Environmental performance of aerospace storage systems

Design and application of an environmental assessment model for small part storage systems at an aerospace part distributor

Msc Transport, Infrastructure and Logistics

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The impact of storage systems on the environmental performance of aerospace warehousing

Design and application of environmental assessment model for small part storage systems at an aerospace part distributor

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Preface

This thesis was written for the master Transport, Infrastructure and Logistics at the TU Delft. The project was supported by an aerospace service provider, who provided me with the opportunity to study aerospace part storage. This was a very interesting subject to study for my thesis and I am very grateful for this chance.

At the start of my thesis some hardship was experienced in finding the right subject. An aerospace service provider wanted more insight into their carbon footprint and offered a subject on a spare parts distribution model with an included carbon constraint. This was however deemed impossible due to the lack of information present on the carbon footprint involved in these processes. In cooperation with my TU Delft supervisors and Kaveh Alizadeh on behalf of an aerospace service provider, I was able to find a subject that encompassed the wishes of the TU Delft and the aerospace service provider and I am very proud to have written my thesis on it.

I would like to thank Dingena Schott for her assessment and guidance at the initial and final phases of my thesis. Thanks to Jaap Vleugel and Wouter Beelearts van Blokland for their supervision and support throughout my thesis. Thanks especially to Kaveh Alizadeh for the guidance, opportunity, interesting discussions and the good times I have experienced at the aerospace service provider. Finally I would like to thank my parents and my partner for their support and everlasting faith.

A.J. van Bruggen
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Abstract

Social and political pressure has made emissions an increasingly important subject for companies. The extension of the sustainability reporting mandate by the EU has increased the necessity for carbon transparency for companies in Europe. Warehousing and distribution account for 13% global supply chain emissions and can be an important factor in reducing company emissions. The traditional trade off in warehousing storage systems between cost, service level and emissions has mostly been in favor of cost and service level. Now however, emissions are becoming just as important to companies. This paper investigates the emission levels of manual and automated storage system, specified to aviation standard parts. Aviation standard parts are chosen as these are commonly stored using automated systems, due to the high degree of accuracy needed and the quantities involved in this sector. Current knowledge does not provide insight into the environmental footprint of automated and manual storage systems for small parts. This paper aims to fill this gap by combining literature research and expert consulting to gain insight into the carbon footprint of storage systems and modelling to gain insight into operational energy consumption. Finally, a case study is performed at an aviation parts dealer for empirical evidence on storage system emissions.

Summary

Carbon emission is currently one of the most important subjects for improving sustainable business activities. The EU has also increased the necessity of carbon transparency for companies. The fields of transport and distribution are large players in this regard. Warehousing and distribution facilities in fact account for 13% of global supply chain emissions. As such, improving the sustainability in these areas can be a beneficial strategy for companies to increase profit and increase social and political standing. In recent years, different storage systems have been developed and researched that offer benefits for warehouse and picking operations. These storage systems can increase warehouse throughput, accuracy and decrease cost. A clear difference that can be identified are part-to-picker and picker-to-part systems. Part-to-picker systems are automated and offer a pick job to the picker. In contrast, picker-to-part systems are non-automated and pickers gather pick jobs from the dedicated storage space in the system. The literature offers different methodologies for improving throughput, accuracy and space requirement of these systems as well as comparing the different storage systems with each other. Environmental performance is barely represented, with just a few simplistic sustainable measures for specifically transport and routing within the warehouse and a comparison between the part-to-picker and picker-to part systems is not available.

This thesis aims to fill this gap by designing an environmental performance assessment model and applying this to a case study. The model is used to compare the environmental performance between the different storage systems. An aviation parts distributor is chosen for the case study. The aerospace service provider has a warehouse in Hoofddorp. This warehouse contains various standard parts offered to their customers. At least 36.000 standard parts are present. The main research question to be answered is: *What impact do storage systems for aviation standard parts have on the environmental performance of a warehouse?*

The considered storage systems are applicable to small part storage and have differing benefits. The picker-to-parts systems considered are bin-shelving and modular drawers. Bin shelving are racks that are filled with bins, modular drawers are cabinets with drawers that contain many small compartments. These two systems do not differ much, although modular drawers can store many different parts with a low volume and bin-shelving can contain a higher volume, however not as many different parts. The part-to-picker systems considered are:

- Vertical lift module (VLM): A large rectangular box that contains shelves in which compartments can be made. A pick face is present at waist height where shelves are placed as a pick job is made. An extractor is used to move the shelves from their location to the pick face and returning it. This system offers a dense storage option that can make use of the vertical dimension.
- Vertical carousel: Comparable to the VLM. However instead of having an extractor grab and return shelves, this system contains a vertical carousel of bins that turn the right bin to the pick face when a pick job is performed.
- Miniload automated storage and retrieval (Miniload AS/RS): A large rack system containing bins. An extractor is used to grab and return specific bins. This extractor is able to move parallel to the rack horizontally and vertically. When a pick job is performed, the extractor moves to a specific bin and brings it to the pick face. When the picker finishes the job, the bin is returned. This system is very accurate and can also make use of the vertical dimension.
- Horizontal carousel: Carousel system that turns horizontally. A large system of bins that also has a pick face. The system turns the correct set of bins to the pick face. This system can however not make use of the vertical dimension.

These for system are each common for small part warehousing. For the environmental performance comparison the carousel systems are not included. The vertical system is expected to have a higher operational power consumption than the VLM because the full contents of the carousel is moved with each pick job. The horizontal carousel is not included because it cannot make use of the vertical dimension and will therefore have a substantially higher space requirement. The aerospace service provider uses a combination of bin-shelving and four VLMs to store a total volume of 388 m^3

The literature identifies three major factors that influence environmental performance. These are lighting, HVAC and material handling. Lighting is dependant on the equipment used and the space requirement of the storage system. HVAC is also dependant on space requirement and the corresponding volume as well as the isolation of the warehouse. Finally, material handling includes the operational and stand-by power consumption of the storage system. As a result, the KPIs used to determine environmental performance are space requirement and CO_2 emissions.

The model initially derives the space requirement of the specific storage system. The volume to be stored is used in conjunction with the storage volume of the storage system to determine the space requirement. Using the lumen method, the lighting intensity and power consumption is determined. The space requirement and building height are used to determine HVAC requirements using the degree-days method where external temperatures and isolation quality determine the power consumption.

Material handling is a more complex subject. For each considered part-to-picker system, different material handling operations are performed. The VLM only has the vertical extractor and moves a shelf for each pick cycle. The miniload AS/RS has an extractor that moves horizontally and vertically and picks just a single bin for each pick cycle. For each system, average pick cycles are developed and in conjunction with the amount of picks per year the operational power consumption is determined. Stand-by power consumption is determined by comparing these systems to a common lift system.

Using these three facets, the environmental performance assessment model can determine the yearly emissions resulting from the use of the considered storage systems. The case study is applied and the initial results show that the VLMs and miniload AS/RS perform substantially better with respect to environmental performance. To expand the analysis potential of the results, investment cost and operational cost are considered. The automated systems also perform better on operational cost but do require a large initial investment, especially the miniload AS/RS. Figure 1 compares the storage configuration present at An aerospace service provider with the mentioned storage systems for the considered factors.

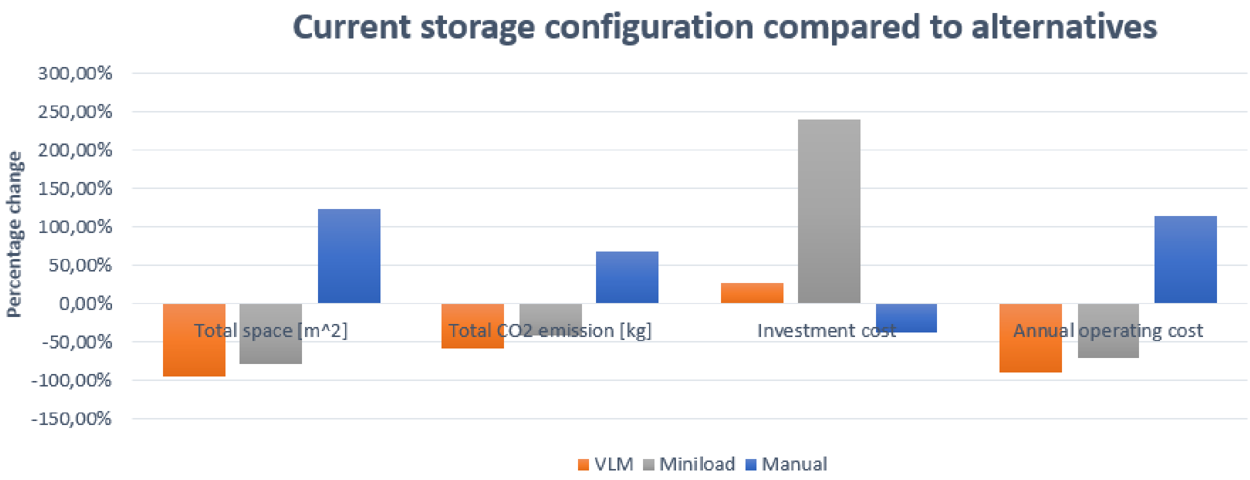

Figure 1: Comparison of current storage configuration and the considered alternatives

Further analysis is performed to identify important internal and external factors that influence the environmental performance of the considered storage systems. The factors that are identified are:

- Warehouse dimensions: The building height and desired aisle length in which the storage system operates.
- Building characteristics: This factor entails the equipment used for lighting as well as the quality of isolation in the warehouse.
- Picking policy: The method in which the automated systems are used, specifically the application of dedicated picking time slots to reduce stand-by power consumption.
- System characteristics: Related to the specific characteristics of a storage system. For instance; bin density, bin volume, aisle width and stand-by power consumption
- Storage volume: The total storage volume to be stored. This influences the total space requirement and also the amount of automated storage systems needed.

From these factors three different scenarios are developed that each consider a combination of these factors. The scenarios are:

- *Scenario 1: Dedicated time slots and efficient storage policy*

  In this scenario, management has focused on reducing energy consumption from material handling. By reducing the average picking cycle, more picks can be fulfilled within a certain time frame. This results in smaller picking time slots and a reduction in operational and stand-by power consumption for the automated storage systems.

- *Scenario 2: Parts, safety stock and demand increase*

  New customers have been attracted and as a result, new parts have to be kept in storage. On top of this, demand of existing customers has increased as the aviation industry recovers from the recent pandemic. To account for this increased demand the considered company has chosen to increase the safety stock of their parts, increasing the storage volume further.

- *Scenario 3: Warehouse relocation & re-investment*

  The warehouse is relocated and with the importance of sustainability increasing, the main decision criteria are economic and environmental performance. As a result, investment in lighting and HVAC are applied as well as choosing warehouse dimensions that are in line with the main decision criteria.

Scenario one shows that by reducing the stand-by power consumption of the automated systems, a large reduction in carbon emissions can be realized. It can be concluded that for the situation at the aerospace service provider, the systems have a substantially larger share of stand-by power consumption than operational. The second scenario simulates increase in demand and customers in the future, the results identify the storage system that is most robust with respect to these factors. The miniload AS/RS has the smallest relative increase and can therefore be identified as most robust. The VLM system still has the lowest emissions however. In scenario three a warehouse design is chosen to optimize space requirement for each storage configuration and investments are applied in lighting and isolation. The manual storage system is affected the greatest with an almost 50% reduction, showing that investments in warehouse equipment are an important factor when reducing carbon emissions. This effect increases as the space requirement increases. Also the automated systems are greatly affected due to the use of the vertical dimension. The space requirement of these systems is reduced by around 40%. Of the three scenarios the third shows the most potential to reducing carbon emissions.

The main research question of this thesis is: *What impact do storage systems for aviation standard parts have on the environmental performance of a warehouse?* The impact of storage systems on environmental performance of an aviation standard part warehouse has been shown to be great. The current age offers many different options for storage and each have a different effect. The manual systems generally perform worse on space requirement and carbon emissions due to the higher space requirement. Of the considered automated systems the VLM can definitely be advised as this system has shown to result in the least carbon emissions. The miniload AS/RS also performs relatively well in the initial case study as well as the scenarios, however this system requires a greater investment than VLMs and does not offer a higher environmental performance. Important recommendations to reducing the carbon emissions of current storage configurations are:

- Investing in lighting and isolation has been shown to have the greatest effect on carbon emissions
- Warehouse design is also an important factor and when relocating, the storage systems used should be taken into account
- When using automated systems, gain insight into the share of operational and stand-by power consumption to know in which area the greatest improvements can be made

Finally, the model has different use cases and can be applied for many different situations. The model can evaluate current systems, forecast environmental performance of storage systems and aid in the design of future warehouses. It can be used by an aerospace service provider to increase decision-making potential with respect to environmental performance of storage systems

Contents

1 Introduction

The steady increase of greenhouse gas (GHG) emissions over the recent years has lead to governments setting regulations to reduce company emissions. At the moment the EU has set the goal to decrease carbon-dioxide emissions by 55% by 2030 compared to 1990 (Commission, 2021). In 2021 the EU introduced the corporate sustainability reporting directive (CSRD), mandating large companies to report their company activities that have a social or environmental impact from 2025 and onward (Verheijke et al., 2021). Also, a strategy for increasing sustainability and/or reducing social and environmental impact is expected. This directive has increased the need for carbon transparency as 9 out of 10 companies fail to properly measure the emissions they produce (Degot et al., 2021).

Due to social and political pressure, some firms have already adopted the sustainable execution of logistic activities as a business strategy and competitive advantage (Dey et al., 2011). A large part of emissions in the industry sector results from storage and transportation activities as it is estimated to account for 5,5% of global GHG emissions (Fichtinger et al., 2015). Besides the political awareness for the increasing amount of GHG in industry, companies are also realizing that financial benefits are possible with the sustainable use of materials and products (Plambeck, 2012). Company inventory systems suffer from the triple trade-off between service level, costs and environmental impact. Increasing service level in turn increases inventory costs and might increase the carbon footprint as a result of expediting (Rahimi et al., 2017). This trade-off makes the consideration of carbon footprint in inventory systems a complex subject as, at the least, three objectives have to be taken into account.

Research on emissions in supply chain operations are, for the greater part, related to transportation as this is the primary cause of emissions in a supply chain (Ubeda et al., 2011). Warehousing and distribution facilities also have a substantial impact on GHG emissions though, as it is estimated to account for 13% of global supply chain emissions (Doherty et al., 2009). In recent years this has become a more popular subject for research and numerous papers have been published that either propose a framework for warehouse emission calculation (Zajac, 2011) or integrate inventory policy and warehouse operations to analyse the effect emissions can have on decision making (Fichtinger et al., 2015). An important factor for these papers are the storage systems used in the warehouse, as this mostly determines the size requirements. The environmental footprint of a warehouse is based on lighting, conditioning, equipment and size (Ries et al., 2017). Although automated storage systems can decrease warehouse size by a substantial margin (Azadeh et al., 2017), energy consumption rate increases, especially compared to manual warehouses where no transport equipment is used. Current research on automatic part-to-picker systems does not provide sufficient insight into this trade-off (Azadeh et al., 2017). It is assumed that, due to the reduction of space required, the total energy consumption decreases. The literature does not extend to this topic however and an empirical study to prove this assumption is missing.

To study the trade-off between level of automation and emissions, a product stream is chosen to be applied to the warehouse storage system. The aviation industry has been steadily increasing in the last 20 years and maintains a complex supply chain (Mazareanu, 2021). Large aircraft parts require an assortment of smaller parts and standard parts to connect these together. Due to the increasing size of the modern aviation business, the volume and dependency of these standard parts is becoming troublesome for traditional logistics (Xue et al., 2020). Common practice in the industry is using an automatic storage and retrieval system (AS/RS) to sort and collect the parts to realize the complex logistics involved (Xue et al., 2020). These standard parts are small and can be picked manually, although this does reduce efficiency. Due to this character, aviation standard parts are chosen as the product stream to be studied.

This thesis aims to answer the question; What impact do storage systems for aviation standard parts have on the environmental performance of a warehouse? To this end, literature research is done on current warehouse storage systems for small parts, as well as defining the optimal way of determining environmental footprint of the considered system. This is done by recording the amount of carbon emissions resulting from storage systems. The literature research is supplemented with expert consulting in the field of aviation warehousing, aviation service provision and part-to-picker systems. A basic model is used to simulate yearly operations, allowing for experimentation for different scenarios. To provide empirical evidence, the carbon footprint of a part distributor in the aviation industry will be analysed and used as input for the model. The company to be analyzed is a global independent aerospace service provider. Applying a case to the model will allow for empirical evidence on the resulting emissions of a manual and automated storage solution. The scope of the project entails common storage systems applicable to aviation standard parts. Standard aviation parts are considered, this includes all parts that do not require certification and have a standardized shape and quality (bolts, nuts, nails, etc.). Environmental performance is taken into account in the form of carbon emissions and this extended with the financial consequences resulting from the application of alternative storage systems.

This report is structured as follows: First in section 1 the problem is introduced and the research questions, methodology and literature review are provided. In section 2 the small part storage systems commonly used in the industry are introduced. In Appendix B the case study context is elaborated on. In section 3 the KPIs for determining environmental performance of storage systems are identified. In section 4 the environmental assessment model is built and elaborated on. In Appendix C the environmental assessment model is applied to the case study for different alternatives and the initial results are introduced. In section 6 the methodology and development for scenarios are introduced and in section 7 the scenarios are applied to the model. Finally in section 8 and section 9 the final conclusions are made along with topics of discussion and general recommendations.

1.1 Research questions

The goal of this thesis is to gain insight into the environmental footprint of automated and manual storage solutions for small parts. To this end, the following research question is formulated:

What impact do storage systems for aviation standard parts have on the environmental performance of a warehouse?

To answer the main question, a set of sub-questions is formulated. The sub-questions are related to topics essential for answering the main research question.

