Nils-Petter Santala Johansen

Storage of different length SKUs utilizing the block stacking method

Master's thesis in Global Manufacturing Management
Supervisor: Fabio Sgarbossa
Co-supervisor: Mirco Peron

June 2021

Master's thesis

NTNU
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Summary

This thesis aimed to explore how the block stacking storage method can be applied to stock-keeping units (SKUs) of different lengths for the purpose of developing a mathematical model that can determine the lane depth and arrange the different length SKUs into storage rows. The research was structured based on three research questions; 1) How can block stacking be applied for warehousing of SKUs with different lengths? 2) What is a suitable placement of different length SKUs in a block stacking warehouse? 3) What is a suitable storage policy of different length SKUs in a block stacking warehouse?

A literature study was conducted to get a good understanding of the existing literature on block stacking storage. In addition, a single-case study was performed at Skogmo Bruk to obtain empirical data for the thesis, where data was collected through interviews, site observations, and documents made available. The research methods and data created a solid base for answering the research questions and develop the mathematical model.

The literature study identified that accessibility to the SKUs and space utilization are the key factors to make the block stacking method function. Further, from the case study of Skogmo Bruk, the third factor of detailed product descriptions was obtained. Two methods were selected for the configuration of the storage rows, tiers and cutting stock. The tiers method was later chosen as the preferred method because it is easier to implement and provide similar results to cutting stock when the number of slot sizes exceeds five. The class-based storage policy, combined with allowing blockage for the less popular products, was argued to be the best fit for storage of SKUs with different length in a block stacking warehouse based on the findings in the literature study and case study.

The mathematical model developed from the findings of the literature study and case study shows that the block stacking method can be applied to SKUs of different lengths. Furthermore, the model provides the lane depths for the SKUs, the number of lanes required to store the SKUs, and configures storage rows using the tiers method.

Keywords – Block Stacking, warehouse, lane depth, storage row, storage policy

Sammendrag

Denne masteroppgaven utforsker hvordan lagermetoden block stacking kan benyttes på lagerenheter (SKU'er) av ulike lengder for å utvikle en matematisk modell som kan bestemme lagerdybder og arrangere de ulike lagerenhetene inn i lagerrader. Oppgaven er strukturert etter tre forskningsspørsmål; 1) Hvordan kan lagermetoden block stacking brukes for å lagre lagerenheter med ulike lengder? 2) Hvordan burde lagerenheter med ulike lengder plasseres i et lager som følger block stacking lagermetodikken? 3) Hva er en hensiktsmessig lagringspolicy for lagerenheter med ulike lengder i et lager som følger block stacking lagermetodikken?

En litteraturstudie ble gjennomført for å få en god oversikt over den eksisterende litteraturen om block stacking. Denne ble etterfulgt av en case-studie ved bedriften Skogmo Bruk for å innhente empiriske data til oppgaven. Informasjon og data ble samlet inn gjennom intervjuer, observasjoner på stedet og tilgjengeliggjorte dokumenter. Forskningsmetodene la et solid grunnlag for å svare på forskningsspørsmålene, og for utviklingen av den matematiske modellen.

Litteraturstudiet identifiserte tilgjengelighet til lagerenhetene og plassutnyttelse av lageret som de to viktigste faktorene for block stacking metoden. Videre, gjennom case-studien av Skogmo Bruk, ble en tredje faktor identifisert – detaljerte produktbeskrivelser. To metoder ble vurdert for konfigurasjon av lagerradene, tiers og cutting stock. Metoden tiers ble valgt som den mest passende grunnet at den var enklere å implementere, og at den gav tilnærmet like resultater som cutting stock metoden når antallet lagerplasstørrelser oversteg fem. Den klassebaserte lagringspolicyen, kombinert med å tillate blokkering av de mindre populære produktene, ble funnet å være den beste løsningen for lagring av lagerenheter med ulike lengder, basert på funnene i litteraturstudien og case-studien.

Den matematiske modellen som ble utviklet på bakgrunn av funnene i litteraturstudiet og case-studiet viser at block stacking kan bli tilpasset til å fungere for lagerenheter med ulike lengder. Modellen leverer lagerdybden for de ulike lagerenhetene, antall lagerplasser som trengs for å lagre alle lagerenhetene, samt konfigurerer lagerradene basert på tiers metoden.

Nøkkelord – Block Stacking, lager, lagerdybde, lagerrad, lagerpolicy

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1 Introduction

This chapter first presents the theoretical and practical motivation for this thesis. Followed by the research questions and the objectives used to guide the research process. Next, the research scope is defined and described. Then, a short section going over the research development. Lastly, the overall structure of the thesis is listed.

1.1 Theoretical and practical motivation

The warehouse is a crucial aspect of the supply chain, and its role can determine whether a company is successful or not (Baker and Canessa, 2009). The role of the warehouse in the supply chain is to store or buffer products (raw material, work-in-process, finished products) at and between the point of origin and point of consumption (de Koster et al., 2007). For making the warehouse efficient, the storage unit, the storage system and the equipment need to be suitable for the products that are to be stored in the warehouse, and they should not conflict with each other (Rouwenhorst et al., 2000). For storage of pallets, there are numerous ways of doing it as described by Bartholdi and Hackman (2014) pallets can be stored on the warehouse floor with the use of block stacking, or they can be stored in racks (single-deep rack, double-deep rack, push-back rack, drive-in or drive-through rack, and pallet flow rack). For this thesis, storage on the warehouse floor with the use of block stacking will be the only method taken into consideration.

The term block stacking refers to a unit load storage system consisting of placing pallets of stock-keeping-units (SKUs) on top of one another on the warehouse floor (Derhami et al., 2020). Block stacking is a cost-effective and easy to implement storage method in terms of not having to have complex warehouse infrastructures such as shelves and racks; the only requirement is open floor space for storage (Derhami et al., 2017). Use of the block stacking method is typical in many industries like food, beverage, appliances, paper, wood products and so on (Tompkins et al., 2010).

The block stacking storage method typically operates under one of the three storage policies; (1) dedicated storage policy, (2) shared storage policy, or (3) class-based storage policy (Venkitasubramony and Adil, 2019b). The dedicated storage policy is simple, every SKU gets a specific location within the warehouse, and that specific SKU is the only SKU that can be stored in that location (Bartholdi and Hackman, 2014). The shared storage policy allows SKUs to be placed at any given empty storage location within the warehouse (Venkitasubramony and Adil, 2019b). The last policy, class-based, is a combination of the dedicated and shared policy where the different SKUs are divided into different classes, and each class gets a specific location within the warehouse where SKUs within that class can share that space (Kay, 2015).

Literature highlights the importance of determining the optimal lane depth for the storage lanes in a block stacking warehouse (Venkitasubramony and Adil, 2019b; Derhami et al., 2017, 2019). Several factors need to be considered for determining the optimal lane depth, such as the number of aisles, cross-aisles, bay depths, and type of cross-aisles. Lane depth affects both the material handling cost and the space utilization of the warehouse (Venkitasubramony and Adil, 2019b). Effects of the lane depth and the number of aisles can be seen by the phenomenon referred to as honeycombing or honeycomb loss (Venkitasubramony and Adil, 2019b). Honeycombing can be viewed as a measurement of space utilization as it measures empty storage spaces within the warehouse. Having deep storage lanes creates more empty spaces over time than shallower storage lanes (Venkitasubramony and Adil, 2019a).

Literature on the topic of block stacking focuses for the most part either on storage of standard pallets (Rojanapitoon and Teeravaraprug, 2018; Derhami et al., 2020; Venkitasubramony and Adil, 2019b; Accorsi et al., 2017; Venkitasubramony and Adil, 2019a, 2020; Derhami et al., 2017, 2019), where optimal lane dept, space utilization and minimizing material handling cost are vital aspects. The other area that block stacking plays a considerable role is in determining the optimal placement of shipping containers with respects to the number of relocation's (Yang and Kim, 2006; Caserta et al., 2011; Shin and Kim, 2015; Jang et al., 2013).

Skogmo Bruk is a relatively small factory producing impregnated wood products, such as planks, poles and beams. The production of these products is fairly efficient given that the raw materials are in place and ready to be used. The finished goods are stored in a large outdoor warehouse. The warehouse is operated with a single operator, using a truck loader. The stored products in the warehouse use the block stacking method; pallets are placed on top and in front of each other in storage rows. The products are placed in a random arrangement with considerable gaps between each storage slot, taking up much of the outdoor space. Having observed the ineffective use of storage space motivated this thesis to investigate ways to utilize the block stacking method better to give a more compact and efficient storage solution.

This thesis aims to start filling the gap in the block stacking literature on how to apply the block stacking storage method to SKUs that have different lengths. A comprehensive and detailed review of the block stacking method identifies the crucial factors to consider for further development. As well, to review and examine the genuine case of Skogmo Bruk. Before drawing the strings together, providing a method to apply the block stacking method to the storage of different length SKUs and providing an efficient warehouse solution. The research of this thesis will first and foremost be intended for the lumber industry, more specifically the companies that deal with the wood products when they have been processed into planks, poles and beams. But nothing restricts the research from being applied to other industries with similar product dimensions and storage methods, such as in the construction industry with the storage of concrete hollow-core slabs.

1.2 Research questions and objectives

The overall scientific goal for this thesis is to explore and develop a mathematical model for more effective storage of large products (in this case, wooden planks, poles and beams) that are similar in their packaging dimensions except for the lengths of the packages, with use of the block stacking method. Three research questions and associated objectives have been developed to drive the research forward to achieve this goal.

Research question 1:

How can block stacking be applied for warehousing of SKUs with different lengths?

Research question one aims to explore which factors of the block stacking method that is essential for the method itself and how they can be applied or adjusted to handle SKUs of different lengths. For answering this question, a thorough review of existing literature on block stacking will be essential to derive the important factors to consider for implementation of SKUs that have different lengths into the block stacking method. Further, the identified factors will be applied to a model that is designed for handling SKUs of different lengths.

Research question 2:
What is a suitable placement of different length SKUs in a block stacking warehouse?

Research question two aims to explore how the specific placement of a SKU(s) may affect the overall efficiency of a block stacking warehouse and if the SKUs of different lengths affect the problem. By specific placement in this thesis means arranging the SKUs strategically to reduce the time spent searching for a SKU and the time spent to store and retrieve the SKUs. For answering this research question, a review of the literature combined with the findings from the case study will be required. The findings from the research question will be incorporated into the mathematical model.

Research question 3:
What is a suitable storage policy of different length SKUs in a block stacking warehouse?

Research question three aims to investigate the effect that the different storage policies have on a block stacking warehouse that accommodates SKUs of different lengths. For answering this research question, a review of the literature related to the storage policies used in block stacking warehouses will be required. The characteristics of the different storage policies will be evaluated against findings from the case study to conclude which storage policy is best suited for storing different length SKUs.

1.3 Research scope

The scope of the thesis can be defined in terms of the following:

- the block stacking method and its components
- the placement of SKUs in a block stacking warehouse
- the storage policies for SKUs in a block stacking warehouse

In terms of the block stacking method, this thesis concentrates on the factors and components that the block stacking method is built upon to adapt and adjust it to accommodate SKUs that have differences in the lengths of their packaging. Lane depth of the storage rows is one of the key components of the block stacking method, the number of storage lanes to be able to store the necessary amount of SKUs is an essential factor, and the aisles within the warehouse is a crucial factor to consider in order to facilitate access to the SKUs. Combining these factors and components of the block stacking method focuses on reducing the waste of space, both the waste of space within the storage lanes (honeycombing-loss) and for the entire warehouse.

In terms of placement of the SKUs, this thesis will concentrate on the specific placement of SKUs that will give structure, accessibility and consume less time when storing and retrieving the SKUs. The scope will be limited to the storage row configuration of the different length SKUs. The SKUs will be placed in the storage row orientated with the longest side facing out to the aisle. The research into the best placement for the different length SKUs will first consist of evaluating a suitable method, followed by implementing the method into the mathematical model. Testing the performance of the methods regarding space utilization and travel distance to store and retrieve the products is outside of this thesis's scope.

In terms of storage policies, this thesis will focus its attention on the three most common storage policies used with the block stacking method; dedicated, shared, and class-based (Venkitasubramony and Adil, 2019b). The storage policies will be described, and factors that are important to store SKUs of different lengths will be extracted. The research into what storage policy will be best for storing SKUs with different lengths will be limited to qualitative reasoning. The goal is to use logical reasoning based on the factors of the storage policies to justify the choice of storage police for storage of SKUs with different lengths.

1.4 Research development

The research development of this thesis is illustrated in figure 1.1. It shows that the specialization project conducted at NTNU in the autumn of 2020 and a preliminary literature review made up the starting point for this thesis. The specialization project and the literature review made up the research problem, which resulted in defining the research questions, research objectives and the research scope. This again brought the need for a literature study and a case study. From the literature study and the case study, a mathematical model was made. The theoretical and empirical findings from the literature study and the case study, combined with the findings from the mathematical model, formed a solid base for discussion and a conclusion for the master thesis.

