified for how long the respondent had worked on the site and if he or she had worked there before implementation of Co-Pilot. The second part of the interview guide was called data collection and contained questions aiming to support, clarify and explain the previously received performance and production data and its results. The third and last section of the interview guide was named evaluation and consisted of a few questions to let the respondents speak freely about their opinions regarding Co-Pilot.

The last part was mainly supposed to enable an analysis of how Co-Pilot can be further developed and improved, whilst the second part was used to understand identified differences from before and after implementation of Co-Pilot. Both parts were of a semi-structures nature as they call for discussion and argumentation. All questions can be found in appendix A and appendix B. All interviews were carried out in person on the site and were recorded. Both interviews were performed in Swedish as this was desired by the interviewees.

3.4.10 Analysis of Interviews

The methodology applied to analyze the conducted interviews was based on and adapted from the thematic analysis framework proposed by Vaismoradi et al. (2016). The first step of the analysis was to transcribe the recordings. Everything that was said during the interviews, both by the interviewer and the interviewees, was carefully written down.

Secondly, the transcriptions were thoroughly read through several times and important quotes or information were marked and a note explaining its importance was added. It could be information that was repeated multiple times, was surprising, could be related to the previously received data or that was highlighted by the interviewees themselves as very important.

Thirdly, all the marked information was grouped into different categories based on their resemblance. Information and quotes that were similar to each other or that treated the same subject were put in the same category. In total, five categories were created and all were given appropriate names that described their content. Moreover, one of these categories included a lot more quotes than the other four and therefore this category was also divided into five subcategories.

4

Results

This chapter presents the final results of the study. Firstly, results are presented individually for each use case. Secondly, all data results are summarized and the use cases are compared to each other. As Use Case 1 and 2 are very similar, their site operation parameters are compared to each other at the end of the Use Case 2 section. Lastly, the interview results are presented.

Throughout the chapter, values in all tables are colored green or red depending on if they are positive or negative results. What is considered a positive result depends on the category. For example, increases in loaded tonnes per hour are positive, while increases in fuel consumption are negative.

4.1 Use Case 1

The data results from Use Case 1 are divided into production, productivity and CO_2 quotas. Further, results are presented from the validation of results discussion. As previously mentioned, Use Case 1 will be compared to Use Case 2 in the next section.

4.1.1 Production

Four production data categories were studied for Use Case 1: machine hours, number of loads, loaded tonnes and fuel consumption. Table 16 presents the percentual change in these categories, from 2019 and 2020. The corresponding difference in yearly tCO_2 is also included in the table. To ease comparison, the corresponding difference in tCO_2 per machine is also presented. Loaded tonnes do not have a direct impact on CO_2 emissions, hence no corresponding difference in emissions is presented. As seen in the table, all production categories are decreasing after the implementation of Co-Pilot. Machine hours represent the biggest percentual decrease, followed by loaded tonnes, fuel consumption and number of loads.

Table 16: Percentual change before and after implementation of Co-Pilot at Use Case 1 and the corresponding difference in tCO_2 emissions for all production data categories

	Change (%)	**ΔtCO_2**	**ΔtCO_2/machine**
Machine hours	-26.4%	-922	-109.8
Nr of loads	-20.7%	-656	-78.1
Loaded tonnes	-24.3%	-	-
Fuel consumption	-22.6%	-542	-64.5

To further visualize the production categories' impact on CO_2 emissions, their share of the total decrease is presented in figure 13. As seen in the figure, machine hours is the biggest contributor. Note that these decreases do not represent the actual decreases in emissions on site, but the translation of decreases in production measures.

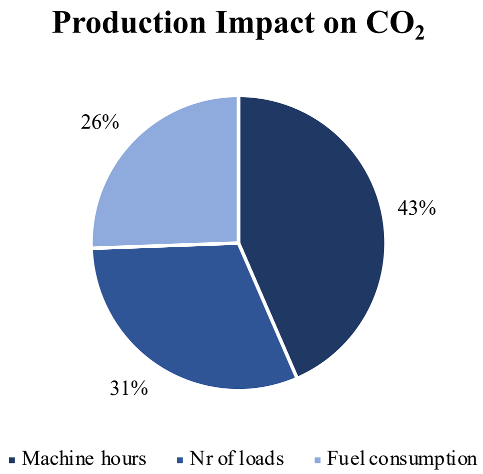


Figure 13: Categorical impact on the total decrease in CO_2

Figure 14 presents bar charts of all production categories during each month in 2019 and 2020. As seen in the figure, machine hours and fuel consumption decrease during all months. Number of loads and loaded tonnes increase in January and June, but decrease during all other months. Even though the values in the chart are not translated into CO_2 emissions, the relationship would be the same if translated. All production data are shown in appendix C.

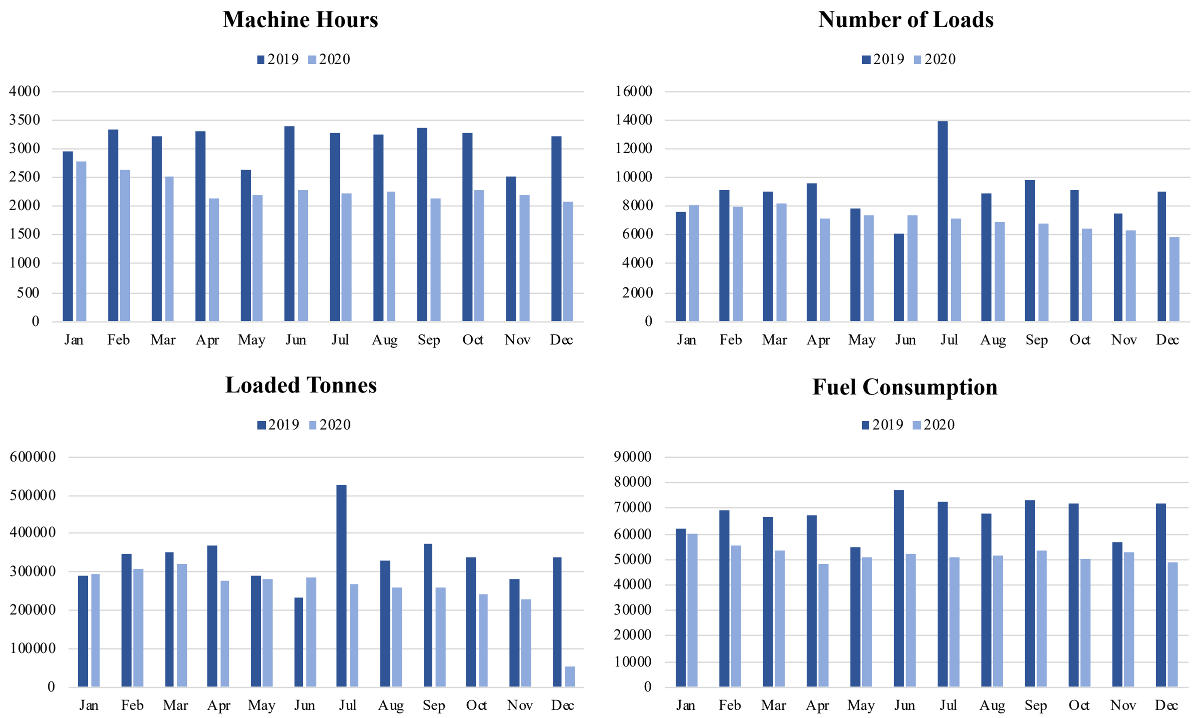


Figure 14: Production category values each month during 2019 and 2020 at Use Case 1

The production category values were also normalized based on the loaded tonnes. The percentual changes after normalizing the values are presented in table 17. As seen in the table, number of loads and fuel consumption are increasing, if assuming that loaded tonnes remained the same. On the other hand, machine hours are decreasing. This means that in 2020, the number of loads and fuel consumption per loaded tonne increased.

Table 17: Percentual changes after normalizing the production values at Use Case 1

	Change (%)
Machine hours$_n$	-2.81%
Nr of loads$_n$	+4.80%
Loaded tonnes$_n$	±0.00%
Fuel consumption$_n$	+2.24%

4.1.2 Productivity

Three productivity rates were analyzed for Use Case 1: fuel burn rate, cycle rate and loading rate. The percentual changes in these rates are presented in table 18. As seen in the table, they are all increasing. For cycle and loading rate, this is positive, as the productivity is increasing. On the other hand, an increasing fuel burn rate means that more fuel is consumed per hour, which is considered negative.

Table 18: Percentual change in productivity rates at Use Case 1

	Unit	**Change (%)**
Fuel burn rate	l/h	+5.19%
Cycle rate	#/h	+7.83%
Loading rate	t/h	+2.89%

4.1.3 CO_2 Quotas

The final result of the data analysis at Use Case 1 is the CO_2 quotas. Yearly, machine hours and loaded tonnes per tCO_2 are both decreasing, while nr of loads per tCO_2 is increasing. Hence, two out of three results are negative. The yearly percentual changes are presented in table 19.

Table 19: Percentual change in the CO_2 quotas at Use Case 1

	Unit	**Change (%)**
Machine hours	h/tCO_2	-1.61%
Nr of loads	$\#/tCO_2$	+2.27%
Loaded tonnes	t/tCO_2	-11.4%

Looking at the monthly percentual changes, there are significant differences. As seen in figure 15, nr of loads and loaded tonnes per tCO_2 follow the same pattern, with the highest increase in June. Machine hours per tCO_2 has more negative changes, even though the deviation interval is smaller than for the other two quotas.