- *SQ1: What storage systems are used for aviation standard parts?*

  This question is focused on identifying the storage systems that are relevant for aviation standard parts.

- *SQ2: What warehousing and distribution factors affect the environmental footprint of a storage system?*

  To identify the right elements to be considered when analysing the environmental performance of a storage system

- *SQ3: What are the storage system performance measures for an environmental assessment?*

  The metrics that can be used to evaluate the environmental performance of a storage system are found.

- *SQ4: How can an environmental assessment model be formulated for small part storage systems applicable to aviation standard parts?*

  The relationships between the previously mentioned elements and performance measures are elaborated on and a model is made to simulate these relationships.

- *SQ5:What new configurations of storage systems can be applied at an aerospace part distributor?*

  Based in the previously identified storage systems, this question aims to identify how other storage systems would be implemented at the considered case study.

- *SQ6: How do these configurations perform on the environmental performance measures compared to the current situation?*

  Evaluation of the previously mentioned configurations with the basic model developed with sub-question four.

- *SQ7: What external and internal factors influence the carbon footprint of storage systems?*

  The parameters resulting from this question will be used for the creation of scenarios to determine how the environmental footprint reacts to certain changes in metrics.

- *SQ8: What scenarios can be formulated based on external and internal factors?*

  Aimed at developing the right scenarios to analyse environmental performance of the storage configurations.

- *SQ9: How do the configurations of storage systems perform for the formulated scenarios?*

  Evaluation of the storage configurations' environmental performance for the different scenarios, allowing for conclusions to be made based on different internal and external factors affecting the carbon footprint.

1.2 Methodology

The methodologies used for this study are introduced here. A combination is used, first a literature review is done to gain insight in the available knowledge relevant to the topic, this is supplemented with expert consulting. Next a model is developed based on previously gained knowledge. With this model, the case study is performed using input from the studied company. Finally, scenario analysis is used to expand the results from the previous application and add to the value of the analysis.

1.2.1 Research

Literature is used to gain insight in the current knowledge with respect to warehouse storage systems and building energy consumption. The results are given in subsection 1.3, the knowledge gap for this research is introduced and the importance of the subject is elaborated on. The literature review is supplemented with expert consulting

1.2.2 Data analysis

For the case study, data needed for the application of the framework is collected from an aerospace service provider. Information on storage volume, picking activities, building characteristics and warehouse operations is important for the successful execution of the case study and for gaining reliable empirical evidence. Most case specific information is gained from databases available at the aerospace service provider, other knowledge is gathered by consultation with professionals present at the company.

1.2.3 Scenario analysis

After application of the model, scenarios are developed. This is done by first identifying important external and internal factors and applying a sensitivity analysis to these factors. Factors for which the results are concluded to be sensitive are used in scenario development. The scenarios developed will try to simulate real world possibilities as best as possible, while still trying to provide a wide spectrum of results.

1.3 Literature review

The literature review is performed on three different topics. The small parts storage systems for aviation standard parts are analyzed and described first in section 1.3.1. The methodologies available for calculating warehouse emissions are reviewed in section 1.3.2 and finally the warehousing operations in the aviation industry are reviewed in section 1.3.3.

1.3.1 Small part storage systems

With regard to small parts, storage solutions can be divided into two groups; picker-to-parts and parts-to-picker systems. Picker-to-parts systems are static and goods are stored in a fixed position, for instance in shelves or drawers. The employee is expected to head to the part for picking, resulting in a simple and inexpensive storage system. Examples of picker-to-parts systems are: Bin shelving, modular drawers and gravity flow racks (Smith, 1998; Sharp et al., 1991). Goetschalckx et al. (2002) provides a design procedure for evaluating warehouse performance using different static storage and picking technologies. In the article, two storage systems are analysed, namely bin shelving and modular drawers. Bin shelving is made up of a number of shelves along the aisles of the storage space, bins are located in the shelves for the storage of parts. Modular drawers consist of cabinets that, in turn, consist of horizontal drawers in which parts can be independently stored (Goetschalckx et al., 2002). The article provides a schematic for calculating efficiency and cost for either alternatives and proposes research into the efficiency and cost of part-to-picker systems.

Parts-to-picker systems are dynamic and goods are expected to be delivered to the picker, usually supported by an automatic system. These systems offer a higher space utilization, due to less room needed for picking activities and the utilization of vertical space. Examples of these systems are: Horizontal/vertical carousels, vertical lift modules and miniload AS/RS (automatic storage/retrieval system) (Daria et al., 2015). A VLM (vertical lift module) consist of a column with extractable trays, these trays are inserted/extracted by a device. The device travels up and down the column to offer a specific tray to the picker (Daria et al., 2015). Carousel systems are a series of bins on shelves that are rotated by a mechanism. Horizontal carousels rotate these shelves horizontally and vertical carousels vertically. A special form of the carousels is the rotary rack, this system can also move the shelves independent from each other (Foley, 2003). Miniload AS/RS consists of a deep storage rack with containers alongside the aisles. A storage and retrieval machine picks the necessary items and consolidates them on a conveyor (Lerher et al., 2014).

Most literature on storage systems consists of picking and product allocation studies for increasing efficiency and decreasing cost (Goetschalckx et al., 2002; Daria et al., 2015; Foley, 2003; Zaerpour et al., 2019; Khachatryan, 2006). Few articles are focused on energy consumption resulting from the automated systems, Lerher et al. (2014) contributes to this topic by formulating an energy efficient model for a miniload AS/RS. Meneghetti & Monti (2013), Meneghetti et al. (2015) and Meneghetti & Monti (2014) also focus on energy efficient storage assignment, operations and rack shape for automated storage systems. A stacker crane is considered and energy efficient storage strategies are recommended. The literature is lacking however, with respect to the resulting CO_2 emissions when switching from static storage to dynamic storage for small parts.

1.3.2 Warehouse carbon footprint mapping

To determine energy consumption of manual storage systems, the environmental footprint of a warehouse is used. Storage is a large part of warehouse space utilization and the emissions resulting from building characteristics are directly linked to storage space. In this section articles related to carbon footprint mapping in warehouses are reviewed.

Zajac (2011) considers energy consumption in warehouses and proposes a general strategy for calculating the energy consumption in these warehouses. The strategy is based on loading/unloading operations, heat exchange, material handling equipment and picking policy. The paper shows the economic benefit that this strategy can have on the equipment used to handle materials and warehouse layout as these can be optimized to lower energy consumption in a warehouse. This paper is however mostly focused on reducing energy consumption to save money and does not focus on the emissions and the trade off a green warehouses can have with profit. An integrated classification scheme for warehouse emissions is provided by Ries et al. (2017), considering warehouse operations with respect to energy consumption and material handling. Empirical data from warehouses in the US was used to analyse the four most common warehouse types. The types analyzed were block-pallet storage, wide aisle racking, narrow aisle racking and automated storage and retrieval systems. The classification scheme used allows researchers and managers to asses the emissions of warehouses, but is limited to a factorial analysis and does not integrate inventory decisions with respect to warehouse operations. Although the paper offers insight into sustainable options for material handling, research is heavily focused on building characteristics and energy consumption with respect to lighting, heating and air conditioning.

Wild (2021) proposes global standards for the calculation of carbon emissions in supply chains, especially with the introduction of the CSRD this is an important consideration. At the moment most standards for emissions calculation exist for specific regions or environments (supply chain characteristics, transportation modes etc) (Wild, 2021). The research provides a handy overview of metrics and reporting directives for the calculation of carbon output. Fichtinger et al. (2015) alternatively introduces a model that integrates inventory ans warehousing decisions to asses the environmental footprint of the warehouse and operations. Xin et al. (2019) takes a broader approach and analyzes factors that influence green warehousing, taking governmental, societal and financial factors into account. Xin et al. (2019) shows that a sustainability focus in warehousing is a more complex problem than can be expected. Lewczuk et al. (2021) actually analyses energy consumption for multiple warehouse layouts, from manual to fully automated. Only large scale pallet based variants are taken into account though, small parts storage is not considered. The paper does provide insight into the metrics and parameters needed to calculate building and operational energy consumption for different warehouse technologies. Tappia et al. (2015) also considers the environmental impact of automated warehousing and analyses the trade-offs made with respect to economical and environmental aspects for AS/RS and AVS/RS systems. Different storage and throughput capacities are analysed for environmental impact and compared.

1.3.3 Warehousing in the aviation industry

The aviation industry is a complex and and heavily regulated. Aircraft part manufacturers have to be certified for the specific part that they manufacture to demonstrate that the parts are manufactured according to the accepted procedures and materials (Mas et al., 2014). Certified manufacturers gain the OEM status, the same concept exist for the aftermarket services in the airline industry. Maintenance, repair and overhaul (MRO) can only be performed by certified companies (Rezaei Somarin et al., 2018). This limits decision making with respect to supplier choice as well as increasing workloads to and from the warehousing resulting from all the paperwork requirements. Standard parts are also an important part of the aviation supply chain, due to the complexity of parts, consisting of numerous smaller parts, standard parts are essential for the assembly of these parts.

Xue et al. (2020) states that due to the high volume and dependence of the standard parts in modern aviation, traditional logistics are not sufficient. The articles proposes an automatic storage and retrieval system (AS/RS) to cope with the requirements of aviation standard parts, showing that these parts do require an efficient and transparent logistic system. Li & Lu (2014) also reiterates that standard parts are complex due to the operating frequency and variation. An aircraft can contain as much as 800,000 standard parts and on top of that, standardization applies to all parts and increase the need for quality control (Li & Lu, 2014). Lan et al. (2021) explores precision sorting technology specific for aviation standard parts and states the importance of accurate picking for standard parts when assembling an aircraft.

1.3.4 Conclusion

As mentioned in subsubsection 1.3.1 literature is lacking when it comes to a direct comparison between static and dynamic storage solutions for small parts. Literature with respect to automated storage solutions is mostly focused on stacker cranes, the optimal storage policy and energy efficient operations. Insight into the environmental footprint when switching to and from manual and automated solutions can aid companies with the goal of decreasing emissions in a more and more environmentally focused society. This study aims at identifying environmental performance of different storage solutions for small parts. The results and model can aid companies in finding the right storage alternative based on carbon footprint.

1.4 Expert consulting

In this section the interviews performed are introduced as well as providing the benefits of performing these interviews.

1.4.1 Warehouse energy consumption

To gain a better understanding of case-specific warehouse metrics at the aerospace service provider, the SHEQ-manager is interviewed. Martin de Jong, manager responsible for safety, health and quality at the Hoofddorp location for the aerospace service provider is interviewed. This interview has helped to collect context data for the aerospace warehouse as well as providing insight to common practices with respect to warehouse building and operations. Also, the current difficulties and operations to determining carbon footprint are identified. subsection A.2 shows the full interview conducted with Martin de Jong.

1.4.2 Part-to-picker systems

Martijn Rijnbeek, the contact of the aerospace service provider at the storage system manufacturer, is interviewed. This interview provided in-depth information about the specific system present at the aerospace service provider. Information on different systems offered by this company is also collected as well as factors influencing power consumption. The full interview can be found in subsection A.3.

1.4.3 Aviation standard parts

To gain further knowledge on aviation standard parts, a program manager from the aerospace service provider is interviewed to gain knowledge on the requirements for standard part storage and retrieval. Also, the knowledge is used to gain a better understanding of the scale that standard part variety has for aircraft parts. The interview also provides insight into the processes involved in the warehouse and how the warehouse and storage systems are structured. subsection A.1 contains the full interview.

2 Small part storage systems

In this chapter the relevant storage solutions for small parts are determined and elaborated on. The systems are differentiated by the part-to-picker and picker-to-part characteristic.

2.1 Picker-to-part

As mentioned in subsubsection 1.3.1, these systems are static and are not automated. The picker is expected to go to the part for the picking operation. For small parts, not all picker-to-part systems are relevant, a pallet racking system for instance would not be very practical when storing bolts and screws. Relevant systems for small parts would be bin shelving, modular drawers and gravity flow racks (Khachatryan, 2006). These systems allow for bins in which small parts can be efficiently stored, more information on the specific system can be found in subsubsection 1.3.1. The general differences that can be identified for these systems is the space utilization. Modular drawers can fit a large amount of bins in a relatively small area, whereas bin shelving (theoretically) requires more space to store the same amount of items. This difference is compensated though by the low investment costs related to bin shelving compared to modular drawers (Goetschalckx et al., 2002). Lastly, gravity flow racks are a special type of shelving where the shelves are tilted to move cases forward with rollers. This way only one case of a product has to be on the pick face and the rest of the cases can be stored in the back of the shelves. This increases the storage density and allows for less space used for storage. The case have to be replenished form the back of the racks meaning that it never interferes with the picking operation, however additional space needs to be reserved at the back of the racks. The gravity flow rack is definitely more space efficient than bin shelving, however the investment costs are relatively high (Bartholdi & Hackman, 2014).

Figure 2: Bin shelving unit (Retrieved from *India-mart.com)*

Figure 3: Modular drawer unit (Retrieved from *Fas-tenal.com)*

2.2 Part-to-picker

Part-to-picker systems are dynamic systems in which the part is moved to the picker. The picker no longer has to move to a location for a part and parts are picked with higher accuracy due to the automatic character involved in the picking operation (Lan et al., 2021). Daria et al. (2015) introduces the relevant part-to-picker systems currently in use, these are: Horizontal/vertical carousels, vertical lift modules and miniload AS/RS. Each of these systems has their own characteristics and functioning. The carousel systems contain bins connected to shelves that rotate either horizontally or vertically. The vertical lift system is essentially an automated device that picks the correct tray from a stack of trays connected to a column. Finally, the miniload AS/RS is an automated picking device able to pick trays from a rack and place them on a conveyor (Daria et al., 2015). subsubsection 1.3.1 provides more information on the different automated storage systems.

Figure 4: Vertical lift module (Retrieved from *kardex-remstar.be)*

Figure 5: Vertical carousel (Retrieved from *autoscanuk.co.uk)*

Figure 6: Vertical lift module (Retrieved from *mhi.org)*

Figure 7: Miniload AS/RS (Retrieved from *gie-icom.com)*

The horizontal carousel cannot exceed the average human reach height as the picker has to be able to reach the top bin, the VLM, vertical carousels and miniload however can make use of the vertical dimension. This leads to a lower space utilization for the horizontal carousel compared to the other systems. The vertical carousel is comparable to the vertical lift module with an exception being that the load moved with each operation is higher as all bins have to be moved simultaneously. Due to this character, the carousels are not considered in the model as these are expected to have a substantially lower environmental performance.

3 Environmental performance measures

Performance indicators are used to determine the environmental aspect of storage systems. The measures are found from the literature introduced in subsubsection 1.3.2. As mentioned by Fichtinger et al. (2015) and Ries et al. (2017), warehouse emissions are based on three factors. Warehouse size, including lighting and climate requirements, and mobile/fixed material handling. Based on these three factors the environmental performance measures can be identified for storage systems.

3.1 Space requirement

Each storage system has a specific space utilization factor, due to each system having different bin volumes and densities. An important factor when determining environmental performance for warehouses is the size and storage systems determine, for the most part, the size requirement of a warehouse. Therefore the space required when using a certain type of storage system is considered an environmental performance measure as this determines the energy requirements from lighting and HVAC. Although, space requirement also determines the amount of materials and land required for the warehouse building and in that sense has an even greater influence on environmental performance.

3.2 Carbon footprint

Material handling, either fixed or mobile, is the second and third factor identified by the literature. The use of electricity produces CO_2 and therefore the carbon emissions from energy consumption are considered. In the case of the considered storage systems this would entail all energy consumption resulting from storage, transport and picking. For picker-to-part systems this would be determined by the transport equipment, routing policy and pick intensity. For part-to-picker systems, all operational and idle power consumption needs to be considered.

Warehouse building equipment is also included in this measure, the space requirement determines the warehouse size but the specific equipment used for lighting and isolation determines the energy requirement. Therefore this measure considers all material handling activities as well as carbon emissions resulting from energy consumption from lighting and HVAC.

3.3 Conclusion

Sub-question two states: *What warehousing and distribution factors affect the environmental footprint of a storage system?* From the literature these factors are identified as being the warehouse size and accompanying requirements for lighting and HVAC, mobile material handling and fixed material handling.

Sub-question three states: *What are the storage system performance measures for an environmental assessment?* As identified by the literature this question can be answered with the following two measures; First, the specific space requirement of a storage system for a certain storage volume. Secondly, the total energy requirement from material handling, lighting and HVAC.

4 Environmental assessment model

In this chapter the methodology for determining the environmental footprint of the storage solutions is elaborated on. The methodology shown is generally applicable to determine the environmental footprint of manual picking solutions as it is based on warehouse emissions resulting from space utilization.

4.1 Picker-to-part

It is assumed that picker-to-part solutions do not use transport to and form parts and only warehouse building emissions are relevant for the environmental footprint. Fichtinger et al. (2015) determines the warehouse footprint using four factors; lighting energy, HVAC (Heating, ventilation and air conditioning), FMHE (Fixed material handling equipment) and MMHE (Mobile material handling equipment). FMHE refers to conveyor belts or other equipment used in material handling that is static, whereas MMHE refers to forklifts or AGVs, equipment that can move around. In the case of the part-to-picker solutions discussed in this thesis neither of these factors is applicable. Therefore the environmental footprint of the part-to-picker solutions is determined by the space requirements, lighting equipment, lighting intensity, heating and cooling.