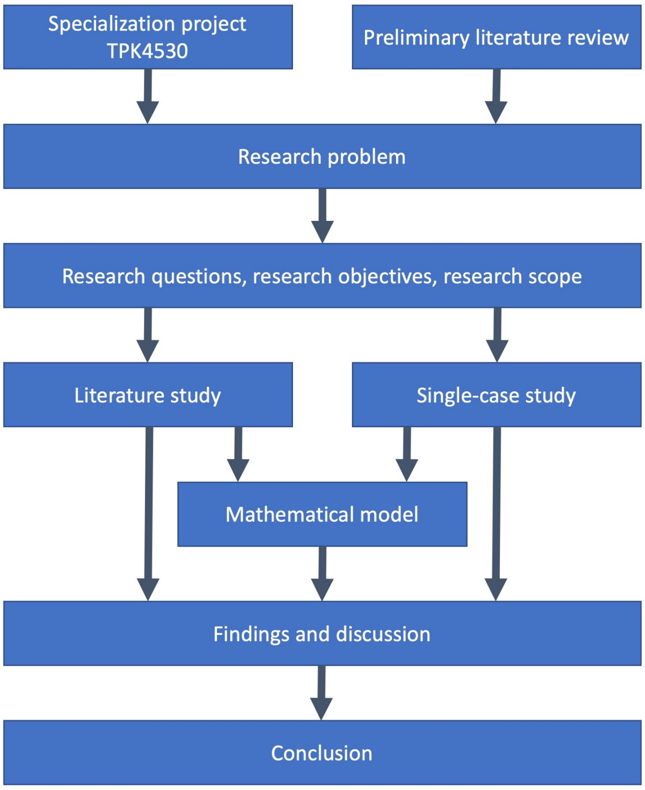

Figure 1.1: Research development of the master thesis.

1.5 Outline of the thesis

This thesis is structured with chapter 1 introducing the theoretical and practical motivation, followed by the research questions and objectives, then the research scope, and lastly, the outline of the thesis. Chapter 2 presents and justifies the methodology used in this thesis, starting with research methodology, followed by the theoretical methods, the empirical methods, and a quality assessment. Chapter 3 provides the theoretical framework of this thesis as a result of the literature study, starting with a detailed description of block stacking as a method, followed by three essential factors of space utilization. Then the three most common storage policies are described, and the chapter ends with the literature findings. Chapter 4 presents the case study of Skogmo Bruk, starting with an introduction to Skogmo Bruk, followed by a description of the current situation, and ending with the case study findings. Chapter 5 presents the mathematical model resulting from the literature study and the case study. Then in chapter 6, the research questions' findings and discussion are addressed, and the contribution, limitations, and further research are addressed. Lastly, in chapter 7, the conclusion of the thesis is presented.

2 Methodology

In this chapter, the methodology's used in this thesis is presented. Starting with defining what research methodology is and justifying the research methods used to answer the research questions and objectives. Next, defining how the literature study was conducted. Then, going over how the case study was conducted in terms of what type of case study was performed, the process of collecting data, and how the data was analysed. Ending with how the research was assessed for quality.

2.1 Research methodology

Research methodology is essentially a systematic procedure to solve a research problem (Kothari, 2004). It can be viewed as the procedure of describing, exploring and predicting a phenomenon by applying methods, scientific tools and techniques (Rajasekar et al., 2013). The methods, tools and techniques of research used to gather data and information are referred to as research methods (Karlsson, 2016).

Quantitative and qualitative

Research methods can be quantitative or qualitative or a combination of both (Rajasekar et al., 2013). Quantitative research is based on the concept of measurement of a quantity or amount, and it is applied to a phenomenon that can be expressed numerically (Kothari, 2004). Rajasekar et al. (2013) brings up the following characteristics to describe quantitative research; a numerical, non-descriptive, iterative process where the evidence is evaluated, results are often presented in either graphs or tables, and it is conclusive. Qualitative research, on the other hand, focuses on phenomena that relate or involve quality (Kothari, 2004). Rajasekar et al. (2013) describes qualitative research as being; descriptive, where reasoning is applied to explain the situation and to be exploratory. In this thesis, a combination of both quantitative and qualitative research has been used. A combination is preferred to get good reasoning behind the numbers or, more precisely, the study's quantitative evidence.

The logic of argumentation

An argument is essentially a series of statements or propositions that are connected to provide support, justification, or evidence to another statement or proposition (Karlsson, 2016). According to Karlsson (2016), an argument consists of three parts: premises, inference, and conclusion. The premise is the statement or proposition that is put forward in the beginning, and the inference is the reasoning process that leads to a conclusion (Karlsson, 2016). The inference or reasoning of an argument can be divided into three types: deductive, inductive, and abductive reasoning (Karlsson, 2016). How they differ from each other is in the way that they structure the three components that they are built upon; rule, observation, and result (Karlsson, 2016). The rule is based on theory, observation is based on empirical evidence, and the result is gained through analysing data (Karlsson, 2016). See figure 2.1 for how the components are structured and put together for the three types of reasoning.

Deduction	Induction	Abduction
Rule ↓ Observation ↓ Result	Observation ↓ Result ↓ Rule	Result ↓ Rule ↓ Observation

Figure 2.1: The three types of reasoning (Karlsson, 2016).

The research in this thesis is based on a combination of existing theory and empirical observations and data. As there is little theory and research on the objective of this thesis, the focus has not been on confirming the existing theory, but on finding the important features that have not yet been described in the literature. As a result of this, the research is closer to an inductive than a deductive or abductive argumentation approach.

2.2 Theoretical methods

The literature study aims to explore the existing knowledge and ideas on the chosen research topic. When researching a topic within a specific field, it is essential to know if the problem at hand has already been solved, and if not, what is the current status of the problem (Rajasekar et al., 2013). The literature study should be conducted in a systematic and structured manner to ensure that a relative complete census of all the relevant literature is established (Webster and Watson, 2002) and it is crucial to be transparent in the steps to facilitate replicability (Tranfield et al., 2003). Being systematic starts with having a plan of how the literature study should be conducted, in terms of keywords, search terms, search strings, and criteria for inclusion and exclusion (Karlsson, 2016).

For conducting the systematic review of the literature, two sets of search terms were listed, see table 2.1. The search terms were selected to cover all potential articles related to block stacking in a warehouse environment. A typical search in one of the databases would look something like this: TITLE-ABS-KEY (("block stacking" OR "floor stacking" OR "floor storage") AND ("warehouse" OR "layout" OR "design" OR "material flow" OR "lane depth" OR "space utilization" OR "optimization")) AND (LIMIT-TO(SRCTYPE,"j")) AND (LIMIT-TO (LANGUAGE, "English")).

Table 2.1: Search terms for the literature study ("Set 1" AND "Set 2").

Set 1	Set 2
Block stacking	Warehouse
Floor stacking	Layout
Floor storage	Design
	Material Flow
	Lane depth
	Space Utilization
	Optimization

One of the important parts of a structured literature study is to establish the inclusion and exclusion criteria (Meline, 2006). The reason for including this type of criteria to the literature study is to establish an objective reasoning about the choice of literature selected. The inclusion and exclusion criteria that is used in this literature study are as listed in table 2.2.

Table 2.2: Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Document type: *Journal article*	Non-English (NE)
	Not related to Warehousing and Block Stacking (NR)
	No full text (NF)
	Vaguely related to Warehousing and Block Stacking (VR)

The literature search was conducted with the following databases; Scopus, Pro Quest, Web of Science, Science Direct and NTNU Bibsys/Oria. Table 2.3 show the search results using the search terms from table 2.1 in the above mentioned databases. Table 2.3 also show the number of selected articles from the respective databases based on the inclusion and exclusion criteria listed in table 2.2.

Table 2.3: Search results in each of the databases.

	Scopus	Pro Quest	Web of Science	Science Direct	Bibsys/Oria
Results	40	378	46	32	27
Selected	18	6	15	5	6

Table 2.4 shows the number of duplicates in the selected articles among the databases. Given the 18 selected articles of Scopus, 3 of the 18 was found on Pro Quest, 15 of 18 was found on Web of Science, 3 of 18 on Science Direct, and 5 of 18 on Bibsys/Oria. This shows that there is a high percentage of overlapping among the databases. After removing the duplicates of the selected articles, the number of selected articles was reduced from 50 to 24.

Table 2.4: Duplication of selected articles among the databases.

	Scopus	Pro Quest	Web of Science	Science Direct	Bibsys/Oria
Scopus	-	-	-	-	-
Pro Quest	3	-	-	-	-
Web of Science	15	3	-	-	-
Science Direct	3	0	3	-	-
Bibsys/Oria	5	2	5	0	-

Additional literature was also found by searching through the reference list of relevant articles. This technique is referred to as snowball sampling and is a common technique used in the early stages of research. According to Jalali and Wohlin (2012), following the snowball sampling technique will give relative similar results as of a database search. In addition to using the snowball sampling technique, the supervisors recommended a few additional articles.

2.3 Empirical methods

To better understand the research problem, assessing it in further detail and from different viewpoints, a case study design is chosen. Using case study as a research strategy allows the focus to be devoted to investigating the dynamic presence of a single event (Eisenhardt, 1989). Case studies can involve either a single case or multiple cases, having multiple methods for data collection, different levels of analysis, and include both quantitative and qualitative empirically generated data (Eisenhardt, 1989; Voss et al., 2002; Yin, 2003). Voss et al. (2002) cites three strengths of using case studies as a research strategy put forward by Benbasat et al. (1987):

1. The phenomenon of interest can be examined in its natural setting, and relevant theory can be extracted from observing the actual practice.
2. Questions like *why*, *how*, and *what* can be answered with a relatively good understanding of the full complexity and nature of the phenomenon.
3. The case method is suitable for early exploratory investigations where the complete picture of a phenomenon is not fully understood yet.

The case study approach was selected as a research strategy for this thesis based on the strengths listed above.

According to Karlsson (2016), case studies can be used for four different research purposes: exploration, theory building, theory testing and theory elaboration/refinement. By exploration, Karlsson (2016) means to discover areas for research and theory development. Theory building focuses on identifying and describing the key constructs, the linkages between the variables, and determining why these relationships exist (Karlsson, 2016). Theory testing test the developed theories and predicts further outcomes (Karlsson, 2016). Lastly, Theory extension or refinement focus on creating an understanding of the new phenomenon and better structure the theories in light of the new observations (Karlsson, 2016). As there is little research on how to store different lengths SKUs in a block stacking warehouse, this thesis will focus on a case study with the purpose of exploration.

2.3.1 Single-case study

According to Voss et al. (2002), there is no clear definition of what a single-case study is. Single cases may give the opportunity to study several contexts within the same case (Voss et al., 2002). Using a single case allows for greater depth in the research and can be powerful, both in the starting phase of theory development and when an abductive approach is taken in the research (Karlsson, 2016). Benbasat et al. (1987) states that in highly exploratory research, a single case may be beneficial as a pilot study, where the goal is to determine the appropriate unit of interest and familiarize with the context of the phenomenon. There is also the possibility that a single-case study that is used for exploration can be followed by a multiple-case study (Benbasat et al., 1987).

Using a single case instead of multiple have limitations. The limiting factor is the generalizability of the conclusion, models or the theory developed from the single-case study (Voss et al., 2002). There may also be other potential problems as the risk of misjudging a single event and exaggerating the available data (Karlsson, 2016). Although the same risks exist in all case research, the chance is mitigated when there are multiple cases, and the data can be cross-referenced (Voss et al., 2002).

2.3.2 Data collection

For collecting data or evidence for a case study, a combination of sources is typically used (Eisenhardt, 1989). Yin (2003) lists six different sources: documents, archival records, interviews, direct observation, participant observation and physical artefacts. The data gathered from these sources may be qualitative, quantitative, or a combination of both (Eisenhardt, 1989). According to Yin (2003), there is no one source that has a complete advantage over the others. One should use a combination of different sources, referred to as triangulation, to study the phenomenon (Voss et al., 2002). The reliability of the data collected will also increase if multiple sources of data can be tied to the phenomenon (Karlsson, 2016).

Much of the data collected for a case study will be collected through interviews (Voss et al., 2002). Interviews can be structured in many ways; they can be unstructured, semi-structured or highly structured, resembling a questionnaire (Voss et al., 2002; Karlsson, 2016). And as mentioned above, the more sources, the more reliable the data will be. Direct observation of the phenomenon can be a great source of evidence; this can be of meetings, processes etc. (Voss et al., 2002). Getting access to such sources requires an ideal prime contact with good knowledge of the operation and can access the necessary data (Voss et al., 2002; Karlsson, 2016).

