Smart Locks – A case study for comparing Digital and Mechanical Locks from a Sustainable Perspective

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June 9, 2023

LUNDS
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Abstract

As carbon dioxide emissions increase along with the global average temperature, sustainable development is becoming more and more important in all sectors, and it is essential to act toward the reduction of emissions to counteract these dire consequences. Companies are expected to operate sustainably and responsibly with a minimized negative environmental impact alongside accelerating their digitalization journey to stay competitive in a rapidly changing environment. The transition from traditional to more digital products often bring an added environmental burden due to electronics and batteries that are characterized by a heavy carbon footprint. This thesis focuses on the transformation from mechanical locks to digital locks from a sustainable perspective.

The study covers an assessment of the environmental impact of three different types of locks that varies from a traditional mechanical lock to a future concept cylinder accessible through a smartphone. The scope of the environmental impact assessment is raw material extraction to the finalized product at the factory gate. Two of the locks are digital products containing electronic components and the hypothesis was initially that the environmental burden of digital locks would be higher compared to traditional locks. Furthermore, it was estimated that digital locks can generate other benefits for downstream customers, for example by minimizing transportation related to key management.

The main goal of the thesis is to determine and compare the direct environmental impact of the locks and to investigate and quantify the potential benefits each lock could generate for downstream customers. This was done by first estimating the direct environmental impact of the locks by conducting a simplified life cycle assessment. Secondly, three use cases were selected as objects of study to quantify if and how the products have impacted reducing their operational emissions. Through interviews with these end-users, the reduced operational emissions due to digital locks were quantified. Another objective was to identify future potential beyond the current surrounding benefits, with a focus on the future concept cylinder.

It was concluded that digital locks on a product level have a higher environmental impact compared to traditional mechanical locks. The future concept cylinder has a significantly larger direct environmental burden on both a product- and a system-level compared to the other products. Additionally, it was found that in two out of the three cases, the reduced emissions were large enough to exceed the direct environmental burden of the digital lock system. For the future concept cylinder, the avoided emissions exceeded the direct environmental burden in one of three cases.

Based on the results, it was concluded that digital products have the potential to reduce emissions among end users and are not necessarily less sustainable compared to mechanical locks despite containing electronics. An important finding was that a digital or future concept system may create behavioural changes at the end users which can result in avoided emissions. Due to the significant size of the avoided emissions among end customers, the thesis also includes a discussion on how this can be included in the reporting of emissions and further considered when moving forward and developing smart products. Based on the findings of this thesis, proposals for future studies and recommendations were made. This thesis has been a complete elaboration between the two authors. Each author has been involved in every part of the process and contributed equally.

Sammanfattning

I takt med att koldioxidutsläppen och den globala medeltemperaturen ökar blir hållbarhet allt viktigare inom alla sektorer. Det är viktigt att aktörer agerar och arbetar för att minska sina utsläpp för att begränsa klimatförändringarnas konsekvenser. Företag förväntas att ta en aktiv roll i sitt hållbarhetsarbete och minimera deras negativa miljöpåverkan. Många företag genomgår samtidigt en digitaliseringsresa för att förbli konkurrenskraftiga i en snabbt föränderlig miljö. Digitaliseringen resulterar bland annat i en övergång från traditionella till mer digitala produkter. Dessa digitala produkter kan medföra en ökad miljöbelastning på grund av elektronik och batterier som kännetecknas av stora utsläpp. Denna studie fokuserar på övergången från mekaniska lås till digitala lås ur ett hållbarhetsperspektiv.

Studien omfattar en bedömning av miljöpåverkan av tre olika typer av lås som varierar från traditionella mekaniska lås till ett framtidskoncept i form av en cylinder med åtkomst via exempelvis en smart telefon. Beräkningen av miljöpåverkan omfattar råvaruutvinning fram till den färdiga produkten redo att distribuera till kunder. Två av låsen är digitala produkter som innehåller elektroniska komponenter och batterier. Den initiala hypotesen var att digitala lås medför en högre miljöbelastning jämfört med traditionella lås. Däremot kan dessa digitala lås skapa fördelar för användarna, till exempel genom att minimera transporter kopplat till nyckelhantering. Syftet med den här studien är att bestämma och jämföra den direkta miljöpåverkan av produkterna samt att kvantifiera de potentiella fördelar som varje lås kan generera hos användarna.

Studien började med att uppskatta låsens direkta miljöpåverkan med hjälp av en förenklad livscykelanalys. Sedan valdes tre användarfall för digitala lås ut med syfte att undersöka om och hur produkterna har haft en inverkan på att minska användarnas operativa utsläpp. Genom intervjuer med slutanvändare kvantifierades de minskade operativa utsläppen till följd av digitala lås. Ett annat mål i studien var att identifiera andra framtida potentiella fördelar med fokus på framtidskonceptet.

Studien fann att digitala lås på produktnivå har en högre miljöpåverkan jämfört med de traditionella mekaniska låsen. För användarfallen visade resultatet att den totala miljöbelastningen av låsen på systemnivå var lägre för systemet med digitala lås jämfört med det mekaniska. Framtidskonceptet har en betydligt större direkt miljöbelastning på både produkt- och systemnivå jämfört med övriga produkter. Resultatet visade även att i två av de tre användarfallen var de minskade utsläppen tillräckligt stora för att överstiga den direkta miljöpåverkan för det digitala låssystemet. För framtidskonceptet översteg de minskade utsläppen den direkta miljöpåverkan i ett av tre fall.

Baserat på resultaten drogs slutsatsen att de digitala produkterna har potential att minska utsläpp hos slutanvändarna även om de på produktnivå har en högre miljöpåverkan. Studien visar att både digitala lås och framtidskonceptets cylinder i låssystem kan skapa beteendeförändringar hos slutanvändarna som resulterar i minskade utsläpp. De minskade utsläppen var av betydande storlek i användarfallen och det kan diskuteras huruvida dessa undvikna utsläpp kan inkluderas i rapporteringen av koldioxidutsläpp vilket bör beaktats i framtida utveckling av smarta produkter. Baserat på resultaten gjordes förslag till framtida studier och rekommendationer. Detta examensarbete är resultatet av ett samarbete mellan författarna. Båda författarna har varit med i alla delar i processen och bidragit till lika delar.

Acknowledgements

We would like to thank the Department of Industrial Management and Logistics and especially our supervisor Magnus Hartfeldt-Berg for his support. Because of his optimism, creative insights and positive energy, no obstacles during the processes have seemed too hard to overcome.

In addition, we would like to express our sincere gratitude to our supervisor Daniel and co-supervisor Aram at the cooperating company, for guiding, pushing, and supporting us through the project. Thank you for all your help and motivation. We would also like to express our gratefulness towards everyone close to us at the office for their kindness and their way of making every day enjoyable, especially Daniel, Johan, Jonas, Martin, and Sara.

We would also like to thank those who took time for us whenever we needed help. Special thanks to Petri, Kai, Pär, Olle, Susanne, Katarina, Shahla.

List of Acronyms

Carbon dioxide – CO_2

Carbon dioxide equivalents - CO_2-eq

Global warming potential – GWP

Life cycle assessment – LCA

Life cycle inventory – LCI

Environmental product declaration - EPD

Green house gas – GHG

Science Based Target imitative - SBTi

Carbon Disclosure Protocol – CDP

Supply chain management – SCM

Sustainable supply chain management – SSCM

Printed circuit board – PCB

Bill of material - BOM

Table of content

1. Introduction

This chapter presents an overview of the background for the thesis, description of the collaborating company followed by a problem description which lay the foundation for the chosen topic.

1.1 Background

1.1.1 DIGITALIZATION AND SUSTAINABILITY

The evolution of new technology has initialized the 4th industrial revolution (Liborio, Berrah and Tabourot 2020). New digital technologies are changing the way companies are doing business and the collaboration between providers and customers. Nonetheless it is changing the customers' expectations on the products and services that are offered. Therefore, companies are accelerating their digitalization journey in order to be competitive and flexible in a rapidly changing environment. (Liborio, Berrah and Tabourot 2020)

Digitalization and new technology are key in creating new smart solutions in line with emerging customer expectations and future products in smart city development. (Su, Hu and Yu 2023; Liborio, Berrah and Tabourot 2020; Smart City Sweden 2023)

In addition to leveraging digitalization to be competitive, companies are expected to operate sustainably with reduced emissions and hence contribute to limit the fatal impacts of climate change (Science Based Target initiative [SBTi] 2021b). Thus, it is of importance to keep track and minimize the emissions emerging from industry which accounts for about one quarter of the global emissions (Intergovernmental Panel on Climate Change [IPCC] 2022; SBTi 2021).

Furthermore, there is an increasing complexity in digital products and services which may bring difficulties when quantifying the environmental impact and emissions. Historically, digital products have usually had a higher environmental impact due to the inclusion of batteries and electronics, which is characterised of heavy carbon footprint raw material and complex supply chains. (Evangelidis and Davies 2021; Andrae 2010)

1.2 Company description

The collaborating company in this thesis, further referred to as the Company, is a global company in the access solution industry. Their solutions cover a wide range of areas such as access control, mechanical and electromechanical locking, and mobile access. They help people all over the world to move with ease and contribute to a safer and more open world with their offerings. (The company 2023) Their products and services are widely used, they have a broad product- and service range customized for different end users and environments. For example, their products may be found in hotels, automated doors, ferries, and pass controls. They emphasise the importance of reliability, trust and safety since their product are a part of people's everyday life and in critical infrastructure e.g., schools, authorities, airports, and hospitals.

The Company is in the forefront of technology and is constantly working on developing their products and services. They are embracing the ongoing digitalization in society and creating new smart digital solutions such as digital locks to substitute the traditional physical lock and keys. (The Company 2023)

1.2.1 DIGITAL LOCKS

Leveraging welfare technology is an important part of the development of societies. New welfare technologies and digital solutions are emerging in different industries. Welfare technology covers all kinds of technology that contribute to improving lives of those who needs it, for example by enhancing security, activity, or independence. (Nordic Welfare Centre 2023)

Businesses in the access solution industry are leveraging digitalization in the development of their products and services of today. The access solution industry has a broad meaning, and it covers products and services for all door environments with both physical security but also access control systems. Some examples of products and services are key cards, pass control, physical lock, and automatic doors. (Dormakaba 2023; ASSA ABLOY 2023)

A digital lock today provides new features and technologies which may enable more efficient flows, improved safety, and transparency in the systems around it. (SKR 2020) There are a variety of digital locks on the market with a wide range of features customized for different end-users and environments. (Dormakaba 2023; ASSA ABLOY 2023) Digital lock is a collective noun for different types of locks that are accessed through an electronic signal. The electronics in the system needs to have an energy input of some kind, for example an integrated battery. (Hellberg 2020) The carrier of the signal to the lock may vary, it could be a credit card, a tag, or a mobile phone with an app for accessing the lock system. An application in a mobile device can connect to the lock through Bluetooth or a digital key could be used that needs to download an authorization in order to unlock. Some digital locks still allow one to use a mechanical key while other does not. (Hellberg 2020)

1.3 Problem description

As the cooperating company continues the digital transformation, there is a potential risk of increased environmental impact due to their digital products containing batteries and electronics, which their traditional mechanical product does not. The company signed up for Science Based Target initiative in 2020, causing their sustainability goals to be to halve their emissions by 2030 and to reach net zero in 2050 (SBTi n.d.a). To ensure that the environmental impact is minimized, the company wants to investigate the environmental impacts of direct production of their locks and the potential reduction of operational emissions and surrounding benefits for their downstream customers.

The reduction in indirect use and surrounding benefits are for example optimized transport delivery for products or services, less transportation connected to physical key management, and an overall more flexible operation. Additional benefits include less need to change locks and keys if keys are lost.

The main question to be answered is: *Is the potential added environmental burden of batteries and electronics justified if they could enable the potential for downstream customers and users to become more sustainable?*

1.4 Purpose of study and expected deliverables

The purpose of the thesis is to evaluate and compare the potential surrounding benefits of digital locks compared to the increased environmental impact in order to get an understanding of if they can be justified due to the potential for reduced emissions for downstream customers. The scope for the direct environmental impact is the cradle-to-gate whereby the focus of reduced emissions and surrounding benefits are between the gate and grave, as visualized in Figure 1.1.

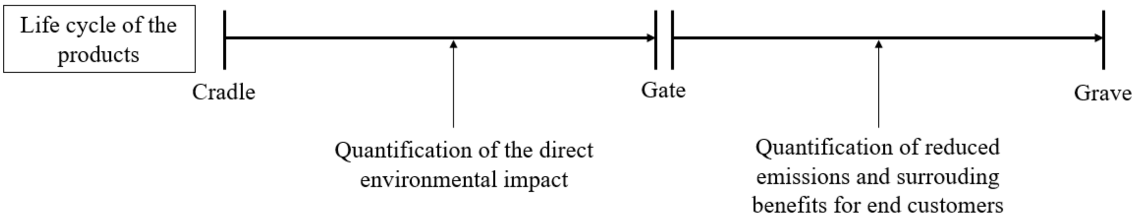

Figure 1.1: Visualization of the focus for the two different parts of the thesis.

The desired outcome of this project is to quantify the direct environmental impact of three different products and to quantify the potential avoided emissions for three use cases from gate to grave for the products. The findings will be the foundation for the final comparison that will answer the research question.

1.5 Focus and delimitation

This report can be divided into two different parts, the environmental impact analysis and the potential avoided emissions quantification.

In the evaluation of the direct environmental impact, focus will be put on the environmental impact of raw material extraction, manufacturing, and transportation as illustrated in Figure 1.2. The scope is cradle-to-gate, which means that everything after the final assembly will be excluded such as transportation to end customers, use, and recycling. Due to the nature of the study and to narrow the scope, the emission factor considered is the carbon dioxide equivalents (CO_2-eq).

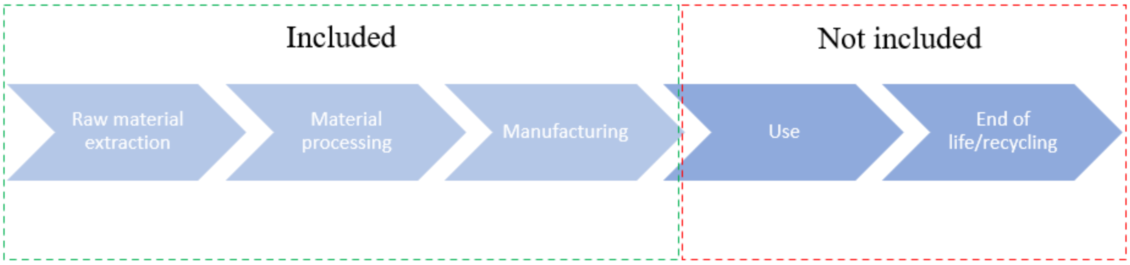

Figure 1.2: Visualization of the system boundaries for the environmental impact analysis

Further, for the evaluation of the environmental impact, a wider system approach for the use cases will be created and utilized. The use cases will mainly be created from interviews with different stakeholders. The selection of use cases aims to capture the potential effects of the digital product including downstream customers' operations, which in the following will be defined as avoided emissions. The focus of the use cases will be to quantify the avoided emissions, limited to CO_2-eq. Three use cases were selected to limit the scope further. The study was conducted in and focused on Sweden.

1.5.1 SELECTION OF PRODUCTS

To execute the comparison, three different locks were selected with different characteristics based on input from the Company (2023). The locks included in the study are the following:

- Mechanical lock - A traditional physical key and cylinder.
- Digital lock – An electromechanical lock, referred to as a digital lock consisting of a cylinder and a physical key containing electronics and batteries. The key is programmable to access several cylinders.
- Future concept cylinder – A self-sufficient lock cylinder without battery that is all digitally accessible through a e.g., mobile device.

The traditional mechanical key is a standardized mechanical key defined by ARGE (European Federation of Associations of Lock and Builders Hardware Manufacturers) and represents a generic and approved mechanical cylinder and key in Europe. The concept is to fit a specific key to a specific cylinder, and a unique physical key is usually needed to unlock the cylinder. (The Company 2023)

The specific digital lock was chosen as a representative of a generic digital key that can be applicable for all use cases included in this report. The lock consists of a digital key, containing metal, plastic and electronics, and a cylinder containing primarily metal and little electronics. The key is programmable in order to create access, in practice, this means that one key can be used to access multiple cylinders. (The Company 2023)

The future concept cylinder is a hypothetical product but represents a keyless lock solution where most if not all access barriers are removed. The concept includes using for example a mobile device to unlock cylinders, where the access is shared through an app or other software. (The Company 2023)

1.6 Report structure

The following Table 1.1 shows the structure of the report and presents the content in the different sections respectively.

Table 1.1: Showing the structure of the report.

Chapter	Summary
1 Introduction	This chapter gives an introduction to the topic in addition to an overview of the thesis by presenting the background, the collaborating company and the problem description. Lastly, the purpose of the study including the scope will be presented.

Chapter	**Summary**
2 Methodology	The methodology chapter gives an overview of different research approaches and methods to consider, and further the selected ones are stated. In addition to this, the approach for data collection and data analysis are presented. Further, the research's credibility is discussed. Lastly, the execution of the research is presented in addition to the work breakdown structure.
3 Literature review	The literature review presents the relevant literature connected to the topic of the thesis. It provides a theoretical foundation including various perspectives on the topics. The chapter will start with presenting sustainability in the supply chain, including sub-topics such as reporting of environmental impact and potential reporting of avoided emissions. Moving on, this chapter will present the life cycle assessment and topics relating to this which constitute a cornerstone of the thesis. Further the environmental impact of digitalization and smart city development will be discussed. Connecting to the second part of this thesis some background information will be provided regarding the use cases and environments where the different keys will be studied. Since a simplified LCA will be conducted on the keys, some background information regarding relevant manufacturing processes and materials is provided to get a better understanding of the scope of the LCA.
4 Empirical study pt 1	This chapter starts off by going through the proceeded steps for the simplified LCA. Further, the data and information needed for the assessment will be presented such as scope, component specifications, mapping of supply chain and processes, and lastly assumptions and simplifications that were made in the LCA.
5. Empirical study pt 2	In the second part, the result from the case-study for the three different cases are presented. Key findings from interviews with stakeholders are highlighted in addition to relevant data and statistics that will support the understanding of how the keys affect the surrounding flows and operations. This chapter will lay the foundation for quantifying the potential avoided emissions enabled by digital locks. The gathered input on the future potential of digital locks connected to smart city development will also be presented.

Chapter	**Summary**
6 Analysis	In this section, the result from the assessment of the direct environmental impact of the products will be analyzed on a product- and system-level covering the cases. Furthermore, the result from the cases and the avoided emissions will be discussed and compared with the direct environmental impact. Moreover, the future potential of digital locks on a system-level will be analyzed in addition to highlighting the challenges with the digital locks of today. The section will also cover a discussion of the potential fourth scope and the accounting of avoided emissions in the reporting of a company's emissions. Lastly, this section will discuss the potential shortcomings of the study and the effects on the result in a sensitivity analysis.
7 Conclusion	This section presents a discussion of the results and connects this to the research question of the study. Further, the future potential of digital locks and recommended future research are presented.

2. Methodology

The Methodology chapter gives an overview of different research approaches and methods to consider. Further, the selected approaches and methods in this study are presented and motivated. Additionally, the approach for data collection and data analysis is presented and a discussion of the research creditability. Lastly, the execution of the research is presented in addition to an illustration of the work breakdown structure to facilitate the understanding of the project's different parts.

2.1 Research approach

A research approach usually starts with defining the phenomenon and unit of analysis that are to be studied. The phenomenon is the concept being studied and the unit of analysis refers to the object or entity being studied. (Olhager 2023a) The two most used approaches for research within logistics and supply chain management are an inductive approach and a deductive approach, and the decision of which to use is highly dependent on the aim of the study. (Kotzab et al. 2006)

2.1.1 DEDUCTIVE

The deductive approach is the dominant research approach for logistics and supply chain management research. The goal of the approach can be described as *"add to the body of knowledge by building formal theory that explains, predicts and controls the phenomenon of interest". (*Kotzab et al. 2006, 21*)* The main goal of the research is therefore to contribute to existing knowledge by describing the phenomenon and later predicting the phenomenon (Kotzab et al. 2006). The deductive approach can be divided into three steps, *Literature Review, Formal Theory,* and *Field Verification* (Woodruff 2003). In the first step, the literature review, the appropriate literature is reviewed to gain an understanding of the phenomena and to develop a framework that specifies relevant variables and expected relationships between them. In the second step, a formal theory is created based on existing theory. This theory should be able to generate predictive statements which could later be tested by real-world data. The last step includes collecting data to test the hypothesis and verify the formal theory. (Kotzab et al. 2006)

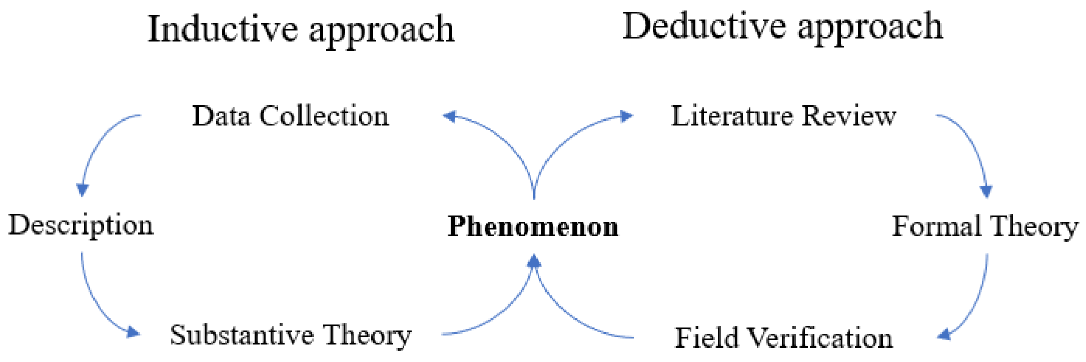

Figure 2.1: Visualization of the Inductive and Deductive approach (Woodruff, 2003) referred to in (Olhager 2023a)

2.1.2 INDUCTIVE

The aim of the inductive path is to *"…understand the phenomenon in its own terms"* (Hirshman 1986, cited in Kotzab et al. 2006, 20). This approach can, like the deductive approach, be divided into several steps, *Data Collection, Phenomenon Description,* and *Substantive Theory* (Woodruff 2003). The first step is to create an understanding of the phenomenon through field studies. In the second step, qualitative research is used to describe the phenomenon, by for example interviews with open-ended questions and using multiple data sources. The last step is to build a substantive theory based on the descriptive data. The outcome is detailed data explained from a general perspective, demonstrating a relationship of variables. (Kotzab et al. 2006)

2.1.3 THE BALANCED APPROACH

Kotzab et al. (2006) describe a third research approach called the balanced approach, sometimes referred to as the abductive approach. (Olhager 2023a) The balanced approach can be seen as a combination of the deductive and inductive approaches where the researcher fluctuates between the two (Kotzab et al. 2006). By tracking back and forth between the approaches, a more balanced perspective can be attained which is suitable when dealing with complex circumstances. When studying a complex phenomenon, it can be beneficial to start by trying to fully understand the phenomenon with an inductive approach and then using a more deductive approach for studying the potential relationships between variables in the phenomenon. (Kotzab et al. 2006)

2.1.4 SELECTED APPROACH

The problem investigated in this thesis can be seen as complex and dynamic. The results are everchanging and contain many internal and external stakeholders combined with limited previous research on the topic. Additionally, the cooperating company has not previously investigated the issue on a broader level, increasing the complexity. The different subjects in this thesis are dynamic and to fully understand these in a balanced way and to accurately combine the results, the best approach is a combination of inductive and deductive. (Kotzab et al 2006) Therefore, based on the characteristics of the issue, a balanced approach was selected as the research approach.

2.2 Research methods

There are five commonly used research methods: case research, action research, design science research, survey research, and quantitative models (Olhager, 2023a). This chapter briefly explains the concept of some of the methods.

Case research: A case study refers to the study of either a single case or several cases, where a case can be defined as a observable occurance limited by time and space (Olhager 2023a). The aim of a case study is to study the phenomenon in its natural setting (Voss, Tsikritsis and Frohlich 2002).

Action Research: Action research is an interactive research method with the purpose of finding a solution to a real-life problem and contributing to science (Gummesson 2020). The research is conducted in real-time and its primary purpose is to create change (Olhager 2023a).

Design Science Research: Design science research can be used to identify how a design influence its outcomes in specific contexts (Olhager 2023a).

Survey Research: The primary purpose of survey research is to collect quantitative information from a sample through surveys. It requires a standardized format to be useful and can contribute to a better understanding or explanation of a circumstance. (Forza 2002; Olhager 2023a)

Quantitative Models: Quantitative models can be either mathematical modeling or simulation. The research method is used to create and identify relationships between variables. (Olhager 2023a)

Literature Review: A literature review is conducted for several reasons. It is commonly an important step in research since it supports and influences the other stages of the research (Seuring and Gold 2011). A literature review is for example to identify the collective knowledge of a topic, build an understanding of the concepts or suggest research methods that might be useful, as well as to support the identification of a topic, question, or hypothesis. (Rowley and Slack 2004) There are two common search strategies for conducting the review. The first one is citation pearl growing, which is the approach of starting with a few documents and finding more relevant literature through them. The second is successive fractions, where instead the strategy is to reduce a large set of documents by eliminating the non-relevant documents. (Rowley and Slack 2004)

2.2.1 SELECTED RESEARCH METHOD

The selected research method for this thesis was an embedded single case study with multiple units of analysis. An embedded case study involves more than one unit of analysis, which is applicable in this thesis, and is not necessarily limited to qualitative data. (Scholz and Tietje 2002) The case study strategy was selected based on the aim to describe the problem without having control over the environment. Furthermore, the authors were convinced that the research needed both quantitative and qualitative data, which further strengthens the use of a case study. (Yin 2018; Scholz and Tietje 2002)

Additionally, a literature review was conducted in order understand the theoretical concepts and terminology needed to create a foundation for the thesis and to strengthen the analysis. The purpose of the review was also to collect knowledge of the phenomenon that is studied. (Olhager 2023b) The search strategy for the literature review was citation pearl growing and conducted by searching through library catalogs, such as LUBsearch, to find books and scientific articles covering the themes of the thesis and then to elaborate on the findings. In addition, search engines such as Google were used to find additional information on the areas. Keywords for the literature review were:

Sustainable supply chain, Life cycle assessment, Sustainability, Digitalization, Smart City Development, Environmental impact of digitalization, Sustainability reporting, Avoided emissions, Manufacturing process keys, digital locks, digital locks in a smart city.

2.3 Data collection methods

In an embedded case study, it is common to collect data from structured or focused interviews as well as surveys, questionnaires, and sampling of data. Which method is most appropriate depends on the type of case investigated. (Scholz and Tieje 2002) Due to the scope of this project, several data collection methods were used. This section aims to describe different methods used for data collection and how these are applicable in this study.

2.3.1 DATA COLLECTION

To create a better understanding of the products investigated and their full potential, a thorough research for internal data was performed. This was done by speaking to product owners, salespeople, production workers, and other relevant employees at the Company. Other corporate documents and information were supplied by the Company. Some of the documents and data were classified as confidential and are therefore left out or coded in this publication with respect to the company.

The environmental impact of the cylinders has been collected through environmental product declarations (EPDs) available for the cylinders investigated. For the keys, bill of material (BOM) files and technical information for calculating the environmental impact were collected mainly through shared Excel files and drawings, alongside the actual product to take apart and investigate further.

2.3.2 QUANTITATIVE DATA

Quantitative data is data that can be measured and evaluated *(*Björklund and Paulsson 2014). The quantitative data in this report are mainly collected through spreadsheets provided by the Company and material shared during external interviews. The quantitative data provided for the environmental impact analysis was product characteristics, components, material composition, weight, and volumes. The quantitative data collected through interviews was data from end users, operational characteristics, and statistics on usage among others.

2.3.3 QUALITATIVE DATA

Qualitative data is information that describes a situation in words and is useful to understand a problem better. The data show great diversity and include most human communication and behavioural, most commonly in text form. (Gibbs 2018)

Observations

Collecting data through observation is a way of gathering data by observing the phenomenon and can be used to facilitate the understanding of situations and to simplify the development of research and hypothesis (Bryman 2022). Direct observation is a way to collect information regarding areas that involve behaviour and occurrences in natural situations. Direct observations can be divided into two different forms, participant observations where the observer takes part in the activities, and non-participant observation where the observer only observes from the outside. (Olhager 2023b) In this research, the observations were non-participant observations.

Interviews

There are three main ways of performing an interview for collecting qualitative data: unstructured interview, semi-structured interview, and structured interview (Björklund and Paulsson 2014).

- *Unstructured interview* is a form of interviewing where the interview is like a conversation with very few questions decided beforehand.
- *Semi-structured interview* is an interview where some questions and focus areas are decided beforehand, but depending on the interviewee’s responses or reaction, the interview is flexible to change and navigate in different directions.
- *Structured interview* is an interview where all questions are decided beforehand and are asked structured in a certain order.