4.1.1 Space requirements

To determine the space requirements of the storage system, the continuous model introduced by Bodner & Govindaraj (2002) is used. Here the number of bins or drawers is determined by the aggregate volume of the parts that need storing. This model is also called the fluid model because the storage volume is modelled as a fluid. The amount of units is determined by dividing the storage volume by the unit capacity. Next the number of units per aisle is determined. This is done by calculating the number of units possible per aisle based on aisle length and unit size. Finally, the number of aisles is determined by rounding up the number of aisles needed to allow for sufficient units. It is assumed that all aisles have the same dimensions. For bin shelving the shelf width is determined by the bin size and the total space requirements results from the surface of the aisles and shelves. The modular drawer width is determined by the drawer depth, the total space requirement results from the aisle surface and the surface of the modular drawers.

$$A_{total} = 2 \cdot (n_a \cdot L_a \cdot d_s) + L_a \cdot W_a \cdot n_a \tag{1}$$

Where:
A_{total} = Total space requirement (m^2)
n_a = Number of required aisles
L_a = Aisle length (m)
d_s = Storage depth (m)
W_a = Aisle width (m)

The aisle length and width are determined based on the dimensions of the warehouse and the required space for pickers walking through the aisles. The storage depth is determined based on the bin dimensions and the storage system used. Bin shelving requires access to the picking face for each bin, therefore storage depth is determined by the bin length (Goetschalckx et al., 2002). For modular drawers, the storage depth is determined by the dimensions of the drawers. The surface area for storage is thus determined by the amount of aisles divided by two, because each aisle can contain two sides of storage racks. The total aisle surface is then added to reach the total required surface area. To determine the required amount of aisles the following formula is used:

$$n_a = \left\lceil \frac{\frac{V_s}{V_b}}{2 \cdot \rho_a \cdot L_a} \right\rceil \tag{2}$$

Where:

V_s = Storage volume to be stored(m^3)
V_b = Bin volume (m^3)
ρ_a = Aisle bin density (bin/m)

L_a = Aisle length (m)

The bin density is dependent on the type of storage used, modular drawers have a higher bin density than bin shelving as more bins can be fitted into the drawers. The exact bin density can be determined with the dimensions of the bins and drawers/shelves used. The storage volume to be stored is case specific and can be seen as input to the model.

4.1.2 Lighting

The lighting requirements in the warehouse are determined by first evaluating the required illumination for the activities that have to be performed. Small parts order picking is a precise activity and requires ample illumination due to the visual tasks involved. Ries et al. (2017) recommends at least 300 lux for traditional warehousing. To find the energy consumption resulting from lighting, the lumen method is used. The lumen method determines the amount of luminaries needed based on the lux requirements, room dimensions and luminary characteristics. Muhamad et al. (2010) describes the formula for the Lumen method as follows:

$$N = \frac{A \cdot E}{F \cdot n \cdot MF \cdot UF} \tag{3}$$

Where:

N = Number of luminaries required
A = Surface area to illuminate (m^2)
E = Required lux (lx)
F = Initial lamp lumen (lm)
n = lamps per luminary
MF = Maintenance factor
UF = Utilization factor

The number of lamps per luminary and the initial lumen are dependent on the chosen lighting equipment. The utilization factor is the ratio between the lumen that reaches the surface area and the lumen output of the lamp. This factor is given by the manufacturer for standard conditions. To determine the UF for varying situations the reflectance of the walls, roof and floor are needed, as well as the room index. RI (room index) is a ratio that shows how the height of a building compares to the length and width. The formula for RI is as follows:

$$RI = (L \cdot W)/(H \cdot (L + W)) \tag{4}$$

From here the reflectance of walls, the floor and the roof is needed, this is dependant of the colour and paint present on each surface. The relation between reflectance and the UF is shown in Table 1, the reflectance values for ceiling, walls and roofs combined with the room index result in a value for the utilization factor.

Table 1: Utilization factor table for lighting (Muhamad et al., 2010)

Utilization factor											
Room Reflectance			**Room Index**								
Ceiling	**Wall**	**Floor**	**0.75**	**1**	**1.25**	**1.5**	**2**	**2.5**	**3**	**4**	**5**
0.7	0.5	0.2	0.43	0.49	0.55	0.6	0.66	0.71	0.75	0.8	0.83
0.7	0.3	0.2	0.35	0.41	0.47	0.52	0.59	0.65	0.69	0.75	0.78
0.7	0.1	0.2	0.29	0.35	0.41	0.46	0.53	0.59	0.63	0.7	0.74
0.5	0.5	0.2	0.38	0.44	0.49	0.53	0.59	0.63	0.66	0.7	0.73
0.5	0.3	0.2	0.31	0.37	0.42	0.46	0.53	0.58	0.61	0.66	0.7
0.5	0.1	0.2	0.27	0.32	0.37	0.41	0.48	0.53	0.57	0.62	0.66
0.3	0.5	0.2	0.3	0.37	0.41	0.45	0.52	0.57	0.6	0.65	0.69
0.3	0.3	0.2	0.28	0.33	0.38	0.41	0.47	0.51	0.54	0.59	0.62
0.3	0.1	0.2	0.24	0.29	0.34	0.37	0.43	0.48	0.51	0.56	0.59
0	0	0	0.19	0.23	0.27	0.3	0.35	0.39	0.42	0.46	0.48

The maintenance factor determines the decrease in light output resulting from aging or pollution, an MF of 0,8 can be assumed as a rule of thumb (Parmar, 2020).

To determine the energy consumption of lighting the kWh of the luminaries is needed. This can be found with the hours of active lighting per day and the lighting characteristics. LED lamps are for instance more efficient than fluorescent tubes with higher lux production at a lower wattage. Due to losing less power to heat LED lamps can be up to 80% more efficient. In Appendix C example calculations are given.

4.1.3 HVAC

To determine energy requirements for heating and cooling, the degree days method is used. This method measures the amount of days and degrees that the mean external temperature differs from the desired internal temperature. For instance, if the desired temperature is $25°C$ and the mean external temperature of that day is $20°C$ this would result in five degree-days (Christenson et al., 2006). The degree days method differentiates between cooling degree days and heating degree days, as these can have different energy requirements. Equation 5 shows the formula for determining the heating degree days.

$$HDD(\theta_d, \theta_e) = x_k \sum_{k=1}^{n} (\theta_d - \theta_e) \tag{5}$$

$$x_k = \begin{cases} 1 & if \quad \theta_e \leq \theta_b \\ 0 & otherwise \end{cases} \tag{6}$$

θ_d gives the threshold temperature for heating, θ_e indicates the external temperature and k stands for the days in the year.x_k is a binary variable that indicates when heating is needed and prevents negative degree days. This same method can be used for cooling degree days as shown in Equation 7. Here the threshold temperature is subtracted from the external temperature to indicate the amount of degrees to cool.

$$CDD(\theta_d, \theta_e) = y_k \sum_{k=1}^{n} (\theta_e - \theta_d) \tag{7}$$

$$y_k = \begin{cases} 1 & if \quad \theta_e \geq \theta_b \\ 0 & otherwise \end{cases} \tag{8}$$

Degree days indicate the amount and duration of heating/cooling needed. To determine energy consumption from this metric the heat loss coefficient is needed. This is influenced by the materials used for the walls and roof of the warehouse. The heat loss coefficient indicates the heat transfer occurring between the inside and outside climate and is formulated as watt per squared meter Celsius ($W/m^2\,°C$), where square meter is based on the wall and roof surface area. This can be determined using specific isolation materials present in the wall and ceiling, along with the amount of windows and their U-values. Using this factor, the amount of degree days can be used to formulate the kWh requirement for heating and cooling.

$$E_{HVAC} = (HDD + CDD) \cdot h \cdot A_w \cdot 24/1000 \tag{9}$$

Where:

E = HVAC annual energy consumption(kWh)
h = Heat loss coefficient ($W/m^2\,°C$)
A_w = Wall and roof surface area (m^2)

Degree days indicate the amount and duration of heating/cooling needed. To determine energy consumption from this metric the heat loss coefficient is needed. This is influenced by the materials used for the walls in the warehouse. The heat loss coefficient indicates the heat transfer occurring between the inside and outside climate and is formulated as watt per squared meter kelvin (W/m^2K), where square meter is based on the wall surface. Using this factor, the amount of degree days can be used to formulate the kWh requirement for heating and cooling.

4.2 Part-to-picker

In this chapter the environmental assessment model is extended to the part-to-picker systems chosen in section 2. The model will address determination of space requirement and the operational and idle power consumption metrics for each system.

4.2.1 Space requirement VLM

To determine the specific space requirement for each system certain parameters for the specific configuration have to be known. The total storage volume can then be related to the storage volume of a module. For the miniload AS/RS this would be the total storage volume of one rack, which is also dependent on the desired aisle length and warehouse height. The VLM dimensions are not dependent on desired aisle length.

Table 2: Parameters for determining the space requirement for VLMs

Parameter	Description	Unit
V_s	Shelf volume	m^3
H_v	Buidling height	m
L_v	Module length	m
W_v	Module width	m
ρ_v	Module shelf density	$shelves/meter$
L_{pf}	Length pick face	m

The parameters required for determination of the total area for VLMs are mostly aimed at the dimensions of the VLM and the internal shelves. With these factors the storage volume per module can be calculated and along with the dimensions of the modules, the total required area can be determined. it is assumed that half a meter of space is left between the top of the module and the warehouse ceiling. This leaves sufficient room for any electrical wiring or tubes. The following variables result from calculation of the surface area.

Table 3: Variables for calculating the space requirement for VLMs

Variable	Description	unit
S_v	VLM storage volume	m^3
n_v	Amount of VLMs	#
$L_{v,total}$	Total length of configuration	m
$W_{v,total}$	Total width of configuration	m
$A_{v,total}$	VLM total space requirement	m^2

The following equations show how the total space requirement is determined for the VLM. It is assumed that the VLMs are placed directly next to each other with the pick faces in the same direction. n_v is rounded up to the nearest positive integer in this case because only whole VLMs can be placed.

$$S_v = v_s \cdot H_v \cdot \rho_v \tag{10}$$

$$n_v = \frac{S}{S_v} \tag{11}$$

$$L_{v,total} = L_v + L_{pf} \tag{12}$$

$$W_{v,total} = W_v \cdot n_v \tag{13}$$

$$A_{v,total} = L_{v,total} \cdot W_{v,total} \tag{14}$$

$$\tag{15}$$

First the total storage volume per module is found by multiplying height and shelf density with the volume per shelf. Then the amount of VLMs can be determined by rounding up the fraction of the total storage volume and storage volume per module. The total length of the configuration is found by taking the length of a module and adding the total length required for the pick face. Now the total area can be calculated by multiplying the width of all modules by the total length of the configuration.

4.3 Space requirement miniload AS/RS

The method for the miniload follows a similar structure as for manual storage system. The system is basically a large rack with bins, where enough room in the aisle must be available for the extractor to move perpendicular to the rack. The following parameters are used in the calculation model for space requirement of a miniload AS/RS

Table 4: Parameters for determining the space requirement for miniload AS/RS

Parameter	Description	Unit
V_b	Bin volume	m^3
ρ_m	Bin density	$bins/m^2$
H	Building height	m
L_a	Desired aisle length	m
W_a	Desired aisle width	m
W_m	Miniload width	m
L_{pf}	Length of the pick face	m

Bin volume, bin density, aisle width and aisle length will be used in the same manner as in subsubsection 4.1.1 where the total storage volume of a rack is determined based on these factors. For the miniload however, building height also plays an important role. The vertical dimension can be used in this case and it is assumed that half a meter of space is left between the top of the rack and the warehouse ceiling. This leaves sufficient room for any electrical wiring or tubes. Once again, sufficient room should be available at the pick face to collect parts from the bins, therefore the length of the pick face is taken into account. Based on these parameters and the model, the following variables result from the calculation of space requirement.

Table 5: Variables for calculating the space requirement for miniload AS/RS

Variable	Description	unit
S_v	Miniload AS/RS rack storage volume	m^3
n_v	Amount of miniload AS/RS racks	
$L_{m,total}$	Total length of configuration	m
$W_{m,total}$	Total width of configuration	m
$A_{m,total}$	Miniload AS/RS total space requirement	m^2

The rack storage volume relates to the total storage volume of a single rack and there are two racks present in each aisle. The width of the system is based on the width of a rack and the desired aisle width, with a full aisle containing two racks and the aisle itself. The following variables show how the total required area is determined for the miniload AS/RS.

$$S_v = L_a \cdot H \cdot \rho_m \tag{16}$$

$$n_v = \frac{S}{S_v} \tag{17}$$

$$L_{m,total} = L_a + L_{pf} \tag{18}$$

$$W_{m,total} = n_v \cdot W_m + \frac{1}{2} \cdot n_v \cdot W_a \tag{19}$$

$$A_{m,total} = L_{m,total} \cdot W_{v,total} \tag{20}$$

$$\tag{21}$$

The first three equations follow a familiar structure compared to the VLM and Manual space requirement calculations. The width of the system however is now determined by the total amount of racks and their specific width as well as the aisle space required for each rack. As two racks can be placed on either side of an aisle, a single rack only requires half of the empty aisle space. Therefore the aisle width is multiplied by this factor to gain the total system width. Once again the total area of the system is determined by multiplying the total length and width.

4.3.1 Power consumption VLM

All systems perform a certain cycle for a picking activity. The energy consumed during this cycle determines the operational energy consumption of the automated system. This factor is dependant on the mass moved during the cycle, the acceleration and the maximum velocity of the extractor. In the case of a VLM and a miniload AS/RS, only the bins/shelves that contain the item to be picked are moved. Equation 22 shows the general method for calculating operational energy requirement for these systems.

$$E_o = \eta \cdot P \cdot t_{cycle} \cdot n_c \tag{22}$$

Where:
E_o = Operational Energy consumption
η = Motor efficiency
P = Work during cycle
t_{cycle} = Mean cycle time
n_c = yearly amount of cycles

The work during cycle and the mean cycle time are challenging to determine however and can not simply be observed. As mentioned previously, many factors influence the work required for a certain movement. Factors such as mass, speed, acceleration and distance are important for measuring the work required during a cycle. A VLM cycle consists of three phases in two parts. Firstly, the extractor heads towards the pick face with the shelf in acceleration, constant velocity and deceleration. Then the pick job is performed and the shelf has to be returned to its origin. The extractor takes the shelf back in acceleration, constant velocity and deceleration. Based on the three phases as well as the metrics required for calculating work, Table 6 shows the parameters necessary for calculating the energy requirement of a vertical lift module.

Table 6: Parameters for calculating the operational energy consumption of VLM

Parameter	Description	Unit
m	Shelf weight	kg
v	Extractor speed	m/s
a	Extractor acceleration	m/s^2
m_e	Extractor weight	kg
g	Acceleration due to gravity	m/s^2
H	Building height	m
H_p	Height of the pick face	m
η	Motor efficiency	$\%$
n_p	Yearly amount of picks	$\#/year$
E_s	Stand-by power consumption	W

As mentioned previously, the mass moved, speed and acceleration are needed in order to continue calculations. To find the mean distance travelled per cycle, the total module height is needed as well as the height of the pick face. Finally, movement is powered by a motor which never offers 100% of the energy that it produces. Table 7 shows the variables that result from operational energy calculations.

Table 7: Variables for calculating the operational energy consumption of VLM

Variable	Description	unit
$s_{average}$	Average distance travelled per cycle	m
t_a	Time per acceleration/deceleration	s
t_c	Cycle time at constant speed	s
s_a	Acceleration/deceleration distance per cycle	m
s_c	Cycle distance at constant speed	m
t_{cycle}	Total duration of a full cycle	s
P_c	Work required for constant velocity	W
P_a	Work required for acceleration and deceleration	W
P_{cycle}	Work required during a cycle	W
E_o	Yearly operational energy consumption	kWh
E	Total yearly energy consumption	kWh
t_{active}	Active hours per year	h

Along with the variables a schematic of a VLM is provided in Figure 8. The rest of the section provides the step-wise methodology to calculating the yearly energy requirement of the VLM system.