Case research is often associated with qualitative data, but this should not limit the researcher to only include qualitative data and not seek to find quantitative data (Voss et al., 2002; Karlsson, 2016). Combining both qualitative and quantitative data can be highly synergistic, according to Eisenhardt (1989). Quantitative data can strengthen the understanding of the qualitative data (Eisenhardt, 1989).

The data collection for this thesis consists of multiple of the sources listed above. Interviews were conducted with the manager at the case company; he can be viewed as a key contact with excellent knowledge of the operations and have access to all necessary documentation and information. Some of the workers at the case company were also casually interviewed to get a better understanding of specific processes. Documentation in terms of sales data and product mix was also provided by the manager at the case company. Lastly, two factory tours by the manager were done, and one company visit for three days was conducted to get a good understanding of the operations at the case company on a day to day basis.

2.3.3 Data analysis

Analyzing evidence from a case study is at the heart of building new theory (Eisenhardt, 1989), performing the analysis may be difficult as the strategies and techniques are not well defined (Yin, 2003). Nevertheless, Eisenhardt (1989) puts forward two steps to analyze the evidence: analysis of within-case data and searching for cross-case patterns.

The first step, within-case analysis focus on developing detailed descriptions of the data (Eisenhardt, 1989; Voss et al., 2002). Having the detailed descriptions of the case(s) is central to the generation of insight and helps the researcher cope with the amount of data (Eisenhardt, 1989). The overall idea of this process is to get familiar with the case and let the unique patterns emerge (Eisenhardt, 1989; Voss et al., 2002).

The second step, searching for cross-case patterns, focus on enhancing the generalisability of the conclusions drawn from the cases (Voss et al., 2002). For performing this cross-case analysis, there are several strategies for doing so. Eisenhardt (1989) presents a strategy that divides the data by data source, exploiting the unique insights that can be made for the different types of data collected. When one pattern is found in one data source and also in another data source, the finding is more robust and better grounded (Eisenhardt, 1989). The overall idea of cross-case analysis is to force the researcher to go beyond the initial impressions of the case (Eisenhardt, 1989).

Since this thesis focus on a single-case study, performing both of the analysis that Eisenhardt (1989) presents will be difficult as the cross-case analysis is intended for multiple cases. Nevertheless, the first within-case analysis will be conducted to get a good overview of the case and the different data sources, and then a second analysis of pattern matching from Yin (2003) will be performed. Pattern matching works similar to the cross-case analysis but only investigating within one single case.

2.4 Quality assessment

Assessing the quality of the research that has been conducted is an essential step in case research. Quality assessment involves questions to the form and content of the research and how well the research has been conducted can be evaluated based on four criteria put forward by Karlsson (2016); Construct validity, internal validity, external validity, and reliability.

Construct validity seeks to address that what has been claimed to be studied by the researcher actually have been researched in the study (Karlsson, 2016). It also involves how the case research has been conducted regarding data triangulation, data collection procedure, and explanation of data analysis. In this thesis, this has been achieved by having multiple sources for data collection: observation of the operations at the case company, documentation such as sales data and product catalogue, and casual interviews with both key personnel and workers at the case company.

Internal validity concerns the extent to which casual relationships can be examined in terms of pattern matching and having multiple perspectives to the case (Karlsson, 2016). In this thesis, internal validity has been achieved to an extent, and patterns have been drawn by looking at the whole case. Since this thesis is limited to a single-case study, drawing patterns by comparing the case to other cases was not possible.

External validity concerns how findings from one case study can be applied to other similar cases (Karlsson, 2016). In this thesis, the findings from the case study have been compared to findings in theory from the literature study.

Lastly, reliability refers to the possibility of replicating the case-study and to get the same results. For achieving this the work needs to be transparent and have sufficient documentation to how the steps of the research have been conducted (Karlsson, 2016).

3 Literature study

This chapter states the relevant concepts and terms that the research is based upon and present the theoretical background needed for answering the research questions. The first section defines block stacking as a warehouse method. Then, space utilization in a block stacking warehouse is examined. Further, storage policies for a block stacking warehouse are presented. Finally, the chapter closes with a summary of the findings from the literature study.

3.1 Block stacking

Block stacking, also known as floor storage, is the simplest form of pallet storage where pallets are placed on top of another (Rushton et al., 2014). The principle behind block stacking is essentially to have an open storage space where unit loads are stacked on top and in front of each other in storage lanes; the depth of the storage lane is usually between two and ten (Tompkins et al., 2010). The height of the storage lane is normally defined as the maximum number of unit loads that can be stacked on top of each other, restricted by crushability, stability of the loads or building clear height (Tompkins et al., 2010; Bartholdi and Hackman, 2014; Rushton et al., 2014).

Block stacking is an effective storage method when there are multiple pallets per Stock-Keeping-Unit (SKU) and when the inventory is withdrawn or received in large increments (Tompkins et al., 2010). For making the method effective, re-handling should be avoided; each storage lot should only contain one SKU. Once the storage lot is filled, it should be completely emptied before it is refilled to ensure that the product doesn't get "trapped" for a long period of time. This implies that one SKU should have more than one storage lot to facilitate stock rotation (Rushton et al., 2014; Bartholdi and Hackman, 2014; Kay, 2015).

Block stacking works well for storing few products with a high inventory level and is best suited when there is no strict policy of first-in, first-out (FIFO), as the method follows more of a last-in, first-out (LIFO) policy (Rushton et al., 2014). The method has several advantages, such as; good space utilization, flexibility to change in terms of layout design, easy to access inventory, and low capital cost (no need for storage racks) (Rushton et al., 2014). The method is common in many industries like food, beverages, appliances, paper, wood products and so on (Tompkins et al., 2010).

3.2 Space utilization in a block stacking warehouse

When designing a block stacking warehouse layout, a major goal is to minimize the waste of storage space and increase the efficiency of receiving and withdrawal of products. Aisles and cross-aisles can be considered a waste of storage space since it is not directly used for pallet storage (Derhami et al., 2020). On the other hand, aisles are essential for making the storage space accessible; more aisles also creates more storage lanes, making room for different SKUs. Cross-aisles are used for easier access to the lanes and reduce travel distance within the warehouse (Derhami et al., 2019).

There is a significant trade-off between the cost of the storage building and the handling cost (Kay, 2015). Going for a layout that only focuses on maximizing storage space and not facilitate access to the different SKUs would cause a re-handling problem. Having to relocate SKUs due to a lack of access is one of the prominent reasons for decreased efficiency in material handling (Yang and Kim, 2006).

This section presents the important factors to consider when designing a block stacking warehouse in terms of maximizing the space utilization. First, addressing the phenomena referred to as honeycombing as this is an important measurement for the following factors. Secondly, a thorough review of lane depth will be presented. Lastly, by a section going over how to configure the storage rows and how to divide it into appropriate storage slots.

3.2.1 Honeycombing

Honeycombing refers to a phenomenon that occurs when vacant slots are created after retrieval of pallets from a fully stacked lane (Venkitasubramony and Adil, 2019b). With the lane being temporarily dedicated to the specific SKU that occupies the first pallet position within the lane until it is fully depleted (Derhami et al., 2020). The honeycomb phenomenon is aggravated as the storage lanes are deeper due to more pallets needed to be retrieved before it can be re-stocked. Having shallower lanes reduces the honeycomb effect, creating less compact storage space and creating more accessibility in the warehouse space. Making it a very important aspect to consider when designing a warehouse layout utilizing the block stacking method (Venkitasubramony and Adil, 2019a; Kay, 2015).

Figure 3.1 shows a small portion of a block stacking storage area. The lane on the right side has begun to be emptied, creating vacant slots in the storage lane. This empty space is referred to as honeycomb loss; the loss is counted in the horizontal and vertical planes. As mentioned above, this empty storage space can not be filled until the lane is fully depleted of all of its products.

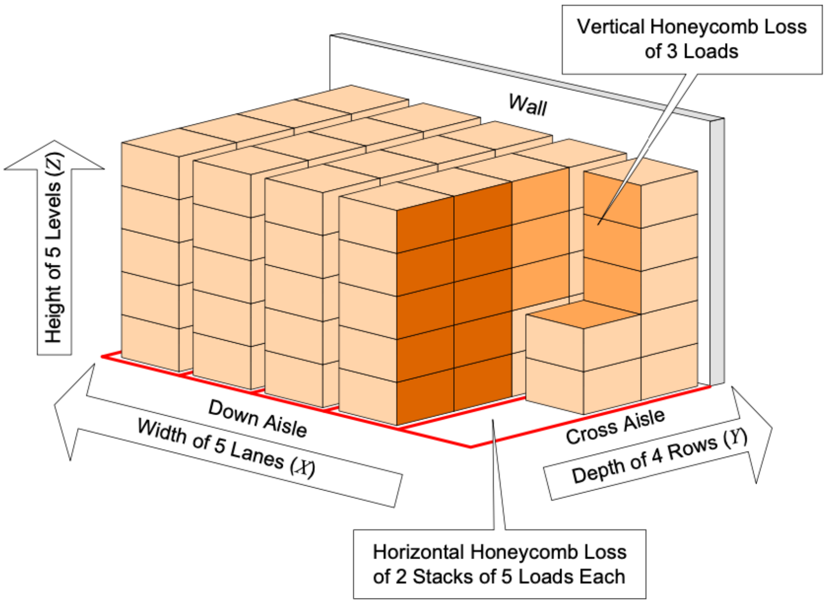

Figure 3.1: Illustration showing the Honeycomb loss (Kay, 2015).

Measuring this effect can be done by looking at the "cube utilization" or, in other words, how much of the total storage space is actually utilized to store product. Equation 3.1 shows how this can be calculated according to Kay (2015).

$$Cube\ Utilization = \frac{Item\ space}{Total\ space} \tag{3.1}$$

For a warehouse that follows the block stacking method, there will usually be more than one storage lot allocated to an SKU so that one of the storage lots can be used for handling the new pallets of incoming goods while the other storage lot is being emptied (Rushton et al., 2014; Kay, 2015). As a result of this practice, many storage rows in the warehouse are likely to be only partially full at any moment in time, and this is referred to as honeycombing (Rushton et al., 2014). According to Rushton et al. (2014), only 70 per cent of pallet positions in a block stacking warehouse are utilized due to honeycombing.

3.2.2 Lane depth

For storing products in a block stacking warehouse, storage lanes are used. Determining the optimal lane depth (or close to optimal) is an important aspect of designing a block stacking warehouse. Should the storage lanes be three pallets deep? Six? Ten? There are a lot of factors to consider for determining this, but they all work towards utilizing the available space in the most effective way possible (Bartholdi and Hackman, 2014). To measure the space efficiency of the warehouse two parameters are used; accessibility and honeycombing (Accorsi et al., 2017). Accessibility space is the part of the lane that makes it possible to access the lane, whilst the honeycombing space is the unoccupied slots within the storage lane that can not be used until the lane is completely emptied, this is to avoid re-handling of the SKUs (Accorsi et al., 2017). Shallow lanes work in favour of accessibility to the lanes and reduce honeycombing, whilst deeper lanes make accessibility harder and honeycomb loss greater (Bartholdi and Hackman, 2014).

Kind (1975) was the first to come up with an expression that describes the optimal lane depth for a single product. Matson and White (1981) continued to develop the problem by determining a single lane depth for all the products in storage. Goetschalckx and Ratliff (1991) follows with an algorithm to compute the optimal lane depth for single and multiple products in a block stacking warehouse, where the results have been compared to various heuristics. De Koster (2010) develops a formula that focuses on minimizing the usage of space to store all the unit loads needed under the condition that the lane can be accessed from two sides (like a drive-through rack). Tompkins et al. (2010) presents a continuous approximation to the optimal lane depth. Bartholdi and Hackman (2014) also presents an approximation to the optimal lane depth, with the focus of maximizing space efficiency for SKU i. Kay (2015) argues that the optimal lane depth is the one that maximizes cube utilization with respect to the best balance between honeycomb loss and down-aisle space loss, Kay (2015) presents a formula for use under the dedicated or shared storage policy. Table 3.1 shows a summary of the lane depth formulas from the literature, and table 3.2 shows the annotations used for the formulas, both of the tables are adopted from Accorsi et al. (2017) with a few modifications.

Table 3.1: Lane depth models. Adopted from Accorsi et al. (2017).

Reference	Model	
Kind (1975)	$k_i = \sqrt{\frac{q_i a}{l z_i}} - \frac{a}{2l}$	(1)
Matson and White (1981)	$k_i = \sqrt{\frac{(q_i + 2I_i)a}{l z_i}}$	(2)
Goetschalckx and Ratliff (1991)	$k_j = \frac{ja}{2l}$	(3)
De Koster (2010)	$k = \sqrt{\frac{a}{ln} \sum_{i=1}^{n} q_i}$	(4)
Tompkins et al. (2010)	$k_i = \sqrt{\frac{aq}{2lz}}$	(5)
Bartholdi and Hackman (2014)	$k_i = \sqrt{\frac{a}{2} \frac{q_i}{z_i}}$	(6)
Kay (2015)	$k = \left\lfloor \sqrt{\frac{a\,[2max(q_i)] - n}{2nlz}} + \frac{1}{2} \right\rfloor$	(7)

Table 3.2: Lane depth models annotations. Adopted from Accorsi et al. (2017).