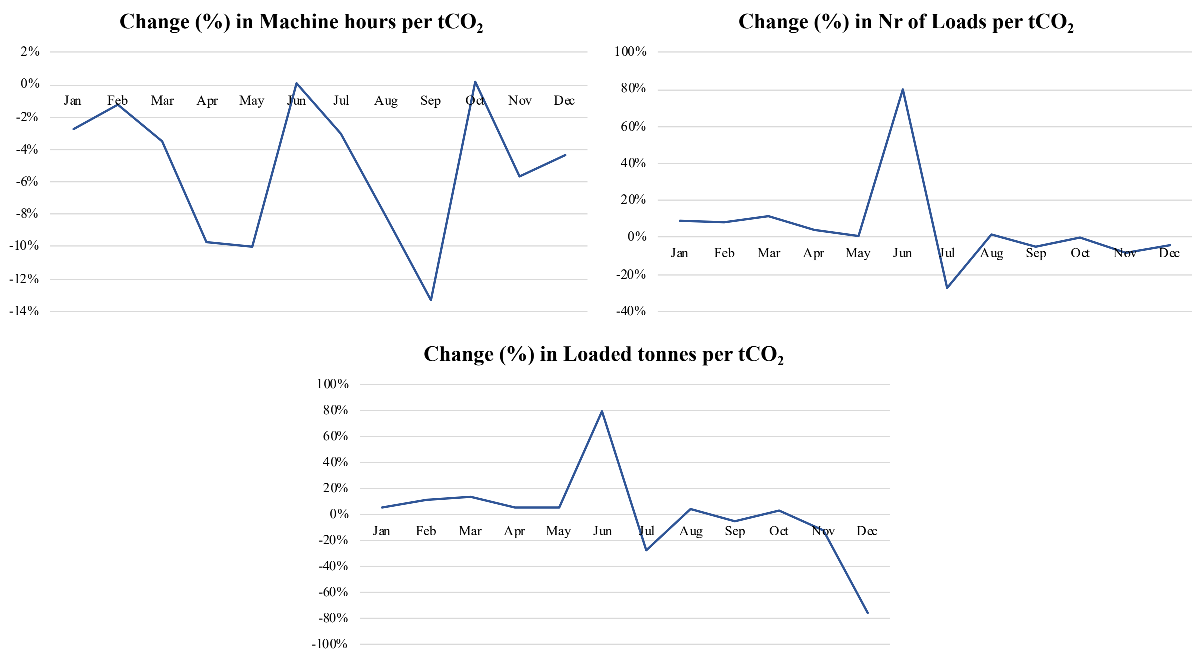


Figure 15: Percentual change in CO_2 quotas at Use Case 1

4.1.4 Validation with Subcontractor

The following list presents insights from the validation of results that was performed together with the subcontractor.

- The pre-implementation data was collected through a previously used system. The system enabled downloading of machine and productivity data. However, it was used solely for fleet management and not by the operators.
- The post-implementation data is more detailed. It is gathered by Co-Pilot and can be downloaded from a separate, but linked, software provided by Volvo.
- Only the dumper trucks have installed and use Co-Pilot. However, the subcontractor wants to implement it in all machines and is currently discussing this with Volvo.
- Both Use Case 1 and 2 perform the same type of work, produce the same material and are located in the same area.
- The subcontractor is not surprised by the negative results. They themselves have identified problems and studied the causes. For example, fuel burn rate was decreasing from 2013 to 2018, but started increasing in 2019. However, the implementation of Co-Pilot is not considered a negative contributing factor.
- Several possible reasons explaining the negative results and trends are highlighted:
  - The site has a high and volatile operator and employee turnover.
  - Operators operate up to eight different machines.
  - The contract changed in 2019, and the subcontractor started supplying not only the machines but also the operators.
  - The site pit is much deeper compared to the second use case site.
  - Normally, almost half of the dumper truck fleet is updated yearly due to wear. Due to the current pandemic, this was not done in 2020.

4.2 Use Case 2

Also the data results from Use Case 2 are divided into production, productivity and CO_2 quotas. Further, results from the validation of results discussion are presented. Lastly, site operation results from Use Case 1 and 2 are compared.

4.2.1 Production

Two data categories were studied for Use Case 2: machine hours and fuel consumption. Table 20 presents the percentual change in these categories, from 2019 to 2020. The corresponding difference in yearly tCO_2 emissions is also included in the table. Once again, the corresponding difference in tCO_2 per machine is also presented. As seen in the table, all production categories are decreasing after the implementation of Co-Pilot.

Table 20: Percentual change before and after implementation of Co-Pilot at Use Case 2 and the corresponding difference in tCO_2 emissions for all production data categories

	Change (%)	**ΔtCO_2**	**ΔtCO_2/machine**
Machine hours	-17.3%	-260	-56.5
Fuel consumption	-21.3%	-222	-48.3

Each category's impact on the total decrease in CO_2 emissions is presented in figure 16. As seen in the figure, machine hours is the main contributor. Although, the difference is only approximately eight percentage points. Once again, note that these decreases in emissions do not represent the actual decreases on the site, but the translation of decreases in production measures.

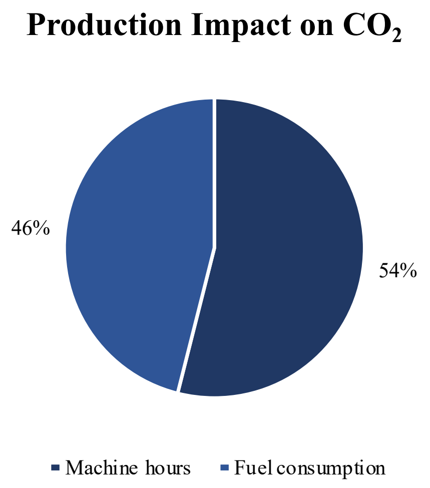


Figure 16: Categorical impact on the total decrease in CO_2

Figure 17 presents both production categories during each month in 2019 and 2020. As seen in the figure, both are increasing in January and June. Further, the fuel consumption increases also in May. This means that number of loads decreases for all months except two, while fuel consumption decreases for all months except three. Even though the values are not translated into CO_2 emissions, the relationship would be the exact same if translated. All production data are shown in appendix D.

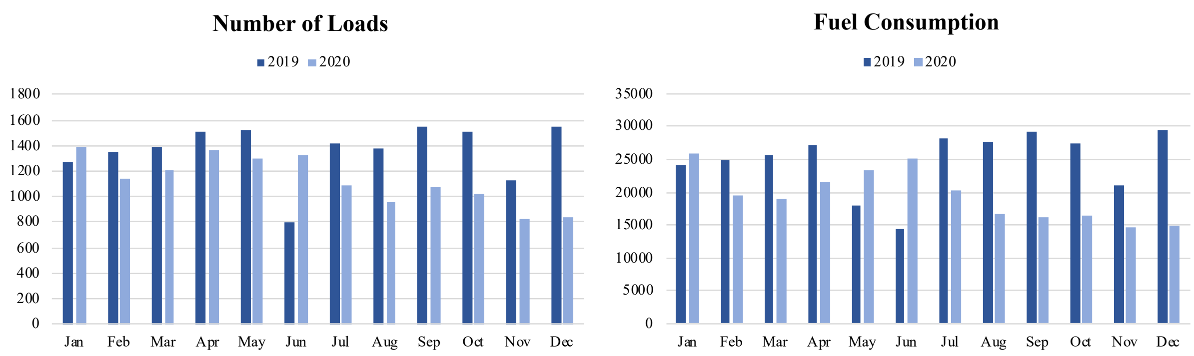


Figure 17: Production category values each month during 2019 and 2020

The percentual changes after normalizing the production values are presented in table 21. As the normalization was based on the machine hours, only the fuel consumption could be normalized. As seen in the table, fuel consumption is decreasing, even after normalization.

Table 21: Percentual change after normalizing the production values at Use Case 2

	Change(%)
Machine hours$_n$	±0.00%
Fuel consumption$_n$	-4.89%

4.2.2 Productivity

Only one productivity rate was analyzed for Use Case 2: fuel burn rate. The yearly percentual change is -4.89%, as seen in table 22. As this means that less fuel is consumed per hour, it is a positive change.

Table 22: Percentual change in productivity rates at Use Case 2

	Unit	**Change (%)**
Fuel burn rate	l/h	-4.89%

4.2.3 CO_2 Quotas

The final result of the data analysis at Use Case 2 is the CO_2 quota. The only computed quota is machine hours per tCO_2. Yearly, the quota is increasing with +15.3%, as seen in table 23.

Table 23: Percentual change in the CO_2 quotas at Use Case 2

	Unit	**Change (%)**
Machine hours	h/tCO_2	+15.3%

There is a lot of deviation in the monthly percentual changes. As seen in figure 18, all months except May and June show a positive percentual change. Although, the amplitudes of the positive percentual changes are different throughout the year.

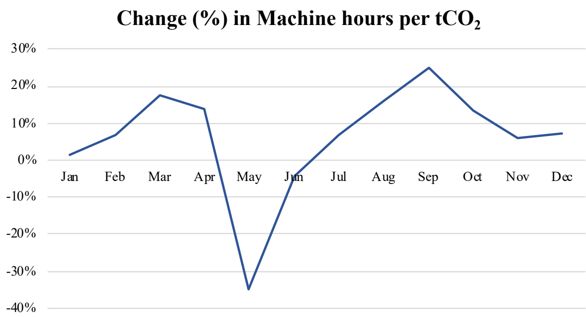


Figure 18: Percentual change in CO_2 quotas at Use Case 2

4.2.4 Validation with Subcontractor

Insights from the validation that was performed together with the subcontractor are presented in the following list.

- Both Use Case 1 and 2 perform the same type of work, produce the same material and are located in the same area.
- The subcontractor themselves have seen great improvements and site results during the last eight years.
- The operator turnover is low and the operators have extensive experience from working on the site.
- The operators operate the same type of machine. As a result, they are highly skilled in the operation of the machines they work with.

4.2.5 Comparison to Use Case 1

To compare Use Case 2 to Use Case 1, the first difference is the number of machines utilized at the site. As previously described, machines may work at both sites during different time periods, as they are supplied by the same subcontractor. Table 24 presents the total number of unique machines utilized at least once during the year before and after implementation at both sites. As seen in the table, all machines worked only at one site before implementation. After implementation, three machines have been active at both sites. There is also a difference in the number of unique machines utilized at the sites. It is even bigger after implementation of Co-Pilot, as the difference before implementation is 5 machines, while it is 10 machines after.

Table 24: Total number of unique machines utilized at Use Case 1 and 2 before and after implementation of Co-Pilot

	Total	Use Case 1	Use Case 2
2019	33	19	14
2020	19	16	6

Further, there is a difference when comparing the average number of machines used per day, according to the descriptions, and the total number of unique machines utilized during the year, in table 24. As presented in the description, on average eight machines operate on Use Case 1 daily during 2020. Compared to the number of unique machines, twice as many unique machines have operated on the site sometime during the year. For Use Case 2, on average five machines are used per day. Compared to the number of unique machines, only one more has worked on the site sometime during the year.