(Björklund and Paulsson 2014)

The interview methods in this study were both unstructured and semi-structured. When interviewing internal stakeholders, the main purpose was to get an understanding of the products and processes based on their point of view, which was why an unstructured approach was selected. For interviews with external customers with the purpose of building use-cases, a semi-structured approach was needed. This was decided since answers to some questions were needed, but for a comprehensive understanding, follow-up questions were necessary.

2.3.4 RESEARCH DATA

Research data is data that has been collected, observed, generated, or created to validate original research findings (Björklund and Paulsson 2014). Both primary and secondary research data have been used in the report. The primary data have mainly been collected through interviews and observations and the secondary data have been based on external research articles. The secondary data have been composed within other research projects and topics but touch upon the objective of this thesis.

2.4 Data analysis

As mentioned, diverse types of data have been collected externally and internally. The data have been used in different ways, either in the assessment of the environmental impact of the products or to analyze the potential of avoided emissions at downstream customers.

For the environmental impact assessment, the collected data from research, interviews, and the Idemat database was used to calculate the environmental impact in Excel, specified as CO_2-eq emissions.

To quantify the avoided emissions for the different cases, the collected data during interviews and shared files were used to map out workflows and transportation flows and to identify the differences in flows depending on the different locks. Further, it was analysed how the digital locks had influenced or could potentially influence the flows for each case compared to using a system with mechanical locks. Focus was primarily put on how the locks influence the transportation flows. A potential difference in transportation distance when using digital versus mechanical locks was then converted to emissions of CO_2-eq.

2.5 Creditability

Analyze the creditability of research conducted is an assessment of whether the findings represent a trustworthy result (Olhager 2023b). The creditability can be examined by reviewing the reliability, validity and objectivity of the study (Olhager 2023b), which is further elaborated on in the following chapter.

2.5.1 RELIABILITY

The reliability of a result can be assessed through a retests procedure to ensure the consistency of the result and thus that it is not a coincidence or affected by potential occurring errors (Yin 2018). Reliability can be tested in terms of consistency among the observers in the study. It is also about the reliability of the measuring instrument and thus that the same result will be received if the tests are repeated. Reliability is also a prerequisite for measurement validity. (Check and Schutt 2012)

According to Höst et al. (2012), certain measures can be taken to achieve or increase reliable measures. Some of these measures have been considered throughout this thesis. The empirical study and analysis have been reviewed by both internal people at the Company as well as the supervisor at Lund University. Additionally, the collection of data has been documented carefully throughout the process as well as all interviews were recorded, documented, and revisited to gain high reliability. (Höst et al 2012)

2.5.2 VALIDITY

To analyze validity in research refers to ensuring that what is measured is what was intended to be measured. Reliability described in 2.5.1 can be seen as a prerequisite for the validity of measurement. This is due to that a circumstance cannot be measured if the measures that are being used give inconsistent results. (Check and Schutt 2012)

Check and Schutt (2012) gives examples of varying validity of measures when examining a person’s age. A measure with high validity is to use the information provided on a person’s birth certificate in addition to the current year to determine the age. A measure with less validity is to ask the person, who could potentially lie and provide a faulty answer. (Check and Schutt 2012)

2.5.3 OBJECTIVITY

Objectivity describes to which extent a study is free from personal opinions (Olhager 2023b). Important aspects for increasing the objectivity are therefore transparency when motivating the choices made in the study and clearly stating what is personal opinions and what is facts. Objectivity can also increase by accurate sourcing and to give credit to the original source, while questioning the objectivity of the sources. (Olhager 2023b)

The authors have aimed to throughout the project stay objective and to question the sources and information provided by stakeholders to not be influenced by bias. The authors believe that the greatest risk of bias is for the external stakeholders wishing to make their operations seem better than they are. Therefore, different perspectives were gathered from the external stakeholders and a lot of the information given in the interviews was double-checked to make sure that the information was reasonable. Assumptions that had to be made for both the environmental impact analysis and the cases have been clearly stated and motivated.

2.5.4 REPRESENTATIVITY

Representativity of a result aims at generalizing it and making it applicable in other scenarios. For case research, it can be an issue to generalize the conclusion since it is performed on a limited and specific case. (Höst et al. 2012) The representativity of a study can be strengthened if the context of the study is well documented and informative (Höst et al. 2012). Therefore, this study includes a detailed and transparent description of the context and the different cases studied as well as a compilation of the cases and discussion how applicable it is to generalize in a more holistic setting.

2.5.5 INCREASING CREDIBILITY

The credibility of a study can be increased by using triangulation meaning that different perspectives and sources will be included to increase the quality and credibility of the study (Björklund and Paulsson 2014).

There are four possible ways to use triangulation to increase the quality, which are method triangulation, data triangulation, evaluation triangulation, and theoretical triangulation (Olhager 2023b). They all refer to using several sources or perspectives on the material. Method triangulation means to examine the phenomenon by using different methods, data triangulation is to use several data sources, evaluation triangulation is to let different people evaluate the same material while theoretical triangulation is to use different theories on the same data. (Olhager 2023b)

The validity and reliability of this study have been increased by applying data triangulation by attaining at least two perspectives on most of the cases investigated. When looking into different cases, the gathering of input has been done with interviewees from different companies in addition to various roles in a company to ensure a fair and balanced perception of the issue studied. Additionally, method triangulation is applied since the different cases aim to describe the problem from different perspectives to gather a thorough understanding. The authors also believe that the quality increases since there are two authors, related to evaluation triangulation, since that makes it possible to evaluate and critically examine each other’s work.

To increase the overall credibility of the thesis, the assumptions made are transparently and well presented, allowing the reader to evaluate the potential shortcomings. Additionally, a sensitivity analysis with a worst-case scenario estimated by the authors and a discussion of the potential shortcomings can be found in section 6.6.

2.6 Research execution

This study began with a comprehensive literature review to create an understanding of the relevant topics and to get an idea of the steps needed in the project to be able to answer the research question. The literature review was performed iteratively during the process of the thesis.

Secondly, an assessment of the direct environmental impact was performed. The assessment covered the three types of locks presented in section 1.5.1 and a simplified life cycle analysis was conducted for each one of the locks. The result implied which of the lock had a greater or less direct environmental impact.

In the second part, a study of the three use-cases was conducted with the goal to investigate whether the digital locks enabled the downstream customers to become more sustainable due to less transportation connected to key management. Different use-cases were discussed with stakeholders at the collaborating company to get a better understanding of the lock’s role in various cases. The selection of use-cases was based on where the digital locks have or could have an impact on the flows in the operations.

Additionally, the avoided emissions were quantified based on the qualitative and quantitative data gathered. Furthermore, the role and potential of digital locks in the future smart city development were also investigated.

Lastly, the parts were connected by summarizing the direct environmental impact of the locks in the system for both the mechanical, digital and future concept cylinder. The direct environmental impact of each lock system was compared with the potential avoided emissions in the system which are enabled by the digital locks or the future concept cylinders. This analysis was be performed for each case. The result will support the answering of the research question. Figure 2.2 illustrates the work breakdown structure of the thesis.

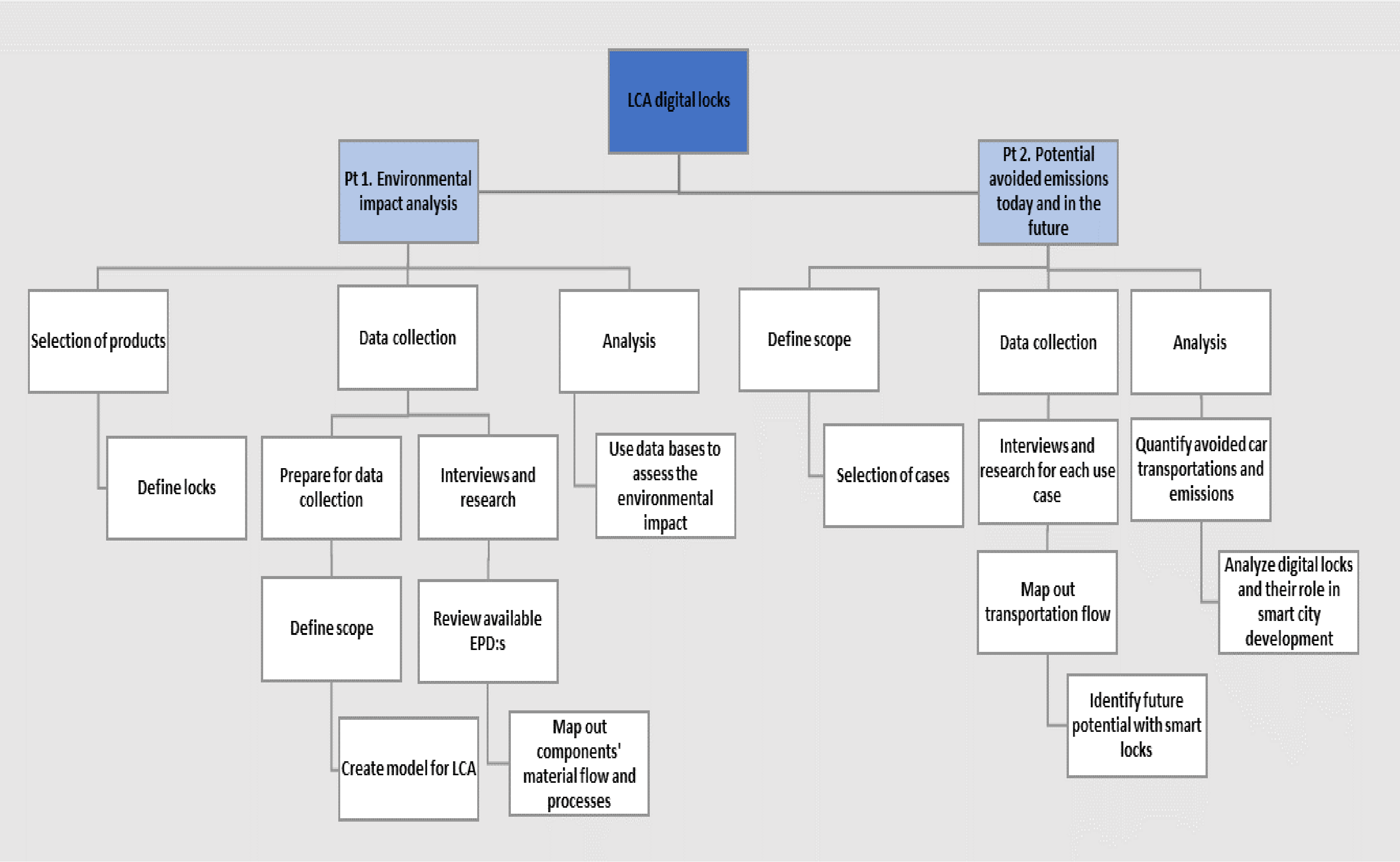

Figure 2.2: Work breakdown structure.

3. Literature review

The literature review presents the relevant literature connected to the topic of the thesis. It provides a theoretical foundation including various perspectives of the topics. The chapter will start of by presenting sustainability in supply chain, including sub-topics such as reporting of environmental impact and a potential reporting of avoided emissions.
Moving on, this chapter will present the Life Cycle Assessment (LCA) and topics related to this which constitute as a corner stone in the thesis. Further on the environmental impact of digitalization and smart city development will be discussed.

Connecting to the second part of this thesis, examples of use-cases where the effects of digital locks have been studied previously will be presented. Since a simplified LCA will be conducted on the keys, some background information regarding relevant manufacturing processes and materials related to locks is provided to get a better understanding of the scope for the LCA.

3.1 Sustainability background

This section will present the underlying sustainability theory and literature for this thesis. According to the World Comission on Environment and Development (WCED) (1987, 8) sustainability is defined as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. Discussions on the definitions of sustainability have been prevalent as the corporate community has taken to the idea (Scoones 2007). The triple bottom line (TBL), which prioritizes economic, social, and environmental factors, is now part of sustainability (Carter and Rogers 2008). New methods of accounting and auditing have been incorporated into company processes as organizations have adopted sustainability and TBL as business objectives (Scoones 2007).

3.1.1 SUSTAINABLE SUPPLY CHAIN

The current fundamental ideas of a supply chain are cross-organizational and cross functional supply-related activities. Supply-related activities are for example procurement, production, logistics and sales. (Nakano 2020) There are several different definitions of supply chain management, one of these are:

"The systemic, strategic coordination of the traditional business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole."(Mentzer et al. 2007, 5)

Supply chain management (SCM) involves both the inbound and outbound flows, including both the focal company, the suppliers and the customers. Supply chains consist of a variety of relationships between multiple organizations and a company's supply chain often involves an upstream and downstream supply chain. (Sarkis 2019) Upstream involves purchasing and inbound logistics while downstream involves different types of customers. Closing the loop of supply chains and incorporate reverse logistics is about bringing the materials and goods back to the loop and reusing it. (Sarkis 2019) One of the fundamental aspects to consider is that a supply chain historically has been focusing on the cost and profit goals of all companies involved (Menzer et al. 2007).

Sustainable supply chain management (SSCM) can be considered as an extension of the SCM concept, whereas more than the economic aspects are considered (Rausch-Phan and Siegfried 2022). Historically, there have been great economic incentives to offshore production sites and by doing so, creating longer and more complex supply chains. With this, the negative social and economic consequences of a supply chain have arisen and gained more attention. (Seuring and Muller 2008) Seuring and Muller (2008) argues that a supply chain should be constructed so that it can meet the needs of today without compromising the future. Since the SSCM model includes the three aspects of sustainability, it can be compared to the “triple bottom line”. The triple bottom line is a framework that emphasizes the focus on social and environmental responsibility for businesses in addition to profitability and considers the impact of an organization´s operations on the three dimensions of sustainability; social, environmental and economical. (Financial Strategist 2023)

3.1.2 GREEN GROWTH

Green growth (GG) can be defined in different ways. The World Bank defines GG as *“growth that is efficient in its use of natural resources, clean in that it minimizes pollution and environmental impacts, and resilient in that it accounts for natural hazards and the role of environmental management and natural capital in preventing physical disasters.”* (World Bank 2012) The Organization for Economic Co-operation and Development (OECD) defines it as *“fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies”* (OECD 2011, 9).

The main idea of Green Growth is to ensure that natural resources continue to offer the resources and environmental services that are essential to our well-being while promoting economic growth and development (OECD 2011). To do this, it must stimulate investment and innovation to support long-term growth and create brand-new business prospects. Innovation is one of the most crucial components of green growth since it can change current ways of doing things and help growth decouple from depleting natural resources. There is a need for initiatives to ensure greener growth because it could lead to increased resource shortages, air and water pollution, climate change, and permanent biodiversity loss. (OECD 2011)

3.1.3 REPORTING OF EMISSIONS AND PARTNERSHIP INIATIVES FOR SUSTAINABILITY

Carbon dioxide (CO_2) is a greenhouse gas well known for its important linkage to global warming (Britannica 2023), the phenomenon of increasing average air temperature on earth (Mann 2023). The greenhouse gases can be evaluated based on their global warming potential (GWP), which is describing their potential to cause global warming depending on how long it stays active in the atmosphere. CO_2 is the reference greenhouse gas for estimating the global warming potential and has a 100-year GWP of 1. (Eurostat 2014) All other greenhouse gases have their own GWP, depending on how much more or less global warming potential they have compared to CO_2. Total impact for certain products can therefore be done by

multiplying the weight of greenhouse gases with their GWP, which gives an easy and reliable comparison of different products or services. (Eurostat 2017)
The World Resources Institute and the World Business Council for Sustainable Development are the founders of the Greenhouse gas protocol (GHG) corporate standard. GHG Protocol is a globally used standardized framework to measure and manage the reporting of greenhouse gas (GHG) emissions for companies, organizations, countries, and cities. (Greenhouse Gas Protocol 2023)

The standards have become the main methodology for GHG emissions reporting, consisting of scopes 1, 2, and 3. Scope 1 refers to emissions connected to a company's in-house operations and factory emissions. (Ng 2021) Scope 2 covers indirect sources of emissions, for example emissions from energy to run the operations or to power the lightning in a building, either in-house produced or purchased energy. Scope 3, introduced in 2011, has a wider coverage and refers to all other indirect emissions throughout the supply chain of a company. This scope is still voluntary to report. However, it typically contains 90 percent of a company's total emissions. Scope 3 is thus important, and companies are encouraged to disclose upstream and downstream Scope 3 emissions. (Ng 2021)

The Science Based Target Initiative (SBTi) is another sustainability initiative focusing on how companies should work to reach the 1.5 degrees target set by the Paris Agreement. (SBTi n.da) By signing up for the science-based targets, an organization can create an understanding of how much they need to reduce their emissions to avoid the catastrophic impacts of climate change. The target set by the initiative for the cooperating company in this study is to halve the GHG emissions by 2030 and reach net zero by 2050, which is also the recommended target for companies signing up. To be officially submitted, the company must also develop a plan to reach the goals in line with the SBTi criteria. (SBTi n.db; SBTi n.da)

3.1.4 AVOIDED EMISSIONS SCOPE 4

As mentioned above, companies report their emissions categorized in Scopes 1,2, and 3. However, there is a growing interest for a fourth Scope to assess and include the need for so-called "avoided emissions". The increased wish among companies to demonstrate accountability through emissions reporting has caused companies to claim avoided emissions by only showing the best potential impact their products might have. (Wai Mun 2021) Therefore, there is an increased need for guidelines and standards for a fourth scope emissions reporting and The World Resource Institute has developed a framework for estimating and disclosing avoided emissions. (Russell 2018) Avoided emissions are not yet defined but include emissions avoided by using an innovative product or service compared to a conventional method or product. (Wai Mun 2021)

Companies are putting efforts into reporting their emissions while the regulations and requirements for the reporting are evolving. Lenders and insurance underwriters are demanding more insight into companies' emissions along the value chain, creating a need for standardized methods to account for these. (Ng 2021)

CDP is a non-profit organization that supports companies, cities, states, and regions to measure their risks and opportunities on climate change. CDP provides a standard for corporate environmental reporting. (CPD 2023) CDP reports an increase in companies

disclosing their emissions through reporting and CDP wants to continue developing its systems and processes to contribute to better transparency and accountability for reporting of emissions. CDP plans to expand and integrate sustainability reporting to cover a broader scope of issues, potentially including Scope 4 of avoided emissions. (Ng 2021)
Some companies have started reporting avoided emissions, but arguably, the results are questionable. Statisticians and energy experts have warned that it might become a problem that companies tend to bring up only the positive impacts of their products and neglect the negative ones. The result of this can be unreliable information and a risk for companies to be accountable for greenwashing. Therefore, there is a need for better guidelines and standards for reporting a potential Scope 4 and to correctly address the complexity in accounting these kinds of emissions. (Ng 2021)

Scope 4 is not included in the previously mentioned GHG protocol but covers the emissions that can be avoided through a product or service. More than a third of companies participating in a survey made by CDP stated that their products support consumers to decrease their carbon footprint. For example, companies state that products such as cold-water laundry detergents, fuel-efficient tires, and energy-lean data centers help the consumers become more sustainable. (Drauker 2013)

Energy statisticians noted that companies, regarding Scope 4, often compared the emissions of a product against a competitor's product and that this selection might be biased. The experts suggest that a "consequential estimation" should be used, which implies that a company should account for the sum of all system-wide changes in emissions occurring because of the product. (Ng 2021)

As companies are moving towards mandatory disclosure of their emissions, it is also emphasized that Scope 3 should be included. The reporting of Scope 3 seems to have a knock-on effect since companies also become accountable for the emissions in their supply chain and thus put pressure on their suppliers to reduce emissions. (Ng 2021) However, the reporting of Scope 3 is still lagging, even if it might be questionable to introduce a fourth scope already. Alvin Ee, a research associate at the Energy Institute at the National University of Singapore stated the following: *"The concept of Scope 4 emissions provides a better understanding of potential savings in terms of emissions avoidance. It is also a platform for companies which have embarked on product innovation or developing new technologies to showcase their efforts".* (Ng 2021)

To summarize, there are three suggestions on what to consider when accounting for Scope 4. Firstly, make a comprehensive analysis and include not only the positive impacts of avoided emissions and carefully consider the selection of products and what to compare with. Second, be transparent with assumptions since these might impact the result. And lastly, consider the potential spillover impact or change in consumer behavior the product results in. This suggestion refers to providing a holistic perspective while being transparent to ensure that everything is accounted for when assessing avoided emissions. (Ng 2021)

3.2 Life cycle assessment

LCA is a cradle-to-grave environmental analysis tool. Cradle-to-grave includes all steps and stages for a product, typically raw material extraction, processing, manufacturing, distribution, use, reuse, and disposal. (Borrion, Black and Mwabonje 2021) The tool is widely used to assess the environmental impact of a product or service and has developed extensively during the last few decades. Today, an LCA has become a more comprehensive assessment that does not only cover the environmental aspects but also social and economic ones. (Curran 2014) An LCA have several areas of usage, for example, to highlight opportunities to improve the environmental performance of products, work as information for decisions-makers and to help with ecolabelling marketing or the selection of appropriate indicators of environmental performance. (Borrion, Black and Mwabonje 2021)

The idea behind a life cycle assessment is to estimate a products or services impact during the scope defined for the LCA. Different scopes can be used depending on the purpose of the study or which product or service investigated. (Guinée 2016) The broadest scope is to follow the product from cradle-to-grave, but another potential scope is cradle-to-gate. A cradle-to-gate scope typically excludes the use- and end-of-life phase. For a cradle-to-gate assessment, the scope must be well defined and clearly stated to be motivated by the conductor. (Guinée 2016)

There are several benefits with LCAs but also limitations to consider. Some of the main relevant limitations are that an LCA does not analyze the environmental impact of building manufacturing facilities nor the emissions from people traveling to and from the facility in the production stage. (Curran 2014) Besides that, an LCA is usually regional-specific, which includes differences in energy grids from different countries. Therefore, depending on where the product is produced or used, the result will differ, and the result may not be applicable for all kinds of usage. (Curran 2014)

Along with an expanding analysis and scope for an LCA, some challenges are becoming more important. For example, to develop a life-cycle approach for assessing scenarios for sustainable futures and procedures to handle uncertainties and rebound effects. (Guinée 2016) Rebound effects can be defined differently (Coroamă and Mattern 2018). Sorrell (2009, 2) defines it as *“The ‘rebound effect’ is an umbrella term for a variety of mechanisms that reduce the potential energy savings from improved energy efficiency”*. Rebound effects can also be extended to include not only energy but resources in general. (Binswanger 2001; Coroamă and Mattern 2018) Furthermore, it is a useful tool for comparing different products with comparable functions and assessing the environmental trade-offs for each. (Porzio and Scown 2021)

3.2.1 LIFE CYCLE ASSESSMENT, ISO-STANDARD 14044:

Two international standards provide the principles, frameworks, and guidelines for performing an LCA, ISO 14040:2006 and ISO 14044:2006 (Borrion, Black and Mwabonje 2021). ISO stands for The International Organization for Standardization and has developed a technique for understanding and addressing the impact products or services have on the environment. According to ISO 14044, an LCA is defined as *the “compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle”.* (ISO 2006a, 2) According to the ISO standard, an LCA should be carried out in four steps:

A, The goal and scope definition phase

B, The inventory analysis phase
C, The impact assessment phase
D, The interpretation phase
(ISO 2006a).

The increased need for environmental transparency has led to several mechanisms developed to support the publication of environmental information. The ISO 1402X standards include three types of standards for the declaration of environmental aspects, Environmental Labelling (Type I), Self-declared environmental claims (Type II), and Environmental Declarations (Type III). (Ibáñez-Forés et.al 2016)

3.2.2 ENVIRONMENTAL PRODUCT DECLARATION, ISO STANDARD 14025:

An Environmental Product Declaration (EPD) is a document describing a product´s or service´s environmental performances from a lifecycle perspective. It is a type III Environmental declaration compliant with the ISO 14025 standard. An EPD is a result of a life cycle assessment containing the entire life cycle of a product or service. (EPD International n.d) The quantified information in a type III EPD can be based either on an LCA following the ISO 14040 series of standards or information modules. (ISO 2006b) Data from an LCA should be separated into three categories, Life Cycle Inventory analysis (LCI) according to the Product Category Rules (PCR), indicator results of Life Cycle Impact Assessment (LCIA) and other data such as quantities and types of waste produced (ISO 2006b).

Environmental declarations of type III present quantified environmental information regarding a product or service to make comparisons possible between products with the same function. Comparability is therefore crucial, and the standard includes product categories defined as a group of products that can fulfil similar functions. (ISO 2006b) The product categories have Product Category Rules (PCR), a set of rules, demands, and guidelines for the specific product categories (ISO 2006b).

The development of a PCR document is recommended by ISO to be carried out in three steps. Initially, the product category must be defined, including for example the function of a product, its technical performance, and its use. The second step is to find or produce an appropriate LCA. The final step includes specifying common goals and relevant rules for the product category. (ISO 2006b) Common goals and relevant rules are for example predetermined parameters, rules on additional environmental information, requirements for reporting and instructions on how to produce the data required for the declaration. The requirements for comparability should be based on the PCR document and the product category definition and descriptions must be identical to reach comparability. (ISO 2006b)

3.2.3 LCA APPROACH AND FAST TRACK METHOD

Conducting an ISO standard-compliant LCA is a very complex and time-consuming procedure. Most of the LCA manuals focus on the theoretical parts of a Life Cycle Inventory (LCI), Life Cycle Interpretation, and the formalities of reporting. The guidance for LCI has mostly remained abstract and generic. (Saavedra-Rubio et al. 2022; Vogtlander 2012) However, some people, for example students, business managers, and designers manage to perform an LCA that is sufficient for their needs without the LCI nor an extensive report of the analysis. There are different types of LCAs, and all do not fulfill the specific requirements for a full LCI and the reporting of it, which is not always the purpose of performing an LCA. (Vogtlander 2012)

Due to the above mentioned, Joost Voglander, Professor at the Delft University of Technology, proposes that LCAs can be divided into two types: classical LCA and ‘s’ LCA. The ‘Fast Track’ LCA can also be referred to as ‘streamlined’ or ‘simplified’ LCA (McAloone & Pigosso 2017). The classical LCA focuses more on the LCI and the ‘Fast Track’ focus more on the comparison of designs. A ´fast track´ LCA uses the result of classic LCA, primarily data regarding background processes e.g., that is available in databases, as input. The procedure can be summarized by multiplying the inputs and outputs of the LCI, e.g., a list of emissions in addition to required materials and energy, by factors for the single indicator. Examples of single indicators are eco-cost, carbon footprint, or ecological scarcity. These indicators are selected based on the goal of the study. (Vogtlander 2012)

There are different types of single indicators which are categorized as the following, single issue, damage-based, and prevention based. The most used ‘single issue’ indicator is the carbon footprint that corresponds to the total emissions of kg CO_2, or CO_2 equivalent (CO_2-eq). The single-issue indicator makes the calculations simple and transparent, which facilitates the communication of the result. (Vogtlander 2012) On the other hand, it neglects problems caused by other pollutants and is not suitable for a cradle-to-cradle assessment. The ‘Fast Track LCA method’ is also known as ‘The Philips method’ because Philip Electronics was the first company to conduct an “LCA” with this approach. The Fast Track LCA procedure consists of the following steps:

Step 1; Establish the scope and the goal of the analysis.

Step 2; Establish the System, Functional Unit, and System boundaries.

Step 3; Quantify materials and use of energy in the system.

Step 4; Enter the data in Excel.

Step 5; Analyze the results and make conclusions.
(Vogtlander 2012)

In Step 1 details regarding the purpose of the study need to be determined since it will affect the procedure. It needs to be decided whether the purpose of the study is to compare two products or if it is an attempt to decrease the environmental burden of a design. (Vogtlander 2012)

Step 2 covers the specifications and limitations of the product and system for the assessment along with deciding on the service life of the components. The functional unit describes the function of a product or service. For a coffee machine, the functional unit could be 1000 cups of coffee per year. In step two the practitioner should also make a drawing of the product system and the boundaries such as cradle-to-gate or cradle-to-cradle and specify what to include and exclude in the assessment. (Vogtlander 2012)

Step 3 consists of collecting data for the components to be studied e.g., weight, material, processes, and energy consumption. By using a cut-off criterion, the accuracy and relevance of the details can be determined. If data is not available for a material or process, the data gaps can be filled by making assumptions with average or generic data. (Vogtlander 2012) In case of insufficient data, a cut-off criterion may be applied, such as e.g., one percent of total mass and one percent of potential environmental impacts. However, the total neglected input flows shall not exceed five percent. All assumptions and applied cut-off criteria must be documented. (Sustainable Minds 2018; Vogtlander 2012)

Next up, during step 4 the data is added to an Excel calculation sheet. If an indicator value is missing for a material or process in the look-up table, this may be resolved in different ways. First off, examine whether the missing material or process has a large impact on the environmental impact or if it is hazardous, otherwise it might be neglectable. (Vogtlander 2012) Further, search for a substitute for the unknown one that could be comparable. Searching in EPD databases could also help to fill the gap. Another solution is to determine the required energy for the process and calculate its environmental impact. (Vogtlander 2012)

Lastly, in step 5, the environmental impact for all materials and processes can be summarized for the product. The result is then analyzed based on the purpose of the study, e.g., compared with another product. (Vogtlander 2012)

3.2.4 CALCULATING OF CO_2 EMISSIONS FOR TRANSPORTATION

According to the European Commission´s climate target plan (2023/851), covering the GHG emissions from road transport, the emissions have increased by more than 25 percent since 1995 and contribute 20 percent of the EU’s total emissions. The Commission’s Sustainable and Smart mobility strategy emphasizes the transition to zero-emissions vehicles and renewable fuels to reach a reduction of net GHG emissions by 55 percent by 2030 in addition to climate neutrality by 2050. (European Parliament 2023)

The result from a study published by the European Environment Agency in 2020 shows that the average emission of new passenger cars, based on all types of vehicles, in the EU, Iceland, Norway, and the UK were 139,4 grams of CO_2 per km in 2010 compared to 108,2 g in 2020 (Acea 2022).