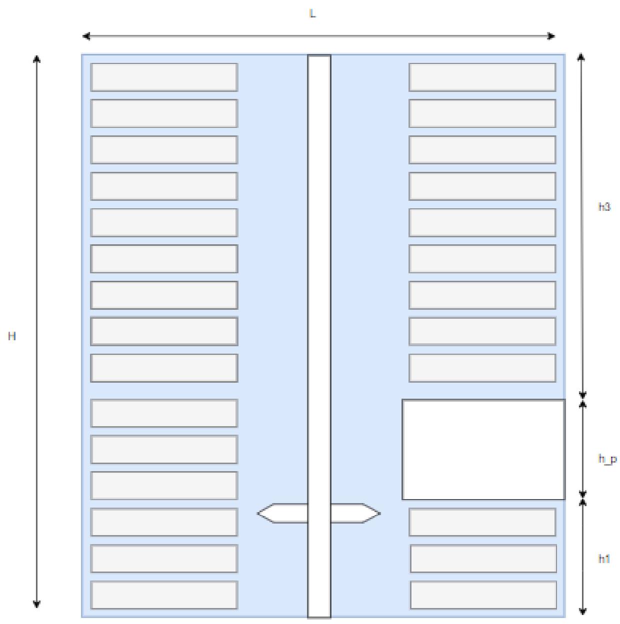

Figure 8: Schematic figure of a VLM

First the average distance that the extractor travels per picking order is determined. The extractor moves to the shelf and continues to the pick face with the extractor. As can be seen in Figure 8 there are two columns of shelves present in the VLM. To determine the average distance that the extractor moves per cycle, the height of the module and the pick face are used. The average distance travelled by the extractor is expressed as the distance at which exactly half of the shelves can be reached. The total height of the module contains two columns of shelves, with the exception being at the pick face. Here only one column of shelves is present. Therefore, twice the height of the VLM accounts for the total height of the shelves minus H_p as there are no columns present here. The average distance travelled can then be found by dividing this factor by two. In the case of random storage assignment the resulting value is the average distance travelled by the extractor.

$$s_{average} = \frac{2H - H_p}{2} \tag{23}$$

As mentioned in Table 6 the speed and acceleration of the extractor are known. Therefore the time and distance of each state per cycle is determined from the relation between speed, acceleration, time and distance. The following equations are used.

$$t_a = v/a \tag{24}$$

$$s_a = \frac{1}{2} \cdot a \cdot t_a^2 \tag{25}$$

$$s_c = s_{average} - 2 \cdot s_a \tag{26}$$

$$t_c = \frac{2 \cdot s_c}{v} \tag{27}$$

$$t_{cycle} = 2 \cdot t_c + 4 \cdot t_a \tag{28}$$

The time spent in acceleration/deceleration is determined by dividing the speed by the acceleration/deceleration of the extractor. Following, the distance travelled in acceleration/deceleration can be determined. $s_{average}$ is the average distance travelled per upwards/downwards movement of extracting a shelf, the distance travelled per acceleration and deceleration is subtracted from $s_{average}$ to determine the distance travelled at constant speed. From this, the time spent at constant velocity per cycle can be determined. Using the relationship $P = m * a * v$ the energy consumption per cycle can now be determined. The forces are determined by the interaction of the extractor, the mass moved, the desired acceleration and the gravitational acceleration. Three states are identified; acceleration, deceleration and constant velocity. The extractor experiences the three states when moving down from picking up the shelf and once again when moving back up to return the shelf. General force analysis leads to the following set of equations for determining the required work during a cycle.

$$P_a = v \cdot (m + m_e) \cdot (g - a) \tag{29}$$

$$P_d = v \cdot (m + m_e) \cdot (g + a) \tag{30}$$

$$P_c = v \cdot g \cdot (m + m_e) \tag{31}$$

$$P_{cycle} = \sqrt{\frac{P_a^2 \cdot t_a + P_c^2 \cdot t_c + P_d^2 \cdot t_a}{2 \cdot t_a + t_c}} \tag{32}$$

The forces applied per cycle are deduced from acceleration and gravity acting on the extractor. Following this, the work for each state can be calculated.The work per cycle can be determined by relating the work for each state with the total time spent in a state during the cycle, Rajković et al. (2019) introduced an equation for calculating the operational energy requirement in this manner. Finally, the energy consumption is found by multiplying work with the duration over which the work is performed.

$$t_{active} = \frac{t_{cycle} \cdot n_p}{3600} \tag{33}$$

$$E_o = \frac{\eta \cdot t_{active} \cdot P_{cycle}}{1000} \tag{34}$$

$$E = \frac{24 \cdot 365 \cdot E_s + E_o}{1000} \tag{35}$$

(36)

The operational energy consumption is extended with the stand-by energy consumption, which is applied for each hour in the year. The storage systems are never fully shutdown and are therefore in stand-by mode during the full year. During operation the electric requirements, active in stand-by mode, will still be active and therefore are also applied during operational hours (Patrão et al., 2010). The VLM has a built in conditioning unit, to regulate the internal temperature. To address this the conditioning power consumption is calculated by only taking the internal volume of the VLMs, so the extra space required for picking is not included.

4.3.2 Power consumption miniload AS/RS

The operational power consumption of the miniload is determined in a comparable fashion. The extractor speed and acceleration are related to the distance and mass moved. The work during a cycle is calculated and energy requirement is found by multiplying this by the active hours of the storage system. Table 8 shows the input parameters used for the operational power model of the miniload AS/RS.

Table 8: Parameters for calculating the operational energy consumption of miniload AS/RS

Parameter	Description	Unit
m	Bin average load	kg
v_x	Extractor horizontal velocity	m/s
v_y	Extractor vertical velocity	m/s
a_x	Extractor horizontal acceleration	m/s^2
a_y	Extractor vertical acceleration	m/s^2
m_e	Vertical extractor weight	kg
$m_{x,e}$	Horizontal extractor weight	kg
p	Picks per year	#
η	Motor efficiency	%
E_s	Stand-by power consumption	W
g	Acceleration due to gravity	m/s^2
μ	Horizontal friction coefficient	$-$

The miniload AS/RS differs from the VLM in multiple areas. The horizontal movement of the miniload is taken into account adding to the work required per cycle. The column to which the extractor is connected travels horizontally with each picking activity where this is required. This extractor has a certain weight and a friction coefficient from interacting with the surface it moves on.

Table 9: Variables for calculating the operational energy consumption of Miniload AS/RS

Variable	Description	unit
$s_{x,average}$	Average horizontal distance travelled per cycle	m
$s_{y,average}$	Average vertical distance travelled per cycle	m
$s_{x,c}$	Horizontal distance at constant velocity per cycle	m
$s_{y,c}$	Vertical distance at constant velocity per cycle	m
$s_{x,a}$	Horizontal distance at acceleration/deceleration per cycle	m
$s_{y,a}$	Vertical distance at acceleration/deceleration per cycle	m
$t_{x,a}$	Time in horizontal acceleration/deceleration per cycle	s
$t_{y,a}$	Time in vertical acceleration/deceleration per cycle	s
$t_{x,c}$	Time in horizontal constant velocity per cycle	s
$t_{y,c}$	Time in vertical constant velocity per cycle	s
t_{cycle}	Total duration of a full cycle	s
$P_{x,a}$	Work required for horizontal acceleration/deceleration	W
$P_{x,c}$	Work required at horizontal constant velocity	W
P_x	Horizontal work required during cycle	W
$P_{y,a}$	Work required for vertical acceleration	W
$P_{y,d}$	Work required for vertical deceleration	W
$P_{y,c}$	Work required for constant velocity	W
P_y	Vertical work required during cycle	W
P_{cycle}	Work required during cycle	W
t_{active}	Annual active hours	h
E_o	Operational energy consumption	W
E	Total yearly energy consumption	kWh

The variables in the model relate to the relationships between speed, acceleration, time and distance for the vertical and horizontal dimensions. From these relationships the work required van be determined for each of the three states previously identified. To determine the total yearly operational energy requirement of the miniload AS/RS the work during a cycle is multiplied by the total active hours in a year. A scematic of a miniload AS/RS is provided in Figure 9.

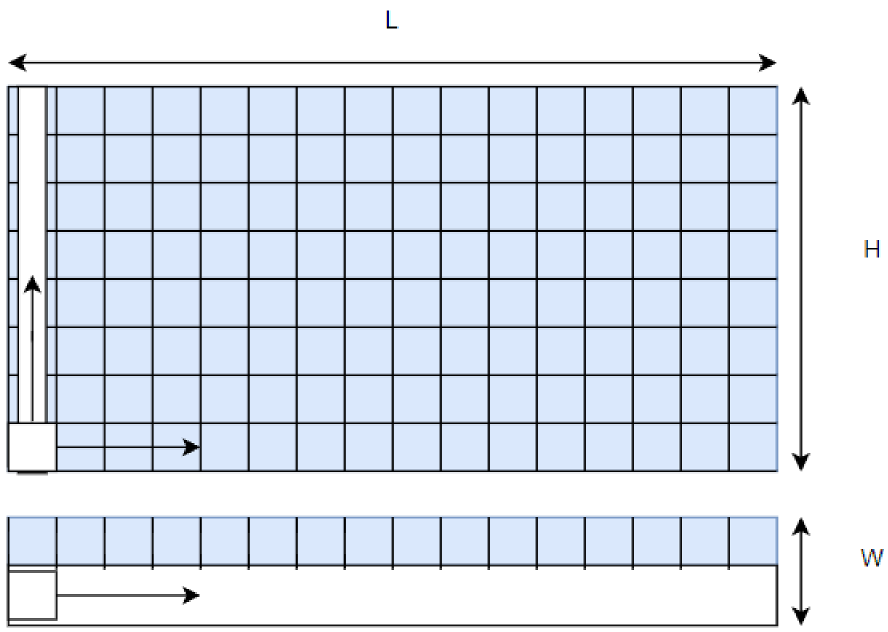

Figure 9: Schematic of a Miniload AS/RS with a side-view (top) and a birds-eye view (bottom)

The following equations show how the time and distance for each state is determined for the vertical and horizontal dimensions.

$$s_{x,average} = \frac{1}{2} \cdot L \tag{37}$$
$$t_{x,a} = \frac{v_x}{a_x} \tag{38}$$
$$s_{x,a} = \frac{1}{2} \cdot a \cdot t_{x,a}^2 \tag{39}$$
$$s_{x,c} = s_{x,average} - 2 \cdot s_{x,a} \tag{40}$$
$$t_{x,c} = \frac{s_{x,c}}{v_x} \tag{41}$$

$$s_{y,average} = \frac{1}{2} \cdot H \tag{42}$$
$$t_{y,a} = \frac{v_y}{a_y} \tag{43}$$
$$s_{y,a} = \frac{1}{2} \cdot a \cdot t_{y,a}^2 \tag{44}$$
$$s_{y,c} = s_{x,average} - 2 \cdot sx, a \tag{45}$$
$$t_{y,c} = \frac{s_{y,c}}{v_y} \tag{46}$$

$$t_{cycle} = MAX(4 \cdot t_{y,a} + 2 \cdot t_{y,c}; 4 \cdot t_{x,a} + 2 \cdot t_{x,c}) \tag{47}$$

The total cycle time is determined by the longest duration with respect to the horizontal and vertical movement of the extractor. Therefore the total cycle time is the highest value with respect to the vertical and horizontal cycle time.

From here the work required per state is calculated with the same methodology used for the VLM. However, the mass of the horizontal extractor and the specific friction coefficient are included in the calculation for the work required for horizontal movements.

$$P_{x.a} = v_x \cdot ((m + m_e) \cdot a_x + (m + m_e) \cdot \mu) \tag{48}$$
$$P_{x,c} = v_x \cdot (m + m_e + m_{e,x}) \cdot \mu \tag{49}$$
$$P_{y,a} = v_y \cdot (m + m_e) \cdot (g + a_y) \tag{50}$$
$$P_{y,d} = v_y \cdot (m + m_e) \cdot (g - a_y) \tag{51}$$
$$P_{y,c} = v \cdot (m + m_e) \cdot g \tag{52}$$
$$P_x = \sqrt{\frac{2 \cdot P_{x,a}^2 \cdot t_{x,a} + P_{x,c}^2 \cdot t_{x,c}}{2 \cdot t_{x,a} + t_{x,c}}} \tag{53}$$
$$P_y = \sqrt{\frac{2 \cdot P_{y,a}^2 \cdot t_{y,a} + P_{y,c}^2 \cdot t_{y,c}}{2 \cdot t_{y,a} + t_{y,c}}} \tag{54}$$
$$P_{cycle} = P_x + P_y \tag{55}$$

The work required for each state in both dimensions is determined and the equation provided by Rajković et al. (2019) is used to relate the work in a specific state to the related time in that state. P_y returns the total work required for all vertical movements in a cycle, where P_x returns the similar value for horizontal movements. The total work required during a cycle is determined as the sum of the horizontal and vertical work. The total operational energy requirement can be found by multiplying the work per cycle with the cycle time and the cycles per year.

$$t_{active} = \frac{t_{cycle} \cdot n_p}{3600} \tag{56}$$
$$E_o = \frac{\eta \cdot t_{active} \cdot P_{cycle}}{1000} \tag{57}$$
$$E = \frac{24 \cdot 365 \cdot E_s + E_o}{1000} \tag{58}$$
$$\tag{59}$$

The total energy consumption is determined by adding the stand-by and operational energy consumption for a year. The stand-by power consumption is assumed to exert power at any given moment because, as mentioned previously, these machines are never fully turned off.

4.4 Conclusion

Sub-question four states: *How can an environmental assessment model be formulated for small part storage systems applicable to aviation standard parts?* This section provides an environmental assessment model based on three factors; Lighting energy consumption, HVAC energy consumption and material handling energy consumption. Based on the storage system characteristics and specific context factors, the total space requirement of a storage system can be determined. The literature provides methods of calculating the lighting and HVAC energy consumption based on the space requirement and the specific lighting and temperature factors present at the considered location. The assessment model shows how these methods can be used in a general fashion and provides a structured model for determination of energy consumption from lighting and HVAC.

Material handling is broken up into two factors, idle and operational energy consumption. According to the specific operational characteristics of the storage system, the model offers a method of calculating the total yearly operational energy requirement. Based on the system specifics, the mechanical work of the system is transformed into operational energy consumption. Idle energy consumption is considered input to the model and is applied throughout the year. The resulting model is able to determine the total yearly energy consumption of VLMs and a miniload AS/RS. The model has been developed and Appendix C applies the environmental assessment model to the introduced case study.

5 Case study application

The different storage systems are compared to the current storage system present at the case study and is based on total space requirement, yearly CO2 emissions and financial factors to add value to the analysis. Operational and investment cost is taken into account for the different systems. Operational cost is determined based on energy and rent cost. Investment cost is based on the cost for bin-shelving units and the cost of the specific VLM and miniload AS/RS configurations. The exact metrics used and applied to the model and information regarding the case study can be found in Appendix B and Appendix C.

The resulting investment cost is determined by relating the meters of bin-shelving, amount of VLMs and miniload racks with their respective cost. Operational costs are related to total electrical and gas energy use as well as total space requirement and warehouse rent cost. Figure 10 shows the comparison of the alternative configurations compared to the current situation for total space requirement, CO_2 emissions, investment cost and operational cost.

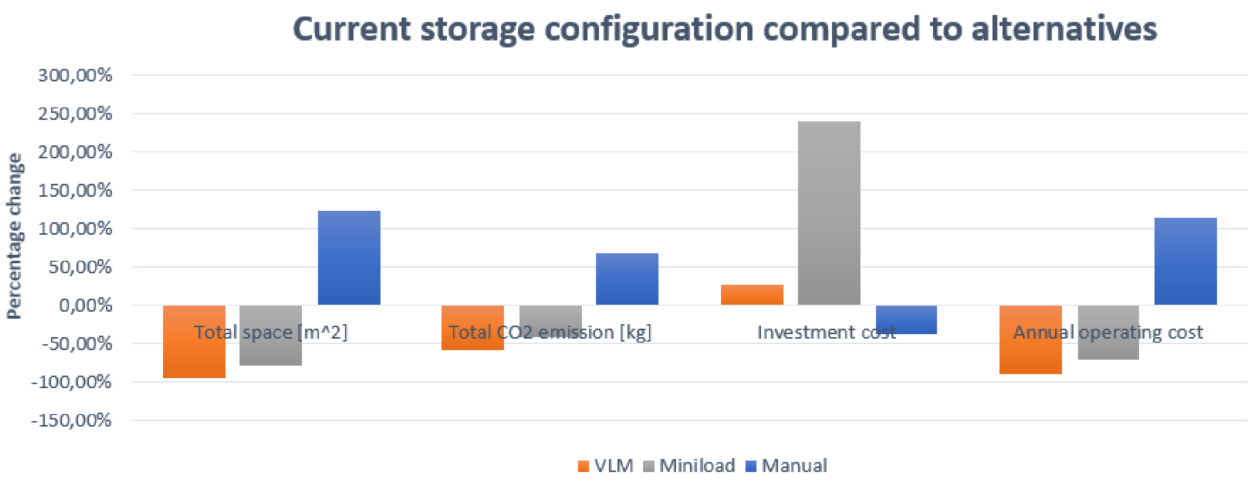

Figure 10: Comparison of current storage configuration and the considered alternatives

The analysis of the different storage configurations shows that the part-to-picker systems do in fact perform better on the environmental performance measures identified in section 3. Due to a lower space requirement, lighting and HVAC energy consumption is substantially reduced. When comparing operational and idle energy consumption of the part-to-picker systems to the energy consumption for lighting and HVAC it becomes clear that the latter accounts for a larger portion of total energy requirement for storage systems. On top of increasing environmental performance, part-to-picker systems also decrease operational costs as a result of decreased warehouse rent and energy costs.

The manual storage system performs substantially worse than the current storage configuration on yearly savings, indicating that even partially investing in a part-to-picker system can be beneficial to financial performance. The investment cost is however the largest drawback. Although the operational cost of part-to-picker systems is lower, the investment cost for a miniload AS/RS would take over fifteen years to recuperate when operational cost is compared to the current storage configuration. The VLM configuration performs best with respect to savings and investment cost, savings are highest for this configuration and compared to the current situation, the investment cost is recuperated within 7 years. When comparing the VLM with the manual and miniload AS/RS configurations it is clear that investing in this system is financially beneficial.

6 Scenario development

To evaluate environmental performance of storage systems and gain insight into the relationships between certain factors and environmental performance, scenarios are developed that variate external and internal factors that have an influence on environmental performance. To this end, the internal and external factors are identified and tested on the intensity at which they affect the carbon footprint of a storage system. The identified factors that have a relatively high influence on environmental performance are then chosen for scenario development.

6.1 Internal factors

Internal factors are defined as factors that can be influenced by the company or person managing the storage system. based on these factors recommendations can be developed on measures to increase environmental performance.

6.1.1 Warehouse dimensions

The warehouse dimensions determine the length of the aisles as well as the height of for instance a VLM. Although this cannot be influenced after the warehouse has been built, this still greatly influences storage system environmental performance. Warehouse height determines for instance the lighting intensity needed to produce the right amount of lux, as well as increasing the warehouse volume that needs to be heated/ventilated. For the case of storage systems that can make use of the vertical dimension, warehouse height can greatly increase/decrease the effective storage volume. Therefore, aisle length and warehouse height are important factors to be taken into account when choosing a storage system.

To asses the effect of aisle length and building height, each factor is varied between 150 and 50 percent for each storage system. The setup of the warehouse dimension analysis is shown in Table 10.

Table 10: Analysis setup of warehouse dimensions

	150%	**125%**	**100%**	**75%**	**50%**
Desired aisle length [m]	75	62,5	50	37,5	25
Building height [m]	16,5	13,75	11	8,25	5,5

Inserting these values into the model for each configuration results in values show in Table 11 and Table 11. Figure 11 and Figure 12 show the sensitivity to carbon emissions for each configuration when varying aisle length and warehouse height respectively.