Table 25 presents yearly averages of all site operation parameters for Use Case 1 and 2. The monthly differences are insignificantly small, which justifies the usage of yearly averages. When comparing Use Case 1 to Use Case 2, they are actually very similar. Even though the size of the sites differ significantly according to the descriptions, average durations, distances and payload are indistinguishable. The main exception is the empty stop duration, and consequently the cycle duration. The yearly average empty stop duration at Use Case 2 is about 40% lower than at Use Case 1.

Table 25: Average site operations parameters for Use Case 1 and 2

	Unit	**Use Case 1**	**Use Case 2**
Cycle duration		19:06	16:19
Empty travel duration		05:38	05:35
Loaded travel duration	mm:ss	05:45	05:12
Empty stop duration		04:34	02:46
Loaded stop duration		00:39	00:51
Cycle Distance		2.03	2.06
Empty travel distance	km	1.07	1.07
Loaded travel distance		0.96	0.98
Payload	tonnes	38.3	38.0

Figure 19 shows the division of average cycle duration at both use case sites. As seen, empty and loaded travel duration are the largest fractions at both sites. Although, stop durations are smaller fractions at Use Case 2. Further, there is a better balance between empty stop duration and loaded stop duration at Use Case 2 than at Use Case 1.

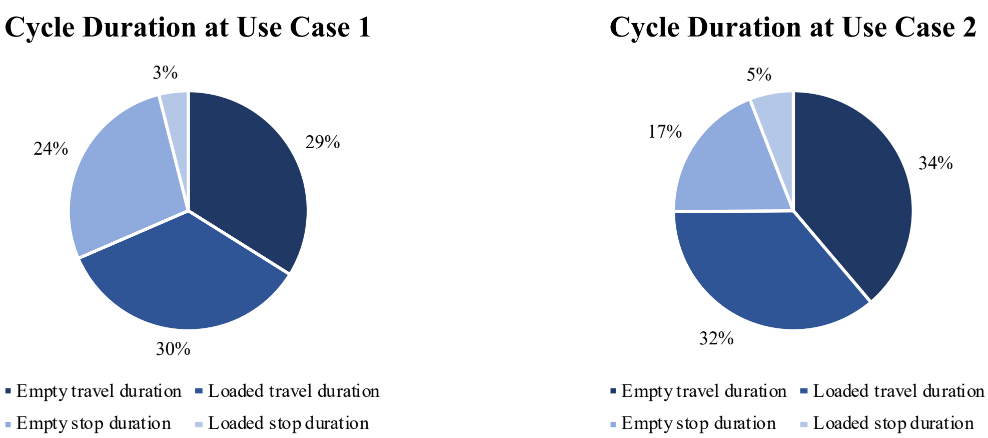


Figure 19: Average division of cycle duration at Use Case 1 and Use Case 2

Table 26 shows the monthly and total number of cycles performed at Use Case 1 and 2 during 2020. In total, 82536 haul cycles are performed at Use Case 1 and 42877 at Use Case 2. This corresponds to a difference of 48%. As seen in the table, this difference is not based on an exception. Throughout the year, almost twice as many haul cycles are performed at Use Case 1 compared to Use Case 2.

Table 26: Monthly and total number of haul cycles at both use cases and the percentual difference

	Use Case 1	Use Case 2	Difference (%)
Jan	7775	4266	45.1%
Feb	8019	3831	52.2%
Mar	8165	4081	50.0%
Apr	6692	4209	37.1%
May	7372	3238	56.1%
Jun	7405	4146	44.0%
Jul	7103	3561	49.9%
Aug	5124	3590	29.9%
Sep	6833	3875	43.3%
Oct	6425	3146	51.0%
Nov	6349	2849	55.1%
Dec	5274	2085	60.5%
Total	82536	42877	48.1%

Figure 20 shows the hourly distribution of the haul cycles at both use cases. Other than a difference in the number of cycles, the chart visualizes a difference in working hours; Use Case 1 has more cycles later in the day than Use Case 2.

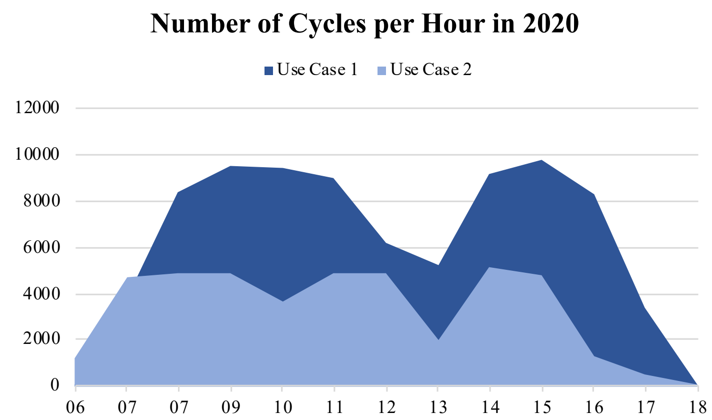


Figure 20: Number of cycles per hour at Use Case 1 and 2 after implementation of Co-Pilot

4.3 Use Case 3

Further, data results from Use Case 3 are divided into production, productivity and CO_2 quotas, and presented accordingly. Results from the validation of results discussion with the transportation manager are also presented.

4.3.1 Production

Several production data categories were analyzed at Use Case 3. Firstly, the production categories number of loads and machine hours. Secondly, the total fuel consumption and the consumption according to the subcategories driving, idling, PTO and AdBlue. Table 27 presents the percentual change in these categories, from 2019 to 2020. The corresponding yearly difference in tonnes of emitted CO_2 is also included in the table. As months were excluded in the analysis, the CO_2 emissions have been converted to represent a full year. To ease comparison to other use cases, the corresponding difference in tCO_2 emissions per machine are also presented. Consumption of AdBlue itself does not emit CO_2, hence no corresponding difference is presented. As seen in the table, all categories are decreasing after the implementation of Co-Pilot.

Table 27: Percentual change before and after implementation of Co-Pilot at Use Case 3 and the corresponding difference in tCO_2 emissions for all production categories

	Change (%)	ΔtCO_2	ΔtCO_2/machine
Production			
Machine hours	-2.45%	-9.20	-3.07
Nr of loads	-0.17%	-0.10	-0.03
Fuel consumption			
Total diesel consumption	-11.9%	-44.1	-14.7
Driving	-17.3%	-60.5	-20.2
Idling	-21.6%	-3.58	-1.19
PTO	-22.1%	-2.80	-0.94
AdBlue	-28.1%	-	-

To further visualize the impact on CO_2 emissions, each category's share of the total decrease is presented in figure 21. As seen in the figure, fuel consumption stands out as the main contributor. The share implied by the decrease in number of loads is only 0.19%, which is displayed as 0% and makes it too small to be visible in the chart.

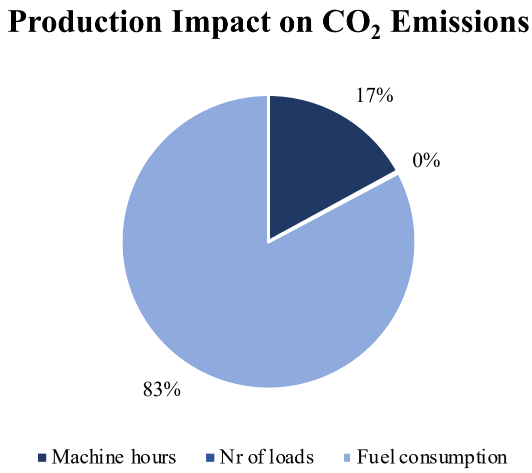


Figure 21: Categorical impact on the total decrease in CO_2

Figure 22 presents both production categories and the total diesel consumption during each month in 2019 and 2020. As previously described, several values in the categories driving, idling and PTO were eliminated. Therefore, no charts are presented. As seen in the figure, machine hours and number or loads follow the same pattern. They are both increasing in March, April, June, July, September and December. Hence, the production categories are decreasing only during 50% of the months. On the other hand, total diesel consumption increases only in June and September. Even though the values are not translated into CO_2 emissions, the relationship would be the exact same if translated. All production data are shown in appendix E.

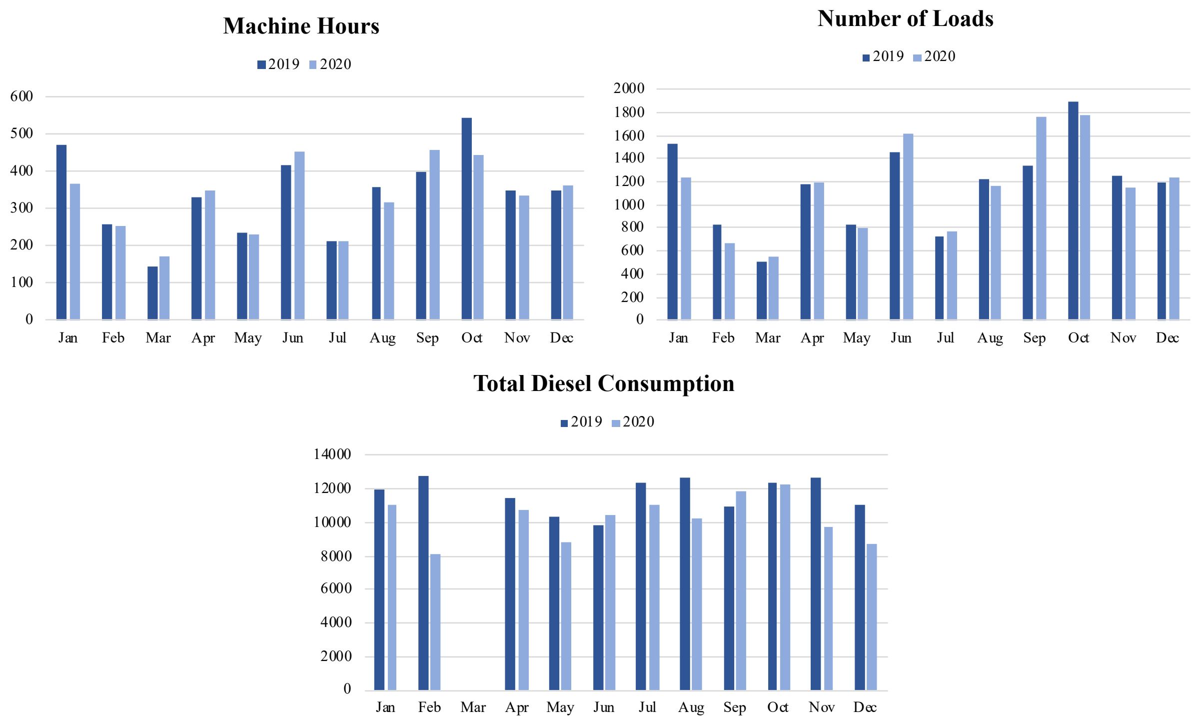


Figure 22: Production category values each month during 2019 and 2020

Further, the production values were normalized based on the number of loads. The percentual changes after normalization are presented in table 28. As seen in the table, both machine hours and fuel consumption are still decreasing. However, the difference compared to the unnormalized values is minimal, as the initial difference in number of loads is only -0.17%.