Regarding the environmental impact of transportation and distribution of freight, the GHG protocol proposes a distance-based transportation method for calculating CO_2 emissions (Greenhouse Gas Protocol 2013). In the proposed method the distance is multiplied by the mass or volume of goods and the relevant emission factor. The emission factor is related to the average fuel consumption, average utilization, average size and mass of the goods, and the transportation mode. (Greenhouse Gas Protocol 2013)

3.2.5 LCA DATABASES AND TOOLS

The most common way to conduct an LCA is to use already collected data from one of the LCA databases available (Ecochain 2023). The software applications have gathered data on different materials, processes, products, energy usage, transportation, and more to offer the possibilities to conduct accurate LCAs easily and time effectively. The currently well-established software tools are GaBi, SimaPro, oneClickLCA, and openLCA, among others. (Ecochain 2023) Depending on the purpose of conducting the LCA, how important accuracy is and the time willing to spend on it can be aspects to consider when choosing software. The main idea is that the user builds a model in the software, uses the available input data, and receives the output for the product or service of interest. (Greenhouse Gas Protocol n.d)

Idemat

Industrial Design & Engineering MATerial database (Idemat) is a database created by SIMF (Sustainable Impact Metrics Foundation), a spin-off of Delft University in The Netherlands. (Idemat 2023) The database contains a compilation of data from peer-reviewed scientific papers, LCI´s made by Delft University and additional information from other databases. The database is free and available for everyone in an Excel sheet. Since it includes some limitations and assumptions and is not as compherensive as official databases, it needs to be used critically and with consideration. (Idemat 2023)

3.3 Environmental impact of digitalization and digital products

The digitalization industry has historically been growing for decades and nothing indicates that this rapid increase of digital products will slow down. (Kotarbra 2017; Paliwa l and Bhutani 2015) Gartner Glossary (2018) defines digitalization as *“The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business”*.

When investigating the industry´s carbon footprint, several aspects should be considered. (Malmodin and Lunden 2018) The focus in this thesis are digital products, containing batteries and electronics, which are characterized by heavy carbon footprint raw material and complex supply chains, increasing the risk of an overall higher environmental burden. (Marques Canal, Cabrera and de Fraga Malfatti 2013) Not only must the direct emissions from the technology be considered, but also the emissions caused by the change in individuals, businesses, and societies´ behavior because of digitalization. (Malmodin and Lundén 2018)

Recent studies have shown that the digitalization’s sectors emissions have decreased as a cause of the increased efficiency of digital solutions. (Malmodin and Lundén 2018) Other studies argue that the digitalization sector instead increases emissions due to higher increased efficiency and higher usage, a kind of rebound effect (Coroamă and Mattern 2019). Coroamă and Mattern (2019) divide digitalization into services that cause a rebound effect or those without a rebound effect. The conclusion is that the ecological footprint keeps growing despite increased digitalization and a strong rebound effect seems to be more common rather than an exception for digital implementations. It can therefore be argued that digitalization does not necessarily indicate lower emissions due to increased efficiency and extended research is needed to understand why and how the higher emission-causing rebound effects occur. (Coroamă and Mattern 2019)

3.3.1 ENVIRONMENTAL IMPACT OF DIGITAL CHANGE

The effects digitalization can have on its surroundings can be divided into different categories with the levels of product, system, and society. The type of change for these levels are optimization, acceleration, and transformation. Figure 3.1 shows how the levels and types of changes are connected. (Pamlin and Jansson 2018)

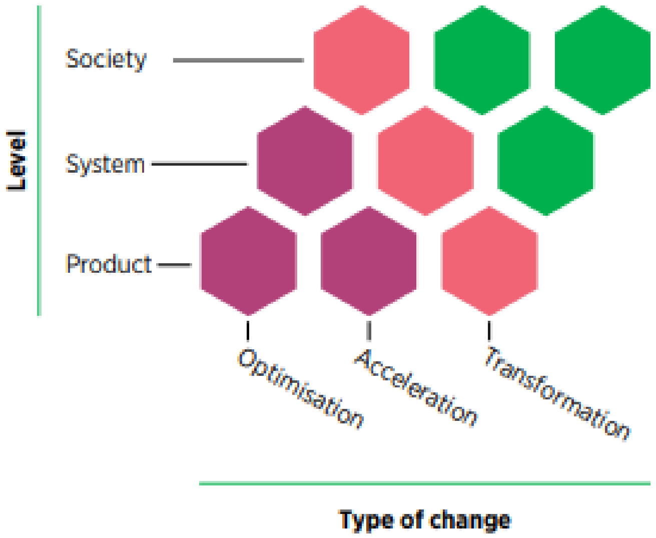

Figure 3.1: Visualization of the levels and type of changes for the environmental impact of digitalization. (Pamlin and Jansson 2018, 16)

Optimization: The implication of digitalization in already existing systems is referred to as optimization. (Pamlin and Jansson 2018) By using digital technology, systems can increase their efficiency. Studies shows that digital solutions can enable a 20 percent reduction of CO_2 equivalents emissions by 2030. (GeSi and Accenture 2015) GeSi and Accenture states that the emissions from the digital infrastructure are expected to decrease over time, while the avoided emissions from using digital solutions are nearly ten times greater than the emissions generated by producing it. Furthermore, development can reduce the trade-off between economic prosperity and ecologically sustainable development by increasing efficiency and the avoided emissions. (GeSi and Accenture 2015) An example of an optimized product is an engine controller for a fossil-fuel-powered vechlie. An optimized system is for example support for smarter vehicle control or a food waste recycling system. On a societal level, optimization usually includes larger systems, for example, a traffic system that evaluates vehicle emissions per km or a system that helps countries become self-sufficient in food waste. (Pamlin and Jansson 2018)

Acceleration: The acceleration type of change means finding the best available digital option and implementing it affluently to reach emission reductions. By making the best solutions the established option, a large number of emissions can be avoided. (Pamlin and Jansson 2018) An article by Arnulf Grubler et al. (2018) has laid the basis of the idea that digital and smart solutions in society have the potential to lower the energy demand instead of shifting towards renewable energy. It can therefore be argued that finding solutions to decrease the energy demand can be more efficient compared to finding new sustainable ways of creating the same amount of energy. (Grubler et al. 2018)

Product acceleration includes, for example, new lighting technology or support for development and implementation of synthetic meat. On a system level, the acceleration change is, for example, the development of control systems for EV charging in a smart city or support for buildings that are net producers of renewable energy. (Pamlin and Jansson 2018)

Accelerating on a societal level refers to, for example, using digital solutions to minimize various kinds of transport through either dematerialization or local production using 3D printers, combined with a entire system based on electrification and hydrogen gas. (Pamlin and Jansson 2018)

Transformation: Transformation with digital solutions include widening the perspective from individual solutions to systems. (Pamlin and Jansson 2018) An important aspect of the transformation strategy compared to the other two is the rebound effects. Even though rebound effects can be both positive and negative, historically, most attention has been on the negative. This is not necessarily the case and depending on the individual, there is a likely effect that they are positive as well. (Pamlin and Jansson 2018)

Product transformation is for example the transition from meat to a more sustainable plant-based option or going from using vehicles to a system with gas/electrical transportation modes that utilizes rest energy from urban facilities. An example of system-level transformation is developing an urban environment that facilitates walking and cycling instead of using vehicles or integrating agriculture into everyday people through smart homes. (Pamlin and Jansson 2018) On a societal level, transformation can be archived by developing systems that integrate nutrition and wellness for optimal sustainability or to develop a more detailed construction plan that creates more sustainable urban environments (Pamlin and Jansson 2018).

3.3.2 ENVIRONMENTAL IMPACT OF DIGITAL PRODUCTS

During the last decades, the electrical and electronic equipment industry has experienced rapid growth due to the increased demand (Ozkan, Elginoz and Germili Bubana 2017). The electronics industry is characterized by its long supply chains that include many indirect environmental impacts associated with the products (Marques Canal, Cabrera and de Fraga Malfatti 2013). Currently, the environmental impact of manufacturing PCB boards and other electronic equipment is not investigated to its fullest and deserves more attention in the future. As the industry grows, there is also an expected falling life expectancy among electronics, mainly due to changes in product design and low recycling rates. (Andrae 2010) Related to recycling, due to the great variety of products, components, age, origin, and manufacturers, electronic waste varies to a point where the recycling processes are complicated and difficult to conduct at an extensive level. Electronic recycling is also a process currently being investigated for making the process better, more efficient, and less energy-demanding. (Andrae 2010)

Energy storage and rechargeable batteries play a crucial role in the decarbonization of energy systems. Conducting LCAs on batteries has some challenges, for example, choice of methodology and scarcity of primary data on battery manufacturing and supply chains. (Porzio and Scown 2021)

Batteries have a complex supply chain and only the production of the battery cell can require sourcing of 20 different materials globally. (Melin 2019) Further, the materials need to pass through several refining stages, often exclusively used for batteries. Lithium-ion batteries (LIB) are not a single battery type but are a denominator for different chemistries used in the negative electrode and cathode, which results in the properties being different and varying environmental impact. (Melin 2019)

A LIB battery contains three main components: the cells with the active material, the battery management system to control performance and safety, and the pack that is the structure of the cells. (Melin 2019) Regarding the energy consumption for producing batteries, the major contributor is the cells which contribute 75 percent of the total energy. The first step in producing a cell consists of mining, conversion, and refining of material. This step contributes 20 percent of the total energy for producing the cell. (Melin 2019)

Another study has found that for an LMO (lithium manganese oxide) battery pack, the material comprises about 30 percent of the total primary energy demand for producing the battery. (Porzio and Scown 2021) Energy use is a driver of the environmental impact during battery manufacturing. Some processes in manufacturing do vary by different types of cells but the main processes that contribute to the environmental burden are common for all types. (Porzio and Scown 2021)

The scope of previous studies differs a lot due to a variety of system boundaries, functional units, and primary data. This restricts the comparability of different technologies. Further, the results of published studies of life-cycle greenhouse gas emissions for batteries vary a lot because of the applied direct energy demand for cell manufacturing and pack assembly. (Porzio and Scown 2021) For batteries, the use phase is often included in an LCA and may vary a due to different purposes. Therefore, it can be appropriate to have the system boundary ending at the factory gate and excludes the use phase and end-of-life. The impact of electricity used in manufacturing batteries can vary due to the amount needed for processing different materials but also because the grid mix can vary by location. (Porzio and Scown 2021)

3.4 Smart city development and digitalization

A smart city is a city that uses advanced technology and data-driven solutions to enhance the quality of life of its citizens. A smart city can be considered a city that uses technology, data, and other digital applications to improve the quality of life and ease decision-making. (Wotezel et al. 2018)

Woetzel et al., (2018) present a model where three layers create the smart city. The first layer is the technology base which creates the foundation of a technology-driven and connected city due to the mass use of smartphones and sensors. The second layer is the app developers and technology providers, where the data is translated, and tools are used for creating insights and alerts. The third layer is usage of available applications for third-party users, for example, citizens, the public, and companies. According to Woetzel et al. (2018), the smart city only succeeds and works as expected if the technology is widely accepted and adopted. Examples of this adoption are for citizens to interpret the encouragement into their every day, for example, to use transit when the demand is low, use less energy, and practice preventive self-care when the healthcare system is experiencing high demand. (Wotetzel et al. 2018)

In recent years, several smart city projects have been implemented globally. Even though changes in social behavior and environmental attitudes are noticed due to smart city initiative, there is a lack of knowledge regarding the success and progress of smart cities. One of the greatest challenges on the subject is that most articles existing today are based on hypothesis and therefore a lack of real evidence and control over the environmental parameters to achieve sustainability. (Su, Hu and Yu 2023)

3.5 Cases for digital lock utilization

Digital locks described in sections 1.2.1 are not necessarily a brand-new concept and have been used in many different settings for years. (SKR 2020) Depending on the purpose of installing a digital lock, both the lock and how it is used can differ significantly, but there are some use cases where digital locks have proven to generate operational benefits. Some of these are presented in the following chapter and have inspired the use-cases selected in this study.

Sveriges Kommuner och Regioner (SKR) states that overall trends in society have influenced the usage and technical development of digital locks. (SKR 2020) These trends are increased safety, streamlined operations, simplifications and integrating digital locks as a part of an ecosystem. Digital locks can streamline and simplify operations by reducing time spent on key management, both related to picking up and dropping off keys and less permission administration. To be able to give access through a single tag or mobile phone is therefore an attractive solution. (SKR 2020) To use digital locks as a part of an ecosystem refers to integrating systems and services, for example, using the same application for different tasks. For example, to access a door, book a timeslot in the laundry room and let delivery personnel deliver packages inside the door using the same application. The overall trend is to use identities instead of physical keys and to give the right person access at the right time. (SKR 2020)

Six different areas in the public sector currently manage permissions and keys. These areas are home care service, waste management, sport and culture, school facilities, blue light personnel, and real estate services. The greatest identified area of improvement in 2020 was the ineffective permissions administration and key management, where there are possibilities to save both time and emissions. (SKR 2020)

3.5.1 HOME CARE SERVICE

Home care consists of various services for elderlies where caregivers visit the elderly' home to perform certain tasks depending on the need of the receiver. Typical services are daily- and nightly supervision, support with medication, and hygiene assistance. The person performing the service is referred to as a caregiver and the person receiving the care is referred to as a caretaker. (Myndigheten för digital förvaltning [DIGG] n.dc)

Most municipalities today use digital to some extent for their home care services. (SKR 2022) Stockholm Stad developed a pilot project between 2017 and 2020 investigating the potential of using digital locks in different aspects of their operations, for example, elderly care and waste management. (Stockholms stad n.da) The purpose of the pilot project was to take the first step towards installing digital locks for elderly care in a city-wide setting. The three most relevant goals that were achievable were identified as improved safety and work environment, decreased environmental impact, and more efficient handling of keys. (Stockholms Stad 2020a) The decrease in environmental impact was mainly based on less expected transport because decreased need for picking up or dropping keys, especially for personnel working during nighttime. (Stockholms Stad 2020b) The result was positive, and the municipality decided to continue installing digital locks to include all home care services by 2022, both private and public actors. (Stockholms Stad 2020b)

SKF states that utilization of digital locks is common among care recipients and households. There are a lot of benefits to implementing digital locks, such as facilitating the receiving of care at home for individuals in addition to improving the efficiency of caregivers by enabling fewer routes to collect physical keys. (Socialstyrelsen 2022; SKR 2020)

”Digitaliseringssnurran” is the result of a project by Post- och telestyrelsen in collaboration with Analysys Mason and RISE ordered by the government (DIGG n.da). “Digitaliseringssnurran” is a tool used to assess the potential efficiency gains of digitalization in municipal operations. The result is based on the implementation of digital services after one and five years. To use the tool a municipality must be selected for the simulation which will affect the calculations. Thus, many of the values are standard for all municipalities based on studies and statistics from Statistiska centralbyrån (SCB). (DIGG n.db) However, it is possible to adjust these for certain conditions in a municipality. The calculations of the potential gains are based on the result of previous digitalization efforts in municipalities. Various parameters and assumptions are based on interviews with municipalities, published reports, and data from databases. (DIGG n.dd) The outputs from the tools are, for example, number of home care receivers, average numbers of visits a day for employees, emergency visits a day and night, and driving distance for planned visits and emergencies (DIGG n.db).

3.5.2 REAL ESTATE

Digitalization in the real estate industry has not yet been fully developed compared to other industries. Some of the current obstacles that hinder the digitalization process of real estate today are the conservative culture, poor incentives for investments, and lack of capabilities in the organizations and industry at large. (Vigre, Kadfors and Eriksson 2022)

Even though most of the actions for a more digitalized industry have been IT-related, many real estate owners have noticed the potential of developing new services. These services are for example smart buildings with the potential to improve access control and to deliver goods both related to the real estate itself and tenants. (Vigren, Kadefors and Eriksson 2022) A focus for the development has recently been to create an eco-system around the buildings to integrate different systems to make the flows and maintenance around the buildings streamlined. Other potential areas of investments have been focusing on energy management and how to use digitalization to create energy savings. (Vigren, Kadefors and Eriksson 2022)

Introducing digital locks in apartment buildings has been discussed frequently in recent years. A municipality-owned real estate company investigated this in 2020. The study showed that increased cost for the digital locks could be justified due to the increased use value for the real estate. It was found that digital locks would increase safety, making the workplace better and more efficient as well as enabling a possibility to increase the service. (SKR 2020)

Another example of where digitalization has been successful is for a municipality-owned real estate company that owns and administers most of the Stockholm municipality pre-schools, elementary schools, and secondary schools. A system for handling keys digitally and decentralized was developed in 2017. (PE Teknik & Arkitektur n.d.) The idea with the system is to store several keys locally at each real estate the company administrates. Whenever a craftsman or subcontractor needs access to certain premises, the subcontractor can receive access to the key cabinet through his or her mobile phone, select a key, and program it to receive access to the premises. The craftsmen can therefore travel straight to the facility for work instead of first going to the head office to retrieve the keys. (PE Teknik & Arkitektur n.d.)

3.5.3 LOGISTIC AND PARCEL SERVICE

The state-owned delivery service company in Norway, Posten, offers an in-home delivery service without the recipient attendant (Rózycki and Kerr 2019). Similar services are available in Sweden in cooperation between DHL and the lock company Glue. (DHL n.d)
The solution works with the help of digital locks where the deliverer receives a temporary code or the consignee unlocks remotely. (Rózycki and Kerr 2019) This kind of solution increases the efficiency of deliveries, improves satisfaction among consignees, and can reduce transportation. Since there is a 100 percent first-time delivery rate, wasteful failed first-time deliveries are avoided, and transportation to and from a pickup point is avoided. (Rózycki and Kerr 2019)

Nighttime delivery is another interesting aspect that potentially can reduce the environmental impact of Business to Business (B2B) deliveries. (Sathaye, Harley and Madanat 2010) Normally, the larger cities in Sweden have a ban for heavy traffic between 10 pm and 6 am when most of the citizens are asleep (Stockholms Stad n.db; Göteborgs Stad n .d; Malmö Stad 2023), but there is currently a pilot project carried out in Malmö where a certain carrier is allowed to deliver between this timespan. (Malmö Stad 2022) The initial benefits with nighttime delivery are less pressure put on the road network during peak hours and less heavy traffic being stuck during peak hours. The reason for this kind of project now being top of mind for several carriers and municipalities is the introduction of electric-driven trucks, which are usually less noisy and disturb residents less. The heavy investment needed for carriers for electric-driven trucks also includes a need to use it more frequently and must be used during nighttime in order to be justified. (Malmö Stad 2022)

A study was conducted in Stockholm in 2021 in a collaboration between Stockholms Stad, KTH, and the research institution Integrated Transport Research Lab (ITRL) with the purpose to study the potential of nighttime deliveries of gods in Stockholm (Von Kern 2021). Shops, restaurants, and hotels e.g., often expect their goods delivered by the morning and the logistic companies must then deliver during the morning rush (Von Kern 2021). Thus, it would be more beneficial to deliver during nighttime without the heavy traffic while still having the gods delivered on time. Stockholm Stad has continued with the project to investigate how the policy of nighttime deliveries will look in the future. (Von Kern 2021)

Another study from 2017, also conducted in Stockholm on the same topic, found that every truck performing nightly deliveries corresponds to three trucks delivering during the morning rush. During the morning rush, three trucks are needed to deliver the goods in time due to the time they are stuck in traffic. (Ardell 2017) The results show that using nighttime deliveries may reduce the trucks stuck in traffic and thus the environmental impact of deliveries. The results also show that the average speed was 30-60 percent faster for deliveries delivered during off peak hours. (Ardell 2017)

3.6 Trends in last-mile delivery and the environmental impact

Since the COVID-19 pandemic started, there has been a huge growth in e-retail sales, which has resulted in operational challenges for last-mile deliveries. To manage these challenges, there is a need to develop new innovative delivery solutions. (World Economic Forum 2020) Unattended home delivery is one solution that has future potential to improve customer experience since it enables home deliveries without the attendance of the receiver. (Heid et.al 2018) This type of delivery has several advantages, for example, a longer time-window for delivering and fewer failed deliveries. Thus, unattended home delivery enables improved transport planning for last-mile delivery companies. It is also less costly to offer unattended home delivery compared to a one-to-two hours' time-window. (Hübner, Kuhn, and Wollenburg 2016)

Consumers' selection of last-mile delivery alternatives depends on their acceptance of the available services. Unattended home delivery is one new alternative, and the customers experience of this delivery option is still quite unknown. (Felck et al. 2019) The service can be performed in different ways. Examples of unattended home-deliveries are to deliver inside the front door, deliver in the fridge, or deliver to out-of-home environments such as doorsteps or reception boxes (Olsson, Hellström, and Vakuelnko 2022). A field study was performed in Sweden to gain more insights into customer experience regarding unattended home delivery through a reception box. The result from the field study showed that customers are interested in unattended deliveries but are reluctant to pay extra for it. (Olsson, Hellström and Vakuelnko 2022)

Studies show that unattended delivery service cause security concerns (Stickle et al. 2020; McKinnon and Tallam 2003). There could be a risk with bringing a stranger onto one's property and to have parcels left outside the door accessible for thieves. In the USA, package theft, also called "porch piracy" is an increasing problem for home delivery receivers. (Aegis Technologies 2023) However, the demand for unattended deliveries could increase if people have their lifestyles constrained by staying home to receive a delivery (McKinnon and Tallam 2003).

Out-of-home (OOH) delivery locations, such as Pick-up-Drop-off locations and parcel lockers are becoming a more popular option for deliveries for both businesses and consumers and have not yet reached their full potential. (MAERSK 2023) OOH deliveries can be up to five times more efficient per route compared to home deliveries. The total transportation distance is then reduced which brings sustainability benefits. (Last Mile Experts 2022) Cheah and Huang (2021) imply that by 2023 if all deliveries would be OOH deliveries, this has the potential to reduce the emissions with 103g of CO_2 emissions per parcel delivered.

Giuffrifa et al. (2016) state that the environmental impact of home delivery is three times higher compared to delivery to a parcel locker. The result is based on that the courier needs to travel a longer distance to reach each receiver's home compared to unloading in one place. (Giuffria et al., 2016) For deliveries to parcel boxes, Giuffria et al. (2016) also considered the environmental impact of the distance the consumer travelled by car to reach the parcel locker.

3.7 Utilization rate of facilities and the environmental impact

The building environment today stands for approximately 40 percent of the global energy demand and 30 percent of the energy-related greenhouse gas emissions (United Nations n.d). The highest impact comes from the use phase and the energy demand for operating the buildings. Globally, the floor area is expected to grow by 20 percent by 2030. Additionally, for the building sector to reach its net-zero goal, energy consumption per square meter must decrease by 35 percent compared to 2021. (Delmastro 2022) The average emission for constructing a building is approximately 200-209 kg CO2 equivalents per square meter. (Harris et al., 2021, 2) The consumption depends on the national electricity mix and varies significantly between studies. Some studies estimate it to be 250 kWh/m2, corresponding to 70 CO2/m2, whereas other studies estimate it to be 60-160 kWh/m2, an emission of 40-60 kg CO2/m2 per year. (Harris et al. 2021) In Sweden, the consumption is approximately 105-145 kWh/m2 per year for heating (SCB 2018) and an extra consumption of 100kWh/m2 for electronic equipment. (Mata and Johansson 2017) The average emissions from Sweden's electricity grid are 15 g CO2/kWh, corresponding to approximate emissions between 3 and 3,7 kg CO2/m2. (Harris et al. 2021)

According to Tricore (2021), there are two main ways to archive decarbonization in the building sector, either by improving the insulation or creating less need for heating and cooling. The second way can be to further digitalize buildings, making them smarter and decreasing the need of energy. A smart or "autonomous" building could with the help of technology track people and use real-time data analysis to for example turn off heat and lighting in unoccupied spaces. (Tricore 2021)

Related to this, there is an increasing issue with the utilization rate of buildings. The low utilization rate of buildings in Sweden impacts the efficiency of energy use and make the energy consumption per hour or activity higher than necessary. According to Fjellander et al. (2019), the utilization rate of offices in Sweden is 60-70 percent, but the Swedish company Vasakronan estimates their number to be 10 percent, including all the hours of the day. (Fjellander et al. 2019) Sharing offices could potentially decrease the necessary space between 50-70 percent and reduce emissions with the same number. (Holmin et al. 2015; Fjellander et al. 2019) In Sweden, around 418 000 m^2 of office space is built annually, which is superfluous by looking at the currently available surface. To not build that extra space would save 104 500 tons of CO_2 equivalents assumed an average of 250 kg CO_2-eq/m^2. (Fjellander et al. 2019)

The community needs that account for the most material consumption in Sweden today are buildings and infrastructure, with a total of close to half of all of Sweden´s material consumption. (RE: SOURCE 2022) IVA (2020) argues that there are interests from stakeholders to share premises to a larger extent. Innovation and ideas of how that could work in practice are under investigation. For the construction and real estate industry, the greatest resource efficiency that can take place is to use already existing buildings and their surroundings to a larger extent. The report has a vision that a higher utilization rate of buildings can lead to less use of resources and a positive impact on ecological, economic, and social sustainability. IVA (2020) determines that sharing of buildings can lead to a substantial decrease in resources if, among other aspects, the sharing becomes part of a system of thinking where it fits with society and other flows of resources. Additionally, cooperation between stakeholders is necessary for it to work, where one aspect is for the businesses to design spaces for sharing and reach a higher utilization rate, for example by facilitating access. One of the greatest challenges is also that the solutions must be widely used and accepted. An important aspect of this is a smooth physical access. (IVA 2020)

Marklund and Almqvist divide the current barriers for a shared system in facilities into five categories: behavioral, organizational, physical, legal, and economic. For the physical barriers, locks and access systems are one of the root issues. In a list of 22 prioritized problems for cooperation, one is "*Locking and accessing systems are required to share equipment and premises*". (Marklund and Almqvist 2022, 21) Further, the result from the report states several benefits of increasing the utilization rate of buildings. 2018 Stockholm Stad made 14 school facilities available for civil society organizations, a venture that worked well with minor changes to the facilities, for example, the installation of ramps and the implantation of an access system that did not require physical staff on site. (Stockholm Direkt 2018; Marklund and Almqvist 2022)

3.8 Manufacturing processes of keys

This section will provide some background information regarding relevant manufacturing processes and materials for the products in this study. The data on the environmental impact of processes and materials will be presented along with the simplified LCA in the following chapter 4.

3.8.1 METAL

Metals are an important component in different materials and products today, and the global demand is expected to continue to grow. The increasing demand is both due to the increased use of metal overall and because of the digitalization where metal is used in electronic products, for example, printed circuit boards and integrated circuits. (McKinsey 2022)
The production of metal usually includes ore mining and concentration, smelting or separation, and refining to obtain the element in its metallic form. The methods used can differ, but for all steps, impurities and by-products are separated, increasing the concentration of metal. The metallic form is then the material represented in the periodic table. The material is usually melted in different steps, requiring a lot of energy, often based on fossil fuels inputs or electricity. (Nuss and Eckelman 2014)

Alloy creation and casting

An alloy is a mixture of different elements to obtain certain mechanical and corrosion properties. (Bahadur Singh 2022) The basic principle of an alloy is to create a less ductile metal and improve its durability or ability to withstand heat. There are two main ways to produce alloys, either by heating, melting, and mixing or turning the material into powder and fusing them in high pressure and temperature. (Eagle Alloys 2016) Metal casting is the manufacturing process of shaping molten metal into a solidified form at a particular temperature (Vijavaram 2022). A typical modern casting process contains six stages: melting, alloying, molding, pouring, solidification, and finishing (Salontitis et al. 2016). A casting process usually has a very high design flexibility (Vijayaram 2022) but is also very energy demanding (Salontitis et al. 2016). There are several methods for the process, and the best one to use depend on the material and the required output and quality of the finished product (Vijayaram 2022).