Table 11: Results aisle length experiment

Aisle length [m]	**CO_2 emission Current [kg/year]**	**CO_2 emissions Manual [kg/year]**	**CO_2 emission miniload [kg/year]**
75	21976,90	31422,79	10713,71
62,5	20815,91	31222,40	11161,93
50	20127,12	31949,27	11244,25
37,5	19637,00	32063,54	10996,55
25	19788,36	36025,77	12897,52

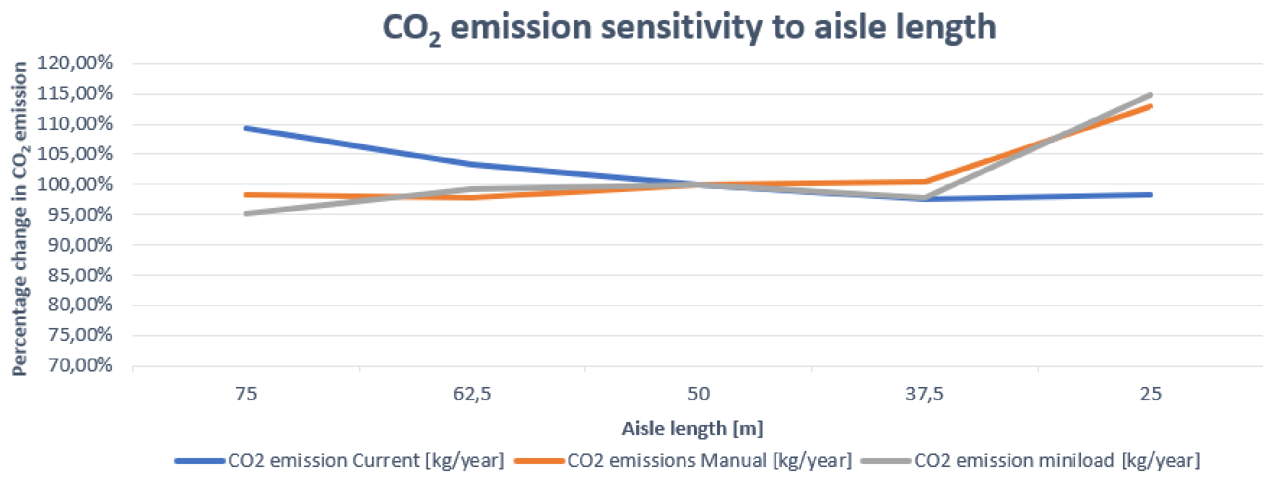

Figure 11: CO_2 emission sensitivity to aisle length for each configuration

Figure 11 shows the sensitivity of the emissions with respect to aisle length. Some interesting relations can be identified, the current configuration performs worse for a longer aisle length and the manual configuration performs better. This could possibly be explained by the varying storage volume present for both configurations. The manual configuration contains a total of 388 m^3 and the current configuration 158 m^3. As a result a long aisle length could reduce the storage utilization of the current configuration compared to the manual configuration, increasing the space requirement with unnecessary bin shelving units. The miniload definitively performs better with a longer aisle length, this is due to the fact that more miniload racks are needed with short aisles. More racks lead to higher stand-by power consumption and in turn increases the total carbon emissions. height [m]

Table 12: Results warehouse height experiment

Warehouse height [m]	CO_2 emission current [kg/year]	CO_2 emissions manual [kg/year]	CO_2 emission VLM [kg/year]	CO_2 emission miniload [kg/year]
16,5	23129,30	37054,49	5248,81	9851,46
13,75	21192,59	35359,13	6159,98	10583,39
11	20127,12	31949,27	8079,91	11244,25
8,25	19580,59	28217,94	9804,20	11905,47
5,5	20970,72	25093,83	13350,41	14276,99

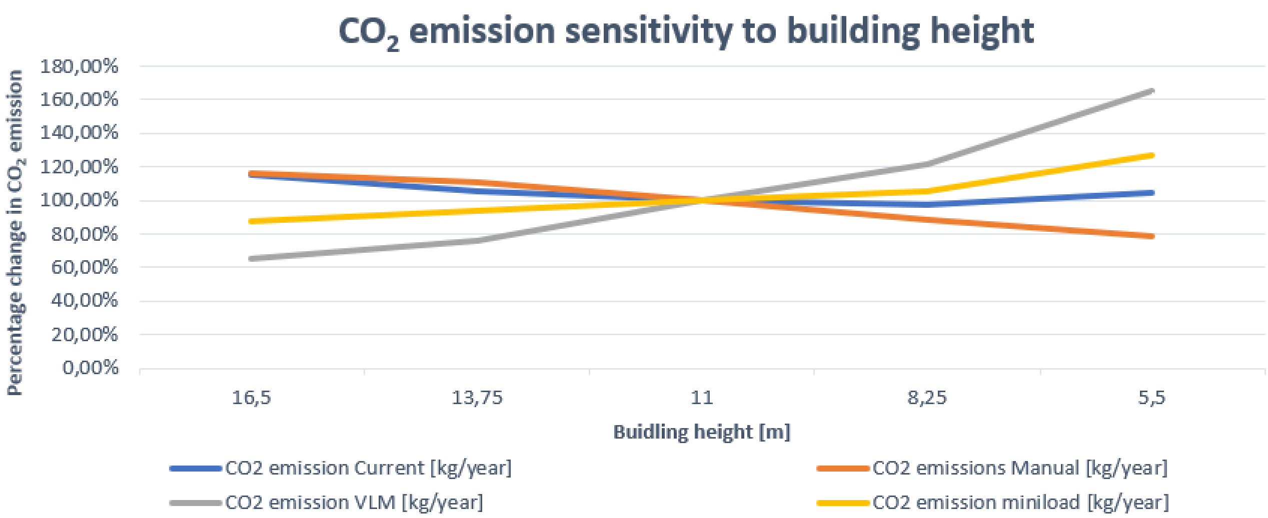

Figure 12: CO_2 emission sensitivity to warehouse height for each configuration

As expected, the part-to-picker systems perform better the higher the building is, the vertical dimension is used and the total space requirement decreases drastically. The manual system however still has the same space requirement but lighting has to be more intensive as the ceiling is now higher and more light is needed to reach the 300 lux requirement. Therefore the carbon emissions increase as building height increases. Building height can therefore be seen as an important factor when choosing between a part-to-picker or picker-to-part solution.

6.1.2 Storage policy

Operational power consumption and mobile material handling are affected by distance travelled for a certain pick job. Different storage policies can reduce the annual average travel time by taking into account the share that different parts have in the total demand. If parts with high demand are placed closer to the pick face the extractor travel time can be reduced by a substantial margin. A well known storage policy in literature and practice is the ABC-class based storage policy (Koster, 1976). Parts are divided in three classes based on their demand rates and high-demand parts are stored closer to the pick face.

To analyse the effect of storage policy on the considered storage systems an ABC class-based storage policy is applied. Parts are divided into A, B and C classes and each account for one third of the total storage volume. Figure 13 and Figure 14 show how the classes are distributed over the VLM and miniload systems.

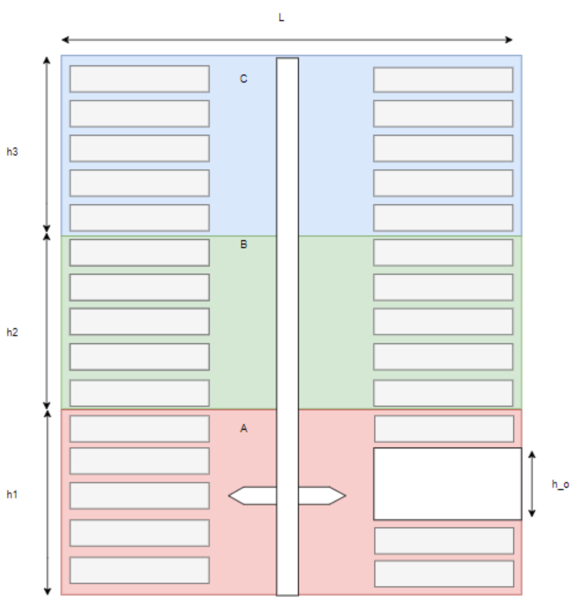

Figure 13: ABC storage policy distribution for the VLM

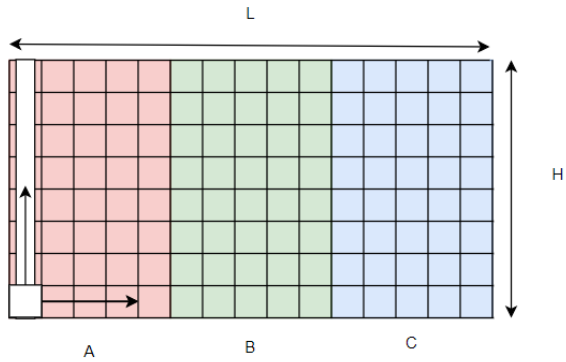

Figure 14: ABC storage policy distribution for the Miniload AS/RS

To determine the resulting operational power consumption of the applied class-based storage system, the distance travelled is weighed by the demand rate of a certain class. First the demand rates of the classes are applied. To gain a better understanding of the effect of the class based storage, four different configurations are applied based on the reliability of demand.

Table 13: Percentage of demand for each class for each configuration

Demand reliablity	**A**	**B**	**C**
High 1	80,00%	15,00%	5,00%
2	70,00%	20,00%	10,00%
3	60,00%	25,00%	15,00%
Low 4	50,00%	30,00%	20,00%

Based on the percentage of demand and storage location of each class, the average distance travelled per pick can be adjusted accordingly. For the VLM system the following equation determines the average distance travelled based on the demand distribution.

$$s_{average} = (\frac{H_v}{6} - h_o) \cdot r_A + (\frac{H_v}{2} - h_o) \cdot r_B + (\frac{H_v}{6} \cdot 5 - h_o) \cdot r_C \tag{60}$$

Where:
$s_{average}$ = Average distance travelled per cycle
H_v = VLM height
h_o = Height of the pick opening
r_A = Demand rate of A parts
r_B = Demand rate of B parts
r_C = Demand rate of C parts

The distance travelled is weighted with the demand rate of the classes. The next equation shows how the average distance travelled is found for the miniload system.

$$s_{average} = \frac{L}{6} \cdot r_A + \frac{L}{2} \cdot r_B + \frac{L}{6} \cdot 5 \cdot r_C \tag{61}$$

Where:
L = Miniload AS/RS rack length

As a result from the decreased travel distances, the total cycle time also decreases. Operational power consumption can then be determined for each of the different storage configurations. The picker-to-part storage is not considered as this would only affect transportation equipment which is not included in the model. Table 14 shows the results of the analysis of the ABC-class based storage policy, as well as the percentage change in CO_2 emission compared to the random storage assignment. In this case only CO_2 emission from a specific storage system is taken into account and emissions from lighting and HVAC are excluded.

Table 14: Results of the analysis of the ABC-class based storage policy

Configuration	**Total CO_2 emission current VLM [kg/year]**	**Percentage change [%]**	**Total CO_2 emission Miniload [kg/year]**	**Percentage change [%]**	**Total CO_2 emission VLM [kg/year]**	**Percentage change [%]**
1	3370,42	99,92%	4137,60	99,71%	5834,48	99,79%
2	3371,05	99,94%	4140,44	99,78%	5837,19	99,84%
3	3371,68	99,95%	4143,28	99,84%	5839,90	99,89%
4	3372,30	99,97%	4146,12	99,91%	5842,62	99,93%

The results show that applying the ABC-class based storage does not result in a substantial decrease in CO_2 emission for any of the storage systems. The largest decrease is 0,29 percent of the machine specific emissions. This is mostly due to the high share of stand-by power consumption compared to operational. Due to the low impact of the ABC-class based storage system, it is not included in the scenario analysis.

6.1.3 Storage characteristics

Storage characteristics entail the amount of parts placed in the bins as a result of for instance increased safety or excess stock. To determine the effect of this factor the bin load, previously assumed to be 30 percent of the maximum load, is varied. The resulting operational power consumption is affected as each pick has an increased mass moved. To asses the effect of bin load on the carbon footprint of the systems, the load in the bins is varied from 50 to 10 percent of the maximum bin load. Table 15 shows the initial setup of the experiment.

Table 15: Analysis setup of bin load experiment

Percentage of max load	Shelf load VLM [kg]	Bin load miniload AS/RS [kg]
50%	102,5	15
40%	82	12
30%	61,5	9
20%	41	6
10%	20,5	3

The bin loads in Table 15 are entered into the model and the results are shown in Table 16. A graph is shown in Figure 15 for visual aid in the analysis of the effect of bin load on total CO_2 emissions.

Table 16: Results of bin load experiment

Percentage of max load	CO_2 emission Current [kg/year]	CO_2 emission VLM [kg/year]	CO_2 emission miniload AS/RS [kg/year]
50%	20205,06	8149,37	11255,24
40%	20166,09	8114,64	11249,74
30%	20127,12	8079,91	11244,25
20%	20088,14	8045,18	11238,75
10%	20049,17	8010,44	11233,26

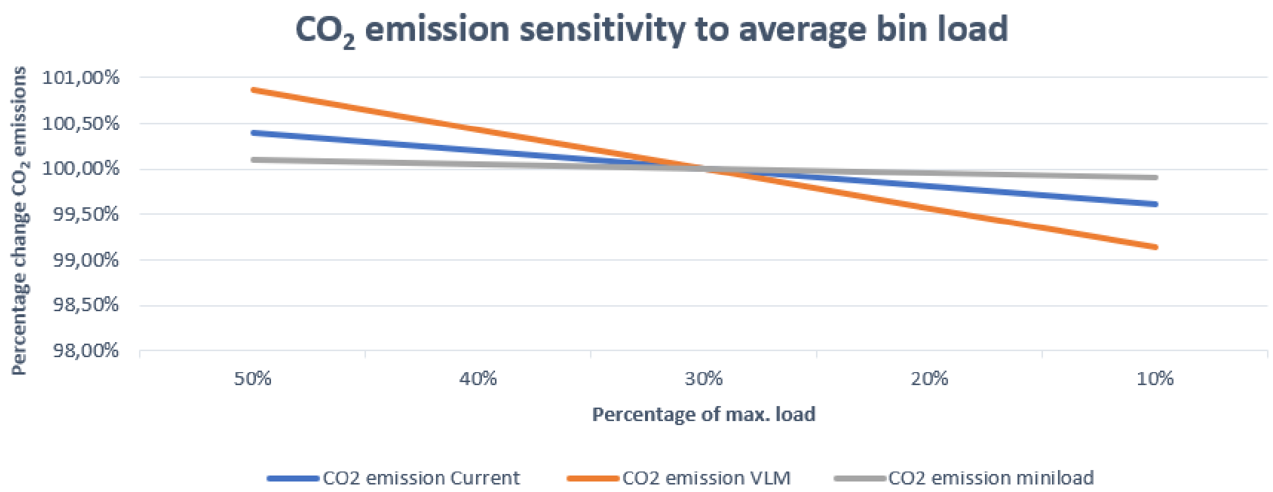

Figure 15: CO_2 emission sensitivity to average bin load for each configuration

Figure 15 shows that the bin load does not affect the total carbon emissions substantially. The VLM configuration is affected most as the shelves have a higher weight than the bins used in the miniload. The VLM configuration also has a higher share of operational energy consumption compared to the current configuration. It can be concluded however, that bin load does not have a high impact on total carbon emissions and will not be included in the scenarios.

6.1.4 Building characteristics

Lighting and HVAC account for a large part of storage system carbon footprint. This is also an area where improvements are possible. Isolation and lighting equipment plays a big role in the determination of energy requirement from the respective factors. The initial case study involves the use of fluorescent tubes, however better and more sustainable alternatives are available on the market. LED (light emitting diodes) and HID (high intensity discharge) lighting equipment has a better lumen to wattage ratio compared to fluorescent tubes. To test the effect of improved lighting equipment on the different storage systems, LED and HID lamp characteristics are used as alternative input to the current fluorescent tubes. Table 17 shows the characteristics of the considered LED and HID lamps.

Table 17: Considered lamp characteristics

	LED	HID
Initial lumen [lm]	10500	10600
Wattage [W]	70	101
Reference	verlichtingnl.nl	techniekwebshop.nl

The experiment is carried out for each of the storage systems. The resulting carbon footprint is shown in Table 18. Figure 16 shows the percentage change in CO_2 emissions compared to the original lighting choice.

Table 18: Results lighting equipment experiment

Equipment	CO_2 emissions current [kg/year]	CO_2 emissions manual [kg/year]	CO_2 emissions VLM [kg/year]	CO_2 emissions miniload [kg/year]
LED	17849,24	25698,46	7901,31	8820,80
HID	19540,44	30372,53	8059,50	9580,08

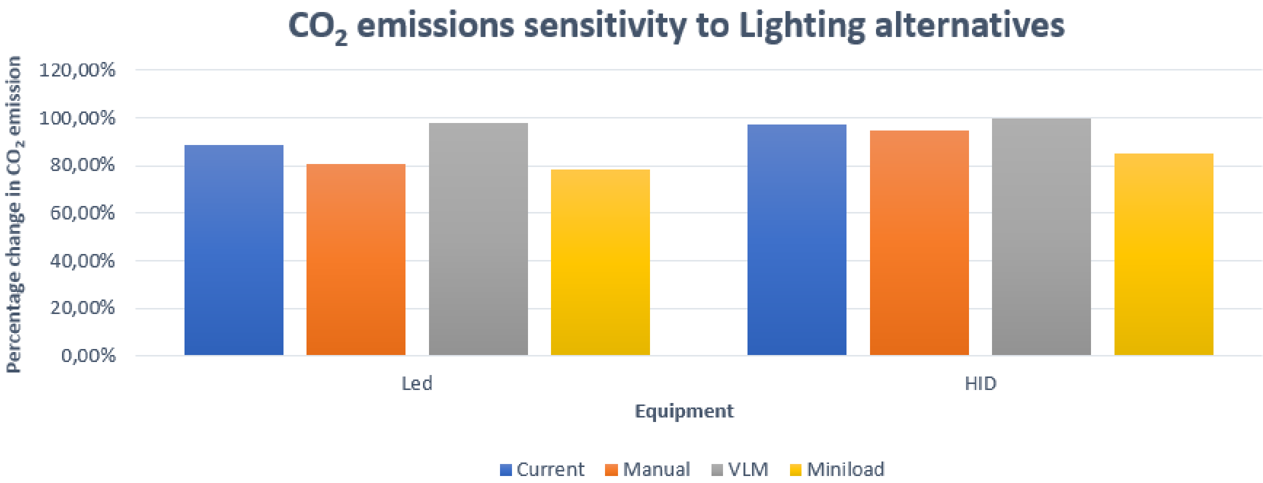

Figure 16: CO_2 emission sensitivity to lighting alternatives for each configuration

As expected, the improvement LED and HID lighting has with respect to lumens and necessary wattage can substantially reduce the total carbon emissions. This effect is stronger as the total space requirement increases, as the manual and current storage systems show the greatest improvement. Due to the substantial reductions observed, the lighting factor will be included in the scenarios.