Table 28: Percentual changes after normalizing the production values at Use Case 3

	Change (%)
Machine hours$_n$	-2.28%
Nr of loads$_n$	±0.00%
Fuel consumption$_n$	-11.8%

4.3.2 Productivity

Two productivity rates were analyzed at Use Case 3: fuel burn and cycle rate. The yearly percentual change in these rates is presented in table 29. As seen in the table, fuel burn rate is decreasing, which is positive as less fuel is consumed each hour. Cycle rate is increasing, which is also positive.

Table 29: Percentual change in productivity rates at Use Case 3

	Unit	**Change (%)**
Fuel burn rate	l/h	-9.00%
Cycle rate	#/h	+2.81%

4.3.3 CO_2 Quotas

The final result of the data analysis at Use Case 3 is the CO_2 quotas. Yearly, machine hours and number of loads per tCO_2 are both increasing, meaning that more is produced per tonne emitted CO_2. The yearly percentual changes are presented in table 30.

Table 30: Percentual change in the CO_2 quotas at Use Case 3

	Unit	**Change (%)**
Machine hours	h/tCO_2	+8.80%
Nr of loads	$\#/tCO_2$	+10.8%

Monthly, there are large differences between the percentual changes. Although, the machine hours and number of loads both follow the same pattern, with negative changes only in January and October. The monthly deviation is presented in figure 23.

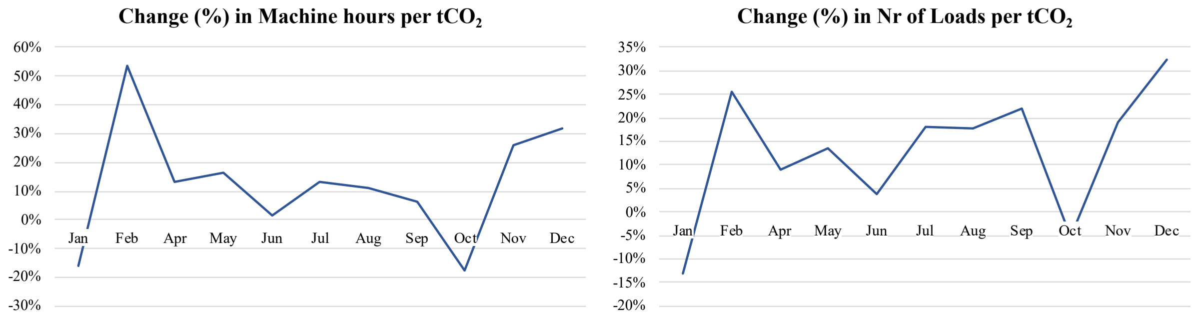


Figure 23: Percentual change in CO_2 quotas at Use Case 3

4.3.4 Validation with Transportation Manager

The following list presents the insights provided by the validation performed together with the transportation manager that may explain the large monthly differences. Moreover, interview results, presented in section 4.5, are also used to understand and validate the results.

- Usually, a two week production stop is planned in February to perform reparations.
- The extruded material differs in terms of easiness to load and transport it.
- The location where gravel is extruded differs from year to year. The distance between these different locations can be up to 400 meters.
- During busy periods, the spare truck can be used to ramp up production. This means that four trucks are active, instead of three which is the ordinary set-up.

4.4 Comparison of Use Cases

To compare the use cases, table 31 presents a summary of all production values. Firstly, Use Case 1 has the biggest percentual decrease in all categories. The difference in emissions per machine is also the biggest for Use Case 1. Secondly, fuel consumption is the most decreasing category at Use Case 2 and 3, while it is the second lowest at Use Case 1.

Table 31: Summary of production categories from all use cases

		Use Case 1	**Use Case 2**	**Use Case 3**
Machine hours	Change (%)	-26.4%	-17.3%	-2.45%
	ΔtCO_2	-922	-260	-9.2
	ΔtCO_2/machine	-109.8	-56.5	-3.07
Nr of loads	Change (%)	-20.7%	-	-0.17%
	ΔtCO_2	-656	-	-0.1
	ΔtCO_2/machine	-78.1	-	-0.03
Loaded tonnes	Change (%)	-24.3%	-	-
Fuel consumption	Change (%)	-22.6%	-21.3%	-11.9%
	ΔtCO_2	-542	-222	-40.5
	ΔtCO_2/machine	-64.5	-48.3	-14.7

Further, table 32 presents a summary of all percentual changes in normalized production values. Firstly, machine hours decrease at both Use Case 1 and 2. Secondly, the fuel consumption decreases at Use Case 2 and 3. Thirdly, the highest, normalized percentual change is the decrease in fuel consumption at Use Case 3. Fourthly, even though the analyzed categories are different, Use Case 1 is the only site with increases after normalization. This means that the efficiency of the site decreased.

Table 32: Summary of all percentual changes after normalizing the production values

	Use Case 1	**Use Case 2**	**Use Case 3**
Machine hours$_n$	-2.81%	±0.00%	-2.28%
Nr of loads$_n$	+4.80%	-	-
Loaded tonnes$_n$	±0.00%	-	-
Fuel consumption$_n$	+2.24%	-4.89%	-11.8%

A summary of all productivity rates is presented in table 33. Firstly, Use Case 3's decrease in fuel burn rate is the biggest single positive change in any rate. Secondly, both Use Case 2 and 3 show only positive results. Use Case 1 has an increase in fuel burn rate, which is considered negative.

Table 33: Summary of all productivity rates from all use cases

	Unit	**Use Case 1**	**Use Case 2**	**Use Case 3**
Fuel burn rate	l/h	+5.19%	-4.89%	-9.00%
Cycle rate	#/h	+7.83%	-	+2.81%
Loading rate	t/h	+2.89%	-	-

A summary of all CO_2 quotas is presented in table 34. Firstly, both Use Case 2 and 3 have only increases in quotas, which is considered positive. Use Case 1 has decreases in two out of three quotas. Secondly, Use Case 2's increase in machine hours per tCO_2 is the biggest single increase in any quota. Thirdly, as the quotas represent the final result of the study, Use Case 2 has the most positive result, followed by Use Case 3. The result of Use Case 1 is considered negative.

Table 34: Summary of all CO_2 quotas from all use cases

	Unit	**Use Case 1**	**Use Case 2**	**Use Case 3**
Machine hours	h/tCO2	-1.61%	+15.3%	+8.8%
Nr of loads	#/tCO2	+2.27%	-	+10.8%
Loaded tonnes	t/tCO2	-11.4%	-	-

4.5 Interviews

This section presents the results from the interviews performed for Use Case 3, divided into five different categories based on the content of the information received. The first category, Employee background information, shortly describes the roles of the interviewees. Secondly, Employee Attitude presents the attitudes expressed regarding the use of Co-Pilot, both currently and right after its implementation. Thirdly, the category Work Procedures describes how the daily work is conducted and the factors affecting it. The fourth category, Co-Pilot Usage, explains how Co-Pilot is used on the site and what positive effects it has had. In addition, this category is divided into the subcategories Planning, Functionality, Performance, Safety and Wheel loader. The fifth and last category, Development Prospects, includes information on possible improvements for Co-Pilot based on what according to the interviewees could work better.

Following some of the categories are pictures including a selection of quotes from the interviews that are a good representation of what was said and the overall results from the interviews. Figure 24 displays the relation between all the categories. In addition, together with each category is some of the most important findings presented in keywords. These are however described more in detail below.

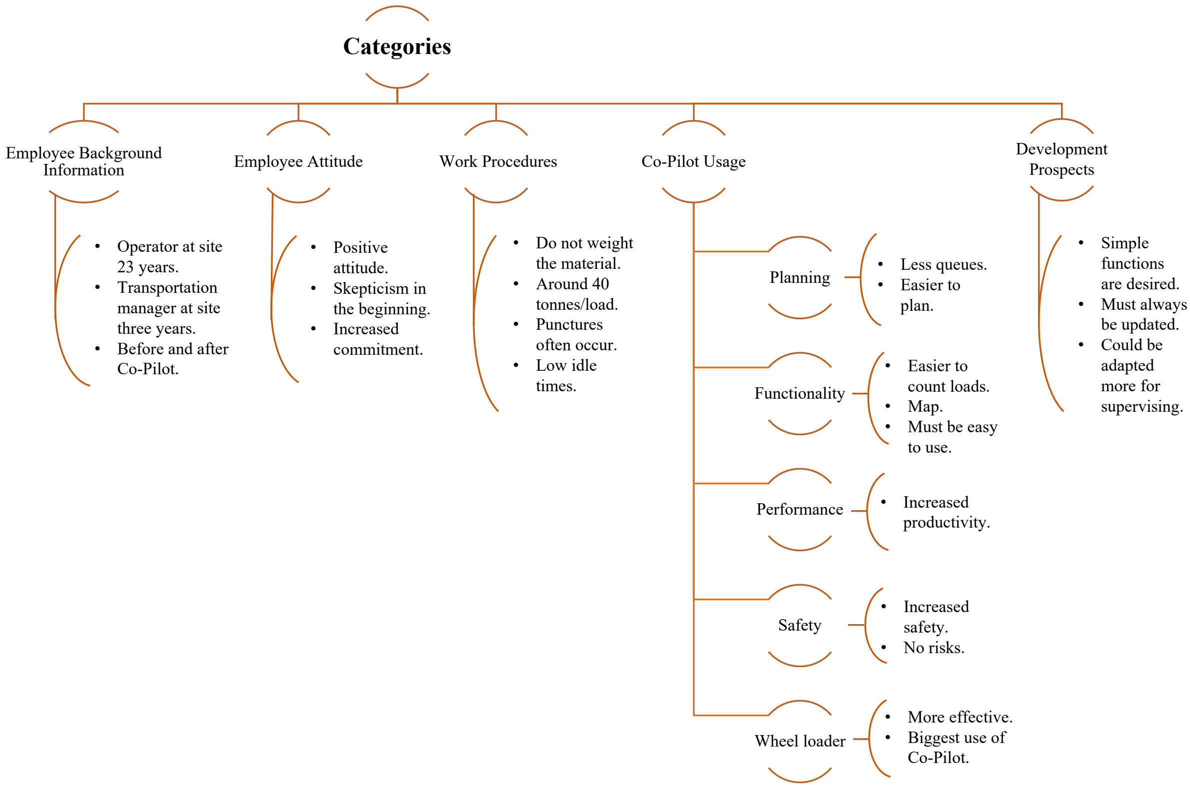


Figure 24: Hierarchy of the interview categories and subcategories together with the most important findings