Rolling

Metal rolling is a common process for metal and most metal products are subject to a rolling process. The casting product is usually hot rolled into a bloom or a slab, which determine the initial forms of the product. (Siddharta 2016; The library of manufacturing n.d) The metal can be rolled into bloom or slabs with different measurements depending on the desired outcome. Metal rolling is usually performed with hot metal, so-called hot rolling, but can also be performed at a solid state, so-called cold rolling. (Siddharta 2016; The library of manufacturing n.d)

Stamping

Metal stamping is a manufacturing process for converting flat metal to specific shapes. The process can vary depending on the complexity of the product or the material, but it usually includes blanking, punching, bending, and piercing, among others. The flat metal sheet is placed in a press, which forms the metal and dies the surface to the desired shape. (Engineering Specialties)

Milling

Milling is usually the last manufacturing method when manufacturing small metal pieces. The purpose is to manufacture high-precision products and parts in different shapes and sizes. Milling is performed with the help of a machine where the workpiece placed on a rotating axis. With the help of small cutters, the workpiece can be formed into the desired finished product. (Thorat n.d)

3.8.2 PLASTIC

Plastics are often derived by the following processes: extraction of raw material from oil, natural gas, or coal, refining process that transforms oil into petroleum products then polymerization, and lastly compounding meaning that materials are melted and blended. (Baheti n.d.)

The plastic Injection molding process (PIMP) is an important technique for plastic components, and it is mainly used to produce solid parts in high volumes and with high precision (Conrad 2021). The process starts with feeding plastic pellets and appropriate additives from the hopper to the injection system of the injection molding machine. The molten plastic is then injected into a mold which creates the final product (Conrad 2021).

3.8.3 ELECTRONICS AND BATTERIES

Printed Circuits Boards (PCBs) are crucial parts of most electrical and electronic equipment (Marques Canal, Cabrera and de Fraga Malfatti 2013). Manufacturing a PCB is usually a complicated process and can include up to 50 steps, where many steps are considered harmful to the environment. There are a great variety of PCBs, for example single-sided boards, double-sided boards, and multi-layer boards. (Marques Canal, Cabrera, and de Fraga Malfatti 2013)

Printed board assemblies (PBA) are the components that are soldered and installed on a circuit printed board, for example, semiconductors, transistors, diodes, capacitors, resistors (Marques Canal, Cabrera, and de Fraga Malfatti 2013). Printed circuit board assembly (PCBA) is the finished board after all necessary components have been installed (Arena n.d). Which components and the amount can differ depending on the electronic device it is to be placed in, which affects the impact from the PBA and the entire PCB (Andrae, 2010).

The production of a PCB can be divided into two steps, the first being the actual board fabrication and the second the manufacturing of PCB. Figure 3.2 shows a simplified production process for both the board and the assembly. (Ozkan, Elginoz and Germirli Babuna 2018)

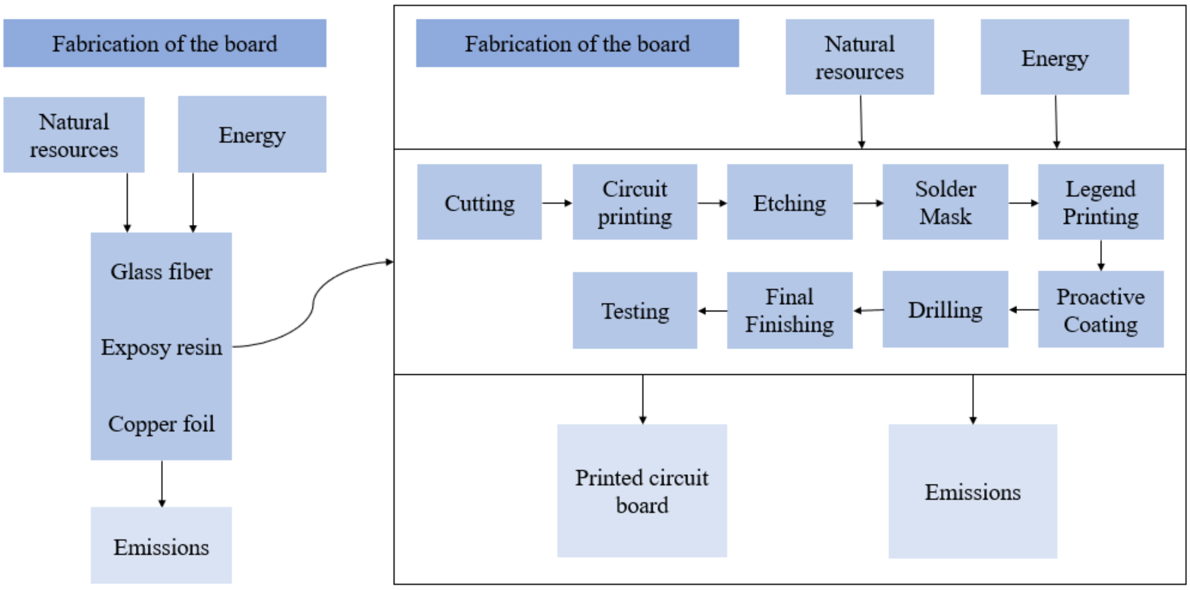

Figure 3.2: Production process of a PCB (Ozkan, Elginoz and Germirli Babuna 2018, 26802)

Lithium and lithium-ion are two types of cell batteries used to provide electricity to consumer products such as cell phones, flashlights, or watches. The main difference between the two types is that a lithium battery is a primary cell while a lithium-ion battery is a secondary cell. (Leone 2018) A primary cell refers to a battery that is not rechargeable and a secondary cell refers to a rechargeable one. Another difference is that lithium batteries have a higher energy density compared to lithium-ion. Composite wise the anode consists of different materials; lithium battery has lithium metal and lithium-ion has various other materials for the anode. (Leone 2018)

Lithium-ion battery (LIB) industry has laid the foundation for manufacturing methods for consumer electronic batteries. Even though, LIB has a different cell design the cell manufacturing processes are similar. (Yangtao et al. 2021)

LIBs are the most common battery chemistry and can be differentiated based on the material of the cathode. The cathode can, for example, consist of lithium manganese dioxide (LMO), lithium nickel manganese cobalt aluminium oxide (NMC), and lithium iron phosphate (LFP). (Porzio and Scown 2021) Further, graphite is commonly used as an anode in these batteries. The life cycle and manufacturing of a LIB consist of extraction of raw material, processing of materials, manufacturing of components, cell manufacturing and module assembly. Cell manufacturing is often divided into the following three phases: electrode manufacturing, cell assembly, and cell finishing. (Porzio and Scown 2021)

4. Empirical study – direct environmental impact

This chapter will present the results of the environmental impact analysis for the mechanical lock, digital lock and future concept cylinder presented in section 1.5.1. The mechanical and digital lock consists of a key and a cylinder. The CO_2 emissions for the cylinders belonging to the mechanical and digital keys have already been calculated internally. Therefore, the environmental impact analysis in this chapter covers the mechanical and digital key and the future concept cylinder to cover all parts of the locks. Lastly, the results are combined with the environmental impact of the cylinders in order to estimate the total impact per lock.

The methodology for a ‘fast track’ LCA described in section 3.2.3 can be divided into five different steps. These steps have been followed as a methodology for estimating the environmental impact of the products and the result will be presented accordingly below. The simplified LCA for the mechanical and digital lock has been performed similarly and will be presented in parallel.

The result from the simplified LCA conducted for the digital and mechanical key will be presented in sections 4.3 and 4.4. Thereafter the environmental impact of the belonging cylinders is presented along with the result for the keys. Further, the result, in terms of both components added together is presented for the digital and mechanical lock respectively.

Lastly, the result for the future concept cylinder will be presented in section 4.6. The details for the future concept cylinder are limited and thus the environmental impact analysis will be supported by the result from the analysis conducted for the keys in addition to the bill of material for the cylinder.

Some assumptions were necessary to make to progress with the result of this section. The assumptions are presented in section 4.7. Therefore, the reader needs to acknowledge and consider the simplifications and assumptions that have been made along the process since this affects the result.

4.1 The scope and the goal of the environmental impact analysis

The scope of the environmental impact analysis is to assess the environmental impact of a mechanical and digital key based on the fast track LCA method presented in 3.2.3. As mentioned in the introduction to this chapter, details regarding the future concept cylinder are limited and therefore do not follow the same steps as for the keys. The results of the future concept cylinder are partly based on the results of the keys and are therefore presented lastly, in section 4.6.

The goal of this study is to create a comparable estimation of the environmental impact of the products. It aims to be a comparison between three products but not an attempt to improve the environmental characteristics of either of them as for now. Carbon footprint, also known as carbon dioxide equivalent, as presented in section 3.1.3, is the selected single indicator for this study.

4.2 System, functional unit and system boundaries:

To specify the scope of the products in the simplified LCA, the functional unit is determined for the different products. The functional unit for a key is to open a lock cylinder. The functional unit of a cylinder is to work as a security device used to close openings by means of a key or an electronic device.

The service life for a cylinder and key respectively may vary and is highly dependent on the utilization rate and the maintenance of the product. Based on input from employees working with the product, the service life may vary from 10 to 30 years, but the service life is estimated to be the same for all products in this study. (The Company 2023) The service life is dependent on the number of cycles rather than just time, a simplification has been made that service life is 10 years even if it might vary. (Dormakaba 2021, ABLOY n.d)

The product system is defined as cradle to gate, including raw material extraction, raw material processing, manufacturing, and transportation to the gate. The same system boundaries are applied for the data gathered from the EPDs for the cylinders.

Due to insufficient data for some components, e.g., confidential details of components or un-accessible data on sub-components from suppliers a cut-off criterion is applied in the assessment, as discussed in section 3.2.3. Sub-components whose weight accounted for less than 2 percent of the total weight of the product may be excluded from the analysis if it was not considered to have a significant environmental impact or hazardous. The total weight of the excluded parts does not account for more than 5 percent of the total weight.

4.3 Quantify materials and use of energy in the system

The following chapter aims to quantify all necessary aspects of the keys to calculate the environmental impact. Firstly, the key components will be presented in terms of technical specifications such as material, weight, and volume. Further, the production processes and supply chain are mapped out for the two products.

4.3.1 KEY COMPONENTS

The weight for the products is shown in Table 4.1.

Table 4.1: Weights for the keys

Product	Weight (g)
Digital key (battery included)	27,5
Mechanical key	14,7

Table 4.2 shows the significant components of the mechanical key. Table 4.3 shows the significant components of the digital key. The mechanical key only exists of an alloy primarily based on copper, zinc and nickel, and the total weight and volume can therefore be equated to the material. The material in the keys is defined with the help of internal BOM files. Due to confidentiality, the exact components, material, and weight cannot be shared, but a coded version is shown in Table 4.3. “Other” in the table refers to screws and other small parts.

Table 4.2: Shows the single component of the mechanical key.

Component	**Approximate amount of entire product (%)**
Metal key	100

The metal part of the digital key is assumed to be the same as for the mechanical key but with different weights. It is therefore estimated that the supply chain and production process are the same for the metal component in both keys.

Table 4.3: Main components of the digital key

Component	Approximate weight of the entire product (%)
Metal key	45
Chassi	16
Rear Cover	11
Front Cover	9
Electronics	5
Battery	13
Other	1

4.3.2 PRODUCTION PROCESS AND SUPPLY CHAIN: MECHANICAL KEY

For calculating the emissions for the mechanical key, the significant production steps and raw material were determined according to the steps of an LCA in section 3.2.3. Figure 4.1 shows the supply chain process. The steps have been determined based on chapter 3.8 in the literature review, through interviews with internal stakeholders and contact with suppliers. Even if the information has been gathered to a great extent, the reader should take notice that this process might differ for different keys and might not represent a generic mechanical or digital key. The greatest simplification has been the steps between raw material extraction to the manufacturing in Spain. The raw material extraction and processing are included in the environmental impact data for each material, but since there is no information available on where the material is extracted, the transportation distance and mode to the manufacturing in Spain cannot be determined and has been left out of the calculations. Additionally, it is assumed that the casting process takes place in Spain without actual confirmation of that. For a more detailed explanation of the assumptions, please see section 4.7.

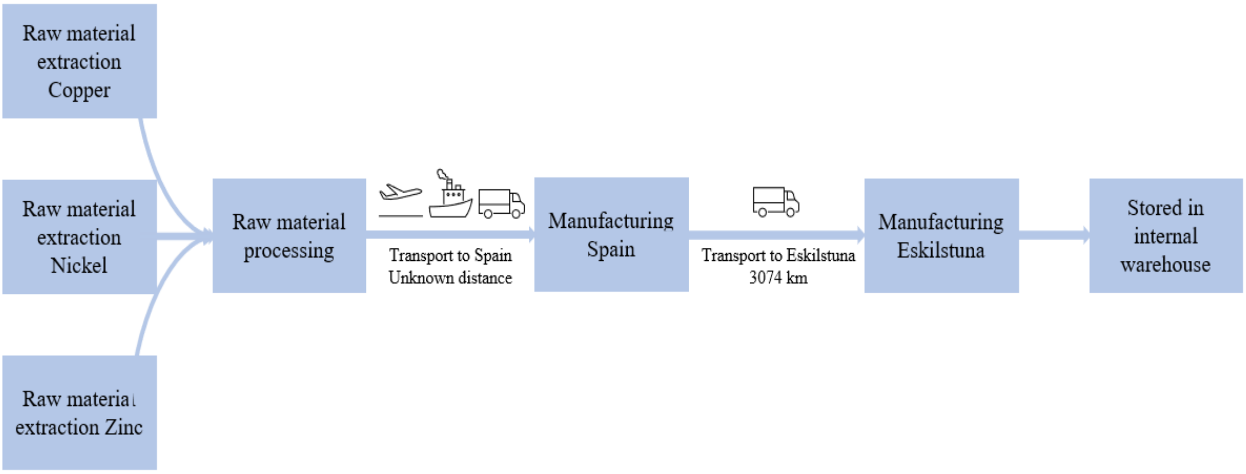

Figure 4.1: Supply chain for the mechanical key

Figure 4.2 shows a simplified production process for manufacturing a mechanical key. Compared to Figure 4.1, the processes of casting, hot rolling and stamping corresponds to the manufacturing in Spain, and the process of milling corresponds to the manufacturing in Eskilstuna.

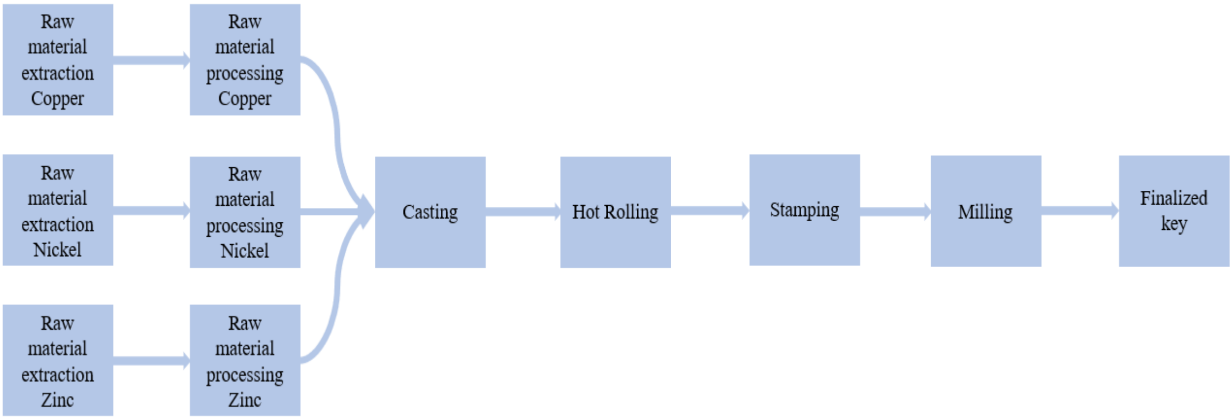

Figure 4.2: Production processes for the mechanical key

Table 4.4: Transportation routes and modes for mechanical key

Component	Material	Start	Destination	Operation	Distance (km)	Mode
Metal key	Alloy	Spain	Eskilstuna	Manufacturing	3074	Truck continental

4.3.3 PRODUCTION PROCESS AND SUPPLY CHAIN: DIGITAL KEY

For calculating the emissions for the digital key, the significant production steps and raw material were determined. Figure 4.3 shows the supply chain map for the digital key. The same simplifications and limitations as for the mechanical key have been made and the reader should notice that this supply chain might not be fully accurate due to non-available information.

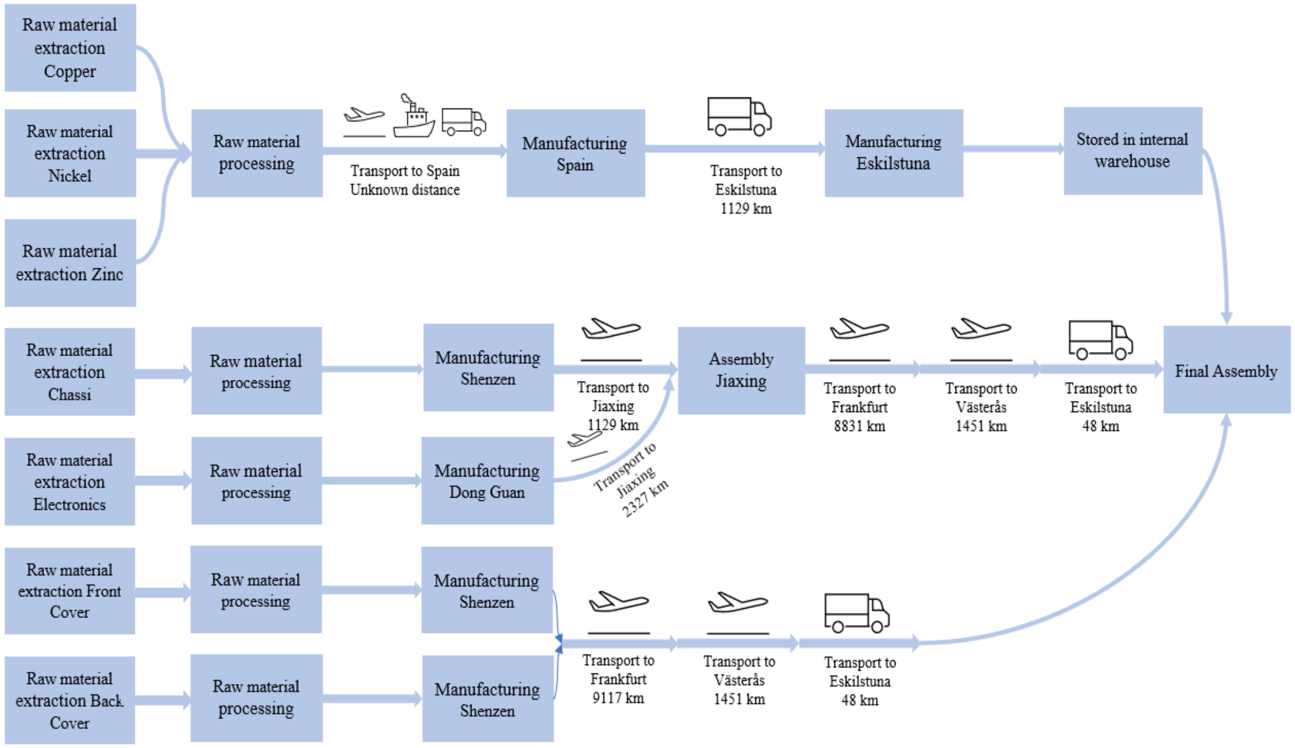

Figure 4.3: Supply chain for the digital key

Figure 4.4 shows a simplification of the production processes of the digital key. For the electronics within the PCB, the entire production process is included in the data for Idemat, which is represented by the manufacturing in Dong Guan. More details about the manufacturing of a PCB board can be found in 3.8.3. The PCB-board is then assembled with the chassi before being transported to Europe.

Regarding the battery for the key, the data used from Idemat is for a similar battery, AA cell lithium-ion cell battery type which covers all the production processes and thus no specific details regarding the processes for the specific battery are available. Due to limited details of the specific battery production processes, the processes are not explicitly illustrated in Figure 4.3 or 4.4. More details about the battery and the assumptions made can be found in section 4.7. More details about battery manufacturing in general can be found in sections 3.3.2 and 3.8.3.

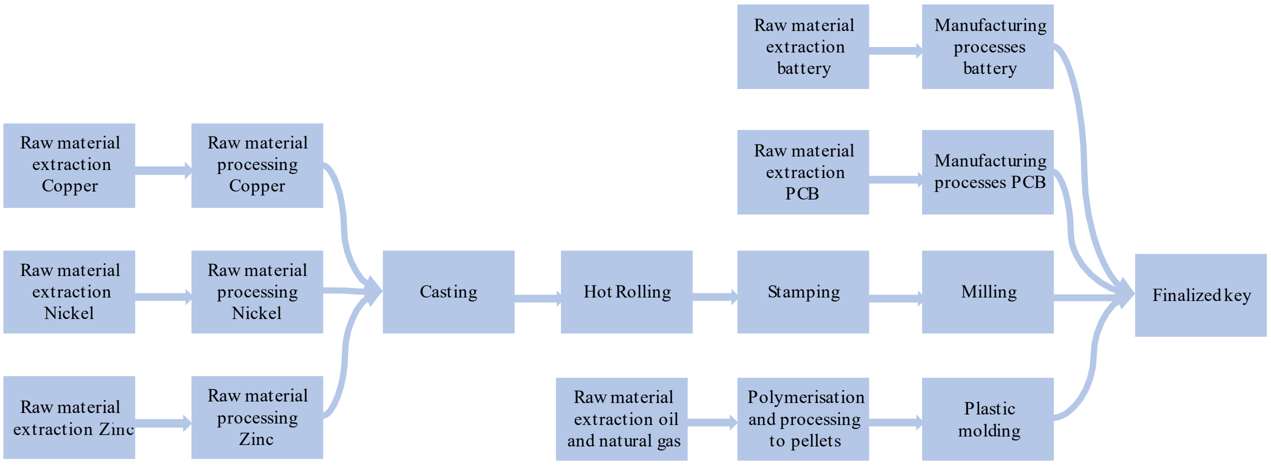

Figure 4.4: Production processes for the digital key

Transportation:

A more detailed explanation of the transportation routes and modes are shown in Table 4.5.

Table 4.5: Transportation routes and modes for the digital key

Component	Material	Start	Destination	Operation	Distance (km)	Mode
Metal key	Alloy	Spain	Eskilstuna	Manufacturing	3074	Truck continental
Chassi	Plastic	Shenzen	Jiaxing	Assembly	1129	Flight continental
		Jiaxing	Frankfurt	Forwarding	8831	Flight intercontinental
		Frankfurt	Västerås	Forwarding	1451	Flight continental
		Västerås	Eskilstuna	Assembly	48	Truck continental
Cover (back and front)	Plastic	Shenzen	Frankfurt	Forwarding	9117	Flight intercontinental
		Frankfurt	Västerås	Forwarding	1451	Flight continental
		Västerås	Eskilstuna	Assembly	48	Truck continental
Electronics	PCB	Dong Guan	Jiaxing	Assembly	2327	Flight continental

Component	Material	Start	Destination	Operation	Distance (km)	Mode
	Battery	Changzhou	Frankfurt	Forwarding	8694	Flight intercontinental
		Frankfurt	Gothenburg	Forwarding	879	Flight continental
		Gothenburg	Eskilstuna	Assembly	321	Truck continental

4.4 Data is entered in excel

Some details that are used for the calculations of the environmental impact of the materials are excluded from the report due to confidentiality. However, a summary of applied materials and processes will be presented in the following section.

The different materials, processes and transportation are entered in Excel and the data from the Idemat database are used to calculate the CO_2 emissions for each step of the supply chain for both the mechanical key and digital key.

Mechanical key:

Table 4.6: CO_2 equivalent emissions for the raw material for the mechanical key (Idemat 2023)

Material	Kg CO_2-eq per kg material
Copper primary	4,14
Zink primary	3,33
Nickel primary	13,10

Digital key:

Table 4.7: CO_2 equivalent emissions of the raw material and components for the digital key (Idemat 2023)

Material or components	Kg CO_2-eq per kg material or component
Copper primary	4,14
Zink primary	3,33
Nickel primary	13,10
PC + ABS	3,40
TPE	3,40
PCB	475,02

Material or components	**Kg CO_2-eq per kg material or component**
Battery	12,00
Steel	0,96

Table 4.8: CO_2 equivalent emissions for the different transport modes (Idemat 2023)

Transportation	**Kg CO_2-eq per ton per km transported**
Truck continental	0,09
Flight continental	1,43
Flight intercontinental	0,58

Table 4.9: CO_2 equivalent emissions for the different production processes used in the calculations (Idemat 2023)

Processes	**Kg CO_2-eq per kg processed or removed**
Casting	0,29 (Wänerholm, 2016)
Rolling	0,90
Stamping	0,52
Milling	0,11
Injection molding	1,20

4.5 Final results

Based on the data collected, the total CO_2 equivalents of the keys are calculated, and the result is shown in Table 4.10. In this table, the battery is not included in the data for the digital key.

Table 4.10: CO_2 equivalent emissions for the keys

Product	**Parameter**	**Unit**	**Amount**	**Raw material**	**Manufacturing**	**Transportation**	**Sum**
Digital key	GWP	kg CO_2-Eq.	1 piece (weight)	0,80	0,05	0,04	0,94
Mechanical key	GWP	kg CO_2-Eq.	1 piece (weight)	0,09	0,04	0,01	0,14

Table 4.11 presents the result for the battery. As mentioned in 4.3.3 the environmental impact of the battery covers a finalized product including raw material supply, distribution, and manufacturing processes. The value for raw material and manufacturing is therefore merged for the battery.

Table 4.11: CO_2 equivalents emission for the battery

Product	Parameter	Unit	Amount	Raw materials	Manufacturing	Transportation	Sum
Battery	GWP	kg CO_2-Eq.	1 piece (weight)	0,04		0,02	0,07

As mentioned in section 2.3.1 the environmental impact of the mechanical and digital cylinders is already estimated and is available in EPDs online. Table 4.12 shows the CO_2 equivalents for two cylinders the the defined system boundaries. (ASSA ABLOY 2016) The data in the EPDs are categorized differently compared to the environmental impact analysis conducted above but represents the same steps. The production in Table 4.12 includes raw material extraction and transportation between manufacturing processes and manufacturing processes. Transportation includes the final transportation to the site in Sweden. The sum for all steps, which is the relevant number in this study, therefore includes the same steps for both cylinders and keys.

Table 4.12 CO_2 equivalent emissions for the cylinders (ASSA ABLOY 2016)

Product	Parameter	Unit	Amount	Production	Transportation	Sum
Digital cylinder	GWP	kg CO_2-Eq.	0,15 kg	1,06	0,004	1,06
Mechanical cylinder	GWP	kg CO_2-Eq.	0,29 kg	1,54	0,09	1,63

Table 4.13 shows a comparison between the two different locks where the emissions from the cylinder, key and battery are included.

Table 4.13: Total kg CO_2 equivalents for the locks.

Product	Unit	Amount	Sum
Digital	kg CO_2-Eq.	1 key, 1 cylinder, 1 battery	2,07
Mechanical	kg CO_2-Eq.	1 key, 1 cylinder	1,77

Table 4.14 shows the percentage of the total emissions allocated to raw material, manufacturing processes and transportation for both mechanical and digital key.

Table 4.14: Allocation of CO_2 emissions for mechanical and digital key

% of total CO_2 emissions	Mechanical key	Digital key
Raw material	69%	85%

% of total CO_2 emissions	Mechanical key	Digital key
Transportation	4%	11%
Manufacturing processes	27%	4%

4.6 Future concept cylinder direct environmental impact

Table 4.15 presents an estimated environmental impact of the future concept cylinder. The details for the future concept cylinder are limited since it is currently only a concept idea. An estimation of the emissions for raw material extraction was calculated based on a BOM file covering materials and components.

However, emissions from manufacturing and transportation were not available due to lack of information. To fill out the data gaps, the result from the CO_2 emissions for the digital key was utilized, see Table 4.14. It was assumed that the allocation of emissions for raw material, manufacturing and transportation for the future concept cylinder could be assimilated with the allocation of emissions for the digital key since they contained similar components. Hence, an estimation of the emissions for manufacturing and transportation could be done due to that the emissions from raw material extraction had been calculated.

Table 4.15: CO_2 equivalent emissions for the future concept cylinder (Idemat 2023 and section 4.5)

Product	Parameter	Unit	Amount	Raw material	Manufacturing	Transportation	Sum
Future concept	GWP	kg CO_2-Eq.	1 piece (weight)	7,00	0,33	0,91	8,23

4.7 Assumptions for assessment of environmental impact and use of data

When conducting the environmental impact analysis, several assumptions and simplifications have been made and there are limitations in the study worth considering for the reader. These are presented in the following chapter. Since the primary purpose of the environmental impact analysis have been to compare the different products, the focus has been to conduct the same assumptions on both products and investigate them in a consistent manner. Therefore, the authors believe the result is trustworthy in terms of its purpose but should be used with caution in other settings.