Isolation quality is another important factor. Initially, the heat loss coefficient is set to be 0,3. The effect of isolation quality is analysed by varying the heat loss coefficient from 0,4 to 0,2. In this case, 0,4 is poor isolation and 0,2 is a substantial improvement in isolation quality.Table 19 shows the resulting carbon footprint of each of the storage systems for the different isolation factors. Figure 17 shows the percentage change in total CO_2 emissions for the different isolation factors.

Table 19: Results isolation quality experiment

HLC $[W/m^2\,°C]$	CO_2 emissions current [kg/year]	CO_2 emissions manual [kg/year]	CO_2 emissions VLM [kg/year]	CO_2 emissions miniload [kg/year]
0,4	23641,42	36919,72	8645,78	12717,03
0,3	20127,12	31949,27	8079,91	11244,25
0,2	16612,81	26978,82	7514,03	9749,49

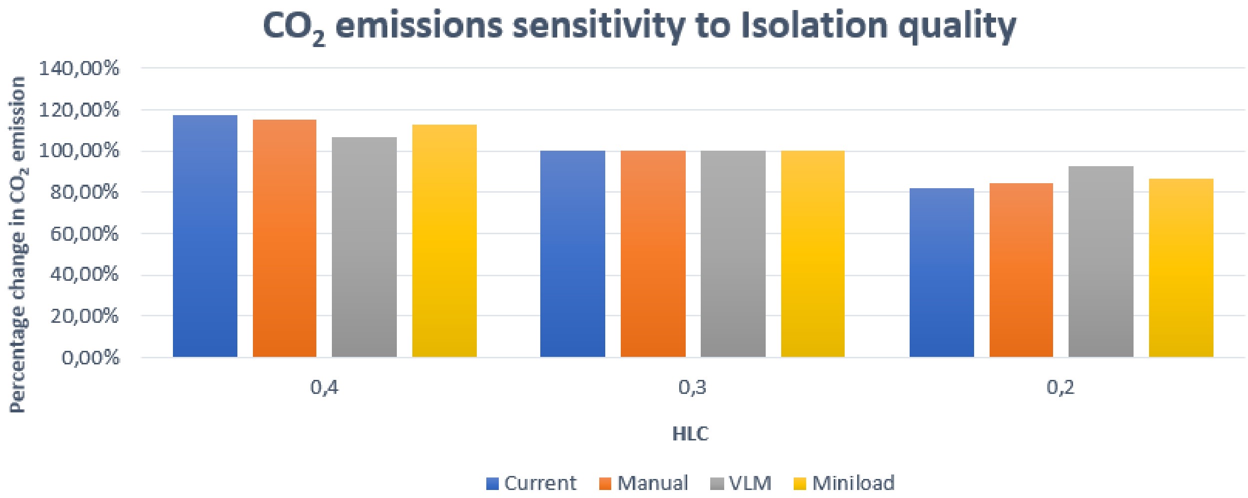

Figure 17: CO_2 emission sensitivity to isolation quality for each configuration

The isolation quality plays a big role in the total energy requirements of a building and the results of the analysis confirm this statement. The isolation quality can indeed increase and decrease the total emissions with a substantial amount. The effect of isolation quality increases, in the same way as identified for lighting alternatives, as the space requirement increases. This is the result of the increased share of HVAC energy consumption as the space requirement increases. It can be concluded that isolation quality can indeed have a substantial effect on total carbon emissions and is therefore included in the scenario analysis.

6.1.5 Dedicated picking time slots

As mentioned in section 4.3.1 the part-to-picker systems are assumed to be in stand-by throughout the whole year. At the moment these systems are never turned off completely. If this was not the case and it was possible to turn the systems off when the picks for a certain period have been fulfilled, specific time slots could be set each day in which all picks for that day are performed. This is expected to result in a drastic decrease in idle power consumption as the systems will not be in stand-by mode for nearly as long as initially considered. To analyse this possibility, it is important to first identify how long this time slot should be to be able to perform all picks. The current configuration is able to relieve a part of the picking intensity from the VLMs with the dedicated bin-shelving mezzanine. Therefore this configuration requires a smaller time slot per day for operating the VLMs. The cycle time and pick duration, identified in Appendix C are used to find the minimum duration of the daily time slots. The time slots are extended by half an hour to account for any delays during picking or starting the machinery. Half an hour was considered due to increased start up and shut down times, as well as any possible problems with software or queuing that can occur when multiple pick jobs are performed in succession. Table 20 shows the results of the picking time slot experiment.

Table 20: Results picking time slot experiment

Variable	**Current**	**VLM**	**Miniload AS/RS**	**Unit**
System energy consumption	1501,19	4361,26	3313,28	kWh/year
Total annual energy consumption	73406,41	14801,65	36003,55	kWh/year
Total annual CO_2 emissions	17103,69	3448,78	8388,83	kg/year
Percentage change	-15,02	-57,32	-25,39	%

The experiment has the biggest impact on the VLM configuration, due to the system energy consumption accounting for most of the CO_2 emissions of this system. Although the current configuration has the benefit of splitting the picks per year between the VLMs and the bin-shelving units, this measure only reduces total carbon emissions by fifteen percent. This is due to the high share of lighting and HVAC energy consumption for this system. The total system energy consumption is reduced by a large margin, however this pales in comparisons with the total energy consumption. It can be concluded though that for each system, excluding manual storage, this is an effective way of reducing total carbon emissions and will be included in the scenarios. Figure 18 offers a visual representation of the resulting CO_2 emissions compared to the base case.

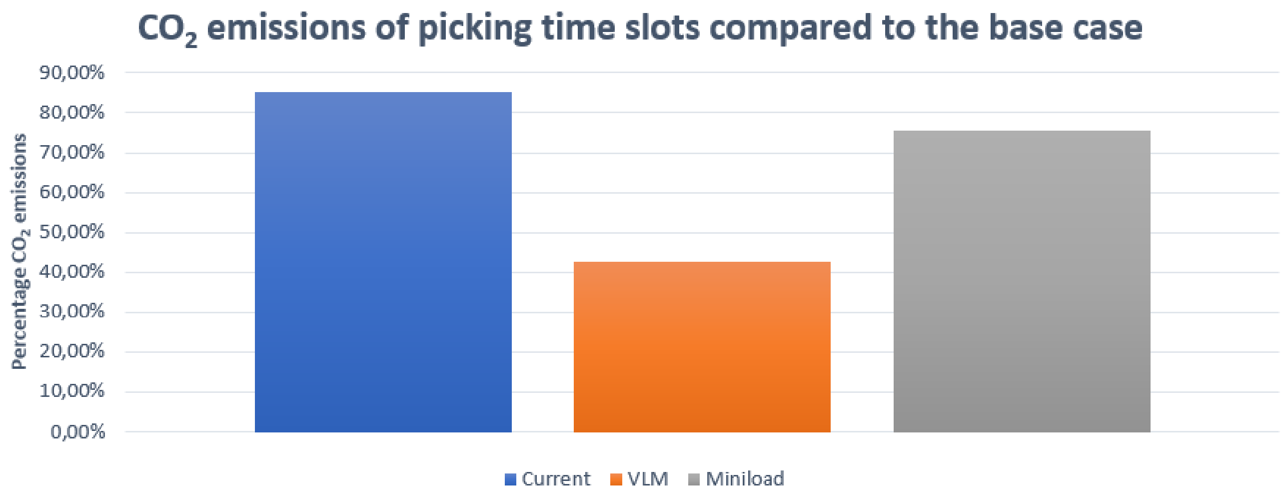

Figure 18: CO_2 emissions resulting from the introduction of picking time slots

Another benefit as a result of the dedicated time slots is that the cycle times of the storage system benefit the total CO_2 emissions of the system as the picking times are shorter as the cycle times are decreased. The storage policy introduced in section 6.1.2 can be combined with this policy to further decrease the total carbon emissions.

6.2 External factors

The internal factors have been analysed and evaluated based on their effect on total carbon emissions. External factors however, are factors that cannot be influenced by the company. Due to this character it is important to include these factors in scenario development.

6.2.1 Market demand

The amount of picks per year determines the amount of cycles the part-to-picker storage system performs in a year. This also determines the ratio between operational and idle power consumption. The evaluate the effect an increase or decrease can have on total carbon emissions, market demand is included in the analysis. Picks per year are varied between 120 and 80 percent and the resulting picks per year are varied and the resulting carbon emissions are shown in Table 21.

Table 21: Carbon emission results from market demand experiment

Picks per year	**CO_2 emissions Current [kg/year]**	**CO_2 emissions VLM [kg/year]**	**CO_2 emissions Miniload [kg/year]**
120%	20133,19	8106,20	11257,76
110%	20130,16	8093,05	11251,00
100%	20127,12	8079,91	11244,25
90%	20124,08	8066,76	11237,49
80%	20121,04	8053,61	11230,73

The results show that market demand does not have a substantial effect on the total carbon emissions of the specific storage systems. The largest changes can be identified for the VLM system as operational power consumption has the largest effect on total power consumption for this system. For visual aid Figure 19 shows the percentage change in carbon emissions for each considered system.

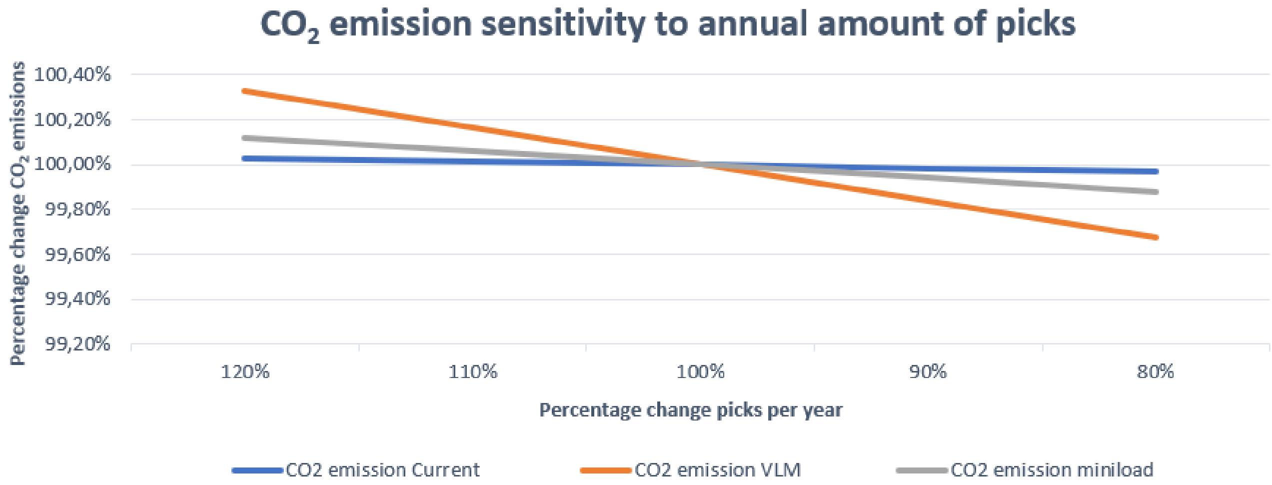

Figure 19: CO_2 emission sensitivity to the amount of picks per year

As mentioned, the VLM and miniload configuration are more sensitive to this factor. This is explained by the ratio of amount of energy from lighting and HVAC and operational power consumption. It can be concluded that the total carbon emissions are insensitive to the total amount of picks per year for each configuration.

6.2.2 Demand forecastability

As mentioned earlier in section 6.1.2, demand forecastability determines the rate at which demand can be forecast. This has a strong relationship with the storage policy applied. The storage policy determines in what manner and where parts are stored. Section 6.1.2 shows that although travel time and operational power consumption diminishes with the use of the ABC-class based storage policy, this does not have a profound effect on total carbon emissions. Demand unreliability does affect the total travel times and operational power consumption. It can also be argued that both the storage policy and demand forecastability can have a stronger effect when analysed in conjunction with picking time slots. The ratio between operational and stand-by hours is smaller in that case and any reductions in operational power consumption could play a big role in the determination of total yearly carbon emissions. Therefore this is one of the relationships included in the scenarios.

6.3 Sensitivity analysis

As a result of the assumptions made in Appendix C, a sensitivity analysis is performed to analyse the effect that the assumptions have on the performance measures of the storage systems. The factors included in the sensitivity analysis are; Aisle width, motor efficiency, extractor weight, stand-by power consumption and total storage volume.

Aisle width is initially assumed to be 1,3 meters, as no forklift is required to pass through the aisle. An employee picks each order manually and 1,3 meters is sufficient space to pass through freely. For the miniload, only the extractor is required to move through the aisles and 0,5 meters are already taken into account with respect to the width of the miniload racks themselves. The assumed 0,2 meters are used to allow for any maintenance necessary to the machine. To asses the sensitivity of space requirement and CO_2 emissions to aisle width, the model is used to vary the aisle width from 120 to 80 percent. The results of the sensitivity analysis is shown in Table 22

Table 22: Results of the sensitivity analysis for aisle width

Aisle width [m]	**120%**	**100%**	**80%**
Current	1,56	1,3	1,04
Manual	1,56	1,3	1,04
Miniload	0,24	0,2	0,16
Space requirement [m^2]			
Current	1359,88	1209,80	1062,44
Manual	3127,71	2782,54	2443,6
Miniload	285,60	280,50	275,40
Space requirement percentage change [%]			
Current	112,41%	100,00%	87,82%
Manual	112,40%	100,00%	87,82%
Miniload	101,82%	100,00%	98,18%
CO_2 emissions [kg/year]			
Current	20389,59	19019,92	17865,40
Manual	34161,40	31949,27	28469,46
Miniload	11337,01	11244,25	11187,20
CO_2 percentage change [%]			
Current	107,20%	100%	93,93%
Manual	106,92%	100%	89,11%
Miniload	100,83%	100%	99,49%

The analysis shows that the current and manual configurations are relatively sensitive to aisle width. The space requirement is substantially affected by the chosen aisle width. The resulting emissions are affected due to the increased space requirement. The miniload configuration does not require a wide aisle and is therefore not affected by this factor as much as the other two considered configurations. It can be concluded that the bin-shelving configurations are relatively sensitive to this factor, however automated systems are not sensitive to the aisle width.

The next factor considered in the sensitivity analysis is the motor efficiency of the VLM and the miniload AS/RS. The motor used in the system is an important part of the resulting energy requirement and is therefore included in the sensitivity analysis. The motor considered is applicable to the operational part of the energy use of the automated systems. The motor efficiency is varied between 95 and 75 percent to analyse the resulting carbon emissions. Table 23 shows the results of the sensitivity analysis for motor efficiency.

Table 23: Results of the sensitivity analysis for motor efficiency

Motor efficiency [%]	**95%**	**85%**	**75%**
CO_2 emissions [kg/year]			
Current VLM	19005,61	19019,92	19038,05
VLM	8059,90	8079,91	8105,25
Miniload	11228,35	11244,25	11264,38
CO_2 percentage change [%]			
Current	99,92%	100,00%	100,10%
VLM	99,75%	100,00%	100,31%
Miniload	99,86%	100,00%	100,18%

The analysis shows that the automated systems are not sensitive to the motor efficiency. There is an effect to be identified however, a higher motor efficiency decreases the operational power consumption of the automated systems by decreasing operational power consumption. As previously identified the share of stand-by power consumption is substantially greater than the share of operational power consumption. Therefore it can be concluded that the systems are not sensitive to motor efficiency because the relative effect of increasing and decreasing motor efficiency is almost negligible.

The following factor analysed for sensitivity is the extractor weight. The VLMs are assumed to have an extractor of ten kilograms, to test the effect this assumption has on the total carbon emissions it is included in the sensitivity analysis. The miniload AS/RS has two extractors, vertical and horizontal. The vertical extractor is assumed to be of similar weight as the extractor used in the VLMs. The horizontal extractor however is a column that spans the vertical dimension of the considered miniload rack and is able to carry the load of both the vertical extractor and the bin moved. Due to this character, the horizontal extractor is assumed to weigh substantially more than the vertical extractor, namely eighty kilograms. Table 24 shows the results of the sensitivity analysis for both the vertical and horizontal extractors.