4.5.1 Employee Background Information

The interviewed operator states that he has worked on the site in turns, both before and after the implementation of Co-Pilot. In total, he has operated trucks and dumper trucks for approximately 23 years. However, he believes that he has used most of the machines available on the site. Further, the transportation manager has had the current role at the company for nine years. He has been supervisor at the site since 2018, so for three years. Both before and after implementation of Co-Pilot.

4.5.2 Employee Attitude

Regarding the attitude towards Co-Pilot, the transportation manager gets the impression that the employees like it. However, it was not as appreciated in the beginning. Right after implementation, there was some skepticism towards it since the display could possibly block the view in the cab. When everything worked fine without flaws, the attitude monumentally changed for the better. The operator states the same, as he believes that especially the older generation might be a bit more skeptical about the new technology. Currently, he is highly positive towards Co-Pilot. Partly because it entails greater commitment among the operators since they at different occasions are contacted by Volvo regarding improvements, and partly since it makes the daily work more fun. He points out that he often looks at the display in order to locate the other operators' positions and thereby plan possible meetings. The transportation manager agrees and adds that the stress level has been lowered since the implementation. Figure 25 presents some of the quotes under this category.

”I guess that the old generation was a bit more skeptical towards it [Co-Pilot] and thought: what are we supposed to use it for? We already find our way around here”
– Operator

Further, it [using the Co-Pilot display] becomes a thing. It is obviously monotonous to just sit and drive all the time. With Co-Pilot, you have something to look at, which I definitely do”
– Operator

”I believe that we are on it pretty fast when things break”
– Transportation manager

”I would say that it [the attitude towards Co-Pilot] is monumentally changed. In the beginning, it was like "oh no not another display in the cab that obscures the view". They [the operators] do already have a lot of stuff in the cab. However, when everything worked without flaws, they themselves realised that it was great! So the attitude has gone from a low level to a high”
– Transportation manager

Figure 25: Quotes regarding Employee Attitude

4.5.3 Work Procedures

The goal at the site is to get as much material as possible from the gravel pit to processing, as they get paid per tonne and thereby get a settlement on how much material has been processed. Therefore, they never weigh the trucks and consequently do not know the exact amount of transported material. However, both the operator and transportation manager approximate it to be around 40 tonnes, whilst the maximum capacity probably is around 45, meaning that they do not load as much as they are allowed to. Moreover, they do not have strict follow-ups on the fuel consumption since this is not included in the economy of the site, only for the owning company. However, the transportation manager mentions that it is still of interest to know how much fuel is consumed.

They usually manage to transport approximately four, sometimes five, loads per hour and there are not a lot of flaws or issues during the daily work. The most common problem is puncture due to the heavy loads. This occurs at least three or four times each week according to the transportation manager. The operator believes that when things like punctures or other issues take place, they are on it pretty fast. Regarding the possibility to dump material at the wrong place, the risk is low as they only have two different places to dump. In addition, the idling time is low since they, according to the operator, rarely have the possibility to stand still. Merely for a couple of minutes during loading. Consequently, the downtime for the site is low. Looking at one entire year, the only noticeable downtime is for two-three weeks during the winter when the crusher is under maintenance. Figure 26 present some of the quotes belonging to this category.

”There is not much idling. We rarely have the time to idle”
– Operator

”Otherwise, it's probably just that you do not turn it [the machine] of... nonsense”
– Operator

”We want to get as much material as possible up from the gravel pit to the processing”
– Transportation manager

Figure 26: Quotes regarding Work Procedures

4.5.4 Co-Pilot Usage

This section describes the five subcategories Planning, Functionality, Wheel loader, Performance and Safety. However, the categories Performance and Safety are shorter than the rest and are therefore presented together.

Both the operator and transportation manager believe that Co-Pilot has reduced the idling time, which also can be seen in the data. Previously, before the implementation, the operators did not know the location of the others and therefore drove as fast as possible in order to be first to loading, dumping and narrow parts of the road. This could result in queues and longer waiting times by the loading and dumping spots. However, now this does not take place anymore as they can see each other and thereby slow down if someone already is, for example, by the loading. Or if there is a meeting at a narrow part of the road, they can easily communicate to ensure that the empty truck is the one slowing down to wait and not the loaded one. In general, the respondent perceives that it is much easier to plan the work. Even without having to use the communication radio at all times. Quotes related to this subcategory are presented in figure 27.

”I believe that there is less idling now [with Co-Pilot] since there is no queuing during loading in the same way as it could be before [without Co-Pilot], when they did not see each other. Previously, they drove on full speed everywhere and all the time. Meaning that if there were any issues down there [by the gravel pit, during loading], all three machines could be waiting in line”
– Transportation manager

”We can see each other, where we are and it makes it easier to plan the driving”
– Operator

”We can see each other and thereby know when you might dare to make an overtake. It is easy to find each other”
– Operator

”Now [with Co-Pilot] we can plan the work without having to use the radio and shout at each other all the time”
– Operator

Figure 27: Quotes regarding Planning

The operator points out the convenience of the fact that Co-Pilot counts the number of completed loads. Previously this had to be done manually by writing down each load. This could easily be forgotten now and then. Except for this, it is mainly the map that is used, not to see where they are going as they already know this, but to locate the other trucks. Whatever Co-Pilot is used for, the operator points out the importance of it having to be easy and uncomplicated for everyone to understand it and wanting to use it even more. For example, once in a while there are temporary operators on the site and they must be able to use it as well. Figure 28 presents two quotes regarding the functionality of Co-Pilot.

”It is really nice and comfortable that the Co-Pilot counts the number loads. Otherwise it is easy to forget. Previously we had to do it manually which made it difficult to remember”
– Operator

”After all, it is the map you look at a lot”
– Operator

Figure 28: Quotes regarding Functionality

Both the operator and transportation manager highlight the positive impact Co-Pilot has had for the operator using the wheel loader. This operator can plan the work significantly better than before and in a highly improved way. As he sees when the trucks are close by, he can be ready with the material to load. Further, if he observes that all the trucks are far away, he can prepare material instead of just waiting. As a result, the transportation manager believes that the wheel loader has become more effective. The operator adds that it was after Co-Pilot was implemented in the wheel loader as well, that the biggest improvements could be seen. It is repeated several times by both the operator and the transportation manager that the operator in the wheel loader has the biggest use of Co-Pilot. Quotes from the interview that highlight the positive impact Co-Pilot has on the wheel loader are presented in figure 29.

"[Name of the operator in the wheel loader] benefits greatly from the Co-Pilot. He really has an extreme use of it because he can see when we [the trucks] arrive. This means that he has the time to prepare when he sees that we are far away"
– Operator

"According to me, the biggest advantage is for the wheel loader operator, and it is that he can plan the work on a whole new level"
– Transportation manager

"Since they put it [the Co-Pilot] in the wheel loader as well, everything has been better"
– Operator

Figure 29: Quotes regarding Wheel loader

Regarding the fuel consumption, the operator believes that it is easier to be more gentle thanks to Co-Pilot. This can also be seen in the data. The transportation manager agrees with this and further states that the increase in productivity most certainly has to do with Co-Pilot. Moreover, it is mentioned that safety has benefited from Co-Pilot and overall there are, according to the transportation manager, no increased risks with the use of it. Rather the opposite.

4.5.5 Development Prospects

The road between the two zones of the site is not only used by the operators. It is sometimes used by civilians as well. However, these civilians are not seen on the displays and can thereby cause queues and consequently slow down the work. In addition, the operator mentions that Co-Pilot is not completely updated at all times. For example, the two dump zones are located close to each other and usually, the operators must enter the first zone to reach the second one. During these times, Co-Pilot can warn as it wrongfully believes that the dumping is done in the passing zone. According to the operator, these warnings are unnecessary as he already knows where to dump the material on this relatively small site. He would rather prefer it to be as easy as possible with simple functions that enable things like "add material", "remove material" and likewise.

Moreover, he mentions that the screen is divided into two parts. One that shows the map and one that displays information regarding the loads. However, it is divided vertically which makes the map really small and consequently the different trucks are visualized on the same location at some times. He means that this makes it more difficult to plan the work as he does not know exactly where the other trucks are. He desires that the screen is divided horizontally instead.

According to the transportation manager, he as a supervisor does not use Co-Pilot as much as he believes could be possible. For example, it is currently possible for him to enter the system and collect the number of working cycles and number of loads per machine. However, he still believes this is easier to do without Co-Pilot. If it would be possible to receive this information automatically by, for example, email as a weekly update instead, he would personally get more out of Co-Pilot. In his opinion, the benefits are entirely for the operators, the working environment and the operations. Figure 30 shows one of the quotes stated by the operator regarding this category.