4.7.1 METAL PARTS

The alloy used in the metal parts of the keys is an alloy made of copper (50-60 percent), zinc (30-40 percent) and nickel (10 percent) (Wieland 2023). The CO_2-eq emissions for raw material extraction are calculated using Idemat data for the basic materials converted to the percentage in the alloy.

Due to the lack of data for this specific alloy, it has been compared to brass and steel for the processes. It is assumed that it can be compared to brass due to the similarities in the composition of the materials. Brass is an alloy made of primarily copper and zinc. The proportion can vary, but a usual modern amount is 67 percent copper and 33 percent zinc and is therefore estimated to be equated to the copper alloy used in this research. (ThoughtCo, 2020)

The environmental impact of creating an alloy can differ significantly depending on the methodology used, which metals are combined and whether the material is recycled or not (Copper Development Association Inc n.d; GreenSpec n.d). Due to the complexity of this process and the lack of data for the casting process in Idemat, data have been collected from an external article. The CO_2 emissions for the casting process are based on the electricity needed to melt the metals and the electricity grid mix of respectively country. (Wänerholm 2016) The production is assumed to take place in Spain since the rolling and stamping take place there. The carbon dioxide emissions for casting one ton of brass in Spain is 285 kg. (Wänerholm 2016)

For the other processes, the Idemat database has been used. For rolling and milling, data is available only for steel. It is assumed that this data can be used to represent the alloy as well. This is based on hardness levels for the different materials. On the hardness Rockwell B-Scale, steel has a value of 88 and yellow brass a value of 55. (Rapid Direct 2021) It is therefore assumed that energy needed for processing steel requires more energy compared to brass, which would indicate a slightly higher value in the environmental impact analysis since the data for steel is used. Since the purpose of the environmental impact analysis is to primarily work as a comparison, the same data are used for both keys and should therefore be comparable.

Furthermore, data for the stamping process is not available in the Idemat database. This process has instead been assumed to acquire approximately the same amount of energy as the deep drawing process. A deep drawing process can be explained as *"Deep drawing is a sheet metal forming process in which a sheet metal blank is radially drawn into a forming die by the mechanical action of a punch"(*Li 2022, 182). The stamping processes can be explained as *"Metal stamping is a manufacturing process used to convert flat metal sheets into specific shapes by using different metal forming techniques – for example blanking, punching, bending and piercing".* (Engineering Specialities Inc n.d*)* Due to the similarities of these processes, it is assumed that they require approximately the same amount of energy. The deep drawing process is calculated for steel and the same reasoning as above is applied for this process as well.

Details for the screws, used in the assembled digital lock, was limited and information regarding the transportation route and details on manufacturing was not available. After some research on the material and production process of screws, these screws were assumed to consist of steel with electroplated zinc coating and the manufacturing processes consisted of either milling or turning. (Wurth, 2023) The processes of milling and turning in Idemat have the same environmental impact and thus either one may be applied in the assessment. The mass of removed material needed to be determined to calculate the impact of the processing of the steel for milling or turning. A classic screw model was studied (Wurth, 2023), and it was assessed that approximately 50 percent of the mass was removed during processing. Further on an estimation of the surface area was done to calculate the impact of the electroplated zinc coating. Regarding the transportation of the screws, a worst-case assumption was made that these are supplied from a large screw manufacturer in Taiwan and then transported to Sweden including some pit-stops. The mass of the screws' accounts for less than 3 percent of the total weight of the product and its contribution to the total environmental impact is assumed to be limited.

4.7.2 PLASTIC

The following materials for the plastic details could be found in the database, polycarbonate (PC), acrylonitrile butadiene styrene (ABS). Data for thermoplastic elastomer (TPE) was not available. The plastic parts mainly consisted of PC material. Due to insufficient information regarding exact weight distribution the plastic parts were assumed to only consist of PC. This simplification was also justified due to that the environmental impact for the different materials did not differ significantly. The data in Idemat used to calculate the CO_2 emissions for the process injection moulding is based on the energy use of “Electricity General Industry”. This industry-wide electricity value is based on 33 percent EU, 33 percent USA and 33 percent China.

4.7.3 ELECTRONICS AND BATTERIES

To estimate the environmental impact of the lithium coin battery some assumptions were made. Due to a lack of information regarding the environmental impact of lithium batteries these were compared and assimilated with the lithium-ion battery. As discussed in section 3.8.3 the chemical composition of the anode in the batteries can vary. Further, previous studies, referring to section 3.3.2, researching the environmental impact of lithium batteries stated that energy consumption during manufacturing is a key contributor. It was also stated in 3.8.3, that even though the cell design may vary between LIB batteries, the manufacturing process is similar. Therefore, even though the material composition may vary, the manufacturing process, with high environmental impact is probably similar.

Idemat was lacking data on the exact type of battery. Data was available for AA cell lithium-ion battery per piece, and this was assimilated to the lithium coin battery that is used for providing energy for the digital key. However, the weight did not align, 15 g for the AA battery versus 3,7 g for the coin battery. This was accounted for by calculating the environmental impact per gram for the AA cell lithium-ion battery and then applying it to the weight of the coin battery.

In addition to this, the environmental burden of the coin battery’s material composition was analyzed to get an understanding of the materials’ contribution to the environmental impact. As mentioned in 3.3.2, the material extraction contributed with one-third of the energy consumption for manufacturing lithium batteries. The calculated CO_2 emissions for the constituent materials represented approximately one third of the total CO_2 emission for the battery that was collected from the Idemat database, thus this ratio was in line with the stated one in the study.

The battery used in the product is provided by a Nordic distributor and there are no available details for the supply chain of these. The manufacturing is assumed to take place in China and then transported to the destination in a similar way as the other components from Asia.

For the PCB, the data provided by the Idemat database are comprehensive since it includes the finalized product including the integrated circuit. (Idemat 2023) The reader needs to take notice that a printed circuit board can be very different, and this value represents a generic case. Due to the lack of exact information on the board and lack of data for different components, it is estimated that the value should represent the actual board good enough.

4.7.4 TRANSPORTATION

In the Idemat database there are different factors to consider in the calculation of the environmental impact of the transportation along the supply chain. The CO_2 emission for the transportation of goods is estimated based on the weight of the product, distance travelled, intercontinental or continental freight and the mode of transportation. The method used to calculate the environmental impact was the distance-based transportation method briefly presented in section 3.2.4.

Regarding the load, the calculations for long-distance road transport are based on the full load of the truck with an empty load back and divided by the maximum load for the truck. Thus, the overall load factor is 50 percent and the functional unit is “per km”, this is for one way distance. The eco-costs for the different modes are based on a load factor of 50 percent for road, 70 percent for air and 80 percent for sea per km.

The data for transportation is selected based on the standard routes and transportation modes for components sent from Spain and Asia respectively. The result is an estimation of the transportation route and there may be some misalignment such as the actual load rate for the different freights and the pitstops along the supply chain. (Vogtlander 2012)

The distances used between locations in the supply chain are based on the shortest distance. The selected pitstops for the components are based on the standard routes but may not include all actual routes. Transportation of raw material, metal, and plastic pellets e.g., to the manufacturing site is excluded in the scope for the keys due to non-available information. However, it is included in the environmental impact of the cylinders due to that this information was included in the EPDs. However, it is stated in the EPDs that this environmental impact is neglectable compared to e.g., processing of raw material and manufacturing, and it is therefore assumed that the exclusion of this transport does not have an impact on the result. (ASSA ABLOY 2016)

4.7.5 MANUFACTURING ENERGY CONSUMPTION

The data for energy use in manufacturing is a general data set and thus is not explicitly measured in the accurate production site.

In Idemat the data for the environmental impact of fuels is provided only for the manufacturing phase. For example, the impact of combustion depends on site-specific factors and should be calculated separately for more accurate results. Another aspect to consider is that the environmental impact of the production of electricity is country-specific and may vary a lot. In Europe it is recommended to take an average since most countries are connected to one common power grid. (Vogtlander 2012)

4.7.6 SUMMARY OF ASSUMPTIONS

Table 4.16: Showing summary of the assumptions.

Components	Affected processes	Assumptions
Key material	Raw material extraction	The key material and the extraction of raw material can be compared to brass and steel due to the similarities in the composition of the materials.
	Processing of material	For the processes of rolling and milling, data is available for steel solely. It is assumed that this data can be used to represent the alloy as well.
Plastic	Raw material extraction	Plastic part consists of a variety of plastic materials, however there is no available data regarding the weight ratio. The assessment was simplified by setting all to PC.
Electronics & batteries	All processes	Due to a lack of information regarding the environmental impact of lithium coin cell batteries these were compared and assimilated with the AA lithium-ion cell battery. The available data for PCB is based on a generic case. Due to the lack of details on the board and lack of data for different components, it is assumed that the value should represent the actual board good enough.
All	Energy consumption in manufacturing	The data for energy use in manufacturing is a general data set and thus is not explicitly measured in the accurate production site.
All	Transportation	The data for transportation is selected based on the standard routes and transportation modes for components sent from Spain and Asia respectively. The load rate is assumed to be in line with the 50% in the data set. Transportation of raw material, metal, and plastic pellets e.g., to the manufacturing site is excluded in the scope for the keys due to non-available details and an

Components	Affected processes	Assumptions
		assumption that it will not have a significant impact.

4.8 Comparability of direct environmental impact

There are some requirements, according to ISO standards presented in section 3.2.2, that need to be considered when comparing two products and their environmental impact gathered in EPDs. As mentioned in 3.2.2, the requirement of comparability is based on decisions from developing the PCR document and the product category definition and description must be identical. The study included the EPDs of two lock cylinders with the aim to be compared. These locks do not belong to the same product category and are therefore not comparable according to the ISO standards.

However, the aim of this study is to compare products with the same purpose: locks used to gain access to spaces. Therefore, considering the aim of this study and the purpose of the locks it is assumed that the comparison can be justified and that the result will be of value for answering the research question. Thus, it is important to acknowledge that the comparison is not aligned with the requirements of the ISO standards when reviewing the result.

5. Empirical study – Use Cases

Several actors have been interviewed to gather information on how digital locks affect transportation flows on a system- or societal level to answer the research question. The actors were chosen since access- and lock solutions along with transportation connected to key management are a part of their operations.

The purpose of conducting the interviews and collecting the data was to understand their current flows, the benefits digital locks can generate from a sustainable perspective and to quantify the avoided emissions thanks to the current digital solution if possible. It was also to get perspectives on how the future concept can increase the benefits and avoid emissions further. Therefore, it will follow a brief explanation of the products and concepts for the reader to understand how it works and how it relates to avoided emissions. The information is based on input from the Company and employees working with the products. This description will complement the product description in section 1.5.1.

The current digital solution consists of a cylinder and a key, but what differentiates it from a mechanical system is that the key is programmable. Therefore, it is possible to manage and share access with a phone application or a physical programming box. By sharing access, one key can access several cylinders if it is approved by the main system. If the access is approved, the user picks a key, programs it to access the desired cylinders, and is then able to unlock the cylinder. The digital system limits the number of keys needed due to that it is programmable and can access multiple cylinders. The programmable key can for example be stored at the location where it is used since it is not usable if the main system has not approved access. (The Company 2023)

The future concept represents an even more unlimited access system. In the use cases, the idea of the future concept is that it can create access to any cylinders at any given time, without the need of a physical key. Inspiration for these cases has been a completely open world with no access issues. (The Company 2023)

5.1 Qualitative data

In the following section, the qualitative data gathered from interviews for each case is presented. For each case, background information is provided with the purpose to give an understanding of the company's operations. Further, more information regarding the workflow connected to key management and locks is presented. The interview guide can be found in Appendix A. This section will lay the foundation for the next step in the thesis, to quantify the potential avoided emissions. Lastly, key takeaways from the interviews are presented.

5.1.1 PARCEL AND LOGISTIC SERVICE

Company A

An interview was conducted with an employee from Company A that works in their Innovation and Development department, where she has been engaged in home-delivery-solutions for business-to-consumer (B2C) customers.

Company A offers parcel- and mail deliveries for business-to-consumer (B2C) and business-to-business (B2B). Company A has a wide range of offerings for its receivers, covering home delivery, parcel box and pickup point. The share of selected offerings to receivers depends on the offering from the retailer and what the customer wants. The interviewee stated that the consumer's choice of delivery is primarily driven by price, convenience, flexibility and how the selling company chooses to advertise the different shipping options.

For home deliveries, the receiver chooses a day and time window when they wish to have the parcel delivered. If the receiver is not home during delivery, the default setting is to leave the parcel outside the door. If the customer wishes otherwise, the parcel is taken back to the terminal and is delivered to a delivery point with other parcels the next morning.

For B2B, Company A is often limited by delivering during normal working hours when the goods reception is open. For deliveries of goods to restaurants and cafes, a requirement is usually to deliver during the morning hours.

Company A mainly gets in contact with digital locks when delivering to receivers in residential buildings, both houses and apartment buildings, and parcel lockers. They have performed in-home deliveries in pilot projects.

Company B

A similar interview as the one with Company A was conducted with an employee working with B2C eCommerce at Company B for further information and a different perspective on the subject.

Company B offers parcel delivery for both B2C and B2B and currently offers home delivery, delivery to the pick-up point, and parcel boxes. Their market share is larger for B2B compared to Company A, but the flows of deliveries are similar to the ones presented for

Company A. The interviewee stated that they offer consumers with a specific digital lock the option of unattended in-home delivery of parcels.

5.1.2 SCHOOL FACILITY MANAGEMENT COMPANY

An interview was conducted with the manager of the installation of digital technology at a company working with school facility management. The company has already implemented digital locks in school facilities and investigated the potential effect digital locks had on their operations. The result of the project showed improvements in the efficiency of key management for subcontractors visiting school facilities for work.

The participant stated early in the interview that they had noticed a significant decrease in transportation due to the digital access system. The digital locks enabled the subcontractors to travel directly to the facilities for work instead of visiting the company's head office between their commissions to retrieve keys.

The batteries in the keys are changed every third year as a standard, unrelated to the state of charge. The battery changes are combined with other maintenance work and according to the interviewee, there is no extra transportation related to the battery changes.

A subcontractor working with the school facility management company estimated that they had reduced their trips by 50 percent after the transitioning to digital locks in the school facilities due to no need for visiting the headquarter to manage keys anymore.

5.1.3 HOME CARE SERVICE

For the home care service case, two municipalities in Sweden were chosen as the object of the study. Municipality A is located in the Stockholm region and has approximately 1500 caretakers. Municipality A was chosen based on its location and the fact that it had quite recently transitioned from mechanical locks to digital locks which enhanced an accurate comparison between the systems. This municipality has been the focus of the case. A second municipality, B, has also been involved in the case, mainly to gather complementary information and perspective.

Municipality A

An interview was conducted with a business developer for home care services for municipality A. In addition to this, interviews were conducted with employees from the supplying home care service companies in the municipality. These employees work operationally with daycare and emergency care.

During the initial interview with the business developer, she stated that the transition to digital lock in the home care services has improved the work environment for employees, the quality of home care service, transparency, and efficiency in the operations. A main takeaway is that the business developer had noticed a significant decrease in the time spent between the visits for the employees. She believed that the decrease in time spent between visits was primarily due to less transportation. The interviewee had also noticed a significant improvement when handling emergency calls. Before digital locks were implemented, the personnel needed to drive to the headquarter to fetch a key if receiving an emergency call. Today, the person closest to the caretaker can travel there straight away.

The employees working operationally at a supplier of home care services have not noticed a significant decrease in transportation after transitioning to digital locks. The schedule and planning of the home care service visits are similar to the time pre- and post-digital locks. On average, an employee visits the office three times a day, the same amount as before digital locks. However, it was highlighted that the flexibility the digital system generates has an impact on the total transportation. The employees stated that deviations during planned home care before digital locks could result in extra transport for the employees. For example, illness, delays in schedule, or forgotten layoffs of keys could result in extra transportation to the head office connected to key management. During the interviews, the deviations varied from once a day to once a week, depending on the company.

The employees stated that a potential future improvement is to make the digital lock system accessible for other operators such as medical care and rehab service. However, a more open system could decrease the sense of safety and control for the caretakers.
Additionally, it was stated that for 30-50 percent of the home care visits in the municipality, the caregivers travel by foot or bicycle, and hence no need for car transportation. The interviewees also estimated that one key for each caretaker was used in the traditional, mechanical system.

Municipality B
In municipality B an interview was conducted with the project manager of digital locks in the home care service. Municipality B is currently in the rollout phase of the digital locks and has completed the implementation in approximately 20 percent of the home care services. They have good results from a successful pilot project which shows that the transition to digital locks had several benefits in line with the results from Municipality A. The interviewee highlighted that the new system enables more flexibility and a quicker response to alarms when the caretakers spend less time on key management and transportation connected to it. This results in an overall reduction of transportation for the municipality.

5.1.4 KEY FINDINGS

To answer the research question, the first aspect was to understand whether digital locks have or can reduce the actor's CO_2 emissions today. The school facility management company and the home care service company, which both currently use a digital system, have noticed reduced emissions primarily due to less transportation connected to key management. The companies in parcel and logistic services, which do not use digital locks to a significant extent today believe that the solutions would not have an impact on their operational emissions.

Since a digital system is not yet used by the parcel and logistics companies, the impact of the locks cannot be confirmed. The result from this case is therefore based on how the stakeholders perceive the outcome would be if the locks were used in their operations. The symbol within parentheses in the following tables, denotes a perception of the possible impact of digital locks.

Table 5.1: Showing the actors perceived impression on how digital locks reduce their operations emissions today: (+): positive impact, (-): negative impact, (.): no impact or no available information.

	Parcel and logistic service	**School facility management**	**Home care service**
The Digital system enabling reduced emissions today	(.)	+	+
Key factors for reduced emissions	.	Less transport	Less transport

It was further investigated how the actors believe their operations could be impacted with the future concept cylinder. As mentioned in the introduction for this chapter, the inspiration for the interviewees when discussing this topic is an open system where the right people always have access to the right places. The interviewees were asked to not consider other barriers and challenges such as regulations or acceptance, and only to consider the access solution.

Table 5.2: Showing the actors perceived impact of digital locks for reduced emissions in the future: (+): positive impact, (-): negative impact, (.): no impact or no available information.

	Parcel and logistic service	**School facility management**	**Home care service**
Future concept system enabling reduced emissions in the future	(+)	(+)	(+)
Key factors for reduced emissions in the future	Nighttime delivery In-home delivery	Increased utilization rate of buildings	Access system accessible for other actors

Nighttime delivery:

The interviewees from the logistic companies stated that if the access issues were removed, it would facilitate nighttime deliveries. Nighttime deliveries include deliveries to companies during off-peak hours when there is less traffic, especially during late evenings and nights. Both interviewees agreed that this could lead to less unnecessary time spent in traffic, a higher utilization rate of vehicles, and the possibility for a further optimized route compared to today.

In-home delivery:

In-home delivery is a service where a parcel delivered to residential buildings is placed inside the house instead of outside or at a pick-up point. Digital locks are an enabler for that. The interviewee from the logistic and parcel service company A believes that digital locks could enable in-home deliveries during the daytime, which could help optimize transportation flows further. The participant from the logistic and parcel service company B concluded that parcel thefts are more and more common abroad and that in-home delivery minimizes the risk of theft while still offering the customers home delivery as a service. Both interviewees stated that for this to work, the use of digital locks among end customers must increase significantly to have the desired effect.

The increased utilization rate of buildings:
Increasing the utilization rate of buildings was a further potential improvement with digital locks according to the interviewee from the school facility management company. Currently, their facilities are usually utilized between 7-17 on weekdays. The interviewee stated that the utilization rate today is low compared to the potential, and a different access system could facilitate the use of buildings after the daily operations. The main challenges with digital locks today and the current barriers have been identified from the interviews and summarized in the Table 5.3.

Table 5.3: The main identified challenges with digital locks today, x represents that the challenge is occurring for the company.

Challenges	Parcel and logistic service	School facility management	Home care service
Digital locks not widely used by consumers	x		
Low acceptance of in-home deliveries	x		
Digital locks not fully integrated in the operating environment	x	x	x

Digital locks not widely used among consumers:
In the interview with logistic and parcel service Company A, the interviewee stated that digital locks are not widely used among consumers making it hard to gain the potential benefits with digital locks in their operation. It requires many locks to have a significant impact on their flows and to enable more optimized operations.

Acceptance for digital locks and digital accessibility:
In line with the previously mentioned, another challenge is the acceptance of digital locks and digital accessibility. Regarding in-home deliveries from logistic and parcel service companies, the perception is that consumers have low acceptance of unattended in-home deliveries. Interviewees from home care services stated that digital locks have a high acceptance among most caretakers. However, some express concerns about not having control over access to their homes. Furthermore, the acceptance of digital locks in public environments is higher, for example, in school facilities.

Digital locks not fully integrated with the access system in the surrounding environment:
Another hindrance to digital locks reaching their full potential is that they are not always fully integrated with the surrounding access system. For example, the home care services expressed that the digital locks are not fully implemented in their operating environment, for example, in laundry and waste rooms. This is also the case for the logistic and parcel service companies if entrances for residential buildings and doors are not equipped with a digital lock.

Reoccurring keywords identified during the interviews are presented in Table 5.4. The keywords represent important aspects of the actors’ operations. The keywords have slightly different meanings for each case which is specified further below Table 5.4.
Table 5.4 shows the stance for the following question connected to the aspects and the influence of digital lock for each case:

How have/can digital locks impact these aspects for the company?

Perceived as positive, negative, or indifferent impact.

Table 5.4: Presents the key aspects and weather these have been influenced by digital locks. (+): positive impact, (-): negative impact, (+/-): both negative and positive impact (.): no impact or no available information.

Key aspects	Parcel and logistic service	School facility management	Home care service
Flexibility	(+)	+	+
Efficiency	(+/-)	+	+
Security	(+/-)	+	+
Time management	(+/-)	+	+
Transparency	(.)	+	+

Flexibility:
All actors stated that flexibility is of importance to them. Logistics companies' customers demand flexibility, and they need to offer services to match the expectations.
The interviewee from logistic and parcel service company A stated that: *“I believe that flexibility is key, to be present where the consumers are and to offer what they want and when they want it”*.

Offering a wide range of delivery options is a way to stay flexible towards end-customers, something digital locks can be an enabler to. For the school facility management company and the home care service in municipality A, flexibility is the possibility to perform commissions whenever necessary and for urgent matters. The digital system used today has increased their flexibility according to the interviewees.

Efficiency:
The logistics companies stated that their efficiency can both improve and impair due to digital locks. Potential improvements are optimized routes, no time restrictions, and less time spent in traffic. On the other hand, both interviewees stated that it would be more time-consuming to leave parcels inside homes instead of outside, decreasing efficiency.

Security:
The interviewee from the school facility management company stated that one benefit of digital locks is a greater sense of security within the facility since it enables one to keep track of for example the visiting subcontractors.

It can be quite difficult to increase the utilization rate of already existing buildings since it is common for public buildings that after the perimeter protection is entered, the entire facility is accessible. The interviewee agrees that an access control system that would allow or decline access to specific doors inside a building could reduce the current issues. In the interviews with the home care services, the interviewee stated that digital locks enable improved transparency and safety for caretakers and caregivers. The system makes it possible to keep track of the visits and generates a recipe for the visit and the time spent with the caretaker, which creates accountability for the work.

Time management:
The school facility management company and home care service stated that digital locks improve time management, referring to less time spent on key management. Parcel and logistic service companies stated that it is probably more time-consuming to perform an in-home delivery compared to a pick-up point or outside door, as stated above related to efficiency.

Transparency:
Digital locks enable beneficial transparency for the home care service, both for the caregiver and the caretaker. As mentioned above, connected to security, the digital lock system makes it possible to keep track of the visits and thus also identify potential bottlenecks in the operations. Increased transparency is also beneficial for the school facility management company, referring to increased security.

5.2 Quantitative data

To answer the research question, the actors with a perceived reduction in car transportation enabled by digital locks have been objectives for quantifying the reduced emissions. These actors are, as stated in Table 5.1, the school facility management company and the home care service in municipality A. The quantitative data for the cases are presented in the following chapter.

Quantitative data was gathered during the interviews and from additional spreadsheets and reports provided by either the Company or external stakeholders. The purpose of gathering the quantitative data was to quantify the potential avoided emissions generated by the entire system and to calculate the total direct emissions for the mechanical, digital, and future concept systems for each case. As mentioned in 5.1.4, this part will focus on the cases with the potential of reduced emissions with digital locks today.

The following sections describe the access systems for the school facility management company and the home care service. Thereafter, the direct environmental impact is calculated using the numbers from Table 4.13 and Table 4.15. Furthermore, data used for calculating the avoided emissions are presented followed by the calculations. The last section presents a future scenario, highly hypothetical, including utilization rate, nighttime deliveries, and in-home delivery with data based on interviews and literature.

5.2.1 SCHOOL FACILITY MANAGEMENT COMPANY

Since the avoided emissions are quantified based on the entire system, the direct environmental impact is quantified on a system level as well. Today, the school facility management company uses a hybrid system with only digital keys but a mix of mechanical and digital cylinders. This is possible since the design of the key makes it possible to access mechanical cylinders if the cut on the key fits the cylinders. The size of the current digital system, including the total number of cylinders and keys, for all facilities was gathered during interviews and is presented in Table 5.5.

Table 5.5: Keys and cylinders for the hybrid system currently used at the school facility management company.

Details of hybrid system	Amount
Digital keys	3200
Digital cylinders	2682
Mechanical cylinders	9467

Due to the research question and scope of the study, the hybrid system has been transformed into what an equivalent digital system would look like, which in this case means changing all digital cylinders to mechanical cylinders. This system will later be referred to as the digital system shown in Table 5.6.

Table 5.6: Number of keys and cylinders in the digital system.

Details of digital system	Amount
Digital keys	3200
Digital cylinders	12 149

Table 5.7 show the estimated number of keys and cylinders if a mechanical system is used. The numbers have been based on input from interviewees.

Table 5.7: Keys and cylinders in a mechanical system based on the number of cylinders and keys used in the current system.

Details of mechanical system	Amount
Mechanical keys	4104
Mechanical cylinders	12 149

Table 5.8 shows the estimated numbers of cylinders for the future concept cylinder in the system.

Table 5.8: Cylinders in a future concept system based on the number of cylinders used in the current system.

Details of future concept system	Amount
Future concept cylinder	12 149

DIRECT ENVIRONMENTAL IMPACT FOR THE SYSTEM:

Based on the details about the systems and the result from section 4.5, the direct environmental impact of the system is calculated for the school facility management company. The direct environmental impact for the systems is presented in Table 5.9 for the hybrid system, in Table 5.10 for the digital system Table 5.11 for the mechanical system and lastly in Table 5.12 for the future concept system. The school facility management company currently use the hybrid system. How the corresponding digital, mechanical and future concept system would look like is based on the hybrid system, information from the interview and understanding of the products. The reader should acknowledge that these systems are therefore based on assumptions and might not reflect reality accurately. The emissions do not cover change of batteries, only initial installation with one battery per key.

Table 5.9: Total direct environmental impact for the hybrid system.

Hybrid system	**Amount**	**kg CO_2-eq (per product)**	**Total kg CO_2-eq**
Digital keys	3200	0,94	3017,62
Batteries	3200	0,07	216,9
Digital cylinders	2682	1,06	2845,80
Mechanical cylinders	9467	1,63	15 475,80
Sum CO_2-eq			**21 556,1**

Table 5.10: Total direct environmental impact for the digital system.

Digital system	**Amount**	**kg CO_2-eq (per product)**	**Total kg CO_2-eq**
Digital keys	3200	0,94	3017,62
Batteries	3200	0,07	216,9
Digital cylinders	12 149	1,06	12 877,94
Sum kg CO_2-eq			**16 112,46**

Table 5.11: Total direct environmental impact for the mechanical system

Mechanical system	**Amount**	**CO_2-eq (per product)**	**Total kg CO_2-eq**
Mechanical keys	4104	0,18	738,37
Mechanical cylinders	12 149	1,63	19 860,08
Sum kg CO_2-eq			**20 598,45**

Table 5.12: Total direct environmental impact for the future concept system.

Future concept system	**Amount**	**CO_2-eq (per product)**	**Total kg CO_2-eq**
Future concept cylinder	12 149	8,23	99 996,2
Sum kg CO_2-eq			**99 996,2**

Figure 5.1 shows a summary of the result from Table 5.10, 5.11 and 5.12.