Annotations
q_i: incoming batch size of SKU i
q: incoming batch size for generic SKUs
z_i: stackability of SKU i
k_i: lane depth of SKU i
k: lane depth for generic SKUs
I_i: inventory of SKU i
l: pallet length of SKU i
a: aisle width
i: 1,..,n SKUs
j: 1,..,m lanes

Derhami et al. (2017) develop mathematical models to find the optimal lane depth that maximizes volume utilization for single and multiple SKUs in a block stacking warehouse under the constraint of finite production rate. The paper studied: infinite production rate, finite production rate where production was higher than demand, and when production was lower than demand. For evaluating the performance of the different models, a simulation model was developed to test against real-world situations. When assessing the finite production model against the existing model in the literature, the results showed that the lane depths ended up being up to twice as deep as they should be.

Derhami et al. (2017) propose the following equation for getting the optimal lane depth for a SKU with a batch of q_i pallets that are instantaneously stored in the warehouse, under the assumptions that the production rate is infinite and the depletion of the warehouse is done at a finite rate:

$$k_i \approx \sqrt{\frac{a}{2}\frac{q_i}{z_i}} \tag{3.2}$$

And for finding the optimal lane depth for multiple SKUs Derhami et al. (2017) presents the following equation:

$$k_c \approx \sqrt{\frac{a\sum_{i=1}^{n}\left(\frac{e_i h_i}{z_i}\right) \times q_i}{2\sum_{i=1}^{n} e_i h_i}} \tag{3.3}$$

where n is the number of SKUs, e_i is the clear height of the warehouse, and h_i is the height of the SKU. Equation 3.3 also follow the same constraints as the lane depth model for a single SKU where n SKUs batches are stored instantaneously in the warehouse and depleted at a finite rate, and the production rate is infinite.

When the lane depths have been calculated the number of lanes required to store all of the SKUs can be found using the following equation from Derhami et al. (2017):

$$\left\lceil \frac{q_i}{z_i k} \right\rceil \tag{3.4}$$

In equation 3.4 k should be a integer value.

Accorsi et al. (2017) propose a decision-support model that assigns the incoming SKUs to the optimal lane depth, storage mode, and storage zone by having the model minimize costs the occur due to space and time inefficiencies. Accorsi et al. (2017) also applies the decision-support model to a real-world warehouse of a renowned brand within the beverage industry, the model showed effectiveness in the day to day lane assignment of SKUs, and it was shown to be a valuable tool to aid the design of a new warehouse.

Venkitasubramony and Adil (2019b) develop a model to decide the optimal lane depth and dimensions for a class-based block stacking warehouse. Venkitasubramony and Adil (2019b) argues that extant literature almost exclusively focuses on space cost and that this is not sufficient. They, therefore, use both space cost and material handling as objectives for the optimization of the design problem. They derived an approximation for optimal lane depth, which minimizes the total cost of operations and has a high degree of accuracy.

Derhami et al. (2019) showed that the traditional model to determine lane depth for a block stacking warehouse underestimated accessibility waste when the model was used to design a layout, as the model only computes the accessibility waste when a lane is occupied. Derhami et al. (2019) therefore developed a mixed-integer program with a new model of wasted storage space to find the optimal lane depths. The new model allows multiple lane depths within the layout and minimizes the waste of space by assessing the different SKUs and assigning them to their appropriate lanes. A simulation was used to test the performance of the model on small to industrial-sized block stacking warehouses.

Derhami et al. (2020) takes another perspective to the block stacking problem by searching for the optimal layout, which includes determining the number of aisles, cross-aisles, cross-aisles types, and bay depths. Derhami et al. (2020) show that material handling cost and space utilization is affected by the lane depths and develop a simulation-based optimization algorithm with respects to the two objectives to find the optimal layout for a block stacking warehouse. Derhami et al. (2020) perform a case study in the beverage industry where results of a new layout following their method can reduce the operational costs for the warehouse by ten per cent.

3.2.3 Storage row configuration

The storage row(s) in a warehouse is just multiple storage lanes put side by side to form a row. If the warehouse had only SKUs with one specific size, creating the storage rows would not require much attention as the slots would be equal. Creating the storage rows when the SKUs can have multiple lengths, on the other hand, requires a method to decide how the storage slots should be arranged in the storage row and also the number of storage slots and the length of the storage slots. Cardona and Gue (2019, 2020) investigates the same type of problem in the vertical space of a storage rack. Following the same principles in the horizontal space of a storage row should be possible.

Cardona and Gue (2019) states that unit-load warehouses typically have a lot of unused vertical storage space and that the storage area is more extensive than it needs to be due to the mismatch between the height of the storage slots and the height of the unit-load. They propose to use storage racks that have multiple slot heights to accommodate the heights of the different unit loads. From their case study of several companies, they found that having multiple slot heights in the storage rack could have potential space savings between 29% and 45% (Cardona and Gue, 2020).

Cardona and Gue (2020) continue their work from 2019 by introducing two methods that generate layouts for unit-load warehouses by allowing multiple slot heights in the storage racks to reduce the wasted vertical storage space, which also will affect the space utilization of the entire warehouse.

The first method presented in Cardona and Gue (2020) is named tiers and follow a simple approach of dividing a storage rack into suitable slot heights and determine how many of such racks that are needed to store all of the products in the warehouse, see figure 3.2 (a). The decision variables for the model are the slot heights $x = (x_1, x_2, ..., x_L)$, the quantities of slots in one storage rack $n = (n_1, n_2, ..., n_L)$, and the total number of storage racks R in the design (Cardona and Gue, 2020). The model's objective is to minimize the total number of storage racks R while maintaining the desired service level α.

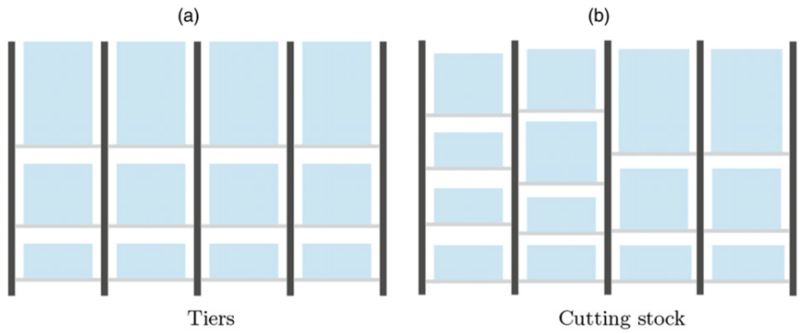

Figure 3.2: Illustration showing (a) tiers and (b) cutting stock (Cardona and Gue, 2020).

The second method presented in Cardona and Gue (2020) is named cutting stock and follows the same objective as the previous method of minimizing the number of storage racks in the design while maintaining the desired service level. For arranging the storage racks into appropriate slots, the model follows the principle behind the framework of the cutting-stock problem (CSP), which has the objective of cutting equal large pieces (storage racks) into smaller pieces (slots) to meet a demand (Cardona and Gue, 2020), see figure 3.2 (b).

The findings of (Cardona and Gue, 2020) in their paper of using multiple slot heights in a warehouse showed a significant reduction of the overall footprint. Results of their case study showed a reduction in the footprint of 25.9%, 31.6%, and 35.4% for two, three, and five slot types, respectively. Testing both the tiers and cutting stock method showed that designs by cutting stock consumed less space; however, Cardona and Gue (2020) also argue that the method of cutting stock is more difficult to operate and recommend using designs by tiers instead. Results also show that the benefit of using the two approaches become more or less the same when the number of slot types exceeds five different slot heights in a design (Cardona and Gue, 2020).

3.3 Storage policies for a block stacking warehouse

A warehouse consists of many storage locations, all with their own unique address (Bartholdi and Hackman, 2014). Having the storage locations in a warehouse has its costs as rent for the warehouse space, heating, security, and so on (Bartholdi and Hackman, 2014). On top of that, the warehouse is often outfitted with shelving or racks, which are capital costs. So, to manage the expenses of having the warehouse, the storage space should be as efficient as possible (Bartholdi and Hackman, 2014).

Several storage policies exist for making good use of the available storage space and making it as efficient as possible. All of the storage policies will have their benefits and drawbacks. So, there will be a need to weigh the pros and cons of each of them to find the best fit for the given warehouse. For this thesis, three of the common storage policies in a block stacking warehouse will be discussed in the following sections.

3.3.1 Dedicated storage policy

The dedicated storage policy is the simplest of the storage policies, where each product is assigned a specific location within the warehouse, and that particular product is the only one that can be stored in that location (Bartholdi and Hackman, 2014). The location that the product is assigned to has a predetermined number of slots that corresponds to the maximum on-hand inventory of that product (Kay, 2015). Having control over the warehouse in terms of where the different products are located is not difficult as the locations do not change and can be marked with a permanent label, popular products can also be assigned to more convenient locations, and workers can learn the locations, making the warehouse more efficient (Bartholdi and Hackman, 2014; Kay, 2015).

The major problem with the dedicated storage policy is that the storage location is reserved for that specific product even if the product is out of stock, making the storage policy less efficient in terms of space utilization (de Koster et al., 2007; Bartholdi and Hackman, 2014). Given that the storage location is dedicated to a specific product assuming that it is initially filled up and emptied as the product is withdrawn, the storage location would then be on average half-empty (Bartholdi and Hackman, 2014). The same phenomenon will apply for all of the other storage locations inside the warehouse; one can expect to see many storage locations nearly empty, half-full, and almost full, although they may have different replenishment cycles. As a result, Bartholdi and Hackman (2014) argues that the storage capacity is only 50 per cent utilized.

With the strict policy of dedicating a specific storage location to a product, there could be an added benefit of assigning popular products to more convenient locations, as mentioned in the first paragraph. Combining the dedicated storage policy with the full-turnover storage policy may give great benefit to the warehouse. The full-turnover storage policy assigns products to storage locations within the warehouse according to their turnover (de Koster et al., 2007). The products with the best turnover are usually located at the most accessible location and closest to the shipping area, whilst the slow-moving products are located at the back of the warehouse (de Koster et al., 2007). The main disadvantage of the full-turnover policy is if there are high fluctuations in the turnovers of the different products as a result of changing demand, this will imply a constant reshuffling of the inventory (de Koster et al., 2007).

3.3.2 Shared storage policy

The shared (or random) storage policy builds on the idea that one product can be assigned to multiple storage locations and not restricted to one specific location (Bartholdi and Hackman, 2014). Incoming pallets are assigned a random (usually the closest) empty storage location within the warehouse (de Koster et al., 2007; Kay, 2015). Following this policy allows new incoming products to be stored at any available empty location instead of waiting until the original product is replenished (Bartholdi and Hackman, 2014). Splitting the product into multiple storage locations allows for faster rotation of the storage locations (Bartholdi and Hackman, 2014). Following this strategy is expected to result in high space utilization of the warehouse (de Koster et al., 2007).

The shared storage policy comes with its drawbacks, unfortunately. First, the constant change of locations for the products as the storage locations are emptied and restocked. This means that the shared storage policy only will work if the warehouse is in a computer-controlled environment (de Koster et al., 2007), as the workers can not learn the locations and must be guided to the correct location (Bartholdi and Hackman, 2014). Secondly, by having smaller storage lots, the process of putting away new products that come into the warehouse can become more time-consuming as the worker have to take it to more than one location (Bartholdi and Hackman, 2014). Lastly, there needs to be a strict policy of picking product from the right location as taking the product from a more convenient location can create discrepancies between the warehouse management software and the physical inventory at the two locations (Bartholdi and Hackman, 2014).

Derhami et al. (2017) brings up the question of allowing blockage or not; blockage means to have more than one SKU in a storage lane. If the warehouse has a wide variety of

SKUs with a low inventory, then justifying dedicating an entire storage lane to one SKU is hard due to the low space utilization (Derhami et al., 2017). Allowing the storage policy to enable blockage causes the problem of relocation to occur, meaning that efforts have to be made to strategically place the SKUs in such a way that the cost of material handling is minimized (Derhami et al., 2017). On the other hand, if the SKUs have sufficient inventory, blockage should not be enabled (Derhami et al., 2017).