"It [the Co-Pilot display] does not have to be that advanced with warnings and such. We already know where to put the material. It could be easier with just the functions to "add, remove, go back" or something like that"
– Operator

Figure 30: Quotes regarding Development Prospects

5

Discussion

This chapter first presents individual discussions of each use case. Thereafter, the research questions and the research approach are discussed.

5.1 Use Case 1

Overall, the results from Use Case 1 are considered negative, as only one out of three CO_2 quotas are positive, as seen in table 19. Although, the production results in table 16 are positive. Most likely, the reason is that other production categories are decreasing more than the fuel consumption. This is verified by the normalized values in table 17. If assuming that loaded tonnes remained the same in 2020, number of loads and fuel consumption were actually increasing. This means that more cycles, and hence more fuel, was used to produce the same amount of material. To achieve positive quotas, fuel consumption has to be the most decreasing factor. This is also connected to site performance. If all production factors are decreasing, Co-Pilot has not made a difference. To improve the site efficiency, other production measures should remain the same, while only fuel consumption is decreasing.

Even though the fuel consumption decreases, the fuel burn rate is increasing, as seen in 18. This is considered negative, as more fuel is consumed per hour. Several reasons explaining the increase were discussed during the validation with the subcontractor. Firstly, the site has had a large employee turnover and the operators have operated several different machines. As a consequence, the operators have not been used to the machines that they have operated. This limits the possibility of managing the fuel consumption. Secondly, all operators were new in 2019, as the contract changed and the subcontractor started supplying operators. This means that no operator had more than one year of experience at the site when Co-Pilot was implemented. Thirdly, the dumper trucks have not been changed or updated during 2020, which impacts the fuel consumption due to wear and maintenance needs. Fourthly, compared to Use Case 2, the pit is much deeper. This of course requires a larger fuel consumption but does not explain the increase by itself.

Throughout the year, there are big differences in both production categories and CO_2 quotas. Firstly, the percentual differences in all production categories are small or even negative in January, as presented in figure 14. This may be related to that Co-Pilot was just implemented. As the system is new to the operators, a run-in period may be required to get familiar with it. Secondly, there are big variations in production and quotas that do not follow a specific pattern. This may be explained by differences in the used number of machines, dept of the pit or transportation distances. As the site and work characteristics differ throughout the year, so will the results.

Further, Use Case 1 is the largest of all studied sites. When selecting use cases, the hypothesis was that the size of the site was related to the possibility of seeing positive results, as effectively managing larger transportation routes would have a larger impact on emissions. As Use Case 1 is the only site showing negative results, this does not seem to be the case. Firstly, the transportation distance of the dumper trucks at Use Case 1 is not longer than at Use Case 2, even though the site is bigger. Secondly, larger fleets are harder to effectively manage, as more coordination and cooperation are required. Also, only the dumper trucks at the site have installed Co-Pilot. The importance of installing the system in other types of machines is probably even greater at a large site.

This all results in several development prospects. Firstly, Co-Pilot should be compatible with and installed in as many machines as possible. This would ease communication, cooperation and coordination. The map function can not support route decisions if all possible obstacles are not visible. Secondly, the future development of Co-Pilot should focus on decreasing fuel consumption to have an impact on CO_2 emissions. Thirdly, operator training and consistency are of high importance. If the operators are not used to the system and know how to utilize its' full potential, Co-Pilot does not impact CO_2 emissions. These aspects should impact development and implementation of the product.

5.2 Use Case 2

In general, the results from Use Case 2 are very positive. Production categories, normalization, productivity rates and CO_2 quotas all show positive changes after the implementation of Co-Pilot. Out of all the use cases, the increase in the CO_2 quota at Use Case 2, machine hours per tCO_2, presented in table 23, is the largest. Looking at the production categories in table 20, fuel consumption is the most decreasing. This explains the positive CO_2 quota and productivity rate, as machine hours and fuel consumption has not decreased proportionally.

Furthermore, these results are confirmed by the validation with the subcontractor. According to the subcontractor, they have seen a positive performance and productivity trend. This may be explained by the fact that the employee turnover is low and that operators have operated the same machines. In addition, the number of machines utilized on the site during 2020 is almost equal to the average number of machines utilized per day. This means that the fleet has not been updated or changed during Co-Pilot's first year of use. In addition, the site haul cycles are very balanced when looking at the cycle duration in figure 19. Empty and loaded travel duration are very equal, while the balance between empty and loaded stop duration is better than at Use Case 1. This means that there are not many weaknesses in site procedures and operations.

Even though the results are positive, there was no available data on number of loads or loaded tonnes before implementation of Co-Pilot. This means that no conclusive findings considering these categories could be achieved. Hypothetically, the results would be similar to the machine hour trend, as they are connected in the results of other use cases. Although, this has not been studied and can not be concluded. To state that Co-Pilot has the largest impact on Use Case 2, the same data categories as for the other use cases should be studied. As these categories are measured today, after the implementation, it is not a development prospect, even though it had a negative effect on the study.

Moreover, the only development prospect at Use Case 2 is that Co-Pilot is installed solely in the dumper trucks; As cooperation is seen as one of the main benefits, it should be installed in all machines operating at the site. In contrast, the staff characteristics at Use Case 2 confirm the need for operator training and consistency. As consistency was mentioned as a success factor by the subcontractor, it should impact the future development of Co-Pilot.

5.3 Use Case 3

Overall, the results from Use Case 3 are considered positive. The fuel burn rate has decreased and the cycle rate has increased, as seen in table 29. Moreover, the CO_2 quotas in table 30 have increased both regarding machine hours and number of loads. Meaning that more hours are worked and a greater number of loads are transported per tonne CO_2. These positive and almost optimal results can be achieved as the differences in machine hours and number of loads are low while the difference in diesel consumption is high, as seen in the production data in table 27. This is verified by the normalized values in table 28. Even after normalization, there is a large decrease in fuel consumption.

As previously described, several of the monthly data on fuel consumption by category had to be removed as the sum of categories clearly deviated from the total fuel consumption. Consequently, solely the total consumption was worth considering when analyzing the results, not the categories. Meaning that the productivity rates and CO_2 quotas are only based on the total consumption. However, if the data on fuel consumption by category would have been more accurate, these could have been considered as well and consequently, even more precise results could have been achieved.

Furthermore, it can be clearly seen that the percentual change in both machine hours and number of loads per tCO_2 deviate in January, as the values for this month are negative compared to the values during the rest of the months in figure 23. However, according to the transportation manager of the site, there were some issues and struggles right after the implementation of Co-Pilot and it required a run-in period for all the operators to get familiar with it and get it to work correctly. This could explain the negative values at the beginning of the year. Moreover, during the interviews, both the transportation manager and the operator expressed how the attitude towards Co-Pilot has changed significantly. Right after the implementation there was a lot of skepticism. This suggests that in addition to getting Co-Pilot to work correctly, a run-in period should be expected in order to enable the operators to get used to and accept the new way of working.

During validation with the transportation manager, it was found that the transported material can differ in size and quality and the transportation distance can vary by up to 400 meters. This can explain why the monthly differences are as large as they are for this site. On the other hand, during validation, it was also stated that there usually is a two week long pause in February. This could however not be seen in the data that was received.

For the production data categories, machine hours and number of loads are currently presented. However, in the received data the category loaded tonnes was also included and displayed the total amount of transported tonnes per week. Nevertheless, this category is not included in the calculations. This is because, during the interviews, it was mentioned by the transportation manager that the trucks are never weighed and therefore the exact amount of transported material is unknown. The noted value is an estimation of 40 tonnes per load. Consequently, the category loaded tonnes was the product when multiplying 40 by the number of loads. Therefore, this category was not included. However, if the trucks would have been weighed, a more precise value could have been received and the category loaded tonnes could also have been included in the calculations and results.

During the interviews, it appears that the idling time is believed to be low as they rarely have the time to stand still. This corresponds quite well to the received data on fuel consumption which shows that, in comparison to for example driving, the idling time is significantly much lower. However, the difference in fuel consumption due to idling is bigger than the difference in fuel consumption due to driving. Meaning that, since the implementation of Co-Pilot, the idling time has decreased more than the driving time. Furthermore, it is during the interviews mentioned that due to Co-Pilot the operators can plan their work better as they are able to locate other trucks on the site. Consequently, queues and likewise do not take place any more. Therefore, it is reasonable to assume that Co-Pilot is a major reason for the decrease in idling time.

Another positive impact of the possibility to better plan the work is the decrease in velocity. As stated by the operator, it is easier to be more gentle while driving and slow down when, for example, there already is another truck being loaded or emptied. Before implementation of Co-Pilot, the operators maintained a higher speed as they did not know exactly where the rest of the trucks were located and thereby tried to reach the loading place as fast as possible. Consequently, they had to idle more often as they had to wait more. Furthermore, it was also stated during the interviews that with Co-Pilot the operators can ensure that in narrow passages, the unloaded truck is the one slowing down in order to let the loaded truck pass first. To sum up, the idling has decreased, suitable speeds are maintained and better decisions can be made during meetings.

Moreover, it is repeatedly highlighted that Co-Pilot has been of biggest use for the operator using the wheel loader. All work has been much more effective since the implementation. For example, the waiting time by the loading spot has decreased. Consequently, the idling time has most likely decreased even further since the wheel loader implemented Co-Pilot as well. It is therefore reasonable to believe that the more machines that utilize Co-Pilot, the bigger and better its' impact will be.

The interviews implied that it is mainly the map function of haul assist that is appreciated and utilized, as it makes it easier to plan the work. Especially for the operator using the wheel loader. The benchmark, see table 4, shows that out of the analyzed solutions, it is only Co-Pilot that has a map function. Therefore, it can be questioned whether the other solutions would fulfill the same needs and achieve the same results.

Even though the results are considered positive for Use Case 3, there are several things that could have improved the outcome even further. Firstly, if loaded tonnes would have been measured, an exact value of the total weight of the transported material could have been achieved. Consequently, the positive impact of Co-Pilot would be even more noticeable. Moreover, this would have made it easier to compare the use case results, as loaded tonnes was available for the first use case. Secondly, the operator mentioned that it sometimes can be out of habit that the machine is not turned off during the times it stands still. By, for example, implementing a function that warns when the truck has been standing still for a long time period without being turned off, the idling time can be decreased even further. Thirdly, it is important that Co-Pilot and its display is easy to understand in order to minimize the run-in time and maximize the operators' willingness to utilize it. In addition, during the times' extra staff and operators are called in, they must quickly understand how to use it without any careful or detailed instructions. To enable this, it is of importance that Co-Pilot is easy to understand and use.