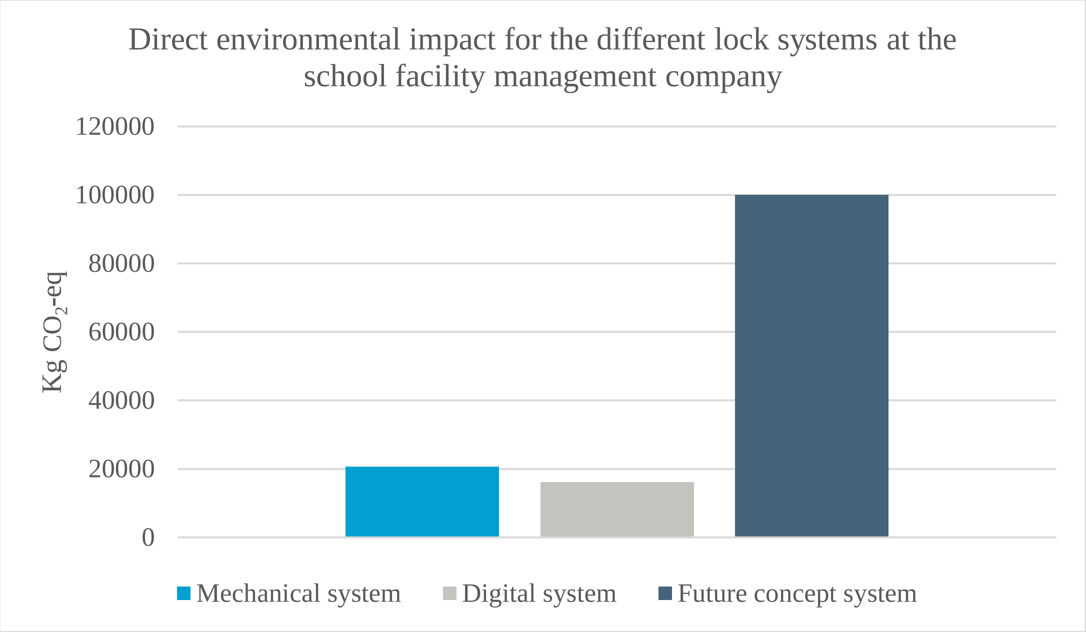

Figure 5.1: Visualizing the direct environmental impact for the lock systems at the school facility management company.

DATA AND CALCULATIONS FOR AVOIDED EMISSIONS:

The annual avoided emissions are calculated with the average avoided distance per trip and total trips per year. The average avoided distance is based on the average distance between the facilities and head office, estimated by the school facility management company and shared with the authors. The distance between the facilities and head office are avoided due to a digital lock system, visualized in Figure 5.2.

The green arrow represents the distance for the subcontractors with the digital system and the red arrows represents the distance for the subcontractors with a mechanical system. The avoided distance in a digital system is therefore estimated to be parts of the red arrows. The avoided distance is defined as the average distance between the head office and all school facilities, which is 19,7 km. This number have been shared with the authors from the school facility management company.

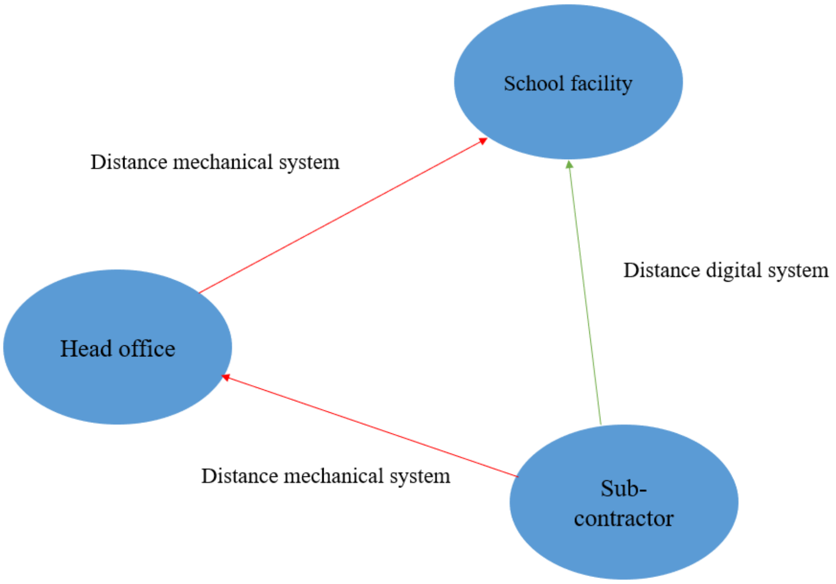

Figure 5.2: Visualization of the avoided transportation distance

The average number of keys issued per month have been collected from the internal system used for tracking the keys. It is assumed that one key issued equal one commission. The operating days are estimated to be 220, two months are excluded when the operation decreases significantly. Only the keys issued by subcontractors are considered in these calculations since those are generating transportation. Keys issued by subcontractors represent 54 percent of all keys issued. Internal personnel issue the rest 46 percent, for example, janitors. The company estimated that before the digital system was implemented, an average of three keys were collected at the head office per visit and used throughout the day. Thus, it is assumed that three commissions should be allocated to one drive for managing the keys.

Table 5.13: Flow details for the company’s operations.

Flow details	Amount	Unit
Average distance avoided	19,7	Km
Keys issued 2022	58 310	#
Operating days	220	#
Amount of issued keys by subcontractors	54	%

The annually avoided distance was calculated using the data in Table 5.13.

Annual keys issued by subcontractors calculated in Equation 1:

$$58310 \times 0{,}54 = 31487 \text{ keys } (1)$$

Since the commissioner on average performs three commission a day, they picked up three keys on average when visiting the head office when using a mechanical system. The annual transportations to and from the head office is therefore divided by three to get the total amount of trips to and from the head office with a mechanical system.

Amount of annual avoided trips calculated in equation 2:

$$^{31487,4}/_{3} = 10495,8 \text{ trips } (2)$$

The yearly avoided km in transportation distance is the distance presented in Table 5.13 multiplied with the trips avoided in a digital system as calculated in equation 2:

$$10495,8 \times 19,7 = 206767,26 \text{ km } (3)$$

Based on Equation 3, the corresponding yearly avoided emissions was calculated. These emissions are dependent on the means of transportation and fuels used by the subcontractors. Based on the data in section 3.2.4 an average of the CO_2 emissions from new cars in the EU has been calculated to 123,1 g of CO_2 emissions per km, based on the years between 2010 and 2021.

$$206767,3 \times 0,1231 = 25453,1 \text{ kg } CO_2\text{-eq. } (4)$$

The yearly avoided emissions for the school facility management company are, according to Equation 4, 25 453,1 kg CO_2-eq.

5.2.2 HOME CARE SERVICES

Table 5.14 provides the general data for the home care service in Municipality A. Table 5.15, 5.16 and 5.17 presents details of number of keys and cylinders in the different systems.

As stated in section 5.1.3 the home care service has approximately one key per caretaker in the mechanical system and the number of cylinders equals the number of caretakers. However, for the digital system, the number of keys is equal to the number of caregivers based on information from interviews.

There are six home care suppliers to the company, which are companies hired by the municipality to perform the home care service. The number of caregivers and caretakers in Table 5.15 is the total number for the entire municipality, all six supplier companies included.

Table 5.14: General data for the total home care service in Municipality A.

General data	Amount
Caregivers	374
Caretakers	988

Table 5.15: Details of the mechanical system in municipality A.

Details of mechanical system	Amount
Mechanical cylinders	988
Mechanical keys	988

Table 5.16: Details of the digital system in municipality A.

Details of digital system	Amount
Digital cylinders	988
Digital keys	374

Table 5.17: Details of the future concept system.

Details of future concept system	Amount
Future concept cylinder	988

DIRECT ENVIRONMENTAL IMPACT FOR THE SYSTEM:

Based on the details in Table 5.15, 5.16 and 5.17, in addition to the result from section 4.5, the direct environmental impact was calculated for the different systems connected to the home care service in municipality A. The emissions do not cover change of batteries, only initial installation with one battery per key.

Table 5.18: Total direct environmental impact for the mechanical system.

Mechanical system	Amount	Kg CO_2-eq (per product)	Total kg CO_2-eq
Mechanical keys	988	0,14	136,50
Mechanical cylinders	988	1,63	1 615,09
Sum CO_2-eq per system			**1751,59**

Table 5.19: Total direct environmental impact for the digital system.

Digital system	Amount	Kg CO_2-eq (per product)	Total kg CO_2-eq
Digital keys	374	0,94	351,01
Digital cylinders	988	1,06	1 047,28
Batteries	374	0,07	25,35
Sum CO_2-eq per system			**1423,64**

Table 5.20: Total direct environmental impact for the future concept system

Future concept system	Amount	Kg CO_2-eq (per product)	Total kg CO_2-eq
Future concept cylinder	988	8,23	8132,05
Sum CO_2-eq per system			8132,05

Figure 5.3 shows a summary of the environmental impact of the different lock systems.

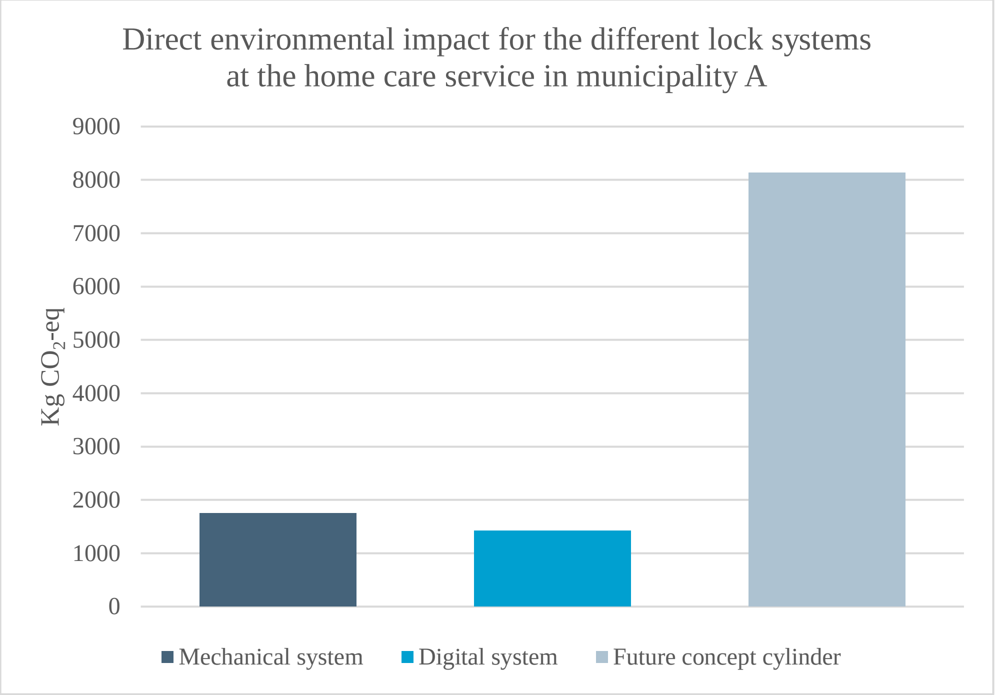

Figure 5.3: Visualizing the direct environmental impact for the lock systems at the home care service.

DATA AND CALCULATIONS FOR AVOIDED EMISSIONS:

The calculations of avoided emissions are based on information from municipality A and from one of the suppliers of home care service in the municipality. During interviews with employees working operationally with home care service, the interviewees were asked to draw a typical workday for the caregivers on a map in the operative area. From the map, the average distance between the caretakers and head office was estimated, see Table 5.21. Based on information from interviews in section 5.1.3., from a supplier of home care service, deviations could happen once a day up to once a week in their operations, which resulted in extra transportation before the digital lock system. Hence, the average distance travelled due to deviations could constitute an avoided distance when transitioning to digital locks. Due to confidentiality, the map and specific locations are not presented. The average distance was calculated based on six geographical locations in the municipality.

Table 5.21: General data on operations for municipality A.

General data on operations	
Average distance travelled between home care visits and office (one way)	4,4 km
Frequency of deviations	1/day – 1/week

Table 5.22: General data of supplier of home care service in municipality A.

General data of home care supplier in municipality A	Amount
Caretakers	170

It was assumed, referring to section 5.1.3, that a deviation results in an extra car transportation for the caregivers back and forth to the office, thus doubling the distance presented in Table 5.21. It is assumed that the home care service operates all weeks and all days in a year e.g., 52 weeks and seven days per week.

The yearly potential avoided distance for the home care supplier is calculated by using data in Table 5.23. First off, the annual number of deviations are estimated by multiplying the frequency with the number of weeks in a year as shown in Equation 5.

$$Frequency\ of\ deviations \times Number\ of\ weeks\ in\ a\ year\ = Deviations\ per\ year \quad (5)$$

As stated in section 5.1.3, 30-50 percent of the visits for the supplier of home care service are reached by bicycling or walking. Therefore, it is assumed that an average percentage of 40 percent can be excluded from the total amount of deviations per year, assumed that all deviations do not result in extra transportation by car. The number of deviations connected to car transportation is calculated by Equation 6.

$$Deviations\ per\ year \times 60\% = Deviations\ per\ year\ connected\ to\ car\ transportation \quad (6)$$

Further, the next step was to multiply the result from Equation 6 with the average distance travelled between the home care visits and office as shown in Table 5.23. The result of the potential avoided distance in a year is presented in Table 5.23.

Table 5.23: Annual avoided distance due to deviations for the supplier of home care service.

Frequency of deviations	Deviations per year	Deviations per year connected to car transportation	Average distance travelled between home care visits and office (km)	Potential avoided distance yearly (km)
1/week	52	31	8,8	274,56
4/week	206	125	8,8	1098,24
7/week	364	218	8,8	1918,4

Based on data in section 3.2.4, an average of the CO_2 emissions from new cars in the EU has been calculated to be 123,1 g of CO_2 emissions per km, which is used to find the corresponding avoided kg CO_2 for the result in table 5.23.

It is assumed that the frequency of deviations and the result in Table 5.23 depends on the number of caregivers and caretakers for the supplier of home care service. Further, it is desired to have the result scalable for the entire municipality. Therefore, the result was divided by the number of caretakers for the supplier of home care service in Table 5.22.

Table 5.24 presents the result based on different frequencies of deviations and potential avoided emissions yearly per caretaker.

Table 5.24: Potential avoided emissions based on the frequency of deviations.

Potential avoided kg CO_2-eq yearly	Deviations 1/week	Deviations 4/week	Deviations 7/week
For supplier of home care service in total	33,80	135,20	236,16
For supplier of home care service per caretaker	0,20	0,80	1,39

Further, the avoided emissions per caretaker, in Table 5.24, was multiplied with the total number of caretakers in the municipality, from Table 5.14. The potential avoided emissions for different frequency of deviations were calculated for the total home care service in municipality A, see Table 5.25 for result. The result assumes that the occurring deviations results in extra car transportation to the office due to key management before the digital system.

Table 5.25: The yearly avoided emissions for municipality A based on different frequency of deviations.

Frequency of deviation	Potential avoided kg CO_2-eq per year
1/week	196,4
4/week	785,7
7/week	1375

In addition to the results above, additional data shows an increased efficiency in operations since transitioning to digital locks from mechanical ones. Data on the efficiency of the supplier of home care service companies is based on the performance of four suppliers and is based on all caretakers. The efficiency is measured by the percentage of time spent between home care visits for caregivers and time spent with the caretakers. This timestamp data was available before and after the implementation of the digital locks.

There have been no other significant changes in the daily operations that would impact the efficiency and thus it is assumed that the transition to digital locks has had a positive impact on their efficiency. As mentioned in 5.1.3, the digital locks have had a generally good impact, and if the increased efficiency is due to less transportation is difficult to determine. According to the interviewee, the time between visits is mainly transportation between caretakers and her perception was that the increased efficiency is partly due to less transportation.

Data based on caregivers at four different companies in the municipality shows that the time the caregiver spends with the caretaker has increased since implementing the digital system. The data is based on 374 caregivers in total and the result is showed in Table 5.26 and 5.27.

Table 5.26: Percentage of time not spent at the caretakers for four different suppliers 2018 and 2022.

Supplier	Mar-18 (%)	Jun-18 (%)	Dec-18 (%)	Mar-22 (%)	Jun-22 (%)	Dec-22 (%)
Company 1	57	54	45	41	44	41
Company 2	45	51	46	45	45	44
Company 3	51	52	49	47	48	45
Company 4	58	54	56	52	56	53

Table 5.27: Showing percentage of average time not spent at caretakers for the different suppliers 2018 and 2022.

Supplier	2018 (%)	2022 (%)	Standard deviation
Company 1	52	42	57,1-46,9
Company 2	47	45	49,6-44,7
Company 3	51	47	51,9-49,4
Company 4	56	54	57,6-54,4

A standard deviation analysis shows that eleven of twelve of the numbers from 2022 are lower than the standard deviation for the data from 2018. Since every data point except for company two is lower than the standard deviation span, it can be assumed that there has been an increase in efficiency, and it is not a coincidence.

The reader needs to consider that the increase in efficiency can depend on other factors and not only because of increased efficiency due to the transition to digital locks. As stated in the result in section 5.1.3, the digital system has limited the time spent on key management, which is probably also a reason for less time spent in-between visits. Additionally, increased efficiency can depend on factors nonrelated to the accessing system, such as a higher competence among caregivers or the locations of caretakers. Since the caretakers are everchanging, more of them could be located closer to each other or the office in 2022 compared to 2018, something that would also be a factor for the higher efficiency regardless of the accessing system. Due to the uncertainties with this data, no potential avoided emissions related to this have been calculated.

5.2.3 FUTURE POTENTIAL AVOIDED EMISSIONS

This chapter aims to quantify and discuss the future potential with digital locks and future concept cylinders, as presented in section 5.1.4. It should be considered that this section is hypothetical and based on several assumptions and simplifications of reality.

Utilization rate

As stated in section 3.7, a higher utilization rate is needed in the real estate sector for it to become more sustainable. Furthermore, an increased utilization rate would require an access solution that is not limited to a few actors, but instead accessible to everyone that requires access. Therefore, the future concept cylinder is the object of study when discussing an increased utilization rate. Increased utilization rates are, for example, sharing spaces, such as the example in the literature review, section 3.7, but also using facilities during more hours of the day. For this case, the school facility management company´s facilities have been used as inspiration. The average energy consumption is based on the Swedish average and the reader should take acknowledge that this does not represent the actual energy consumption for the company.

Table 5.28: General data for the school facility management company´s facilities.

General data	Amount
Real estates	600
Facilities	3000
Square meters	1 800 000

The school facilities, as presented in section 5.1.2, are primarily utilized Monday to Friday between 7-17 o’clock and it is estimated that the buildings have the potential of being used until 22 o’clock and during weekends, referring to section 5.1.4. Table 5.29 summarizes the details regarding utilization.

Table 5.29: The current-, potential- and total utilization rate for the school facility management buildings.

Utilization	Details utilization	Hours a week	Utilization rate
Current	Monday – Friday, 7-17	50 h	59 %
Potential	Monday – Friday, 7-22 Saturday – Sunday, 10-15	85 h	100 %
Maximum utilization	All hours	168 h	-

Based on the total square meter the school facility management company operates showed in Table 5.29, the annual emissions for the energy consumption of the school facility management company were calculated. The energy consumption is estimated to vary with the Swedish average, between 205 and 245 kWh/m^2 per year. The CO_2 emissions per kWh are 0,015 kg. (Mata and Johansson 2017) Therefore, the annual emissions are between 5 535 000 and 6 615 000 kg CO_2-eq. The average between the annual emission is used in the following calculations.

The emissions occurring outside of the potential utilization rate have been removed from the total in the calculations since these emissions would occur regardless of increased utilization rate. The energy consumption allocated to the potential usage according to Table 5.29, is limited to 3 073 660 kg CO_2-eq a year. It is assumed that the facilities can be utilized during all 52 weeks of the year. Table 5.30 shows how the energy consumption "waste" can be reduced with a higher utilization rate. As shown in Table 5.30, the waste decreases as the utilization rate increases.

Table 5.30: The yearly energy consumption, allocated to the period when the facilities are not utilized.

Hours utilized per week	Utilization rate (%)	Energy consumption "waste" per year during no utilization (kg CO_2-eq)	Difference per 5 h (kg CO_2-eq)
50 (current)	0,59	1 265 625,0	180 803,6
55	0,65	1 084 821,4	180 803,6
60	0,71	904 017,9	180 803,6
65	0,76	723 214,3	180 803,6
70	0,82	542 410,7	180 803,6
75	0,88	361 607,1	180 803,6
80	0,94	180 803,6	180 803,6
85	1	0	180 803,6

The result in Tables 5.29 and 5.30 enables a calculation of the energy consumption of today to 695 kg CO_2-eq per hour for all m^2.

To determine the potential impact, the future concept cylinder can have on decreasing the environmental burden of buildings, different scenarios have been investigated. Firstly, it is of great interest to understand how much the utilization rate must increase to correspond to the environmental burden of the future concept cylinder.

A break-even point can be set when the direct environmental burden of investing in the system, with the future concept cylinders, equals the potential reduction of energy consumption that comes along with an increased utilization rate.

As stated in Table 5.12, the direct environmental burden for the future concept cylinder is 99 996,2 kg CO2-eq. To find the break-even point, these emissions have been removed from the energy consumption waste for the current utilization rate.

Table 5.31: How many extra hours that the facilities must be utilized to reach the break-even point for the future concept cylinder.

Hours utilized per week	Utilization rate	Energy consumption waste	Difference
50 (current)	0,59	1 265 625,0	
52,8	0,62	1 165 628,8	99 996,2

Table 5.31 shows that if the utilization increases by approximately 2,8 hours per week for all square meters, the corresponding energy consumption “waste” is equal to the emissions for investing in the future concept cylinder system in one year.

6. Analysis

This section contains an analysis of the result from the direct environmental impact assessment on a product- and system-level. Furthermore, the result from the cases and the avoided emissions are discussed and compared with the direct environmental impact. Moreover, the future potential of digital locks on a system-level are analyzed in addition to highlighting the challenges with the digital locks of today. In addition to this, the potential fourth scope and the accounting of avoided emissions in the reporting of a company’s emissions will be covered. Lastly, this section will discuss the potential shortcomings of the study and the effects on the result in a sensitivity analysis.

6.1 Direct environmental impact

By looking at the result presented in Table 4.13 and Table 4.15, both the digital lock and future concept cylinder have a higher direct environmental impact compared to the mechanical lock. This study has therefore shown that products containing electronics have a higher impact compared to products that do not contain any electronics.

The PCB boards included in the future concept cylinder is approximately three percent of the total weight of the cylinder but account for 79 percent of the environmental impact of the raw material. For the digital key, the PCB board are approximately 5 percent of the total weight but accounts for 87 percent of the environmental impact from the raw material, visualized in Figure 6.1.

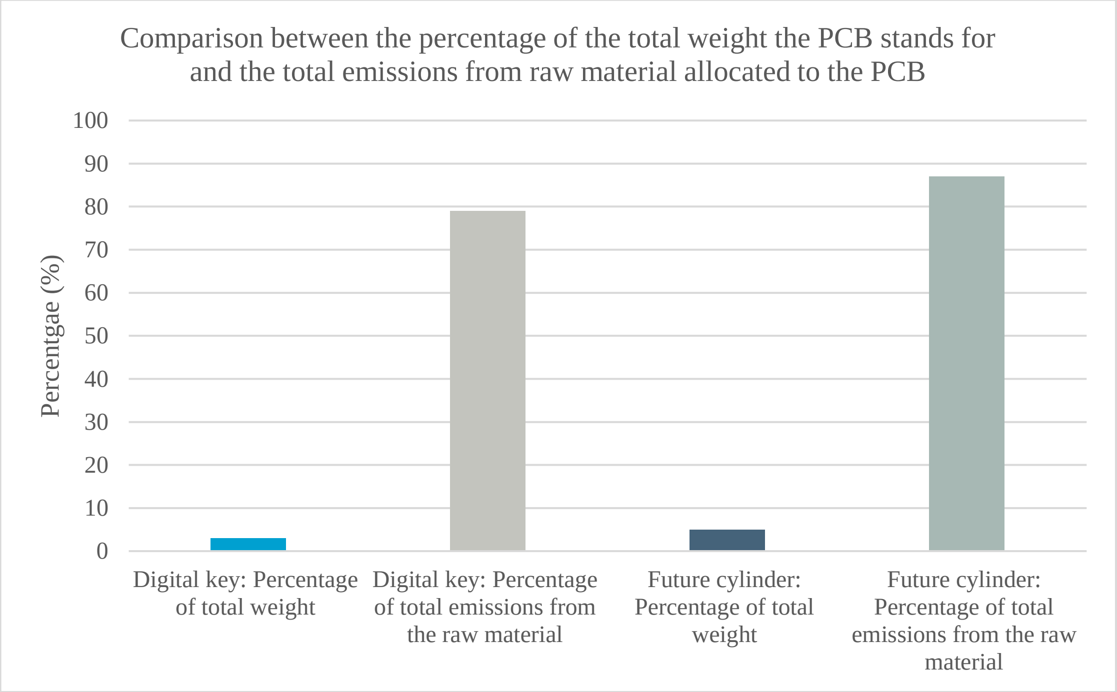

Figure 6.1: Visualization of the percentage of the total weight the PCB stands for compared to the environmental impact of the PCB have in the products.

The direct environmental impact of the digital key is more than six times larger compared to the mechanical key. Similarly, the emissions generated by the future concept cylinder are approximately 6,5 times larger than the digital cylinder and four times larger than the mechanical due to the increased amount of PCB in the future concept cylinder. In Table 4.7 it is stated that the PCB board stands for a very large impact compared to other materials or components. Therefore, the size and amount of PCB boards used in the product have a significant impact on the result and should be minimized, from a sustainable perspective.

The result in Table 5.10-5.11 and Table 5.19-5.20, when comparing the mechanical and digital system, show that the total impact for the keys is higher in the digital system and the total impact from the cylinders is higher for the mechanical system. Due to the larger number of cylinders needed compared to keys, the overall impact is higher for the mechanical system in both cases. The digital system enables a reduction of keys which decreases the total emissions from the digital.

The difference in emissions between the digital and mechanical cylinder occurs in the production stage, where the mechanical cylinder has approximately 33 percent higher emissions compared to the same stage for the digital cylinder, referring to Table 4.12. The higher environmental impact can depend on different factors such as a more energy intense manufacturing or a different composition in the alloy. However, this has not been investigated further. Since the number of cylinders is not flexible, the environmental impact for the mechanical system will be higher even if the numbers of keys are the same in both systems.

Overall, the cylinders have the highest impact on the environmental burden for all systems. As mentioned above, there is usually a need for more cylinders compared to keys as well as the possibilities to limit the number of cylinders in a system are low since a door with a lock require a cylinder. The future concept cylinder has a significantly higher environmental impact compared to the other products. The reason for this product having such high impact is because of the extended use of electronics as discussed in the first section of this chapter. Since the electronics are what highly impacts the environmental impact, the total impact on system level depends on which product that contain electronics. What differentiates the future concept cylinder on a system level is that the electronics are included in the cylinder instead of the key. Since there is usually a need for more cylinders compared to keys, it is reasonable that the environmental impact on a system-level is significantly higher for the future concept system compared to the digital and mechanical systems.

Since digital locks cause higher emissions on product-level, they can be justified from a sustainable perspective if they enable a system with less total environmental impact or behavior changes causing avoided emissions. The implementation and design of the digital system in this study have managed to already cause less environmental burden due to less emissions from the cylinders and reduction of keys. The future concept cylinder needs avoided emissions in order be justified from a sustainable perspective.

Other things that could influence whether it is justified are the service life of the products and the end-of-life phase. As stated in section 4.2, the service life of the products has been difficult to determine since it is highly dependent on the number of cycles rather than time. Due to that the digital locks contain electronics it is highly likely that the service life of these is lower compared to the mechanical products only containing metal. However, this has not been confirmed and thus it is not considered in the study.

The end-of-life phase is outside the scope of this study and has therefore not been included in the calculations. This should be considered by the reader since the environmental impact of mechanical and digital locks may differ in the end-of-life phase. As mentioned in section 3.3.2 the recycling of electronics is overly complicated and difficult and it is therefore possible that the digital product has a higher impact and lower recycling rates in the end-of-life phase compared to the mechanical.

6.2 Comparison of direct and avoided emissions

The following chapter will present a comparison of the direct environmental impact of the different systems and the avoided emissions for the different cases. The comparison will lay the foundation for answering the research question. Based on input from interviews, referring to section 5.1.2, it is assumed that the battery is changed every third year for both cases. It is changed on routine and regardless of the state-of-charge. The service life for the different locks is set to ten years, referring to section 4.2. After ten years the system will be replaced with new products. The following chapters will analyse the different cases separately followed by a compilation of the cases. The result is based on the scenario of acquiring a new system with locks after the previous system have reached its end-of-life.

6.2.1 SCHOOL FACILITY MANAGEMENT COMPANY

The direct environmental impact of the system and potential avoided emissions were presented in 5.2.1. Table 6.1 summarizes Table 5.9, 5.10 and 5.11 with the result from Equation 4.

Table 6.1: Comparison of direct and avoided emissions for the different systems.

System	Direct environmental impact (kg CO_2-eq)	Additional emissions every third year (kg CO_2-eq)	Avoided emissions per year due to less transportation (kg CO_2-eq)
Mechanical system	20 427,09	0	0
Digital system	16 111,10	216,9	25 453,1
Future system	99 996,2	0	25 453,1

As mentioned above, the total direct environmental impact is less for the digital system compared to the mechanical. The future system has the highest environmental impact.