3.3.3 Class-based storage policy

The concept of class-based storage builds on the two previously discussed storage policies and can be viewed as a combination of both of them (Kay, 2015; de Koster et al., 2007; Larson et al., 1997). Classes are usually formed by criteria (i.e., demand, product type, size); a common approach is to use Pareto's method. The idea is to take the top moving products (around 15 per cent of the stored product that accounts for roughly 85 per cent of the total turnover) and form a fast-moving class (de Koster et al., 2007; Larson et al., 1997). Generally, there is created three such classes based on how fast the products move, and they are typically named A-, B-, and C-items (de Koster et al., 2007). The classes are placed at dedicated locations in the warehouse, and within the space of the class, the products can share the storage slots (Kay, 2015; de Koster et al., 2007; Larson et al., 1997). The ability to store the product randomly within the classes allows for flexibility to accommodate fluctuation in the inventory levels (Larson et al., 1997). Resulting in a storage policy that increases the floor space utilization, decreases the material handling costs, and allows for flexibility (Larson et al., 1997).

3.4 Literature findings

3.4.1 Key factors of block stacking

The first research question aims to explore and identify the key factors of the block stacking method and how they can be applied or adjusted to SKUs of different lengths. By summarizing the findings in the literature study regarding block stacking, honeycombing and lane depth, this section contributes to answering the first research question.

Block stacking is a storage method where SKUs are placed in front and on top of each other forming storage lanes on the warehouse floor (Tompkins et al., 2010; Rushton et al., 2014). The method is effective when there are multiple pallets of SKUs and when the inventory is withdrawn or received in large increments (Tompkins et al., 2010). One SKU should have more than one storage lane to facilitate stock rotation (Rushton et al., 2014; Bartholdi and Hackman, 2014; Kay, 2015). The storage lanes follow the last-in, first-out (LIFO) policy, and the lanes should be completely emptied before a new product is placed in the storage lane (Rushton et al., 2014).

Accessibility is a key factor in a block stacking warehouse. Aisles and cross-aisles make it possible to access the different products in the warehouse. More aisles create more storage lanes, and cross-aisles are used for easier access to the lanes and reduce travel distance (Derhami et al., 2019). If the warehouse were to maximize the storage space available, more than one SKU would be placed into a storage lane inflicting the re-handling problem. Having to relocate SKUs due to a lack of access is one of the foremost reasons for decreased efficiency in material handling (Yang and Kim, 2006).

Space utilization can be considered as another key factor for the block stacking method. Space utilization considers all space that is not used to store products to be a waste of storage space. Aisles and cross-aisles can be regarded as a waste of storage space since it is not directly used for storage (Derhami et al., 2020). Waste of storage space can also occur within the storage lanes. A storage lane is temporarily dedicated to that specific SKU that occupies the first pallet position in the lane until it is fully depleted (Derhami et al., 2020). Vacant slots are created in the storage lane as pallets are taken out; this phenomenon is referred to as honeycombing (Venkitasubramony and Adil, 2019b).

Adjusting the depth of the storage lanes will affect honeycombing. Shallow lanes reduce honeycombing, and deep lanes make the honeycomb loss greater (Bartholdi and Hackman, 2014). Numerous authors have presented models to determine the optimal lane depth for single and multiple SKUs. The lane depth models have gradually become more complex and accurate as more research has been conducted on the topic. Derhami et al. (2017) develop mathematical models to find the optimal lane depth that maximizes volume utilization for single and multiple SKUs in a block stacking warehouse under the constraint of finite production rate. When evaluating the finite production model against the existing model in the literature, the results showed that the lane depths ended up being up to twice as deep as they should be.

3.4.2 Storage row configuration

The second research question aims to identify a way to make the placement of SKUs structured, accessible, and less time-consuming. Cardona and Gue (2020) present two methods for minimizing the vertical waste of space in storage racks named tiers and cutting stock. Applying the methods to the horizontal plane of a storage row would mean that instead of focusing on the height of an SKU, the length of the SKU would be in focus.

Following the tiers approach for the configuration of the storage rows would result in storage rows with an equal configuration of the storage slots. By this, the method would take a set of slot lengths $x = (x_1, x_2, ..., x_L)$ determined by the length of SKUs that are to be stored and the number of slots $n = (n_1, n_2, ..., n_L)$ required to be able to store all of the SKUs and distribute them equally over R storage rows. This makes all of the storage rows equal in terms of having the same amount of storage slots with a given length, and the number of storage row R will be given by the number of storage rows that are required to store all of the SKUs.

Following the cutting stock approach for configuration of the storage rows would result in unique storage rows where every row is different. By this, the method would take a set of slot lengths $x = (x_1, x_2, ..., x_L)$ determined by the length of SKUs that are to be stored and the number of slots $n = (n_1, n_2, ..., n_L)$ required to be able to store all of the SKUs and distribute them to the storage rows so that the waste of space is minimized.

Important aspects to consider is that the cutting stock method consumed less space. Still, it is more challenging to operate than the tiers method, and Cardona and Gue (2020) recommend using the tiers method instead. The findings from Cardona and Gue (2020) also showed that the two methods became more or less the same in terms of space utilization when the number of slot types exceeded five.

3.4.3 Storage policies findings

The third research question aims to identify the differences between the three storage policies (dedicated, shared, and class-based), to form a basis for evaluating which of the three storage policies that are best suited for warehousing of SKUs with different lengths. Table 3.3 show some of the important characteristics of the three different storage policies.

Table 3.3: Storage policies characteristics

Storage policy	Characteristics	Reference
Dedicated	Each SKU has a dedicated storage location	(Bartholdi and Hackman, 2014)
	Needs to have enough space for maximum on-hand inventory	(Kay, 2015)
	Low space utilization (50%)	(Bartholdi and Hackman, 2014)
	Good structure	(Bartholdi and Hackman, 2014; Kay, 2015)
Shared	SKUs can share the different storage locations	(Bartholdi and Hackman, 2014)
	High space utilization	(de Koster et al., 2007)
	Constant change in locations for the SKUs	(Bartholdi and Hackman, 2014)
	Need warehouse management software	(de Koster et al., 2007)
Class-based	Classes have dedicated locations, SKUs within classes can share storage location	(Kay, 2015)
	Classes are configured according to some form of criteria	(de Koster et al., 2007; Larson et al., 1997)
	Good space utilization	(Larson et al., 1997)
	Lower material handling cost	(Larson et al., 1997)
	Flexibility	(Larson et al., 1997)

Whether or not to allow blockage is also an important consideration when deciding on the storage policy. The decision depends on the variety of SKUs and the inventory level that are to be stored in the warehouse. If there is a wide variety of SKUs and a low level of inventory blockage should be allowed according to Derhami et al. (2017). And if the inventory is sufficient to justify dedicating an entire storage lane to a SKU, then blockage should not be enabled (Derhami et al., 2017).

4 Case - Skogmo Bruk

This chapter presents the empirical information that was collected during the case study of Skogmo Bruk. The chapter starts with a general introduction to Skogmo Bruk. Then the chapter goes into the current situation at Skogmo Bruk, describing the products, layout, material flow, and material handling. Finally, the chapter ends with a summary and a discussion of the case findings.

4.1 Introduction to Skogmo Bruk

Skogmo Bruk is a relatively small company in the northern part of Trøndelag that produces impregnated wood products, such as planks, poles and beams. Their production can be divided into two segments - standard production and customized production. The standard production accounts for approximately 85% of their total sales and the customized accounts for the last 15%. For the production of standard products, the products only go through a single process, which is the impregnation process. The customized production, on the other hand, allows for special dimensions and lengths of the products before they go through the impregnation process.

Skogmo Bruk has a large market share in Norway, serving the market from just above Trondheim and up to the northern part of Finnmark. Having such a large area to supply requires good distribution logistics. Skogmo Bruk has solved this problem by shipping most of their products by boat from the nearby harbour of Namsos, and smaller deliveries to nearby locations are done by truck.

Skogmo Bruk is a part of an industry cluster called Skogmo Industry Park. Skogmo Industry Park is a competence and development company owned by the companies in the park to facilitate development, innovation, and cooperation with the 54 different companies within the park.

4.2 Current situation

In this section, the current situation at Skogmo Bruk will be described according to the empirical information collected. The information described in this section is important to the understanding of the case company and for working towards improving the warehouse logistics. So, this includes a description of the products in section 4.2.1, a breakdown of the current layout in section 4.2.2, then the material flow is described in section 4.2.3, and lastly, the material handling in section 4.2.4.

4.2.1 Products

Skogmo Bruk makes and sells a large variety of impregnated wood products. The wood goes through an industrial process that uses a pressure chamber to make the impregnated wood products. In short, the impregnation chemicals are pressed into the wood inside the pressure chamber. Impregnated wood is for outdoor use, and there are different impregnation chemicals and processes depending on the environment that the wood will be used in. By impregnating the wood, it will have much better protection against rot and insect infestation and an increased life span compared to non-impregnated wood.

There are two main classifications of impregnated wood: class A and class AB. The first class, class A, is used on products that will be used in the ground or in freshwater, typically products like a lamppost, fence post, and wood for the quay. The second class, class AB, is used on wood that will be used above ground, like wood panelling for a house or wood for building a terrace. Skogmo Bruk also produces a few products with a third type of impregnation called creosote. Creosote is a heavy-duty imprecation typically used for lampposts and cable posts that will be exposed to the elements for a long time.

Skogmo Bruk provides 25 different product groups with a total of 207 variations in dimensions altogether. Table 4.1 show the different products group with their respective number of variants. The total number of variations is without counting in the different lengths of the products. The standard lengths the Skogmo Bruk operates with on most of their products are from 3000 mm to 5400 mm with 300 mm intervals, in total nine different standard lengths. The standard products are packaged in standard packs that are 1000 mm in width and 500 mm in height; there can also be double-packs that are

1000 mm x 1000 mm. Packaging dimensions for non-standard products and products such as poles and beams will not follow the standard packaging dimensions.

As mentioned in the introduction of this chapter, Skogmo Bruk has two product segments; standard products and customized products, with 85% and 15% contribution to the total sales, respectively. The customized products consist of adjusting the standard products to meet the customer's requirements. Skogmo Bruk offers the following customization; finger jointing of the wood to make the product to the desired length (up to 11 meters at max), splitting the wood to get a dimension that is not in the standard selection. Lastly, they can do a planing process on the surface of the wood to make it smooth.

Table 4.1: Product groups with the number of variants.

Product group	Variants
Uhøvlet Skurlast Boks - Trykkimpregnert CU Klasse A	12
Uhøvlet Skurlast - Trykkimpregnert CU Klasse A	24
Konstruksjonsvirke C24 - Fingerskjøtt Gran	9
Konstruksjonsvirke C24 - Trykkimpregnert CU Klasse A	9
Konstruksjonsvirke C24 - Fingerskjøtt - Trykkimpregnert CU Klasse A	2
Konstruksjonsvirke C24 Justert - Trykkimpregnert CU Klasse AB	19
Rekker/Lekter Justert - Trykkimpregnert CU Klasse AB	11
Trekantlekt Justert - Gran	1
Trekantlekt Justert - trykkimpregnert CU klasse AB	1
Rektangulær Kledning - Fingerskjøtt Gran	9
Rektangulær Kledning - Trykkimpregnert CU Klasse AB	18
Rektangulær Kledning - Fingerskjøtt - Trykkimpregnert CU Klasse AB	6
Profilert Kledning - Trykkimpregnert Cu Klasse AB	8
Profilert Kledning - Royalimpregnert	1
Altanrekke - Trykkimpregnert CU Klasse AB	2
Vannbrett - Trykkimpregnert CU Klasse AB	2
Takbord/Takrenne/Takkrok - Trykkimpregnert CU Klasse AB	3
Gulvbord TG - Trykkimpregnert CU Klasse AB	2
Terrassebord - Trykkimpregnert CU Klasse A	4
Terrassebord - Trykkimpregnert CU Klasse AB	7
Terrassebord - Royalimpregnert	2
Sylinderdreide Gjerdestolper - Trykkimpregnert CU Klasse A	10
Sylinderdreide Stolper - Trykkimpregnert CU Klasse A	22
Koniske Stolper 150mm - Trykkimpregnert CU Klasse A	12
Koniske Stolper 150mm/170mm - Kreosotimpregnert Marint Bruk	11

By looking into the sales data of Skogmo Bruk from 2020, it turned out that of the 207 different products that Skogmo Bruk sells, only 36 of those products made up 80% of their total sales. Table 4.2 shows a list of the 36 products with the total amount of sales in NOK, meters, and cubic meters, respectively. Studying the list further indicates considerable variations in terms of sales going from the top product to the products further down the list. Out of the 36 products in table 4.2 19 products are of class AB, 12 products are of class A, and 5 products are impregnated with creosote.

Table 4.2: 36 products accounting for 80 percent of sales at Skogmo Bruk.