5.4 Research Questions

The purpose of the project was to analyze how the changes in performance and user behavior implied by Co-Pilot impact the CO_2 emissions of the equipment. This section discusses fulfillment and findings related to the three research questions. The research questions are repeated individually, and followed by their respective discussion.

1. **What are the differences in user behavior and equipment performance before and after having implemented Co-Pilot?**

The first difference that is common among all use cases is that the fuel consumption is decreasing after the implementation of Co-Pilot. As seen in the interviews, this may originate from better planning and prioritization. For example, the map function visualizes if there is already a queue at the loading location or if two dumper trucks will meet in a narrow passage. This allows the operators to optimize their speed and collaborate with other operators. Looking at the fuel consumption categories at Use Case 3, idling time is one of the most decreasing, which validates this explanation. However, the need for a run-in period is identified. This means that these effects are not instant, but appear when the operators are used to and feel familiar with the system.

Another difference is that all production measures are decreasing. Even if this is common for all use cases, it is not necessarily desired. To achieve better efficiency, number of loads and loaded tonnes should increase or remain the same, while the fuel consumption is decreasing. On the other hand, machine hours itself do not say much about efficiency. Although, if it decreases while fuel consumption decreases even more and loading categories remain the same, it does contribute to improved efficiency. If machine hours decrease while the fuel consumption increases, production is less efficient.

At two use case sites, more is produced per emitted tCO_2. This insight is provided by the CO_2 quotas. To have an increasing quota, fuel consumption has to be the most decreasing production measure. This means that the original difference implied by Co-Pilot that positively impacts CO_2 efficiency is the decreasing fuel consumption. To further improve the quotas, other production measures would need to remain as stable as possible. This is only the case at one of the three use cases, at all others, they are decreasing significantly.

2. **How large is the quantitative difference in CO_2 emissions implied by the changes in user behavior and equipment performance?**

As previously described, Co-Pilot's quantitative impact has been analyzed by looking at production categories, productivity rates and CO_2 quotas. As desired decreases in CO_2 emissions should be achieved without compromising efficiency or production, the quotas are seen as the final result. Looking at the quotas, the results are positive for two out of three use cases. The interval of quantitative difference implied by Co-Pilot starts at a decrease of 11.4% and ends with an increase of 15.3%. As the biggest site is the one with the negative results, this impact is not connected to the size of the site.

On the other hand, quantitative emissions are of course connected to the size of the site. For example, the decrease in fuel consumption is 22.6%, 21.2% and 11.9% for Use Case 1, 2 and 3 respectively. Translated into tCO_2, the difference in emissions is 922, 222 and 44 tonnes respectively. The translations are misleading, as they state that the impact of Co-Pilot is greatest at Use Case 1. This is not the case, as the fuel burn rate at the same time has increased. Therefore, productivity rates and CO_2 quotas are used to draw conclusions and state the quantitative impact of Co-Pilot, to make sure that the results are rightfully connected to differences in user behavior and equipment performance.

3. **How can Co-Pilot be further developed to improve its' impact on sustainability?**

To begin with, the first suggestion on future development is based on the data analysis and results. As previously discussed, the single factor that has the highest impact on sustainability is fuel consumption. This should be utilized in the development of Co-Pilot. For example, the display could contain a gauge, visualizing when the fuel burn rate is in or out of a sustainable interval. Further, the operator stated in the interviews that idling is sometimes a consequence of ignorance of simply forgetting to turn of the engine. This could be incorporated in the fuel visualization, for example by notifying the operator when the vehicle has been idling for too long.

Several other suggestions are based on interview findings and the validation with the subcontractor and transportation manager. Firstly, incorporating the product in all machines that are used on the site was identified as a success factor. Hence, Co-Pilot, the sales offer and implementation should be developed to support, reward and be compatible with as many different vehicles and units as possible to improve the impact on sustainability. Secondly, the importance of operator training, run-in periods and familiarity with the system was highlighted. To ease these procedures, the goal of future development should be to make the interface and functionality of Co-Pilot even easier. As stated in the interviews, it happens that temporary staff has to manage the display on short notice. Similarly, Use Case 1 has a high operator turnover. These are further reasons to make the system as user-friendly as possible.

5.5 Research Approach

In general, the research approach of the study is accurate, as the research questions can be answered. Although, there are aspects that could be improved or executed differently to achieve even more satisfying results. Also, part of the project's purpose was to apply a method that is scalable and enables similar studies of other products in the future. Research approach factors that impacted the results or could have fulfilled the purpose even further are discussed in this section.

Firstly, the study was challenged by the fact that only limited data is available from before the implementation of Co-Pilot. As Co-Pilot itself supports collection of data, almost all possible use cases have performance and productivity data after implementation. On the other hand, the availability of pre-implementation data depends entirely on what the company or site desired and decided to collect several years ago. To faultlessly compare the use cases to each other, the methods of data collection should be the same. Moreover, the collected data categories should have been the same for all use cases. However, this is almost impossible to accomplish, as it depends solely on the companies and sites.

Secondly, the collection problem also impacts the quality of the data that was received from the selected use cases. The pre-implementation data from the first two use cases were collected from a performance tracking system that was used before the implementation of Co-Pilot. From the third use case, it was a compilation of manually reported data. This means that the margin of error is much larger for the third use case, as human errors can not be eliminated. To draw accurate conclusions based on the results, the impact of human errors should be minimized. To achieve this, certain data points from the third use case were eliminated.

Thirdly, the limited categories of data impact what measures can be analyzed. To achieve accurate results, all measures have to be based on correct data. For example, it would have been interesting to compare the fuel consumption to the transportation distance. However, transportation distances at Use Case 1 and 2 were only available after implementation. Even though it could be assumed that the distances were similar before the implementation of Co-Pilot, the insecurity of the results would be high. The same assumption problem applies to the amount of transported material. Desirably, it would have been compared to the fuel consumption, but the data was not available from all use cases. As the studied sites, conditions and work procedures are rapidly changing, assumptions were avoided. As a consequence, all desired measures could not be studied.

Fourthly, when concluding the quantitative difference implied by the changes in user behavior and equipment performance, one major difficulty is the impact of other circumstances than Co-Pilot. Even though the subcontractor and transportation manager can not identify other causes, there is a risk that Co-Pilot is not the only or major contributor. However, this risk can not be eliminated when real use cases are studied. To minimize the risk, the impact should have been studied by for example an experiment on a site that has never used Co-Pilot. For example, half of the fleet could have installed Co-Pilot while the other half operate as usual. In this way, Co-Pilot would be the only difference and consequently explain different results. However, as collaboration and coordination are highlighted as major benefits, implementing Co-Pilot in fractions of the fleet would not utilize its' full potential.

Fifthly, to elevate the research approach, further interviews, observations and site visits should have been performed. Due to the time and scheduling limits, visits and interviews were only performed at one of the use cases. Desirably, this should have been performed at all use cases and on a greater scale. For example, only one operator and one manager were interviewed. To draw conclusions based on qualitative findings, more interview objects would have provided broader perspectives and more insights. Further, the sites should have been visited and observed, to be able to identify unspoken differences and effects implied by Co-Pilot.

Lastly, Co-Pilot is still a new product under fast development. This impacts the study in several ways. To begin with, there are not many sites that use it, which limits the possibility of choosing desired use cases. Another pertinent point is that not all sites that utilize the product have implemented it in all machines. Out of the three selected use cases, only the third had installed Co-Pilot in all machines. Even though, data from all machines could not be collected before the time limit of the study. As collaboration and visibility are considered important benefits of Haul Assist, holistic site impacts should have been studied. Further, another problem is the limited understanding of the impact of Co-Pilot. When selecting use cases, the hypothesis was that larger sites would show more positive results. As this does not apply to the studied use cases, this kind of knowledge could have impacted the research approach.

On the other hand, the results of the project contribute to further knowledge of monitoring construction equipment and sites. As this is the first study of Co-Pilot's impact on sustainability, the results and research approach insights should impact future research. The fact that the product is still under fast development also enables improvements and development of functionalities, improving and visualizing the impact on sustainability.

6

Conclusion

This chapter presents the conclusions, by answering the research questions. Thereafter, recommendations on future research are presented.

6.1 Conclusions

To answer the first research question, Co-Pilot decreases the fuel consumption of construction sites. Further, this study shows that all production categories decreased after implementation. At a majority of the studied sites, the productivity was improved. Similarly, the sustainability increased as more was produced per tonne emitted CO_2. The difference in user behavior that explains these improvements is mainly the operator's ability to prioritize and plan the daily work.

To answer the second research question, the largest quantitative decrease in emissions due to decreased fuel consumption is 22.6% while the smallest is 15.3%. The largest increase in CO_2 productivity is 15.3% while the largest decrease is 11.4%. These CO_2 quotas, the final result of the study, are presented in table 35.

Table 35: Summary of all CO_2 quotas

	Unit	Use Case 1	Use Case 2	Use Case 3
Machine hours	h/tCO2	-1.61%	+15.3%	+8.8%
Nr of loads	#/tCO2	+2.27%	-	+10.8%
Loaded tonnes	t/tCO2	-11.4%	-	-

To answer the third and last research question, future development of Co-Pilot should focus on decreasing fuel consumption while increasing other production measures. This is identified as the single factor contributing most to increased sustainability. This can be done for example by visualizing a fuel consumption and sustainability status to the operators at all times. More specifically, development should focus on decreasing idling and queuing time to improve the impact on sustainability. Lastly, to ease full utilization, the development should strive to make Co-Pilot even easier to use and understand.

6.2 Future Research

It is proven that Co-Pilot has an impact on CO_2 and sustainability. Therefore, conducting more research in this area is of importance. During future studies, a bigger number of construction sites should be included to receive more accurate results that reflect the reality even better. In addition, the studies should be performed at sites where interviews and observations can be performed on a larger scale in comparison to what was done in this study. By observing the sites during longer periods of time, unspoken differences, that the operators do not notice themselves, could possibly be identified.