Figure 6.1 illustrates the CO_2 emissions for the digital system, future concept cylinder system and avoided emissions respectively, based on Table 6.1. The graph aims to visualize the break-even point, meaning the point where the accumulative avoided emissions reach the environmental impact for acquiring the system. The two dashed lines represent the CO_2 emissions related to acquiring the digital and future concept system based on the results from Table 6.1. The emissions are constant for the future concept cylinder. For the digital system, there is an increase every third year because of battery changes, but since this impact is relatively small compared to the total, it is not visible in Figure 6.1. The filled line represents the accumulative avoided emissions based on the result from chapter 5. Thereby, it aims to create an understanding of if or when the environmental burden of the digital and future system can be justified from a sustainable perspective.

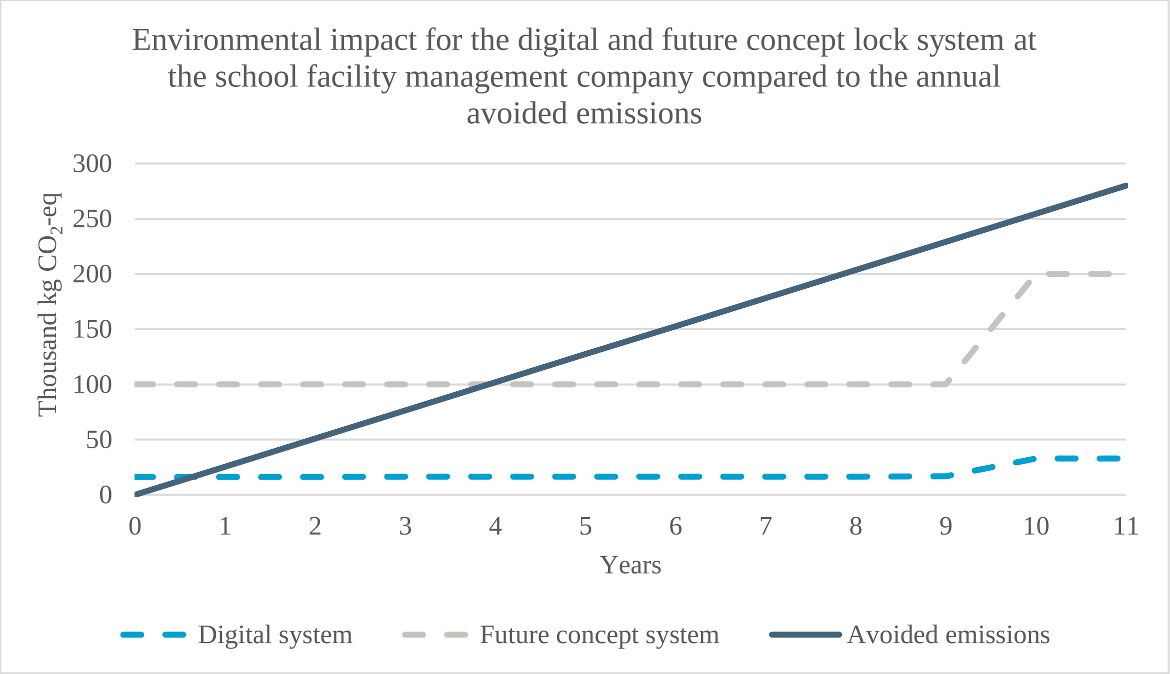

Figure 6.1: Visualization of the accumulative yearly avoided emissions in comparison to the constant environmental burden of the digital and future concept lock system.

The future concept cylinder is expected to generate the same benefits and avoided emissions are therefore applicable to that system as well, even if the current solution is the digital one. As visualized in the graph, it takes less than one year of operations with digital locks for the avoided emissions to reach the direct environmental burden of the digital system. Similarly, it takes approximately four years for the future concept cylinder system. During the service life, the environmental savings will be significantly higher compared to the environmental burden of acquiring the systems.

6.2.2 HOME CARE SERVICES

In section 5.2.2, the direct environmental impact of the system and the potential avoided emissions were presented. Table 6.2 summarizes the important findings from Table 5.18, 5.19 and 5.20. The result presented in 5.2.2 was depending on the frequency of deviations, which varied from once a week to seven times a week, and it was based on data from the supplier of home care service. Further, the data corresponding to deviations occurring four times a week, the average frequency, will lay the foundation for analyzing the environmental impact for the lock systems and avoided emissions for municipality A.

Table 6.2: Comparison of direct and avoided emissions for the entire system.

Kg CO_2-eq	**Direct environmental impact**	**Additional environmental yearly**	**Avoided emissions per year due to less transportation**
Mechanical system	1 788,28	0	0
Digital system	1 425,02	26,18	785,7
Future system	6 912,2	0	785,7

From Table 6.2 it can be stated that the direct environmental burden for the mechanical system is larger than for the digital system. The future concept cylinder system still has the highest direct environmental impact.

The digital system and the future concept system enable potential avoided emissions due to fewer deviations resulting in car transportation back and forth to the office to manage keys. The yearly avoided emissions correspond to more than 50 percent of the direct CO_2 emissions for acquiring the digital lock system. For the system with the future concept cylinders, the avoided emissions correspond to approximately 10 percent of the total amount of direct CO_2 emissions for acquiring the system.

Figure 6.2 illustrates the lock system's CO_2 emissions with the digital lock, future concept cylinder, and avoided emissions. The two dashed lines represent the level of CO_2 emissions related to acquiring the system with digital locks and future concept cylinder respectively. The level of CO_2 emissions is constant for the future concept cylinder. For the digital system, there is an increase every third year because of the battery changes, but since this impact is relatively low compared to the entire impact, it is not visible in Figure 6.2.

The solid line represents the avoided emissions, based on deviations occurring four times a week, enabled by the digital lock system presented in Table 5.25. The future concept cylinder is expected to generate the same benefits for less transportation and thus the avoided emissions are therefore applicable to that system as well.

The avoided emissions accumulate over time and can be compared to the level of direct CO_2 emissions from acquiring the digital locks or the future concept for the system. As visualized in the graph, it takes approximately two years of operations with digital lock and the avoided emissions to justify the direct environmental burden of the digital system. The result shows that the avoided emissions enabled by the future concept cylinder in the home care service are not large enough to justify the high environmental burden of the future concept cylinder.

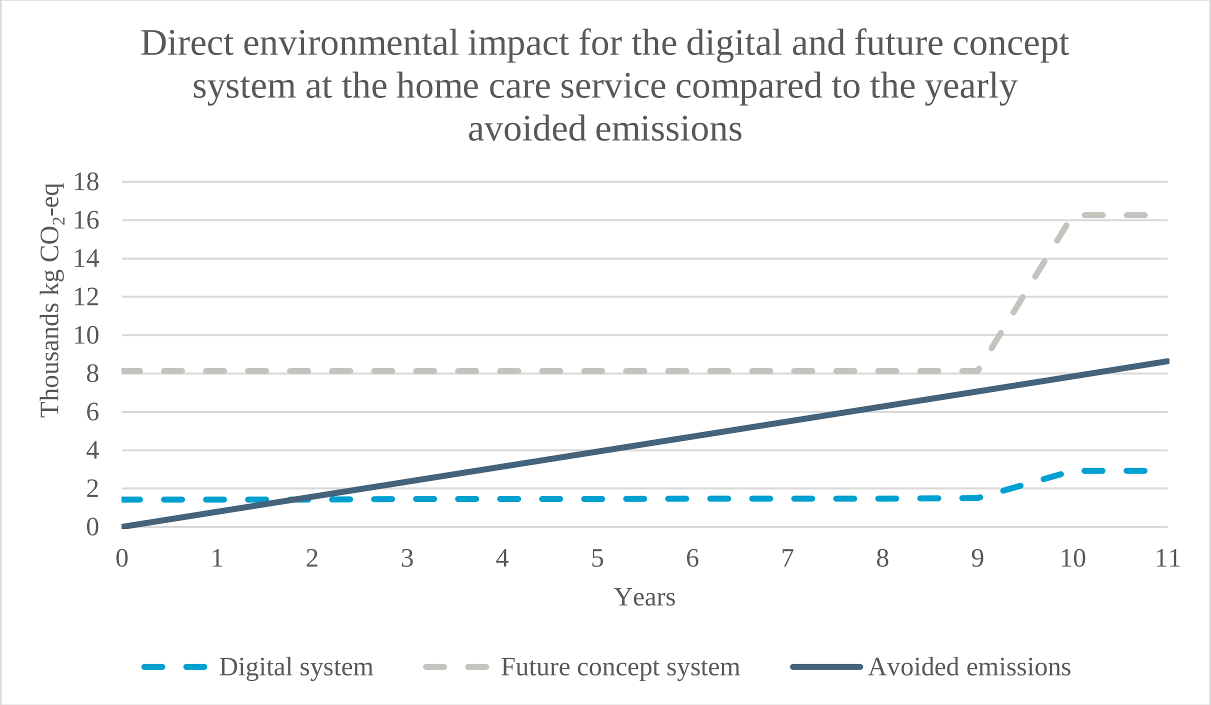

Figure 6.2: Showing the direct environmental impact of the lock systems compared to the accumulative avoided emissions per year for the home care services in Municipality A.

There are some shortcomings and assumptions to consider in the estimations of the avoided emissions for the home care service that will be presented in section 6.6.

The data on increased efficiency for the home care service presented in Table 5.27 determined that the efficiency has increased. Avoided emissions cannot be quantified from the increased efficiency, but the result is still interesting since it supports the result from 5.25. It is highly likely that the efficiency has increased due to less transportation connected to deviations since the home care service transitioned to digital locks.

6.2.3 PARCEL AND LOGISTICS SERVICES

From the qualitative data in section 5.1.1, it was clearly stated by the interviewees from the logistics and parcel companies that digital locks would not improve their transportation flows nor decrease their emissions. With this result, investing in digital locks aimed to be used by the logistics companies will result in a higher environmental impact compared to traditional locks.

What differentiates this case from the other two is that this would require two separate actors to cooperate for it to work. Both the school facility management company and the home care services have full control over their access system. For locks on residential buildings, the residents would be responsible for the locks while the parcel and logistics companies would use them. The companies therefore lack control, and it is more difficult to design a system that would benefit them. But as presented in section 5.1.1, even if the companies could design and use a digital system in collaboration with all customers, the currently available solutions would still not have a significant impact on decreasing their transportation.

Therefore, if a digital lock is installed today with the only purpose of getting in-home deliveries, the environmental burden would be higher for the digital lock compared to a mechanical one and can therefore not be justified from a sustainable perspective.

However, it was stated that in-door deliveries and nighttime deliveries have the potential to increase the efficiency of parcel and logistic service companies. Nonetheless, neither the consumers nor society fully support or accept these alternatives yet. In-home delivery to consumers and nightly deliveries to businesses could enable the parcel and logistic service companies to not be limited to delivery windows and thus optimize their routes further. But as stated in the qualitative data, crucial aspects for this to work is much wider usage and a more integrated system. The future concept cylinder is therefore an inspiration for future potential regarding this and it will be further discussed in section 6.3.1.

6.2.4 COMPILATION OF THE CASES

The result from the case studies has shown that two out of the three cases have managed to decrease their operational emissions thanks to digital locks. The size of the avoided emissions is highly related to the number of trips and the transportation distance that decreases, which is dependent on what the operation looks like for each customer. Taking the school facility management company as an example, the average distance between the head office and the school facilities is much larger compared to the average for the home care service, since they operate in the entire city of Stockholm compared to the home care service that only operates in one smaller municipality.

The result from the cases shows that key factors in the operations that enable for avoided emissions are significant car transportation and a high number of keys used in the operation. It can therefore be assumed that the findings in these cases can be applicable to other actors with those operational characteristics, for example, real estate companies, other home care services or physiotherapist.

Another interesting aspect both cases have in common is that the direct environmental impact is lower for the digital system compared to the mechanical. Because of this, it is reasonable to believe that a digital system will cause a lower environmental impact even in other cases if a customer chooses between installing a new mechanical or digital system. Lock systems on the other hand is based on products with relatively long service life and it is reasonable to think that if a customer implements a digital system, they do that because of the additional benefits it generates rather than that the old system have reached its end of life. Implementing a new system before the old needs to be changed will increase the overall impact, and in that case, the avoided emissions generated from a digital system becomes even more interesting.

The result shows that the digital system seems to be beneficial when considering a closed system where one actor has control but is more difficult to implement in operations requiring an open system accessed by different actors. The future concept cylinder can facilitate access control and potentially create avoided emissions for this the operation requiring a more open system.

6.3 Potential with future concept cylinder

As digitalization continues, there will be more and more opportunities for smart products in society. This study has primarily focused on the benefits that current solutions bring in addition to capturing the future potential with the future concept cylinder. Even if the future concept cylinder does not generate any sustainability benefits beyond the digital product as for now, its potential lies in future changes to society and our behavior. This future potential will be discussed further in the following chapter.

When analyzing the environmental impact of the future concept cylinder, both the current avoided emissions and the future potential avoided emissions are included. Since the initial environmental impact of the future concept cylinder is significantly higher compared to the digital lock, it can only be justified from a sustainable perspective if it generates further benefits and avoided emissions compared to the digital lock. Since the future concept cylinder is not currently used, it can only be speculated what additional behavioral changes and avoided emissions it could generate. The future potential found in the interviews and stated in Table 5.2 is further analyzed in the sections below.

As mentioned previously in chapter 5, the future concept cylinder represents a future product with the aim of creating a flexible and open system. An example of an open system connected to the home care services is to allow access for all actors that need to enter a caretaker’s home, which could be medical services, physiotherapists, and paramedics. Systems like these will have the possibility to integrate users into the access system more easily and to minimize the barriers currently created by locks. From a sustainable perspective, it is most likely that different flows in society that never have to adapt to when a door is open can be optimized and thereby minimizing the emissions, which was found both in the literature review section 3.5.3 and in the qualitative data in section 5.1.4.

6.3.1 IN-HOME DELIVERY TRENDS AND ENVIRONMENTAL IMPACT

Based on the result from the interviews with companies working with logistics and parcel service in section 5.1.1, in-home deliveries will not enable them to reduce their emissions due to less transportation as stated in section 6.2.3. They offer what the consumers want and as for now the consumers are driven by the price for delivery options and thus, they are not willing to pay more for in-home deliveries, referring to 5.1.1.

However, this might change in parallel with changes in society, consumer behavior and needs. For example, consumers expect short delivery time, and the demand might get stricter in the future and the alternative of in-home deliveries could become more beneficial compared to going to a pick-up point. In addition to that, the preference for outside the door deliveries of parcels might change if there is an increase in thefts in Sweden, trends in Europe are showing an increase in this kind of “porch piracy” as mentioned in section 3.6.

From the interviews presented in 5.1.1, it was stated that it would be beneficial to be able to deliver parcels independent of the delivery window which could be enabled by digital locks. In-home deliveries without delivery windows can enable the companies to further optimize their routes, both to avoid heavy traffic and to potentially decrease their car transportation during deliveries. Previous studies, as discussed in section 3.5.3, also emphasize the potential of increasing efficiency in delivery operations with un-attended home delivery for the parcel and logistic service companies. However, studies presented in 3.6, found that the environmental burden is generally less when delivering to parcel lockers compared to home delivery due to less transportation.

6.3.2 NIGHTTIME DELIVERIES

Another aspect mentioned by the interviewees was the possibility of nighttime deliveries. As mentioned in 3.5.3, this could decrease the unnecessary time spent in traffic due to the congestion of roads during peak hours. Both interviewees also concluded that one barrier for B2B deliveries today is the opening hours of companies. They are usually limited to the opening hours which limits the flexibility. There could be other solutions that would facilitate nighttime deliveries beyond the future concept cylinder, both the interviewees agreed that it would most probably need a secure, transparent access solution that could be used by different actors when needed. The future concept cylinder system would therefore most likely increase the chances of making nighttime deliveries possible.

Another aspect to consider is that, as mentioned in 3.5.3, the current legalization only allows trucks making noise under a certain decibel to drive in urban areas during nighttime in Sweden. Therefore, the trucks performing nighttime deliveries would need to be electric, something that reduces the emissions further but also complicates the progress. Logistics and delivery companies would need to purchase electric trucks and transform their vehicle fleet. It is therefore an interesting aspect but still faces a lot of barriers before it can be a reality.

6.3.3 UTILIZATION RATE OF FACILITIES AND ENVIRONMENTAL IMPACT

As discussed in 5.2.3 and in the literature review, the real estate and building sector stands for 40 percent of the global energy demand. Finding ways to decrease the environmental impact of this sector is therefore crucial to reach global sustainability targets. Identified during interviews with the school facility management company was the low utilization rate and several articles as stated in 5.2.3 were found on the topic of sharing facilities or offices to a greater extent to gain environmental savings.

One of the current issues is the access system for sharing facilities, especially when shared between different actors during various parts of the day, is the access issue as stated in 5.1.4. In section 3.7 and 5.1.4, it was identified that a higher utilization rate of facilities is enabled by a better access solution system to facilitate the utilization for multiple users and to create more modular facilities and rooms to suit different purposes. Smart digital locks can have a significant impact on improving the accessibility of buildings and the future concept cylinder has characteristics that can facilitate the sharing. Increasing the utilization rate by including more hours of the day have been the example in this study but it is estimated that the same reasoning could also apply to sharing spaces in offices or other buildings.

The school facility management company’s lock system has been used to create an example of how the increased utilization can be compared to the direct environmental impact. Table 5.31 showed that the environmental break-even point for investing in a future concept cylinder system was by utilizing all square meters during an extra 2,8 hours per week. An aspect to consider is that for the utilization rate to increase, there must be a demand for more usage. In the case with school facilities, the gymnasium or auditorium would probably have the most demand to be used during weekends and evenings. Increasing the utilization with 2,8 on all square meters corresponds to using 20 percent of the area for an extra 14 hours per week and using 10 percent of the area for an extra 28 hours per week.

Visualized in Figure 6.3 are four different examples of increased utilization rate compared to the direct environmental impact. The avoided emissions in Figure 6.3 are based on section 5.2.3, especially Table 5.30. It is assumed that only 20 percent of the school facilities have the potential to be used for additional activities, and the avoided emissions shown in the figure are based on increasing the utilization of 20 percent of the area for either 2,8,14 or 20 hours per week.

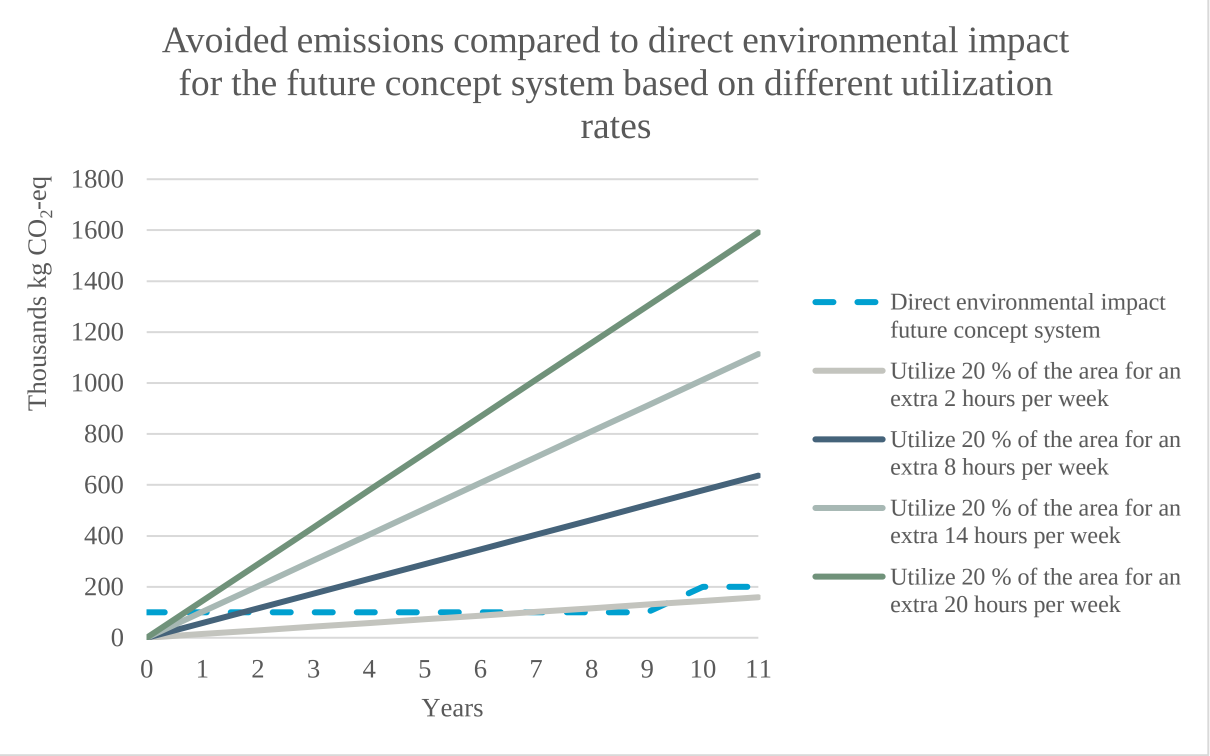

Figure 6.3: Shows the cumulative potential avoided emissions based on different increased utilization rates in comparison to the constant direct environmental impact. All numbers are based on the school facility management company case.

As shown in Figure 6.4, there is potential for avoided emissions when increasing the utilization rate. For all these examples, the avoided emissions exceed the direct environmental burden during the service life of the system. This indicates that for other real estate cases that cannot minimize transportation due to key management, the added environmental burden can still potentially be justified if the utilization is increased. This example is based on the school facility management company and their lock system, other examples would have a different number of cylinders and other potential savings due to increased utilization. This example is based on the average energy consumption per square meter in Sweden and the average emissions per kWh, it is estimated that the same reasoning can be applicable to other cases as well. Thus, an increase in the utilization rate of facilities in society can enable further potential avoided emissions with a significant impact.

Figure 6.4 visualizes both the current avoided emissions based on less transportation from Equation 4 and the potential avoided emissions based on increased utilization rate, Table 5.30, for the school facility management company. Comparing Figure 6.4 to Figure 6.1, the break-even point is reached much earlier when including the potential for increased utilization rate as well, only increasing 20 percent of the area for an extra 2 hours per week has a significant impact and the break-even point is reached after approximately 2,5 years compared to 4 as shown in Figure 6.1.

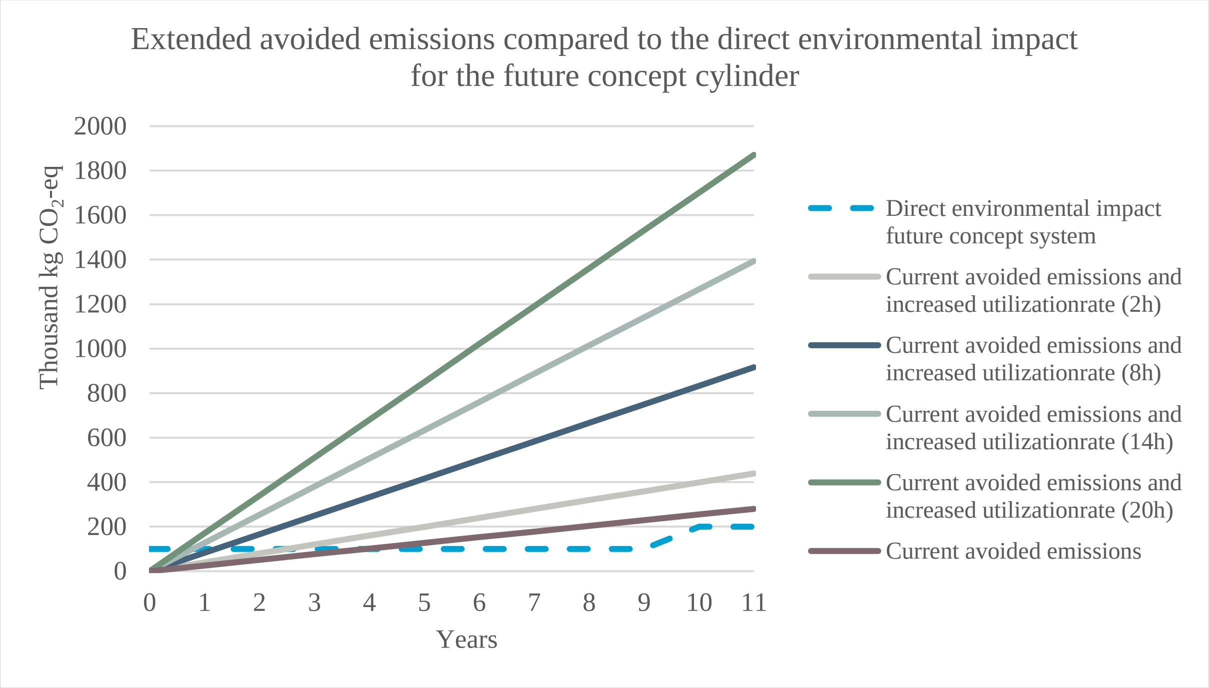

Figure 6.4: Showing the cumulative potential avoided emissions based on different increased utilization rates combined with the current avoided emissions in comparison to the constant direct environmental impact. All numbers are based on the school facility management company case.

What should be considered when discussing this potential is that not all the environmental savings can be allocated to the locks since a transformation towards more sharing requires other enablers as well. But since the potential savings for increased utilization is of a significant size, it is possible that the break-even point would be reached within the service life even if all avoided emissions are not allocated to the lock system.

Further, a higher utilization rate of existing facilities in society in general can potentially result in less need for new constructions which will reduce the CO_2 emissions connected to the construction industry. Less need for new construction and better use of the existing facilities can be seen as environmental savings of CO_2 emissions.

6.4 Challenges with the current digital solution and potential improvements

Based on the information gathered during this study there are some challenges that has been identified with the digital locks of today. These challenges are a hindrance for the digital locks to reach their full potential for the users and surrounding environment, at least in the specific cases covered by this study.

One issue that was identified from the case with the school facility management company was that the batteries are not used to their full potential. This issue deviates from that it is not possible to get an overview of the energy level for the keys in the system. Therefore, the batteries are changed on routine to limit the risk of having discharged batteries. To ensure a minimized environmental impact, the battery changes should be optimized and thus that might be something that could be supported by the lock system.

Another issue that was brought up by the parcel and logistic service companies in section 5.1.4 is the low acceptance for utilizing digital locks to their full potential for consumers, for example related to in-home deliveries. In parallel with more consumers having digital locks in their homes and acknowledging benefits such as unattended in-home deliveries, these might become more accepted in the future. In addition to this, it is also about behavioral changes and getting used to and trusting digital products compared to traditional products.

One recurring aspect is that the digital lock system can be seen as a closed system due to the physical key that makes it harder to share access with externals. The future concept cylinder would probably enable a more open system due to no need for a physical key.

6.5 Avoided emissions

In 3.3, different kinds of digital change and their impact on surrounding benefits and reduced emissions were discussed from a product, system and societal level. For the cases researched in this thesis, the product itself has nothing to do with nor has a direct impact on limiting the emissions. As of now, it can be argued that a digital lock system that creates great opportunities for reduced emissions is either a transformation or acceleration change on a system level, depending on how extensive the system is. Additionally, the future concept can instead be compared to a transformative or accelerated change on a societal level since the aim is to integrate several different stakeholders into the same system. As stated in the article in section 3.3, a transformative change on a societal level is a quite dramatic change, but it also comes with great potential. What is interesting to consider is that it is only the behavior changes that the locks can generate that enable the avoided emissions since the products itself does not enable reduced emissions.

The reduced emissions because of behavioral changes have throughout this thesis been referred to as avoided emissions. As discussed in section 3.1.4, the definition of avoided emissions as a concept is not yet completely defined but includes emissions that are avoided by using a certain product or service compared to a conventional method or product. This definition is applicable in the cases investigated in this thesis.

As mentioned in chapter 3.1, sustainability is becoming increasingly important for companies, both to reach sustainability goals and to create positive narratives and augment brand value by demonstrating accountability through avoided emissions. One of the greatest concerns for companies regarding this is that it is equally common for a negative impact of certain products as a positive impact, something that should be included as well. As of today, avoided emissions are not included in the standardized reporting, but it can still be a way for consumers and stakeholders to make informed decisions. What should be considered when discussing this is that avoided emissions have so far been used as a competitive advantage, where companies are trying to position their products as more sustainable compared to their competitors’ products thanks to the avoided emissions they generate.

The way avoided emissions have been referred to and discussed throughout this thesis is to create an understanding of whether digital products can create sustainable benefits now and in the future. The purpose of the avoided emissions is therefore to guide the innovation department developing new products rather than trying to include these in the reporting.