Product name	NOK	m	m^3
F 28×120 TERRASSEBORD CU IMP AB	7 058 949	599 589	2015
F 48×148 K-VIRKE JUSTERT CU IMP AB	3 901 815	166 629	1184
F 48×198 K-VIRKE JUSTERT CU IMP AB	2 295 493	71 651	681
F 48×098 K-VIRKE JUSTERT CU IMP AB	2 005 238	131 818	620
F 75×200 SKURLAST UHVL CU IMP A	1 170 827	17 154	257
F 50×150 SKURLAST UHVL CU IMP A	1 118 872	42 928	322
F 36×048 REKKE JUSTERT CU IMP AB	775 366	123 816	214
F 22×148 REKT KLEDN FS CU IMP AB	689 410	43 362	141
F 50×200 SKURLAST UHVL CU IMP A	677 300	19 676	197
F 75×150 SKURLAST UHVL CU IMP A	617 344	11 633	131
F 150×5000 STOLPE KONISK KREO KL M	597 064	520	46
F 19×148 REKT KLEDNING CU IMP AB	485 402	44 411	125
F 36×148 K-VIRKE JUSTERT CU IMP AB	484 641	24 990	133
F 140×2000 STOLPE AUTOVERN CU IMP A	477 653	4 464	147
F 100×200 SKURLAST UHVL CU IMP A	462 743	5 292	106
F 75×175 SKURLAST UHVL CU IMP A	445 850	11 211	147
F 22×173 REKT KLEDN FS CU IMP AB	423 781	26 361	100
F 150×12000 STOLPE KONISK KREO KL M	370 540	89	19
F 38×150 SKURLAST UHVL CU IMP A	358 560	16 632	95
F 150×200 SKURLAST UHVL CU IMP A	347 125	2 520	76
F 48×048 REKKE JUSTERT CU IMP AB	317 155	34 015	78
F 19×123 REKT KLEDNING CU IMP AB	314 415	31 701	74
F 48×148 K-VIRKE JUSTERT CU IMP A C24	298 405	11 947	85
F 36×073 REKKE JUSTERT CU IMP AB	295 263	29 521	78
F 21×095 TERRASSEBORD CU IMP AB	284 211	35 363	71
F 32×150 SKURLAST UHVL CU IMP A	272 479	12 484	60
F 19×098 REKT KLEDNING CU IMP AB	262 692	31 797	59
F 28×120 TERRASSEBORD RILLET CU IMP AB	253 291	7 945	27
F 150×10000 STOLPE KONISK KREO KL M	237 819	79	14
F 150×6000 STOLPE KONISK KREO KL M	236 164	143	16
F 30×048 REKKE JUSTERT CU IMP AB	229 549	36 715	53
F 22×198 REKT KLEDN FS CU IMP AB	226 925	12 266	53
F 48×073 REKKE JUSTERT CU IMP AB	214 085	16 008	56
F 28×120 TERRASSEBORD CU IMP A	213 693	15 267	51
F 150×7000 STOLPE KONISK KREO KL M	206 867	115	15
F 23×048 REKKE JUSTERT CU IMP AB	206 030	37 788	42

Figure 4.1 shows the total amount of meters of product sold by Skogmo Bruk in the year 2020. The graph shows considerable variations in the sales over the year, and there is a significant increase in sales in the summer months, with July being the month with the highest number of sold meters of product. This shows that Skogmo Bruk is in a market with large seasonal variations. The same type of variation can be seen in the sales data for each individual product that Skogmo Bruk offers.

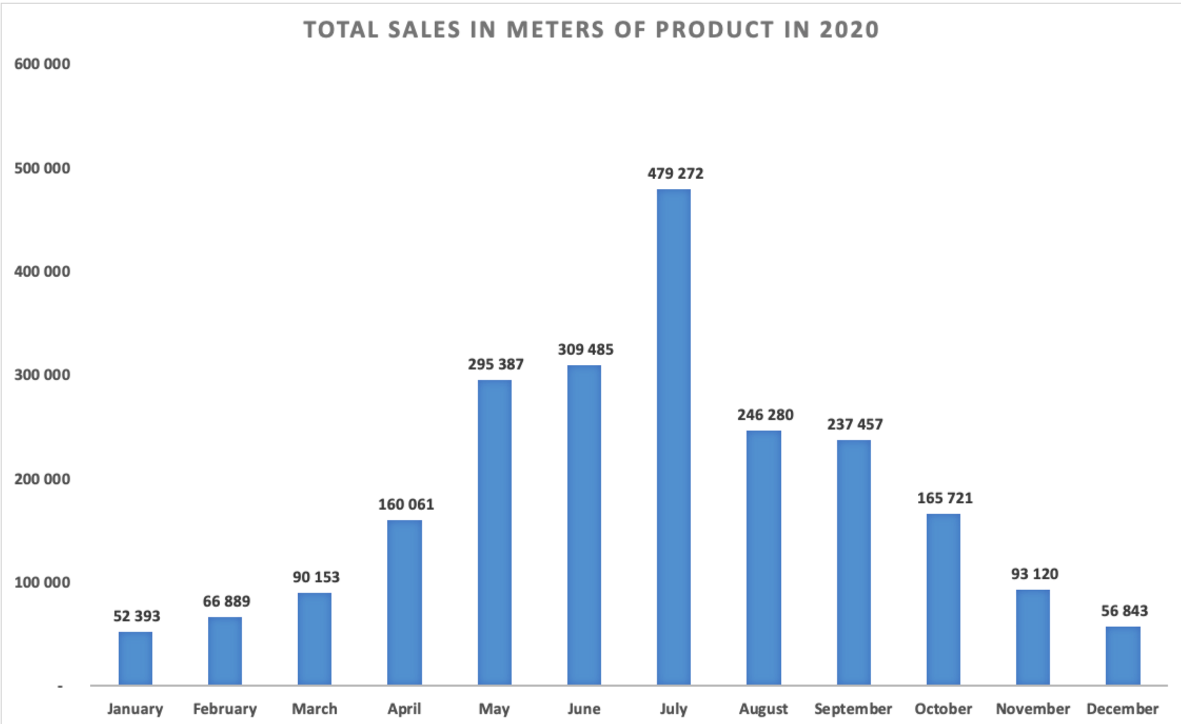

Figure 4.1: Total sales in meters of product

As described earlier in this section, most standard products come in packs of 3 meters to 5,4 meters in length with intervals of 0,3 meters. Unfortunately, Skogmo Bruk does not have unique item numbers for the product with a specific length; they only have it for the product itself. This means that it is hard to know exactly how many packs or meters of a product with a specific length that has been sold, but according to the manager at Skogmo Bruk, there is a relatively even distribution of meters sold over the nine standard lengths. So, let's say, for example, that a product X has sold a total of 9000 meters, then the 9000 meters should be relatively evenly distributed over the nine different lengths of the product (1000 meters of product X with the length of 3 meters, 1000 meters of 3,3 meters, etc.).

4.2.2 Layout

Skogmo Bruk has a large property of around $30000m^2$ where they have their production facility, warehouse, and office. The layout of Skogmo Bruk is shown in a flight photo in figure 4.2; the photo shows three main structures and a large outdoor warehouse. The outdoor warehouse is the key area of interest in this thesis. The outdoor warehouse takes up most of the space that Skogmo Bruk has available. Looking closely at the photo in figure 4.2 reveals that most of the area is used as aisle space and not as storage space; aisle space is, of course, important to get access to the products. The outdoor warehouse currently applies a block stacking storage method with a shared storage policy.

Figure 4.2: Current layout at Skogmo Bruk, photo from kart.gulesider.no.

Figure 4.3 shows a flight photo of the entire area that Skogmo Bruk operates on; the coloured blocks highlight specific areas of interest. First, the orange blocks (1) represent the area that Skogmo Bruk stores most of their raw material inventory. Secondly, the yellow block (2) is a small warehouse that holds raw material inventory; the building is essentially only a roof to cover the raw material from rain to keep it dry and ready for further processing.

The two blue blocks (3) and (4) represent the buildings where the production processes take place. Block number (3) is where the impregnation process takes place. Here they have three pressure cambers; one pressure camber for producing class A products and two pressure chambers to produce class AB products. Outside of building (3), there is dedicated space on both sides for the finished impregnated products to "drop off" after the impregnation process; this is an important step for letting the excess chemicals drip off onto a concrete platform and not pollute the soil.

Figure 4.3: Current layout of Skogmo Bruk with illustrations of the different areas, photo from kart.gulesider.no

Block (4) represents the building where the production of customized products take place. Within the building, they have four machines; the first machine makes the finger joints, the second machine presses two finger-jointed products together after the glue have been applied and then cut the product to a specific length. The third machine can split the product down to smaller dimensions, and a last machine is a planing machine for getting a smooth surface on the product. At one end of the production facility, they also have a small work-in-process storage area where products that have been through finger-jointing and glueing can be stored to let the glue settle and make the joint strong. In addition, they can regulate the temperature in this room to make the process of hardening the glue go faster.

Lastly, the green block (5) represents a new warehouse that Skogmo Bruk has built at the beginning of 2021. The warehouse will have plenty of room for products with its $1200m^2$ of floor space. The plan for the warehouse is to store the products that Skogmo Bruk sells the most, to keep them protected and try from the elements.

4.2.3 Material flow

The material flow at Skogmo Bruk can be divided into two main flows. The first being the production of standard products, and the second being the production of customized products. Skogmo Bruk sold over 9000 m^3 of impregnated wood products in the year 2020, according to the sales data. With standard products accounting for 85% and customized products 15% of the total sales, there is a significant difference in the amount of the two flows. The following two paragraphs will go into detail about the material flows of standard products and customized products.

For the production of standard products that make up approximately 85% of the total production, the flow is relatively simple. First, the raw material is delivered by a supplier and placed in one of the raw material storage areas. Then, as production orders are sent out, the raw material is moved into the impregnation chambers and impregnated with one of the two types; A or AB. The duration of time in the pressure chamber depends on the product's dimension and the grade of the impregnation required. After the impregnation process, the newly impregnated product has a short duration of stay right outside of the pressure chambers at a specially made platform to let excess chemicals drip off. Then the finished product is moved to a storage slot awaiting transportation to the customer.

The customized products, on the other hand, go through a bit more processing before being ready to be impregnated. The process starts the same way as the standard products, with the raw material being delivered from a supplier and placed into raw material storage. Then, the raw material is taken into the production facility. In the production facility, there are a few different options; the product can undergo either (1) finger-joint for special lengths, (2) planing process for the surface, and (3) splitting process for special dimensions, or it can go through several of the processes. The processes that the products go through all depend on the specifications that the customer has requested. If the product undergoes the finger-joint process, it has to go through another step of letting the glue that binds the two wooden pieces together harden and settle. This is done in a work-in-process storage room at one end of the production facility. After the customization is done to the product, they are stacked together and sent to the impregnation chamber. From this point, the customized product follow the same processes as the standard products.

Combining the knowledge of the layout at Skogmo Bruk and the description of the material flow highlights a few interesting elements. First, the placement of the raw material in relation to where it is going to be used. As highlighted in figure 4.3 in the previous section, the raw material storage is spread out over a large area creating both cross-flows and a significant distance to travel for the raw material stored furthest away. Secondly, the layout within the production facility where the customized products are produced is designed so that the product enters and exits at the same place instead of entering at one end and exiting at the other end. This also creates cross-flow in the material handling and possible hold-ups in the material flow if having to wait for products to be moved around.

4.2.4 Material handling

The material handling at Skogmo Bruk consists of manual handling by workers and handling done using a truck loader, forklift, and crane. The most used material handling equipment used at Skogmo Bruk is the truck loader. The truck loader unloads incoming raw material of the supplier's trucks and moves it to its storage location, feeds both the production facility and the impregnation chambers with raw material, moves the finished products to storage, and loads the finished products onto trucks that supply the customers. These processes are done with one truck loader, and the truck loader can be viewed as a key material handling equipment at Skogmo Bruk.

In the small warehouse for some of the raw material, they have a crane in the sealing for utilizing the space, enabling them to stack the products very close together and still be able to access it when they need it. However, this is only the case for the middle part of the warehouse; on the sides of the warehouse, the products are stored using the truck loader.

In the production facility for the customized products, most of the handling of the product is done manually by the workers. The raw material is delivered to the facility entrance by the truck loader before either the whole stack or part of the stack is moved by two workers onto a manual trolley that can be pushed to the workstations within the facility. The products are manually loaded into the machines and unloaded manually before they get moved to the next workstation. Within the facility, they also have an electric forklift that can carry larger stacks of products.

4.3 Case findings

The findings from the case study is presented in table 4.3.

Table 4.3: Case findings

Area	Findings
Product	Large variety of products 25 different product groups 207 variations in dimensions 9 different lengths for the standard products Standard lengths from 3m to 5,4m with 0,3m intervals Custom lengths up too 11m at max High variety of products, low inventory level
Product sales data	Standard products accounts for 85 % of total sales Custom products accounts for 15 % of total sales 36 products account for 80 % of total sales Seasonal demand - sells the most during the summer months
Warehouse and layout	Large property - about 30000 m^2 of space Large outdoor warehouse and two warehouses with roof The products are stored by using the block stacking method The storage rows are unstructured The width of the aisles are wide Mix of both raw-material and finished-goods in some parts of the warehouse, creating cross-flow Time spent searching for products due to lack of structure

4.3.1 Discussion

From the findings in the previous section, it's clear to see that Skogmo Bruk has a high variety of products in many different lengths, stored in a large outdoor warehouse. The pattern that becomes quite clear when investigating the sales data, information from the interviews, and the observations made during the visits shows room for improvement in terms of structure and control over the products and the warehouse.