Table 24: Results of the sensitivity analysis for extractor weight

Extractor weight [kg]	**120%**	**100%**	**80%**
Current	12	10	8
VLM	12	10	8
Miniload vertical	12	10	8
Miniload horizontal	96	80	64
CO_2 emissions [kg/year]			
Current VLM	19023,72	19019,92	19016,12
VLM	8083,29	8079,90	8076,52
Miniload vertical	11247,91	11244,25	11240,58
Miniload horizontal	11247,86	11244,25	11240,63
CO_2 percentage change [%]			
Current	100,02%	100,00%	99,98%
VLM	100,04%	100,00%	99,96%
Miniload vertical	100,03%	100,00%	99,97%
Miniload horizontal	100,03%	100,00%	99,97%

The results clearly show that the total carbon emissions are not sensitive to the weight of the extractor. For each configuration the total carbon emissions are not affected by more than 0,1 percent. Neither the vertical and horizontal extractors of the VLMs and the miniload have a significant effect on the total carbon emissions of the system. It can be concluded that the total carbon emissions are not sensitive to the extractor weight considered for the system.

Idle power consumption was derived from common industrial lift systems. For both the miniload AS/RS ans the VLMs this is considered to be 400 watts. To test the sensitivity of this assumption it is included in the analysis. The stand-by power is varied from 120 to 80 percent of the initial value and the resulting carbon emissions are analysed. Table 25 show the results of the sensitivity analysis for stand-by power consumption.

Table 25: Results of the sensitivity analysis for stand-by power consumption

Idle power consumption [W]	**120%**	**110%**	**100%**	**90%**	**80%**
Current	480	440	400	360	320
VLM	480	440	400	360	320
Miniload	480	440	400	360	320
CO_2 emissions [kg/year]					
Current	19682,79	19351,36	19019,92	18688,49	18357,05
VLM	9224,98	8652,44	8079,90	7507,37	6934,83
Miniload	12063,62	11653,93	11244,25	10834,56	10424,87
CO_2 percentage change [%]					
Current	103,49%	101,74%	100,00%	98,26%	96,51%
VLM	114,17%	107,09%	100,00%	92,91%	85,83%
Miniload	107,29%	103,64%	100,00%	96,36%	92,71%

The results show that this factor can have a substantial impact on total carbon emissions, especially for systems with a large share of system power consumption in the total energy requirement. The VLMs therefore are affected the most by this factor as the energy requirement for lighting and HVAC is smallest here. The miniload however is also affected by a relatively large margin. It can be concluded that the storage system carbon emissions are indeed sensitive to this factor, however this effect is diluted as a consequence of high energy requirements for lighting and HVAC.

The final considered factor for the sensitivity analysis is the total storage volume. The initial storage volume included in the model was derived from the storage of the considered company. This analysis is conducted to find what effect an increase or decrease of this value can have on the total space requirement and the total carbon emissions. Another interesting aspect of this analysis is that it shows what a possible expansion of the current storage capacity would mean with respect to the space requirement in the warehouse and the required lighting and HVAC equipment. To analyse this effect the total storage volume is varied from 120 to 80 percent and the resulting space requirement and carbon emissions are recorded in Table 26.

Table 26: Results of the sensitivity analysis for storage volume

Storage volume [m^3]	**120%**	**100%**	**80%**
Space requirement [m^2]			
Current	1370,23	1209,80	967,84
Manual	3266,46	2782,54	2177,64
VLM	63,12	55,23	39,45
Miniload	280,50	280,50	224,40
Space requirement percentage change [%]			
Current	113,26%	100,00%	80,00%
Manual	117,39%	100,00%	78,26%
VLM	114,29%	100,00%	71,43%
Miniload	100,00%	100,00%	80,00%
CO_2 emissions [kg/year]			
Current	21216,78	19019,92	15909,48
Manual	35526,17	31949,27	25763,64
VLM	9186,49	8079,91	5866,73
Miniload	11244,25	11244,25	9693,13
CO_2 percentage change [%]			
Current	111,55%	100,00%	83,65%
Manual	111,20%	100,00%	80,64%
VLM	113,70%	100,00%	72,61%
Miniload	100,00%	100,00%	86,21%

As a result of an increased storage volume, the total space requirement increases. Notably though, the space requirement of the miniload AS/RS does not increase. This is due to the remaining volume in a rack when considering the initial set-up. An extra rack was necessary to fulfill the total storage volume and this rack still had sufficient volume to accommodate the added storage volume considered for this system. As a result the space requirement and the total carbon emissions were not affected by the increase in storage volume. The reduction in storage volume shows that the carbon emissions are sensitive to the factor for each system though. The space requirement changes by almost the same margin as the total storage volume and as a result the total carbon emissions are affected. Interestingly, the reduction in storage volume has a bigger impact on total carbon emissions compared to a decrease. This is expected to be because of the rounding up used to simulate the amount of aisle, modules and racks of the storage systems. As a result of the reduction, more aisles, modules and racks can be removed than compared to the added amount as a result of the increased storage volume. It can be concluded that the total carbon emissions and space requirement are sensitive to the total storage volume.

6.4 Scenarios

To develop the considered scenarios, the factors analysed in the previous sections are combined to result in different measures or situations that can affect the total carbon emissions of the considered systems. The scenarios are developed based on realistic circumstances and conditions, due to the low presence of external factors that greatly influence the total carbon emissions, mostly internal factors are used for the scenario development. The scenarios are introduced in the following summation;

- *Scenario 1: Dedicated time slots and efficient storage policy*

  In this scenario, management has focused on reducing energy consumption from material handling. By reducing the average picking cycle, more picks can be fulfilled within a certain time frame. This results in smaller picking time slots and a reduction in operational and stand-by power consumption for the automated storage systems.

- *Scenario 2: Parts, safety stock and demand increase*

  New customers have been attracted and as a result, new parts have to be kept in storage. On top of this, demand of existing customers has increased as the aviation industry recovers from the recent pandemic. To account for this increased demand the considered company has chosen to increase the safety stock of their parts, increasing the storage volume further.

- *Scenario 3: Warehouse relocation & re-investment*

  The warehouse is relocated and with the importance of sustainability increasing, the main decision criteria are economic and environmental performance. As a result, investment in lighting and HVAC are applied as well as choosing warehouse dimensions that are in line with the main decision criteria.

The three scenarios are chosen due to the different aspects considered and the factors previously identified to have a reasonable impact on total carbon emissions. Scenario 1 is focused on optimizing material handling for the storage systems, scenario 2 is focused on external influences on storage aspects and scenario 3 is chosen for the focus on building and equipment improvements. In section 7 the scenarios are described in more detail.

6.5 Conclusion

Sub-question seven states: *What external and internal factors influence the carbon footprint of storage systems?*. Factors influencing the carbon footprint of storage systems are considered in this section. The factors are:

Internal
- Warehouse dimensions
- Storage policy
- Storage characteristics
- Building characteristics
- Picking policy
- System characteristics
- Storage volume

External
- Demand forecastability
- Market demand

The effect of these factors on carbon emissions is analysed and the most impactful factors are: Warehouse dimensions, picking policy, building characteristics, system characteristics and storage volume . These factors are analysed further in section 7.

Sub question eight states: *What scenarios can be formulated based on external and internal factors?* The impactful factors mentioned previously are used to formulate scenarios. Three different aspects are analysed per scenario, to provide an encompassing analysis of the storage systems. The three formulated scenarios are:

- *Scenario 1: Dedicated time slots and efficient storage policy*
- *Scenario 2: Parts, safety stock and demand increase*
- *Scenario 3: Warehouse relocation & re-investment*

Each scenario is focused on different factors identified in this section. Scenario one is focused on picking and storage policies, scenario two is focused on storage volume and system characteristics and scenario three is based on warehouse dimensions and building characteristics. The scenarios are further described and applied in section 7.

7 Scenario application

In this section, the scenarios identified in section 6 are applied to the model and the results are analyzed and compared to the base case as well as each other.

7.1 Scenario 1: Dedicated time slots and efficient storage policy

The first scenario is focused on reducing the power consumption of the automated system. Therefore, the manual storage system is not taken into account for this scenario. Dedicated picking time slots are used, similar to the method used in section 6.1.5. Additionally the ABC-class based storage policy is applied to reduce the average time lost during picking. The most reliable policy is applied to the model. The results are expected to have a substantial effect on the miniload AS/RS and VLM configurations as these systems have a high share of system power consumption. Table 29 shows the resulting carbon emissions as a result of the applied measures, Figure 20 shows the resulting percentage of CO_2 emissions compared to the base case.

Table 27: Results of scenario 1: Dedicated time slots and efficient storage policy

Variable	Current	VLM	Miniload
System energy consumption [kWh/year]	1425,67	4136,69	3284,95
Total annual energy consumption [kWh/year]	73330,89	14577,08	35975,21
Total annual CO2 emission [Kg/year]	17086,10	3396,46	8382,22
Percentage change [%]	-15,11	-57,96	-25,45

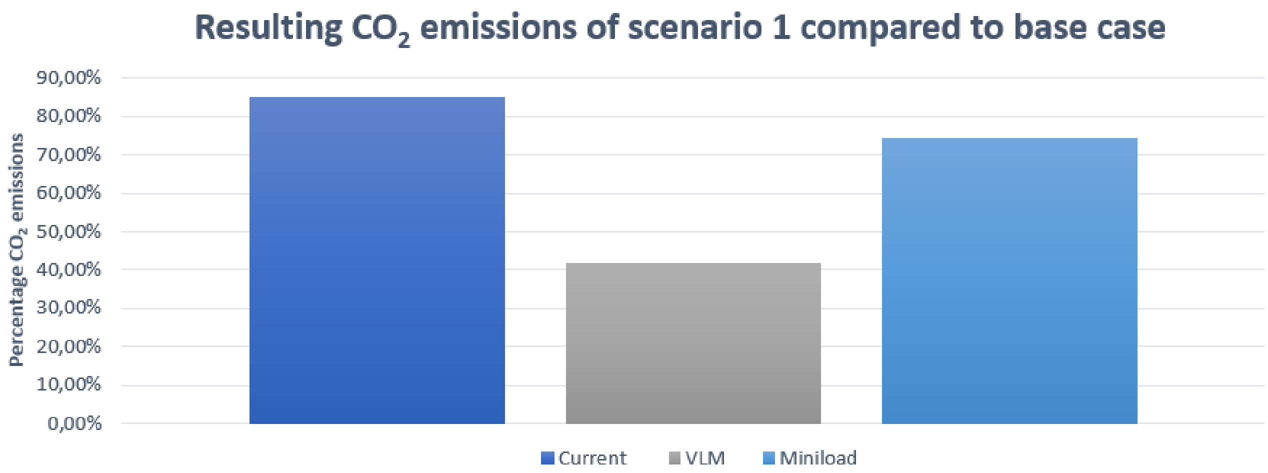

Figure 20: Percentage CO_2 emissions resulting from scenario 1: Dedicated time slots and efficient storage policy

The results show that dedicated picking time slots and an ABC-class based storage policy can substantially affect the carbon footprint of an automated storage system. When comparing the reductions in carbon emissions between the storage systems, the VLM is affected most. This is due to the high share of system energy consumption in the total carbon emissions of the VLM. The current storage system is affected the least due to the bin-shelving section. It can be concluded that the measures introduced for this scenario are effective for reducing the carbon footprint of the considered storage systems.

When comparing the results of scenario one to the results in section 6.1.2 and section 6.1.5, it becomes clear that the ABC-class based storage policy still does not have a great effect on power consumption. The effect is greater though when using picking time slots, however the resulting carbon emissions are not affected more than one percent. This confirms the fact that the stand-by power consumption of the miniload AS/RS and the VLM has a far greater share than the operational power consumption. ' The cost comparison made between the results of scenario one and the initial results of the case study shows that the dedicated time slot measure can also have a great impact on operational costs. For each configuration, more than 3.000 euros can be saved by applying this measure. The saving is compiled of only the energy savings resulting from the dedicated time slots and ABC-class based policy.

7.2 Scenario 2: Parts, safety stock and demand increase

Scenario 2 considers external factors in market demand while also increasing the total storage volume to be stored. The scenario attempts to simulate an increase in business and customers for an aerospace service provider. The degree of increase used in the scenario will be varied to provide more concise results. The storage volume and demand is varied from 120 to 200 percent. Figure 21 shows the percentage change for space requirement resulting from the scenario.

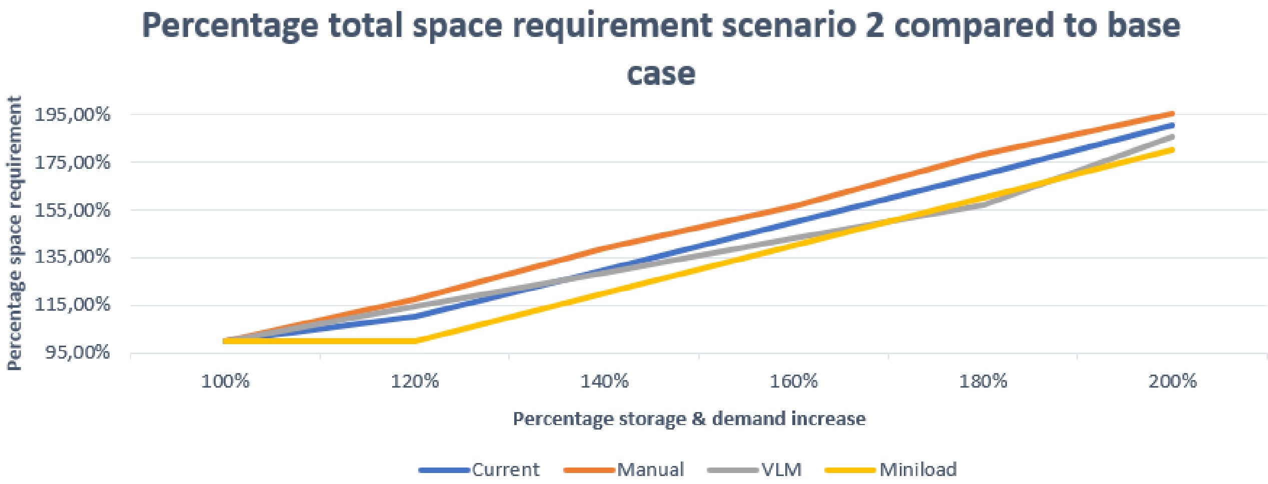

Figure 21: Percentage space requirement resulting from scenario 2: Parts, safety stock and demand increase

The results show that the space requirement increases proportionately to the storage volume. This is in line with the expectations as the increased storage volume increases the necessary storage space. The miniload and VLM configurations have a more discrete increase due to the addition of a single rack/unit as a result of the storage volume increase. Figure 22 shows the percentage change in carbon emissions for each configuration.

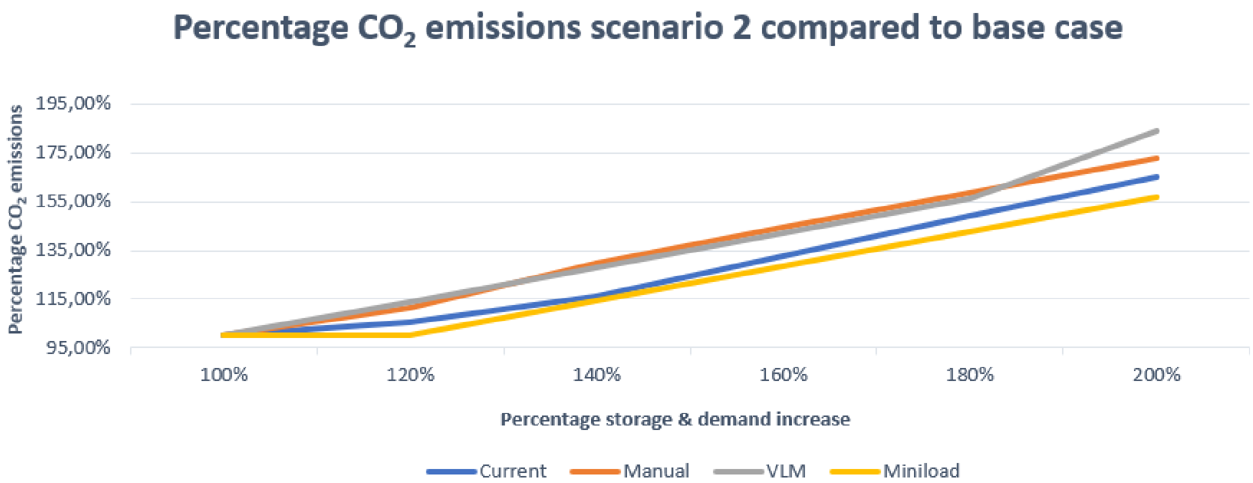

Figure 22: Percentage CO_2 emissions resulting from scenario 2: Parts, safety stock and demand increase

The results show that the CO_2 emissions also increase proportionately to the space requirement and the storage volume. The increase in market demand does not seem to have a big impact on the total carbon emissions as the automated systems do not increase substantially more than the manual configuration. The discrete elements identified previously in the increase of space requirement for the VLM and miniload AS/RS configurations can also be found here. Taking the relative increases into account, the miniload AS/RS seems to be the most robust with respect to an increase in storage volume and market demand. The differences are very small however and in the absolute sense the VLM has the smallest space requirement and emits the least carbon emissions. The scenario offers insight into the robustness of the configurations with respect to storage volume and market demand. The configurations are all affected similarly and the carbon emissions increase proportionately to the storage volume, while the demand increase does not have a substantial effect.

7.3 Scenario 3: Relocation and investment

The final scenario focuses on improving warehouse factors. A new warehouse is considered with dimensions matching the optimal performance of a system identified in section 6.1.1. As mentioned, the main goal of the relocation is improving the environmental performance of the warehouse. Therefore, investments are done to improve the isolation from a HLC of 0,3 to 0,25 $W/m^2\,°C$ and LED lights are used to illuminate the building. The analysis in section 6.1.1 provides an overview of the dimensions are which the storage systems perform better or worse. Based on the analysis, the setup in Table 28 is used for this scenario.