Of course, it would be beneficial for the cooperating company to include these in the reporting as soon as it exists a standardized and accurate way of doing this. If the company would want to include avoided emissions in their reporting as a fourth scope, there are, as mentioned in 3.1.3, several important suggestions to note before doing so. The company has a large product portfolio, and as mentioned it would need to estimate the impact all their products have on consumers’ emissions and include both the positive results a negative in the reporting. The focus should then not only be on products that are expected to reduce customers emissions, but rather an industrial average product if possible.

Moreover, the company needs to be transparent with their assumptions, for example when it comes to the service life of the different products. Another suggestion is to clearly include all potential other aspects that must be considered if including the avoided emissions. These aspects are for example maintenance of the locks that should be included as well in a fourth scope. In order to avoid greenwashing, the authors believe that the avoided emissions should be considered as a guideline for which products that have the potential and which characteristics are needed in locks in order to create avoided emissions. Furthermore, the authors believe that the information is useful for customers and other stakeholders when making decisions.

6.6 Sensitivity analysis

There are important aspects and potential shortcomings in this study that will affect the result and thus needs to be considered. Details and explanations regarding potential shortcomings are explained in this section. Lastly, a worst-case scenario will be presented to assess the impact on the result due to potential shortcomings.

6.6.1 DIRECT ENVIRONMENTAL IMPACT

The assessment of the direct emissions for the keys as presented in section 4 constitute an important foundation in this thesis, and thus it is important to consider that this simplified LCA has been done with limited previous experience and resources. Limitations are both related to the tools and databases used in addition to limitations in details available to perform a comprehensive and accurate assessment.

As mentioned in 3.2.3 a cut-off criterion can be used in a life cycle assessment. In this study the criterion was set to 2 percent, even though previous studies suggested 1 percent. The cut of rule was set to simplify the assessment and thus exclude smaller parts whose weights did not exceed 2 percent. Given that they did not contribute to a significant environmental impact of the product. The total weight of excluded parts consisted of 2,14 percent of the total weight, therefore the potential environmental impact of these components that are excluded is probably neglectable.

Shortcomings in the assessment that are critical and can influence the result is the exclusion of transportation of raw materials to the production site for all components for both mechanical and digital keys. However, in the EPDs for the cylinders it is stated that the environmental impact for that specific transportation route was neglectable, referring to section 4.7.4. This indicate that the corresponding transportations routes for the material for the keys do not have a significant environmental impact.

Other shortcomings in the result are connected to the assessment of the environmental impact of the battery and the PCB. Due to the complexity of these components and data gaps regarding production processes and supply chain, data for the assimilated finalized products was retrieved from the database and used in the assessment. Due to lack of transparency in this data it is difficult to control the accuracy of the result. Other shortcomings in the result can be various neglected processes for the different materials and components e.g., processes connected to metal or plastic parts such as surface treatments.

To ensure that the result of the estimated environmental impact for the key is reasonable it has been compared to the existing environmental impact in EPDs for the cylinders. The assessment presented in the EPDs has a higher validity since it is verified by external parties and aligned with the ISO-standard for conducting an EPD.

Table 6.3: Weight compared to the environmental impact of the digital lock.

Digital lock	Key (estimated)	Cylinder (EPD)
Weight (g)	27,50	148,00
Environmental impact (Kg CO_2-eq)	0,94	1,06

The comparison of the digital components shows that the environmental impact of the key and cylinder are approximately equal. The key has a lower weight compared to the cylinder which could initially imply a lower environmental impact. However, as found in previous studies in 3.3, electronics bring a significant environmental impact and thus the estimated value for the key may be legit in comparison to the cylinder.

As previously mentioned, due to potential gaps in the assessments such as excluded processes and transportation routes in the supply chain e.g., the estimated environmental impact for the key may be rather low. On the contrary, the result in Table 6.3 indicates that the estimated value might be high compared to the cylinder.

The mechanical key only consists of one component, the key material. The data for the environmental impact of this component is re-used and adjusted for the digital key. Due to that the mechanical key consists of one component compared to the digital key which consists of several complex components the estimated environmental impact for the digital key has probably more errors compared to the mechanical one.

Below is a comparison of the environmental impact of the mechanical key and cylinder respectively. As previously mentioned, the data for the mechanical cylinder was retrieved from an EPD in contrary to the data for the key that was estimated based on the conducted simplified LCA.

Table 6.4: Weight compared to the environmental impact of the mechanical lock

Mechanical lock	Key (estimated)	Cylinder (EPD)
Weight (g)	14,7	146

Mechanical lock	**Key (estimated)**	**Cylinder (EPD)**
Environmental impact (Kg CO_2-eq)	0,138159	1,634709

The weight of the cylinder is approximately ten times the weight of the cylinder. Further, the environmental impact for the cylinder is approximately twelve times larger than for the key, this indicates that the result from the conducted LCA can be seen as reasonable. The key and cylinder have similar material composition, however, there are some differences in the ratio of the alloy.

Regarding the future concept cylinder, the assessment of the environmental impact is highly uncertain and hypothetic due to limited details about the product, processes, and its supply chain. However, the result is in line with the previous result showing that more electronics in a digital product brings an increased environmental impact.

Even though the result from the assessment of the direct environmental impact is not completely accurate it is sufficient for the purpose of this study. The result enables a comparison of the environmental impact of the digital and mechanical lock in addition to the future concept lock, which indicates what is bigger and smaller respectively.

6.6.2 CASES, LOCK SYSTEMS AND AVOIDED EMISSIONS

There are various drawbacks to the result of studying cases and quantifying potential avoided emissions in section 5.

The result is based on data or information provided by a manager or employee at the companies studied and thus there is a risk of biased input. It might be of interest to become more sustainable and to have reduced CO_2 emissions in their operations. For example, the average distance between the head office and school facilities (19,7 km) that was shared during the interview with the school facility management company is estimated by them and details for their calculations were not shared. Since the location of all their facilities and head office are public information, the accuracy of the distance has been checked and is assumed to be accurate.

The quantifying of avoided emissions for each case is highly based on assumptions and perceptions from the interviewees. The calculation of avoided emissions in home care service is based on the frequency of deviations before the digital lock system at the specific supplier of home care service in municipality A. It is also depending on the fact that deviations can result in extra car transportation back and forth to the office. Deviations could likely occur more often considering the increased risk of forgetting keys in one’s clothing, mixing up keys, or getting the wrong one for the planned visits when handling physical keys for each caretaker. However, it is hard to estimate the frequency of these deviations.

The future potential of digital locks was discussed with the interviewees from the different cases. It needs to be considered that the outcome of this depends on the interest and openness for future development of each industry and interviewee. Inspiration has also been gathered internally from the cooperating company, which may also have influenced the authors to investigate certain areas more than others.

Another important aspect to consider when reviewing the result is the number of locks and cylinders in the systems for each case. The input regarding these numbers is based on information from interviews in addition to the authors’ perception of the systems. These numbers have a significant impact on the result of the total direct emissions for the lock systems for each case and type of lock. The number of keys and cylinders in the system today, referring to the digital system, is probably accurate. However, these numbers for the mechanical lock system are based on a perception of how the system looked several years ago, before transitioning to digital locks, and thus they may not be accurate.

6.6.3 WORST-CASE SCENARIO

From the shortcomings presented in 6.6.1 and 6.6.2, some are more critical than others and thus should be assessed further in a worst-case analysis. According to Boardman et al. (2014) the aim of presenting a worst-case is to evaluate the result involving the least favorable assumptions. The result analyzed in section 6.2 shows a rather positive result of transitioning to digital locks. Therefore, it is of interest to evaluate the impact on the result of the most critical and least favorable assumptions.

As mentioned in section 6.6.1 the environmental impact for the cylinders is assumed to be correct and therefore fixed in the worst-case scenario for the cases.

The authors conclude that the most critical parts of the environmental impact of the keys are the neglected transportation to the production site in addition to potential gaps in the manufacturing processes for all the lock types. Therefore, the current estimated amount of CO_2 emissions for transportation and manufacturing processes for the keys are doubled to assess a potential worst-case scenario. This results in an increase of emissions of 2 percent for the mechanical lock, 15 percent for the future concept cylinder, and 7 percent for the digital lock. This results in a total of 1,8 kg CO_2-eq for the mechanical lock, 9,5 kg CO_2-eq for the future concept cylinder, and 2,2 kg CO_2-eq for the digital lock. The worst-case values and the actual values are shown in figure 6.5.

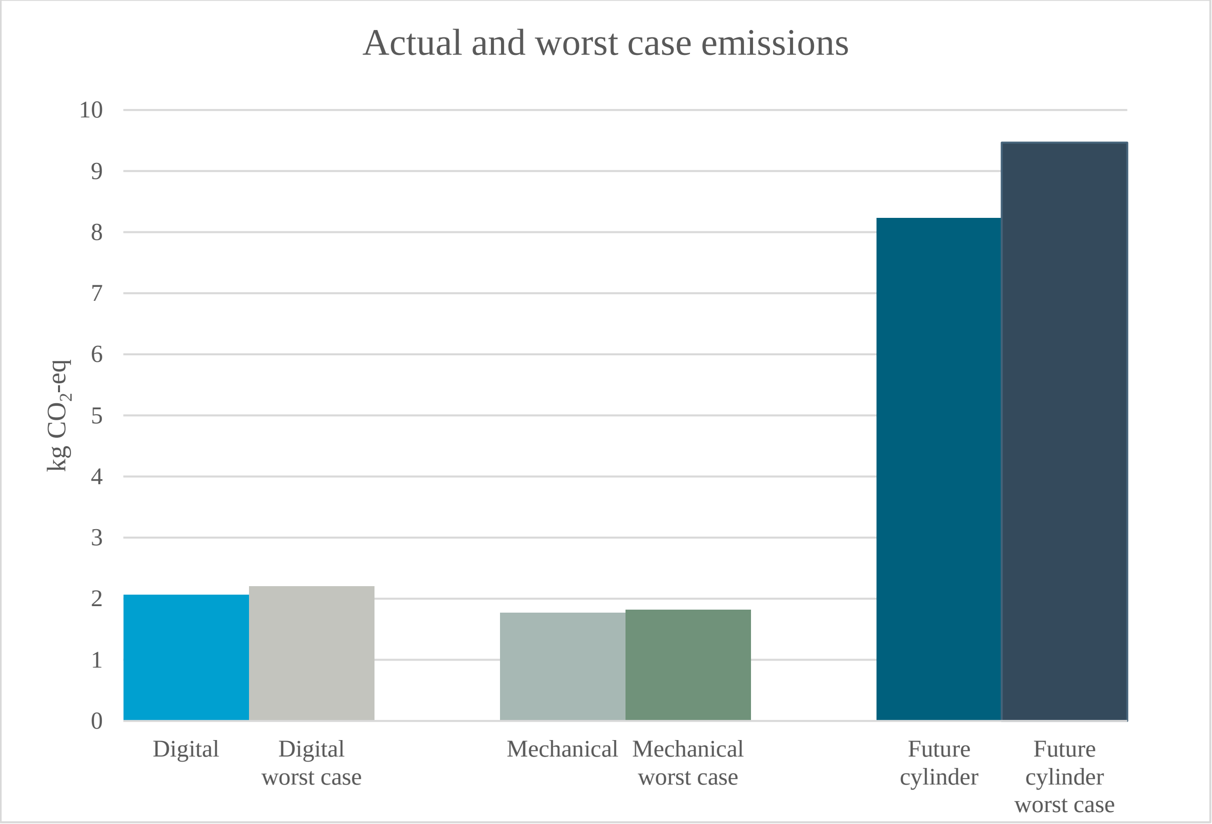

Figure 6.5: Worst-case scenario and actual environmental impact for the different locks

Further, the estimated avoided emissions for home care service might be highly estimated. The frequency of deviations connected to physical key management ranged from once to seven times a week. The result is based on an average of four times a week. The worst-case scenario is therefore set to the frequency of once a week.

The assessment of avoided emissions for the school facility management company is less critical since it is based on real-time data from the lock system and is therefore not changed for the worst-case.

Worst-case for the school facility management company

Figure 6.6 illustrates a worst-case scenario with an increase in the direct environmental impact of the digital locks and the future concept cylinder. The results show that the avoided emissions still exceed the direct environmental impact for both locks and the difference compared to the actual scenario is neglectable. Therefore, even in the worst case, the added environmental burden for battery and electronics can be justified due to the behavioral changes and resulting avoided emissions.

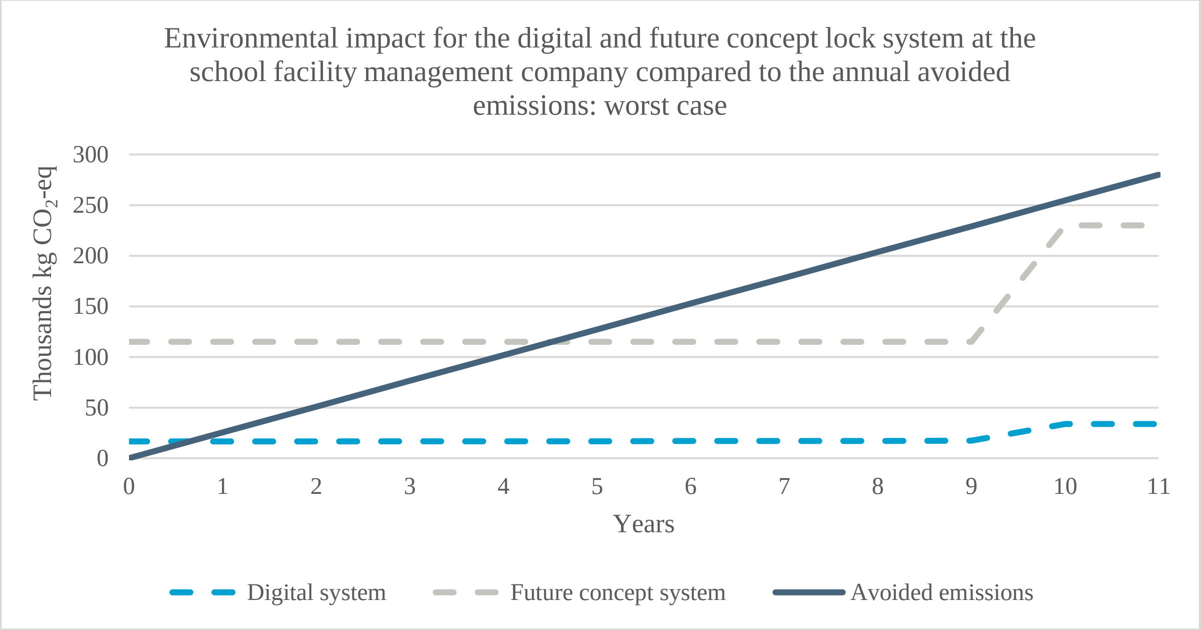

Figure 6.6: Estimated worst case scenario for the school facility management company.

Worst case for the home care service

Figure 6.7 shows the worst-case with an increase in the direct environmental impact and a reduction of the avoided emissions for the home care service. In the worst case neither the environmental impact of digital locks nor future concept cylinders can be justified. The avoided emissions barely exceed the direct emissions from the digital locks and do not exceed the direct emissions from the future concept cylinders.

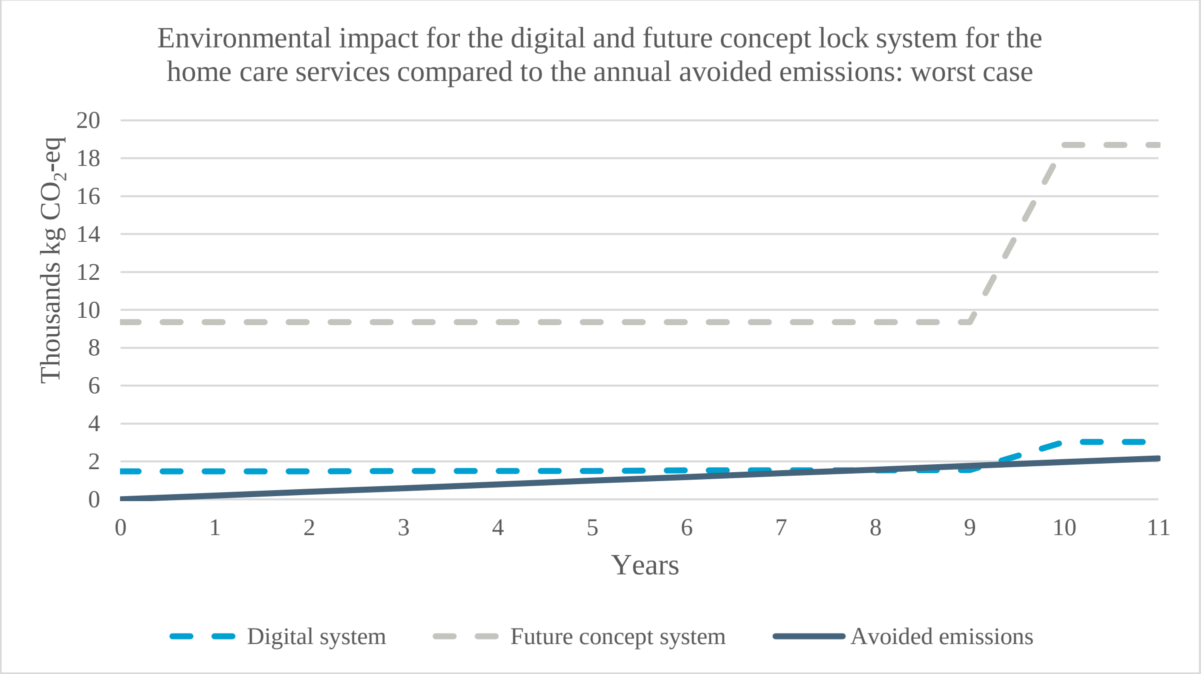

Figure 6.7: Estimated worst case scenario for the home care services.

7. Conclusion

This section presents a conclusion of the results of the research question presented in section 1.2. After that, the future potential of digital locks and recommended future research are presented.

7.1 Discussion of the research question

The aim of this study is to answer the research question in section 1.2:

"Is the potential added environmental burden of batteries and electronics justified if they could enable the potential for downstream customers and users to become more sustainable?"

The result from the empirical study in chapter 4 and 5 lay the foundation for answering the question. The question can be answered from two perspectives: either product-wise or system-wise. Table 7.1 and 7.2 shows a summary of the result used to answer the research question. From a single product perspective, the result shows that there is an added environmental burden of batteries and electronics for the digital locks and the future concept cylinder compared to the mechanical lock.

However, as shown in the result in chapter 5 these digital locks can bring other benefits that should be considered. Benefits such as reduced number of keys needed in a system in addition to enabling behavioral changes at the end users that can result in reduced emissions due to less car transportation connected to key management.

Table 7.1: Summary of the result for the school facility management company.

School facility management company	Mechanical	Digital	Future
Product level (kg CO_2-eq)	1,8	2,1	8,2
System level (kg CO_2-eq)	20 427,1	16560,9	99 996,2
Avoided emissions (kg CO_2-eq)	0	25 453,1	25 453,1

Table 7.2: Summary of the results for the home care services.

Home Care Service	Mechanical	Digital	Future
Product level (kg CO_2-eq)	1,8	2,1	8,2
System level (kg CO_2-eq)	1751,6	1423,6	8132,0
Avoided emissions (kg CO_2-eq)	0	785,7	785,7

From a system perspective, the results show that in two out of three cases there is no added environmental burden when transitioning from mechanical to digital locks. This result is mainly due to that the mechanical cylinder has a higher environmental impact compared to the digital cylinder. The difference in CO_2 emissions for the cylinders in the system is of significant size due to the large number of cylinders. Moreover, the digital lock enabled a reduced number of keys in the system which also contributes to limiting the total direct environmental impact of the digital system. Based on the result from these specific cases there is no added environmental burden for the digital lock systems that needs to be justified. However, for the future concept cylinder there is an added environmental burden due to that these cylinders have a significantly higher environmental impact and do not enable any reduced number of products since the number of cylinders needed is fixed for a system.

Further, to answer the research question, it is of interest to compare the direct environmental impact of the digital lock and future concept cylinder with the avoided emissions. The results show that in two out of three cases, the avoided emissions are of significant size and thus can exceed the direct emissions for the digital locks within two years. For the future concept cylinder, the avoided emissions exceed the direct emission within four years in one case and for the other ones the avoided emissions are not sufficient to reach the level of the direct emissions.

Related to the research question, it can be concluded that in two out of three cases the added environmental burden of digital locks can be justified due to the behavioral changes resulting in avoided emissions. For the future concept cylinder the added environmental burden can be justified in one of three cases. However, it needs to be considered that the avoided emissions are quantified based on the digital locks and not the future concept cylinder. The future concept cylinder with no need for a physical key may result in additional benefits and behavioral changes that can result in even higher avoided emissions compared to the digital locks. For example, the future concept cylinder can facilitate the sharing of spaces and increase the utilization rate as shown in section 5.2.3.

The findings show that the transition from mechanical to more digital locks can most likely be justified from a sustainable perspective, based on the result from these cases. Due to a high direct environmental impact for the future concept cylinder, it requires added avoided emissions for it to be justified. It needs to be emphasized that the outcome of the result is strongly dependent on a few aspects in the operating organization and for the users: keys and key management is a central part of the operations, there are car transportation connected to key management, the digital key and future concept cylinder can enable behavioral changes which the users are embracing and adapting for.

Another finding from this study is that it seems to be a correlation between the successful results from a sustainable perspective when transitioning from mechanical to digital locks and that the users have explicit ownership of the locks meaning that it is a closed system for internal use referring to section 5.1.4. This is probably due to the limitation that the digital locks require a physical key. On the other hand, the result also shows that there are other benefits with a more open system, which requires a fully integrated access system in the operating environment in addition to having the possibility to easily share access to other externals without the use of physical keys.

In addition to the previously mentioned benefits of the digital locks and the future concept cylinders from a sustainable perspective, they can also bring other benefits for the users such as increased safety, transparency, and efficiency in operations. The result is limited to the specific cases, but it can probably be applied to other businesses where keys and key management are a central part of the operations. In 1.1.1 the importance of leveraging welfare technologies, such as digital locks in home care services e.g., was emphasized since it is a crucial part of the development of societies. In line with this, it is stated in 3.1. related to the concept of TBL, that sustainability covers other important factors besides environmental, such as economic and social that also should be considered when companies are assessing their products and sustainability efforts.

To summarize and conclude the findings, the added environmental burden for electronics and batteries in digital locks will most likely be justified if they enable behavioral changes and avoided emissions of significant size. If the added environmental burden cannot be justified, there are a lot of other benefits that should be considered when evaluating the transition from traditional to more digital products. It is important for companies to continue the digitalization journey and develop new smart solutions for consumers, as stated initially in 1.1.1. On the other hand, it is crucial for companies to keep track of their emissions and to understand the added environmental burden of new smart products and report these in line with the guidelines available, as mentioned in 3.1.2. Lastly and most importantly, companies should aim for minimizing their emissions to reach their climate goals and thus contribute to limiting the fatal impacts of climate change.

7.2 Future potential with digital locks

As mentioned in section 3.4 an important layer of a smart city is the technology base which constitutes the foundation for enabling a technology-driven and connected city. Smartphones and sensors in mass can be a part of this technology base and it can be argued that also locks would have an important role in the smart city development. In section 3.4 it is also emphasized that the smart city only succeeds if the technology is widely accepted and adopted, which is in line with the perception from the home care service and parcel and logistic service companies presented in section 5.1.4.

The authors believe that there is a future potential with digital locks and the future concept cylinder and that it can contribute to smart city development. Imagine an open world, where the access hindrances are removed, all flows are optimized and transparent and systems have safe sharing of access. In this study, sections 5.1.4 and 6.3, some future potential improvements with flows in the cases have been presented, which could be enabled by the future concept cylinder.

Of course, there are issues with a generally more open system as well that need to be considered. For example, it requires surveillance of actors who have access and a higher risk for the people responsible for the locks. The control over who enters a home or a building is critical, and in the end, who carries the ultimate responsibility over the access system? If for example a home care service company agrees that other stakeholders can enter the locks they have implemented, are they responsible for issues occurring because of that?

One of the issues with a mechanical and digital lock system is that it can be considered a closed system as mentioned in 6.4. This therefore limits the amount of people who can access spaces or facilities. The future concept cylinder can facilitate an open system where it would be possible to share access more easily with everyone who needs it. For the school facility management company, a more open system would for example mean that they can increase the utilization rate of their buildings. Other stakeholders could make use of their facilities after school hours and easily access the spaces with the use of the future concept cylinder. More than bringing benefits to other stakeholders, it can be argued that it enables a reduced waste of energy consumption when spaces have an increased utilization rate as presented in sections 5.2.3 and 6.3.3. Related to smart city development, an interesting aspect that was brought up in 5.1.4 was the future potential of having modular smart buildings that would facilitate increased utilization rate if spaces can be adapted to multiple purposes.

Having a more open system where the home care service is operating would facilitate for other stakeholders such as relatives, paramedics, or physiotherapists to access the caregiver as mentioned in 5.1.4. The authors believe that it could potentially in the future also facilitate medical care in the home which could reduce the load on hospitals.

As stated in section 5.1.1 the consumers receiving deliveries demands accessibility and flexibility. Hypothetically, this can result in consumers expecting minimal effort for receiving a parcel and thus choosing in-home deliveries in the future. Further, the digital lock and future concept cylinder can facilitate nightly deliveries of gods to for example companies, cafes, and restaurants. As mentioned in section 3.5.3 it would enable more optimized transportation routes and fewer trucks in operation for deliveries which can result in reduced emissions for the parcel and logistic service company.

If the above-mentioned scenarios, enabled by the future concept cylinder, would be a reality and widely established in society, the authors believe that it can result in a significant amount of reduced emissions on a societal level in addition to other benefits for the concerned stakeholders. Nevertheless, the risks, responsibilities and ownership of locks and access systems may become more complex and thus these aspects need to be considered for the continuous development of digital locks.

7.3 Future research on the topic

This study can be interpreted as a first step to understanding how digitalization in general, and digital locks, affect emissions both in the production stage and in the use phase among end customers. However, the result from this study should be treated with caution due to the small sample size and focus on only a few selected cases and products that might not be representative of the entire product or customer range.

Further research could therefore examine if and how this is relevant for other customers and products as well. A topic that has been touched upon several times is the inclusion of avoided emissions in the sustainability reporting. As mentioned, both in 3.1.4 and 6.5, one of the fundamental aspects for including this in the reporting is to investigate the affects all products in a product portfolio have on customer behavior and potential avoided or added emissions. This thesis has primarily focused on digital products that were estimated to have a positive effect from a sustainable perspective, and it is therefore recommended to further investigate how other products beyond those in this study affects end users' emissions.

Another interesting future research would be to widen the scope and to include the end-of-life phase and the recyclability of the different products as touched upon in section 6.1.

Digital locks and their role in the future smart city development is an interesting aspect to investigate further. During the literature research, it was found that there is not a satisfying amount of research conducted on smart city development connected to digitalization and sustainability. Three examples of future possibilities thanks to products like the future concept cylinder have been investigated in the use cases. There are probably other interesting and important aspects related to digital locks and future smart city development that have not been included in this study. It is therefore a recommendation to keep researching these areas to identify more possibilities worth considering.

The results in section 6.3.3 show that there are potential avoided emissions with an increased utilization rate of facilities. As mentioned in 3.7, access solutions play an important role in enabling increased utilization, and therefore it would be of interest to investigate this matter further.

Additionally, for the aspects considered in this thesis, the focus has been on if it can generate sustainable benefits, rather than how. Since one conclusion is that there is great potential for in-home delivery, nighttime delivery, and increased utilization rate in the future, the authors believe it should be investigated further how this could work. More research is needed on how the access system constitutes an enabler or a barrier in order to minimize emissions related to those activities. Due to current barriers, it has been difficult to investigate further as of now, but the authors believe it is of great interest to keep examining this related to smart city development.

Another interesting aspect worth investigating is how strategic partners in an integrated access system can work together. The authors believe it would be of importance to further understand which barriers these partners have, what is crucial for them, and how they would benefit from an integrated system. This could be for example how home care services, delivery personnel and paramedics can work together to all have access to the same locks. What are the current barriers, what would be needed from the stakeholders, and what incentives are there to create such a system?

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Appendix A - Interview protocol

Interviews were conducted with stakeholders in a parcel and logistic service company, a school facility management company, and a home care service. These stakeholders are operating in a various environment, thus the procedure of the interviews varied. However, the main questions were the same and constituted the foundation during the interviews. In addition to the main question some sub-questions and case-specific questions were asked to get an understanding of the companies' operating environment. Below is a summary of the interview protocols, it is not case-specific.

Main questions connected to research question:

Can digital locks enable their operations to become more sustainable compared to the use of mechanical locks? If yes, how?

Can digital lock influence the flows? Perceived effect on efficiency or in the operations in general?

What are the challenges today with digital locks?

What is the future potential with digital locks?

Sub-questions and more case specific:

Background and description of environment such as data on number of cylinder and keys in the mechanical and potentially a digital system.

What does their transportation flows look like today?

Questions regarding data needed in order to estimate and quantify potential avoided emissions such as distances travelled by car in the operations. Frequency of car transportation connected to key management.