On the product side of things, there is a lack of control over the quantities of the different lengths of the products; there is only control over the total amount of the products. Not having complete control over all the different product lengths may cause Skogmo Bruk to have excessive amounts of stock or insufficient amounts, which will most likely mean that the inventory has to be checked often.

The outdoor warehouse applies the block stacking method to their products, but there is room for improvement in structure and control over the warehouse. First, the lane depths and number of lanes should be created so that they facilitate stock rotation. Secondly, there should be a storage policy that allows for better control and structure over the warehouse. To make this possible, the warehouse should be divided into zones and storage rows should be labelled and numbered to create a system that can keep track of where the different types of products are located without searching the entire warehouse. Lastly, the different products should be placed in a practical placement that minimizes cross-flow in the warehouse; for example, the raw material should not, if possible, be mixed in with the finished goods.

5 Mathematical model

This chapter presents the mathematical model for applying the block stacking method to SKUs of different lengths. The model is based on the theoretical findings from the literature study and tested on empirical data from the case company Skogmo Bruk. The chapter starts with listing the notations used in the model, followed by the assumptions made about the model. Then, the model itself is presented with its steps. Furthermore, a section is dedicated to solving the model on three different data sets. Lastly, a discussion of the model is provided.

5.1 Notations

The following notation is used for the mathematical model.

a) Product

l_i	Length of SKU i
w_i	Width of SKU i
h_i	Height of SKU i
q_i	Quantity of SKU i

b) Lane depth

k_i	Lane depth of SKU i
q_i	Incoming batch size of SKU i
z_i	Stackability of SKU i
a	aisle width
i	1,..., n SKUs

c) Tiers

x_i	Slot lengths $x = (x_1, x_2, ..., x_L)$
n_i	Slot quantities for one storage row $n = (n_1, n_2, ..., n_L)$
N_i	Total number of slots of type i in the design $N_i = n_i R$
R	Number of storage rows in the design
χ	Length of the storage row

d) Warehouse

L_W	Length
W_W	Width
W_a	Width of aisles
N_a	Number of aisles
W_{ca}	Width of cross-aisles
N_{ca}	Number of cross-aisles
e	Warehouse clear height
c	clearance between the slots in the storage row

5.2 Assumptions

The model works under the following assumptions.

1. Pallet dimensions width W and height H are the same for all of the SKUs.
2. Length L is the only variable dimension for the pallets of SKUs.
3. Stackability z is the same for all SKUs.
4. Shared lane depth for the SKUs within a group.
5. The batch of q_i SKUs are instantaneously stored.
6. The production rate is infinite.
7. The depletion of the warehouse is done at a finite rate.
8. No safety stock.
9. Storage rows are accessible from one side.
10. Storage lanes are depleted with last-in-first-out (LIFO) principle.

5.3 Model

In this section, the mathematical model is presented, and the steps are described.

Step 1 - Define the product data input

The first step of the model is to define the input data that the model needs, starting with the products. For the products, the height H, width W, and length L needs to be defined, as shown in figure 5.1. In addition, the quantity q_i and the stackability z_i of SKU i needs to be defined.

Figure 5.1: Figure showing the measurement parameters of a product.

Table 5.1 shows how the data for the different SKUs can be listed and defined.

Table 5.1: Example of how to define the product data.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
1	-	-	-	-	-
2	-	-	-	-	-
...					
n	-	-	-	-	-

Next, a few essential measurements of the warehouse has to be defined; figure 5.2 show some of the essential measurements. Starting with the aisle width a, the width of the aisle needs to be large enough to move the largest product and have enough room for the forklift to operate. The length L_W, width W_W, and warehouse clear height e has to be defined to have the boundaries of the warehouse. The input and output entrance has to be defined (in this thesis, the I/O is located in the middle of the long side of the warehouse). Lastly, the maximum and minimum length X that the storage rows can have.

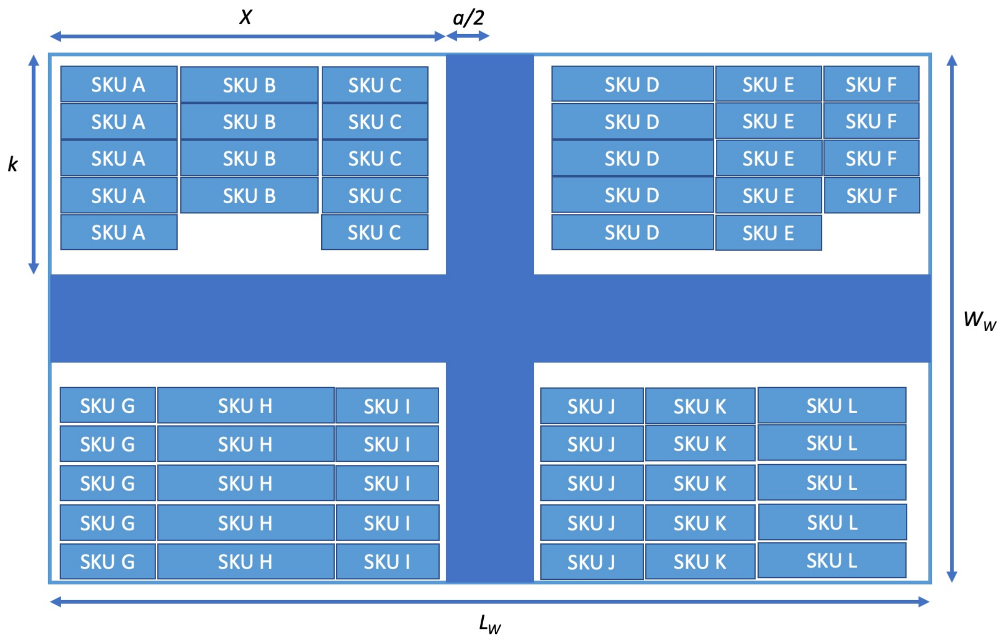

Figure 5.2: Figure showing important measurements of a warehouse.

Step 2 - Determine the lane depths

For determining the optimal lane depth of a single SKU equation 5.1 from Derhami et al. (2017) is used:

$$k_i \approx \sqrt{\frac{a}{2}\frac{q_i}{z_i}} \tag{5.1}$$

where k_i is the approximate optimal lane depth for SKU i measured in units of pallets, a is the aisle width in units of pallets, q_i is the quantity of incoming pallets, and z_i is the stackability of the SKU measured in number of pallets.

Equation 5.1 gives only the option of determining the lane depth for one single SKU. As Bartholdi and Hackman (2014) argues, it would be impractical to allow each SKU to determine their own lane depth and should instead be grouped together to form a shared lane depth. Equation 5.2 is a continuation of Derhami et al. (2017) equation above and allows multiple SKUs to get the same lane depth:

$$k_c \approx \sqrt{\frac{a \sum_{i=1}^{n} \left(\frac{e_i h_i}{z_i}\right) \times q_i}{2 \sum_{i=1}^{n} e_i h_i}} \tag{5.2}$$

where n is the number of SKUs, e_i is the clear height of the warehouse, and h_i is the height of the SKU.

When the lane depth for the SKUs are determined from the equation above, then the number of lanes that will be necessary to store the SKUs can be determined by equation 5.3 from Derhami et al. (2017).

$$\left\lceil \frac{q_i}{z_i k} \right\rceil \tag{5.3}$$

Equation 5.3 needs to be determined by the quantities of SKU i and not the sum of the quantities.

Step 3 - Determine the tiers profile

To determine the tiers-profile, or in other words how the arrangement of SKUs should be in a storage row with respect to the different lengths of the SKUs, this step follows the methodology described in Cardona and Gue (2020).

Input

To start the tiers model there is need for some input data. The slot lengths $x = (x_1, x_2, ..., x_L)$ given by the product description in step 1 and the total quantity of each slot length $N = (N_1, N_2, ..., N_L)$ given in step 2.

Decision variables

The decision variables for the tiers model are the quantities of the different lengths in one storage row $n = (n_1, n_2, ..., n_L)$, and the number of storage rows R in the design.

Objective function

The objective for the tiers model is to minimize the total length of all the storage rows whilst making sure that there is room for all of the SKUs with in the design.

$\chi_{tot} = \sum x_i n_i \times R$

Constraints

The constraints of the tiers model are as follows:

$n_i \times R \geq N_i$

$\chi_{row} \leq \chi_{max}$

$\chi_{row} \geq \chi_{min}$

$R \geq 1$

$\chi_{tot} \geq \sum x_i N_i$

$N_i, n_i, R \in \mathbf{Z}^+$

Output

Output of the tiers model will be a tiers-profile $x_1n_1, x_2n_2, ..., x_Ln_L = \chi_{row}$, the number of storage rows R needed to store all SKUs in the design, and the total length of the storage rows combined χ_{tot}.

Step 4 - Design of the warehouse

To determine the design of the warehouse all of the data from the previous three steps has to be brought together. Starting with the warehouse dimensions length L_W, width W_W, and the location of the input/output for the warehouse. Next, the aisle width a. Followed by the calculations done for the storage row dimensions. For the storage rows, a bit of clearance c has to be added between each slot. Then the layout-design process can begin.

5.4 Solving the model

In this section, the mathematical model in section 5.3 will be solved using three different data sets. The first data-set consists of general data to show how the model is intended to work. The second data-set is based on the case of Skogmo Bruk. And the third data-set is also based on the case of Skogmo Bruk but adjusted in terms of the number of slot types.

5.4.1 General data-set

The calculations done for the general data-set can be viewed in appendix B1.1 and B1.2.

Step 1 - Define the product data input

The first step is to define the data input. In table 5.2 and 5.3 the different SKUs of the general data-set is defined by number i, length L, width W, height H, quantity q, and stackability z. The warehouse space is 80 m in length L_W and 60 m in width W_W, giving a total of 4800 square meters of storage space. The width of the aisles within the warehouse will be set to 4,5 m to accommodate moving the longest products with some clearance. The maximum storage row length is 30 m, and the minimum storage row length is 28,5 m (without accounting for the clearance between the slots).

Table 5.2: General data-set - part 1.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
1	1,50	1,00	0,5	100	6
2	1,50	1,00	0,5	80	6
3	1,50	1,00	0,5	110	6
4	1,50	1,00	0,5	65	6
5	1,50	1,00	0,5	60	6
6	1,50	1,00	0,5	60	6
7	1,50	1,00	0,5	78	6
8	1,50	1,00	0,5	37	6
9	2,00	1,00	0,5	89	6
10	2,00	1,00	0,5	140	6
11	2,00	1,00	0,5	56	6
12	2,00	1,00	0,5	67	6
13	2,00	1,00	0,5	39	6
14	2,00	1,00	0,5	50	6
15	2,50	1,00	0,5	130	6
16	2,50	1,00	0,5	44	6
17	2,50	1,00	0,5	69	6
18	2,50	1,00	0,5	32	6
19	2,50	1,00	0,5	120	6
20	2,50	1,00	0,5	130	6

Table 5.3: General data-set - part 2.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
21	2,50	1,00	0,5	154	6
22	2,50	1,00	0,5	45	6
23	2,50	1,00	0,5	67	6
24	2,50	1,00	0,5	49	6
25	2,50	1,00	0,5	62	6
26	2,50	1,00	0,5	36	6
27	3,00	1,00	0,5	98	6
28	3,00	1,00	0,5	102	6
29	3,00	1,00	0,5	63	6
30	3,00	1,00	0,5	87	6
31	3,00	1,00	0,5	48	6
32	3,50	1,00	0,5	113	6
33	3,50	1,00	0,5	67	6
34	3,50	1,00	0,5	89	6
35	3,50	1,00	0,5	90	6
36	3,50	1,00	0,5	30	6
37	3,50	1,00	0,5	52	6
38	4,00	1,00	0,5	135	6
39	4,00	1,00	0,5	49	6
40	4,00	1,00	0,5	68	6

Step 2 - Determine the lane depths

For the next step of determining the lane depth for the SKUs of the general data-set, the SKUs were sorted from low to high in terms of quantity q and then grouped into four groups of ten SKUs each. Then lane depth equation 5.2 were used to determine the common lane depths for all of the SKUs. The results of the calculations can be viewed in table 5.4, showing both the exact lane depth and the round-up lane depth that is used for further calculations.

Table 5.4: Common lane depths for the four groups of SKUs.

Group	Lane depth	Round-up lane depth
1	3,91	4
2	4,75	5
3	5,52	6
4	6,80	7

After determining the lane depth for the four groups of SKUs, the next step is to determine the number of lanes that each SKU will need to store all of its product. Determining the number of lanes is done with equation 5.3, this is done to each SKU i and not as a group. The total number of lanes N of slot length x can be viewed in table 5.5. Another important measurement that is highlighted in table 5.5 is the total length of one group, which is the minimum requirement to be able to store all of the product.