Table 28: Warehouse dimension setup for scenario 3: Relocation and investment

	Warehouse height [m]	**Aisle length [m]**
Current	8,25	37,5
Manual	5,5	62,5
VLM	16,5	-
Miniload	16,5	75

The VLM and miniload perform better as the height of the warehouse grows, therefore the highest dimension used in section 6.1.1 is applied. The VLM also does not have aisles and is unaffected by a desired aisle length. The current configuration has VLMs and bin-shelving and the desired height of the warehouse is therefore a compromise between the height of the VLM and the volume to be illuminated and conditioned. In section 6.1.1 the configuration performed best at 8,25 meters high and an aisle length of 37,5 meters. Finally, the manual configuration does not require a building height higher than the shelves, therefore the lowest metric for building height is used for this configuration. In section 6.1.1 the manual configuration performed best at an aisle length of 62,5 meters and this is used for the scenario. Table 29 shows the results of the scenario for different warehouse dimensions as well as improved lighting and HVAC. Figure 23 shows the percentage of the total space requirement resulting from the scenario and Figure 24 shows the percentage of total carbon emissions compared to the base case.

Table 29: Results of scenario 3: Relocation and investment

LED & HLC = 0,25	**Warehouse height [m]**	**Warehouse length [m]**	**Total space requirement [m2]**	**Total CO2 emissions [kg/year]**
Current	8,25	37,5	1238,44	14702,59
Manual	5,5	62,5	2695,14	17701,30
VLM	16,5	-	31,56	4888,97
Miniload	16,5	75	168,3	8289,70

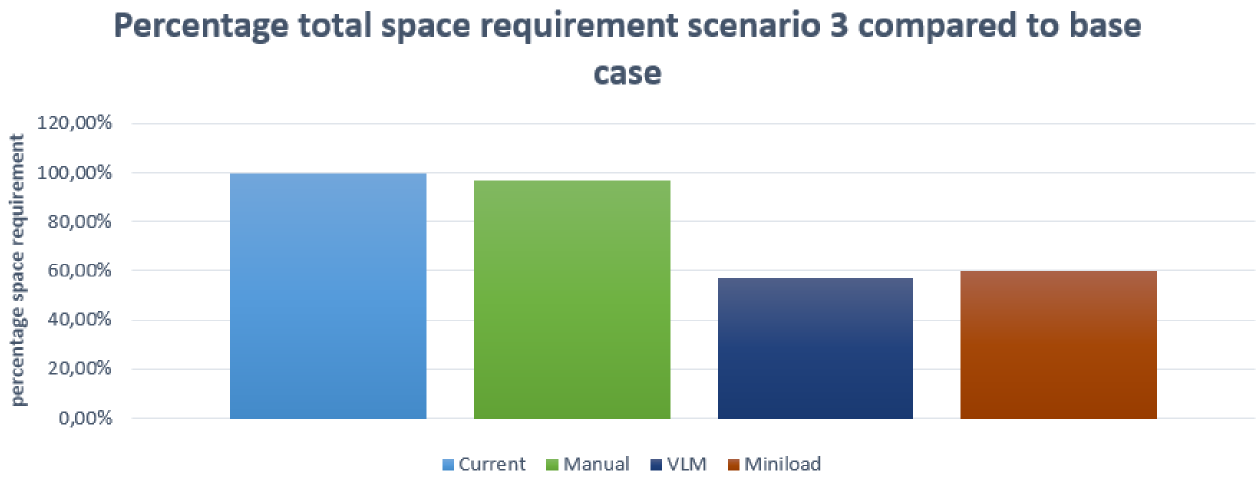

Figure 23: Percentage space requirement resulting from scenario 3: Relocation and investment

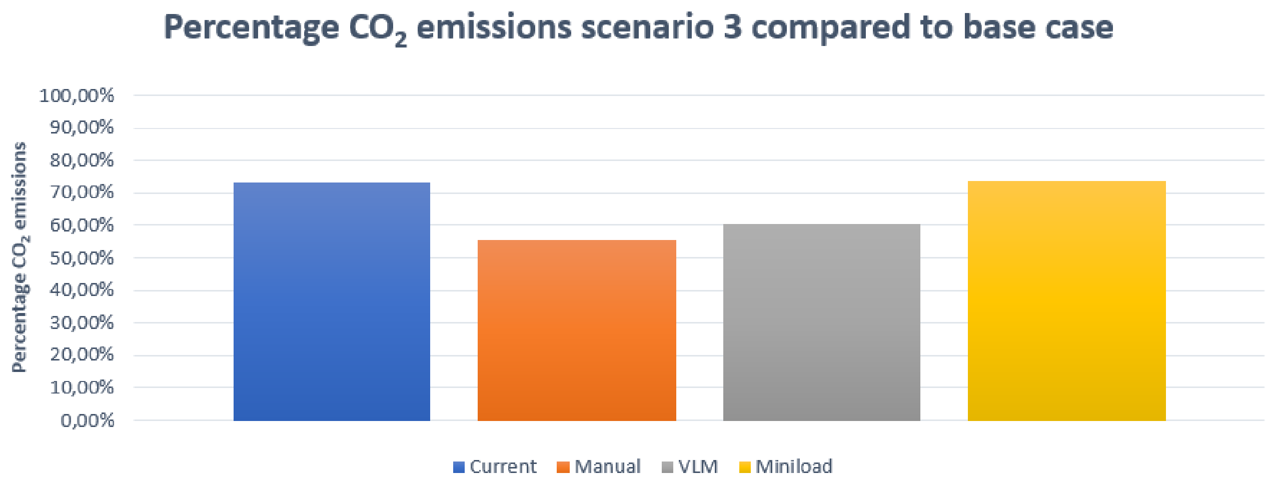

Figure 24: Percentage CO_2 emissions resulting from scenario 3: Relocation and investment

The results show that relocation and investment can have a substantial effect on total carbon emissions and space requirement. Especially the automated systems are affected by the building height, with a reduction of more than 40% in the total space requirement. Combined with LED lights and improved isolation, this results in a 40% decrease in total carbon emissions for the VLM configuration and 26% for the miniload AS/RS configuration. The biggest improvement is found in the manual configuration. Although the space requirement does not decrease substantially, the total carbon emissions are reduced by almost 55% due to the improved lighting and isolation and reduced warehouse volume resulting from the low building height.

The current configuration is not really affected with respect to space requirement, although the warehouse volume is decreased due to the lower building height. Combined with LED lighting and improved isolation, the total carbon emissions are reduced by 27%. It can be concluded that warehouse dimensions can have a great effect on total space requirement for systems that can make use of the vertical dimensions. For systems that cannot make use of this dimension, a low warehouse can substantially decrease the power consumption for lighting and HVAC as this decreases the warehouse volume and increases lighting intensity. improvements in lighting and isolation are also very important factors for warehouse carbon emissions and especially large warehouses are affected by these improvements.

The operational cost is compared to the cost of the initial case study configurations. The results show that warehouse design and investment can realise savings up to 20.000 euros per year. Due to the decreased space requirement and reduced energy requirement, operational cost decreases. The manual configuration is affected the greatest with savings of up to 41.000 euros per year. This configuration is greatly affected by the investment in sustainable equipment and shows how massive the effect of this measure can be on operational cost.

7.4 Conclusion

Sub question nine states: *How do the configurations of storage systems perform for the formulated scenarios?* Three different scenarios have been considered, focused on picking and storage policies, storage volume and system characteristics, and warehouse dimensions and building characteristics. The picking and storage policy scenario showed that the carbon emissions of automated systems can be substantially reduced by applying dedicated picking time slots combined with an ABC-class based storage policy. The current configuration that is a mix between bin-shelving and VLMs is also affected by around 15 percent, which is still a large margin.

Scenario two simulates an increase in business and customers with a increase in demand and storage volume. The space requirement and carbon emissions increase proportionately for all four configurations, although the miniload AS/RS has the smallest relative increase. In absolute sense the VLM performs best however, with the least emissions and smallest space requirement.

Scenario three simulates a new warehouse with dimensions suiting a specific storage system and improved lighting and isolation equipment. This has a great effect on the manual configuration with a decrease in carbon emissions of almost 50 percent, while the space requirement does not substantially decrease. For the VLM and miniload AS/RS configurations this is not the case, due to the high building height that can be applied. The space requirement is reduced by more than 40 percent for these configurations, which has a positive effect on the total carbon emissions as well. The scenario shows that designing a warehouse to suit the specific storage system can have a very positive effect on carbon emissions.

8 Conclusions

This thesis considers four different storage configurations, with the aim of analysing the impact of the choice for a certain storage system on environmental performance. An environmental model is developed to asses the space requirements and carbon emissions resulting from the use of a storage system. The initial analysis is performed at the warehouse of an aviation parts distributor. This analysis showed that the considered automated systems, vertical lift modules and miniload AS/RS, are efficient systems with respect to environmental performance. The space requirement of automated systems is lower than other traditional storage systems, due to the use of the vertical dimension for storage. The current configuration considered, related to the configuration used in practice by an aviation parts distributor, is a mix between bin-shelving and VLMs. When comparing this configuration with the bin-shelving configuration, it can be concluded that the addition of VLMs has a substantial effect on carbon emissions and space requirement. This in turn leads to a reduction in operating cost due to a decrease in power consumption and warehouse rent.

To further analyse the storage systems, factors affecting space requirement and carbon emissions are applied to the model. The effect of these factors on carbon emissions and space requirement is recorded to have an overview of the impactful factors to include in scenarios. These factors are:

- Warehouse dimensions
- Storage characteristics
- Building characteristics
- Picking policy
- System characteristics
- Storage volume
- Demand characteristics

Three scenarios are developed based on these factors. Scenario one considers a picking and storage policy. The results show that applying dedicated picking time slots and an ABC-class based storage policy has a great effect on carbon emissions for the VLM and miniload AS/RS. A reduction of more than 57 percent is identified for the VLM and 25 percent for the miniload AS/RS. The current storage configuration carbon emissions are reduced by 15 percent, which is still a substantial margin. The second scenario simulates the increase in demand and business. Demand and storage volume are increased to 200 percent. The results show that the miniload AS/RS is most robust to the considered increase, although the difference is not substantial. The space requirement and carbon emissions increase proportionately to the storage volume, while the demand increase does not have a substantial effect on the carbon emissions of the VLM and miniload AS/RS configurations. The final scenario considers a newly designed warehouse and investments in lighting and isolation. The results show that applying warehouse dimensions that suit a specific storage systems can have a substantial effect on space requirement for the VLM and miniload AS/RS configurations. Increasing building height can reduce space requirement of these systems by more than 40 percent. The investment in isolation and lighting has a significant effect on the carbon emissions of the bin-shelving and current configurations, due to the high space requirement of these systems.

The main question this thesis aims to answer states: *What impact do storage systems for aviation standard parts have on the environmental performance of a warehouse?* The analysis concludes that the choice of storage system has a great effect on the environmental footprint of a warehouse. The space requirement of a storage system is dependant on the configuration used and the power consumption from lighting and HVAC increases as the space requirement and warehouse volume increases. Automated systems offer a lower space requirement by making use of the vertical dimension and efficient storage options, however the power consumption of these systems increases the total power consumption and carbon footprint. The developed model shows however, that the increase in system power consumption is substantially lower than the power consumption of lighting and HVAC that results from the space requirement that bin-shelving units have. The automated systems can increase the environmental performance of a warehouse by a large margin. This ratio between power consumption from building equipment (lighting and HVAC) and system power consumption can be reduced by investing in more sustainable lighting and better isolation. The total carbon emissions are still lower for the considered automated systems. This can be further reduced with efficient picking and storage policies. The main focus point for reducing the system power consumption for automated systems of aviation standard parts should be stand-by power consumption as, in the considered case, this has a substantially larger share in the total system power consumption.

9 Discussion, recommendations and implications

The main research question of the thesis has been answered, however certain assumptions were made during research and design of the model that need discussing as well as providing interesting topics for further research. Following the discussion, recommendations are given focused on improving environmental and financial performance and choosing suitable storage systems. Finally, the scientific relevance and final deliverable of this thesis are elaborated on.

9.1 Discussion

Firstly, the considered aerospace part distributor has a unique business model where not only their parts are stored but also customer parts. As a consequence, many parts cannot be mixed with the same parts already present in the warehouse because they belong to a customer. This leads to a higher storage space without increasing storage volume. For these parts specific bins are present in the bin-shelving units. Due to this, the results based on space requirement can have underestimated the actual requirements.

Secondly, no transport equipment is used by the considered company, however this could be the case elsewhere. The model does not include transport equipment and does not take routing policies into consideration. This is also an interesting direction for future research. The model considers lighting, HVAC and material handling (in the form of automated storage systems) and could be extended to also include transport and routing of for instance an AGV or a forklift. This could increase the scientific relevance of the model as it then consolidates every aspect of environmental performance of a warehouse. An important side note is that, when analysing environmental performance, transport is mostly used for picker-to-part systems and the model shows that these systems already have a poor environmental performance. This performance becomes even worse with the inclusion of transport equipment.

Not all part-to-picker systems have been taken into account, section 2 identifies four different systems of which two are included into the model and thesis. This was done due to the character of the carousel systems. The vertical carousel is similar to the VLM with an exception being that the system moves all parts in the carousel when picking. This would lead to a higher operational power consumption because the mass moved is higher. As a result only the VLM is taken into account because it is expected to have a better environmental performance. The horizontal carousel is unique due to the inability to make use of the vertical dimension. This is one of the main benefits to using an automated system and therefore it was not considered. For further research this could be an interesting topic as these systems are known to be less expensive when compared to the VLM and miniload AS/RS (Dube, n.d.). For financial analysis this could be an interesting subject.

Section 4 shows how the model is developed. It becomes clear that the model is dependent on a large number of parameters. As a result, the use of the model requires a extensive and clear knowledge of the considered context. This can be seen as a disadvantage to using the model as it can only asses the environmental performance of a configuration and not determine the optimal configuration and structure of a storage system. The dependency on parameters does mean though, that the model can be applied to many situations and is very flexible in use. With sufficient knowledge of the context, it can be used for any warehouse that includes the considered storage systems.

Aside from the parameter dependency, the model does have some limitations. The stand-by power consumption of the automated systems was related to that of a standard lift system. This factor has a substantial effect on system power consumption and unfortunately no clear metrics of this factor were found. The sensitivity analysis also shows that the carbon emissions of the VLM and miniload AS/RS are sensitive to this factor. The model structure allows for variation in multiple parameters, which allows for different metrics to be tested. In this way, the model user can still operate the model without over or under estimating stand-by power consumption. An interesting research subject could be the determination of stand-by power consumption for specific configurations of automated storage systems. Secondly, the model uses a storage volume to approximate the storage requirement of the considered company. As a result, the total storage volume does not accurately represent the required storage capacity. In collaboration with the company employees, it was determined that this was the best way of approximating this value.

9.2 Recommendations

The results of the analysis can be used to offer recommendation on the use of storage systems. The environmental performance of the four storage systems can be improved with measures identified in this paper. Firstly, warehouse isolation and lighting equipment have a very large effect on the environmental performance. When designing a new warehouse or looking for ways of improving warehouse carbon footprint, these aspects should be the first considered investment. In the case of automated systems that contain small standard parts, the operational power consumption will mostly not be substantial compared to stand-by power consumption. This is also an aspect that should be looked at when wanting to improve environmental performance.

The best improvements can be made prior to having a warehouse or when relocating a warehouse. The results of scenario 3 show that applying warehouse dimensions that suit a specific storage system has a very positive effect on the total carbon emissions and operational cost. A higher warehouse when using a part-to-picker system and lower when this is not the case. Combining this with investments in lighting and isolation can result in a decrease in carbon emissions of 50 percent and up to 40.000 euros in savings per year.

Other measures such as dedicated time slots as well as in vesting in part-to-picker systems have also been shown to have a substantial effect on operational costs if a warehouse. Applying this measure as well as extending the share of part-to-picker systems is advised for decreasing financial cost as well as improving environmental performance.

9.3 Scientific relevance

The scientific relevance of this thesis can be found in the model. Two knowledge gaps are identified; a consolidated method to determining environmental performance of a storage system and a model able to determine power consumption of a VLM and a miniload AS/RS The model consolidates three different aspect of determining the environmental performance of a small part storage system, namely lighting HVAC and material handling. This can benefit the future design and operations of warehouses in the aerospace sector, but can also be applied for many other sectors.

The model offers a method for calculating energy requirements of a VLM and miniload AS/RS system without having to record the actual power consumed. This was missing in the literature and did provide some challenges in the initial development of the model for the part-to-picker systems. In the end, the model is able to convert the mechanical processes performed by the systems into power consumption. In the future the model can act as an initial evaluation for the expected power output of these systems.

9.4 Final deliverable

The final deliverable offers multiple use cases. As stated in this thesis, the model allows the user to evaluate alternative storage systems and offer advice based on the space requirement and carbon emissions resulting from a certain storage system. Also, the model offers a method for determining the specific source of power consumption. In the considered case for instance, it was determined that approximately 52 percent of power consumption originated from HVAC and only 15 percent originated from the VLM. This allows for a more effective approach to decreasing carbon footprint.

The model can also aid in certain forecasting activities. The storage and energy requirements of a future storage system given a certain storage volume can be simulated, allowing for a more suitable approach to extending the current storage options. Storage policies can also be applied to the model, allowing the user to evaluate the effects of a certain policy on power consumption and space requirement.

The final use cases are focused on the design of a new warehouse or storage system. The model allows the user to evaluate different warehouse configurations and specific lighting and HVAC equipment. This results in a better understanding of storage system requirements and a more storage system specific structure to the warehouse. Lastly, a storage system can be applied to the new warehouse and structured according to the model parameters that result in the lowest space requirement or carbon emissions.

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A Interviews

A.1 Manager program management Kaveh Alizadeh

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A.2 Manager SHEQ Martin de jong

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A.3 Storage system manufacturer account manager Martijn Rijnbeek

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B Case study overview

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C Case study application

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