Moreover, to receive a holistic perspective of the entire site, several different types of machines should be included in future studies. Not solely dumper trucks, as according to the performed interviews, the results improved even further when additional machines installed Co-Pilot. However, currently Co-Pilot is still under development and is therefore only utilized on a limited amount of construction sites. When it has been further developed and implemented, studies similar to this one should be performed once again. This would hopefully enable the inclusion of several different assists, not only Haul Assist.

Overall, it is of high relevance to perform studies where the results can be derived entirely from the implementation of Co-Pilot. For example, this can be achieved if Co-Pilot is installed on only half of the machines of one site and can be compared to the half that has not installed it. This would ensure that all circumstances are the same. Moreover, it would eliminate the issue of limited data availability before the implementation.

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Appendix

A Questions for transportation manager

Introduction

1. For how long have you been a transportation manager at the site?
2. Have you been working on the site both before and after the implementation of the Co-Pilot?

Data collection

3. In the received data it was estimated that each load is 40 tonnes. How accurate is this information?
4. What is the maximum capacity for the trucks that are used on the site?
5. According to the received data the number of loads and number of worked hours decreased from 2019 to 2020. Do you believe that this is positive or negative?
6. What do you believe the reason for this decrease is?
7. Have you noticed any differences in fuel consumption since implementation of the Co-Pilot?
8. During analysis of the data it has been observed that the productivity per liter diesel has increased. This applies for both the number of loads per liter and the number of worked hours per liter. What do you believe the reason for this is?
9. How often is material dumped at the wrong place?
   a. 1 time each day
   b. 1 time each week
   c. 1 time each month
10. How has this changed since implementation of the Co-Pilot?
11. What is done in order to solve the problem if anything is dumped at the wrong place?
12. How often are there any problems or issues with the machines?
   a. 1 time each day
   b. 1 time each week
   c. 1 time each month
13. What happens if this occur? For example, what is the procedure for maintenance?

Evaluation

14. How is the Co-Pilot used on the site?
15. How do you believe Co-Pilot impacts the work on the site?
16. How does Co-Pilot affect your ability to keep track of everything on the site? For example, the work, the productivity and fuel consumption.

17. How do you perceive the operators' attitude towards the Co-Pilot?
18. Can you give examples of what has improved or deteriorated since the implementation of the Co-Pilot?
19. What do you believe works well and what works worse?
20. Are there any features or functions missing or are there any other ways that Co-Pilot can be improved?

B Questions for operators

Introduction

1. For how long have you been working with the tasks you currently have?
2. Have you been working on the site both before and after the implementation of the Co-Pilot?

Data collection

3. Approximately how many tonnes do you transport per load?
4. What is the maximum capacity for the trucks you drive?
5. What are the reasons for why the truck is idling when it does so?
6. How do you believe the idling times have changed since the implementation of the Co-Pilot? Why?
7. Are there other reasons for why the machine is running without contributing to increased productivity? For example, if you need to communicate with other drivers, machine errors, phone calls or likewise.
8. How has this changed since implementation of the Co-Pilot?
9. How often is material dumped at the wrong place?
   a. 1 time each day
   b. 1 time each week
   c. 1 time each month
10. How has this changed since implementation of the Co-Pilot?
11. What is done in order to solve the problem if anything is dumped at the wrong place?

Evaluation

12. How do you use the Co-Pilot during your daily work?
13. How does the use of the Co-Pilot affect your daily work? For example, is it funnier, more boring, easier och more difficult?
14. Can you give examples of what has improved or deteriorated since the implementation of the Co-Pilot?
15. What do you believe works well and what works worse?
16. Are there any features or functions missing or are there any other ways that Co-Pilot can be improved?

C Production data from Use Case 1

PRODUCTION	Parameter	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Machine hours	2019	h	2964	3329	3233	3316	2642	3385	3282	3240	3364	3274	2521	3214	37764
	2020		2786	2647	2519	2144	2202	2292	2235	2254	2129	2295	2209	2077	27788
	DIFFERENCE		-178	-682	-714	-1172	-440	-1093	-1047	-986	-1235	-979	-312	-1137	-9975
	CHANGE	%	-6%	-20%	-22%	-35%	-17%	-32%	-32%	-30%	-37%	-30%	-12%	-35%	-26%
Fuel Consumption	2019	liter	62109	69245	66598	67286	55026	77209	72613	67937	73486	72057	57091	72064	812720
	2020		59997	55722	53751	48213	50960	52238	50964	51483	53630	50406	53012	48685	629061
	DIFFERENCE		-2112	-13523	-12846	-19073	-4066	-24971	-21649	-16454	-19857	-21651	-4078	-23379	-183659
	CHANGE	%	-3%	-20%	-19%	-28%	-7%	-32%	-30%	-24%	-27%	-30%	-7%	-32%	-23%
Loaded tonnes	2019	tonnes	289023	347239	350954	368779	290514	233747	529242	327696	373851	338841	281241	338450	4069577
	2020		293385	309894	321300	278586	282053	284930	267239	257594	259667	243725	228660	54008	3081040
	DIFFERENCE		4362	-37345	-29654	-90192	-8461	51183	-262004	-70102	-114183	-95117	-52581	-284443	-988537
	CHANGE	%	2%	-11%	-8%	-24%	-3%	22%	-50%	-21%	-31%	-28%	-19%	-84%	-24%
Nr of loads	2019	#	7602	9187	9065	9635	7897	6090	13917	8936	9885	9175	7486	9034	107909
	2020		8034	8019	8165	7170	7372	7405	7103	6906	6833	6425	6349	5839	85620
	DIFFERENCE		432	-1168	-900	-2465	-525	1315	-6814	-2030	-3052	-2750	-1137	-3195	-22289
	CHANGE	%	6%	-13%	-10%	-26%	-7%	22%	-49%	-23%	-31%	-30%	-15%	-35%	-21%

D Production data from Use Case 2

PRODUCTION	Parameter	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Machine hours	2019	h	1267	1345	1383	1502	1521	793	1412	1375	1546	1505	1132	1544	16325
	2020		1383	1136	1210	1363	1293	1320	1088	953	1075	1019	829	840	13509
	DIFFERENCE		117	-209	-173	-139	-228	527	-324	-422	-471	-486	-303	-705	-2816
	CHANGE	%	9%	-16%	-13%	-9%	-15%	66%	-23%	-31%	-30%	-32%	-27%	-46%	-17%
Fuel Consumption	2019	liter	23967	24742	25539	27114	17868	14457	28196	27785	29209	27374	21063	29560	296875
	2020		25845	19597	19030	21616	23267	25199	20350	16615	16224	16348	14563	15002	233658
	DIFFERENCE		1878	-5144	-6509	-5498	5399	10742	-7846	-11170	-12985	-11026	-6500	-14558	-63217
	CHANGE	%	8%	-21%	-25%	-20%	30%	74%	-28%	-40%	-44%	-40%	-31%	-49%	-21%

E Production data from Use Case 3

PRODUCTION	Parameter	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Nr of loads	2019	#	1534	833	507	1174	830	1464,5	733	1219	1336	1901	1255	1191	13978
	2020		1234	668	547	1199	806	1623	771	1160	1767	1785	1149	1245	13954
	DIFFERENCE		-300	-165	40	24,7	-24,3	158,5	38	-59	431	-116	-106	54	-24
	CHANGE	%	-20%	-20%	8%	2%	-3%	11%	5%	-5%	32%	-6%	-8%	5%	0%
Machine hours	2019	h	470	256	144	330	233	417	210	355	397	544	346	348	4049
	2020		365	251	170	350	232	452	212	318	459	445	336	363	3950
	DIFFERENCE		-104,5	-5	25,5	19,7	-1,3	34,375	2	-37	61,75	-98,75	-10,5	14,5	-99
	CHANGE	%	-22%	-2%	18%	6%	-1%	8%	1%	-10%	16%	-18%	-3%	4%	-2%

FUEL CONSUMPTION	Parameter	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Total diesel consumption	2019	liter	11918	12775		11464	10355	9800	12349	12716	10929	12347	12667	11059	128379
	2020		11009	8160		10738	8863	10461	11009	10277	11853	12229	9753	8743	113095
	DIFFERENCE		-909	-4615	-	-726	-1493	661	-1340	-2439	924	-118	-2914	-2315	-15284
	CHANGE	%	-8%	-36%	-	-6%	-14%	7%	-11%	-19%	8%	-1%	-23%	-21%	-12%
Driving	2019	liter	11015	11776	-	-	-	-	-	-	10059	11371	11688	10187	66096
	2020		10201	5023	-	-	-	-	-	-	11057	11336	8970	8092	54680
	DIFFERENCE		-814	-6753	-	-	-	-	-	-	999	-35	-2718	-2095	-11415
	CHANGE	%	-7%	-57%	-	-	-	-	-	-	10%	0%	-23%	-21%	-17%
Idling	2019	liter	509	570	-	-	-	-	-	-	470	551	552	474	3126
	2020		440	253	-	-	-	-	-	-	437	501	453	365	2450
	DIFFERENCE		-69	-317	-	-	-	-	-	-	-33	-50	-98	-109	-676
	CHANGE	%	-13%	-56%	-	-	-	-	-	-	-7%	-9%	-18%	-23%	-22%
Power take-off (PTO)	2019	liter	383	412	-	-	-	-	-	-	388	411	412	386	2392
	2020		368	183	-	-	-	-	-	-	342	376	319	275	1863
	DIFFERENCE		-15	-228	-	-	-	-	-	-	-46	-35	-93	-112	-530
	CHANGE	%	-4%	-55%	-	-	-	-	-	-	-12%	-9%	-23%	-29%	-22%
AdBlue consumption	2019	liter	520	562	-	519	450	423	521	-	434	491	516	459	4894
	2020		463	214	-	307	266	311	263	-	484	463	379	370	3521
	DIFFERENCE		-57	-348	-	-212	-183	-112	-258	-	50	-28	-136	-89	-1373
	CHANGE	%	-11%	-62%	-	-41%	-41%	-27%	-49%	-	12%	-6%	-26%	-19%	-28%

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