Table 5.5: Total number of lanes N of slot length x.

Slot Length x	Group 1 N	Group 2 N	Group 3 N	Group 4 N
1,5	2	7	6	6
2,0	2	7	3	4
2,5	11	6	2	15
3,0	2	3	6	3
3,5	2	2	8	3
4,0	3	0	2	4
$\sum x_i N_i$	59,5	55,5	74	90

Step 3 - Determine the tiers profile

The next step in the model is to distribute the total amount of slots into equal storage rows. This is done by computing the decision variables, objective function, and constraints that are described in section 5.3 into Excel Solver. The results of the calculation can be viewed in table 5.6, showing the number of slots for each storage row, the number of rows required, and the total length for each group, respectively.

Table 5.6: Tiers profile of each group and the number of rows required.

Slot Length x	Group 1 n	Group 2 n	Group 3 n	Group 4 n
1,5	2	4	3	4
2,0	1	4	1	1
2,5	4	2	1	4
3,0	2	2	2	1
3,5	1	1	3	1
4,0	1	0	1	1
Nr. rows	3	3	3	4
$\sum x_i n_i \times R$	85,5	85,5	88,5	114

Step 4 - Design of the warehouse

Now that the product has been distributed into storage rows and the lane depth has been calculated for the storage rows, the process of arranging the storage rows into a suitable layout for the warehouse can begin. Before making the layout, some slight adjustments to the lengths of the storage rows needs to be done; there is a need for a bit of clearance between the slots in the storage row. Table 5.7 show the different groups with their number of slots, the clearance added between the slots, the total length of the storage row, the width (or lane depth), and the number of rows that are required.

Table 5.7: Final dimensions for the storage rows

	Nr. slots	Clearance	Length	Width	Rows
Group 1	11	0,1m	29,5m	4	3
Group 2	13	0,1m	29,7m	5	3
Group 3	11	0,1m	30,5m	6	3
Group 4	12	0,1m	29,6m	7	4

Given a warehouse space of $L_W = 80m$ and $W_W = 60m$, aisle width $a = 4,5m$, input/output to be located at the longest side of the warehouse, and the dimensions of the storage rows from table 5.7 the process of designing the warehouse space can begin. Figure 5.3 show two different alternatives of how the storage rows could be arranged in the warehouse. The alternatives should be evaluated based on some criteria like distance to travel to get an optimal layout, but this is outside of the scope of this thesis.

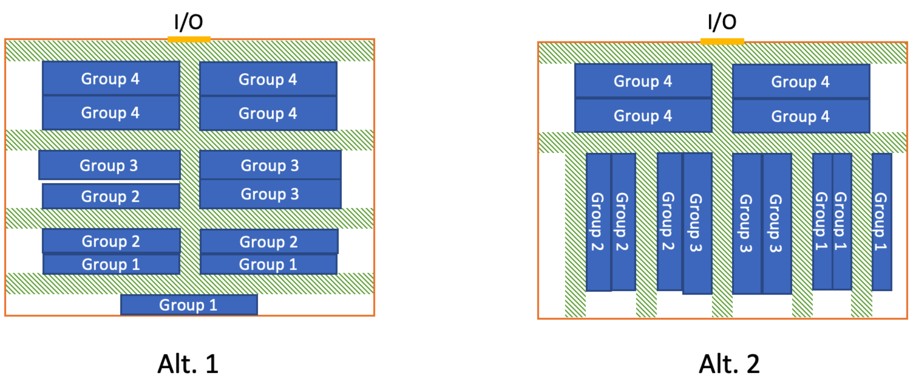

Figure 5.3: Figure showing two different alternatives for the layout of the warehouse.

5.4.2 Case of Skogmo Bruk - nine lengths

The data used from Skogmo Bruk came from their annual sales report of 2020 and a document showing the total amount of sold meters of product per month; the whole data-set can be viewed in appendix A1 and A2. For the calculations done in Excel, view appendix B2.1, B2.2, and B2.3.

A few adjustments and calculations had to be made to get the data set ready for the model. First, the data used in the model only consist of data from the top six products of Skogmo Bruk, but with each of them having nine different lengths, there will be 54 different SKUs. Secondly, the amount of packs of each SKU has to be calculated from the total amount of meters of that product as Skogmo Bruk only have data on the total amount of each product and not for each length of the product. There is also no data on how many meters of a specific length of a product that is sold, but according to the manager at Skogmo Bruk, the sale is relatively evenly distributed over the nine different lengths of the products. Therefore, this data-set assumes an even distribution of the total amount of meters over the nine different lengths. Thirdly, as Skogmo Bruk is heavily affected by seasonality, the calculations will be made for the month that has the highest sales for each product. Lastly, an assumption is made that the warehouse should be able to store half of the product that is sold in the most selling month of the year.

Step 1 - Define the product data input

The first step is to define the data input. Table 5.8 shows the six different products with their respective SKU number. In table 5.9 and 5.10 the different SKUs of the general data-set is defined by number i, length L, width W, height H, quantity q, and stackability z. The warehouse space of Skogmo Bruk is vast, so accounting for the warehouse length and width in this calculation was neglected. The width of the aisles within the warehouse is set to 10 m to accommodate moving the longest products with some clearance. The maximum storage row length is set to 50 m, and the minimum storage row length is set to 37,8 m (without accounting for the clearance between the slots).

Table 5.8: The products from Skogmo Bruk used in this model.

Product name	SKU i
F 28×120 TERRASSEBORD CU IMP AB	1-9
F 48×148 K-VIRKE JUSTERT CU IMP AB	10-18
F 48×198 K-VIRKE JUSTERT CU IMP AB	19-27
F 48×098 K-VIRKE JUSTERT CU IMP AB	28-36
F 75×200 SKURLAST UHVL CU IMP A	37-45
F 50×150 SKURLAST UHVL CU IMP A	46-54

Table 5.9: Data-set Skogmo Bruk - part 1.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
1	3,00	1,00	0,5	21	6
2	3,30	1,00	0,5	19	6
3	3,60	1,00	0,5	17	6
4	3,90	1,00	0,5	16	6
5	4,20	1,00	0,5	15	6
6	4,50	1,00	0,5	14	6
7	4,80	1,00	0,5	13	6
8	5,10	1,00	0,5	12	6
9	5,40	1,00	0,5	12	6
10	3,00	1,00	0,5	14	6
11	3,30	1,00	0,5	12	6
12	3,60	1,00	0,5	11	6
13	3,90	1,00	0,5	11	6
14	4,20	1,00	0,5	10	6
15	4,50	1,00	0,5	9	6
16	4,80	1,00	0,5	9	6
17	5,10	1,00	0,5	8	6
18	5,40	1,00	0,5	8	6
19	3,00	1,00	0,5	7	6
20	3,30	1,00	0,5	6	6
21	3,60	1,00	0,5	6	6
22	3,90	1,00	0,5	5	6
23	4,20	1,00	0,5	5	6
24	4,50	1,00	0,5	5	6
25	4,80	1,00	0,5	4	6
26	5,10	1,00	0,5	4	6
27	5,40	1,00	0,5	4	6

Table 5.10: Data-set Skogmo Bruk - part 2.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
28	3,00	1,00	0,5	7	6
29	3,30	1,00	0,5	6	6
30	3,60	1,00	0,5	6	6
31	3,90	1,00	0,5	5	6
32	4,20	1,00	0,5	5	6
33	4,50	1,00	0,5	5	6
34	4,80	1,00	0,5	4	6
35	5,10	1,00	0,5	4	6
36	5,40	1,00	0,5	4	6
37	3,00	1,00	0,5	3	6
38	3,30	1,00	0,5	3	6
39	3,60	1,00	0,5	3	6
40	3,90	1,00	0,5	3	6
41	4,20	1,00	0,5	2	6
42	4,50	1,00	0,5	2	6
43	4,80	1,00	0,5	2	6
44	5,10	1,00	0,5	2	6
45	5,40	1,00	0,5	2	6
46	3,00	1,00	0,5	3	6
47	3,30	1,00	0,5	3	6
48	3,60	1,00	0,5	3	6
49	3,90	1,00	0,5	2	6
50	4,20	1,00	0,5	2	6
51	4,50	1,00	0,5	2	6
52	4,80	1,00	0,5	2	6
53	5,10	1,00	0,5	2	6
54	5,40	1,00	0,5	2	6

Step 2 - Determine the lane depths

For the next step of determining the lane depth for the SKUs of the data-set of Skogmo Bruk, the SKUs were sorted from low to high in terms of quantity q and then grouped into two groups based on the amount of product they have. Then lane depth equation 5.2 were used to determine the common lane depths for all of the SKUs. The results of the calculations can be viewed in table 5.11, showing both the exact lane depth and the round-up lane depth that is used for further calculations.

Table 5.11: Common lane depths for the two groups of SKUs.

Group	Lane depth	Round-up lane depth
1	3,42	4
2	1,87	2

After determining the lane depth for the two groups of SKUs, the next step is to determine the number of lanes that each SKU will need to store all of its product. Determining the number of lanes is done with equation 5.3, this is done to each SKU i and not as a group. The total number of lanes N of slot length x can be viewed in table 5.12. Another important measurement that is highlighted in table 5.12 is the total length of one group, which is the minimum requirement to be able to store all of the product.

Table 5.12: Total number of lanes N of slot length x.

Slot Length x	Group 1 N	Group 2 N
3,00	2	4
3,30	2	4
3,60	2	4
3,90	2	4
4,20	2	4
4,50	1	5
4,80	1	5
5,10	1	5
5,40	1	5
$\sum x_i N_i$	55,8	171,0

Step 3 - Determine the tiers profile

The next step in the model is to distribute the total amount of slots into equal storage rows. This is done by computing the decision variables, objective function, and constraints that are described in section 5.3 into Excel Solver. The results of the calculation can be viewed in table 5.13, showing the number of slots for each storage row, the number of rows required, and the total length for each group, respectively.

Table 5.13: Tiers profile of each group and the number of rows required.

Slot Length	Group 1	Group 2
x	n	n
3,00	1	1
3,30	1	1
3,60	1	1
3,90	1	1
4,20	1	1
4,50	1	1
4,80	1	1
5,10	1	1
5,40	1	1
Nr. rows	2	5
$\sum x_i n_i \times R$	75,6	189

Step 4 - Design of the warehouse

Now that the product has been distributed into storage rows and the lane depth has been calculated for the storage rows, the process of arranging the storage rows into a suitable layout for the warehouse can begin. Before making the layout, some slight adjustments to the lengths of the storage rows need to be done, and there is a need for a bit of clearance between the slots in the storage row. Table 5.14 show the different groups with their number of slots, the clearance added between the slots, the total length of the storage row, the width (or lane depth), and the number of rows that are required.

Table 5.14: Final dimensions for the storage rows

	Nr. slots	Clearance	Length	Width	Rows
Group 1	9	0,1m	38,6m	4	2
Group 2	9	0,1m	38,6m	2	5

Given the dimensions in table 5.14, an aisle width of 10 m, and that the input/output are to be located at the middle of the top side of the warehouse, the process of making a layout that facilitates access to the SKUs can begin. Figure 5.4 shows two different alternatives to how the storage rows might be configured. The blue blocks represent the storage rows of group 1, and the yellow blocks represent the storage rows of group 2, and the striped green area represent the aisles. The alternatives should be evaluated based on some criteria like distance to travel, but this is outside of the scope of this thesis.

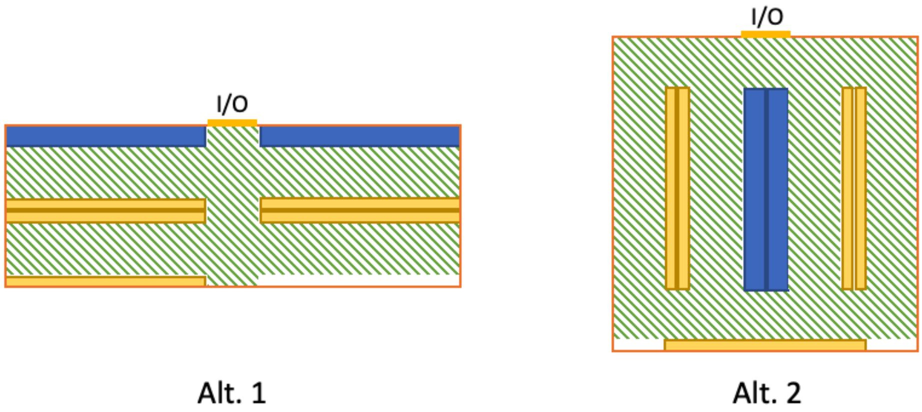

Figure 5.4: Figure showing two different alternatives for the layout of the warehouse.

5.4.3 Case of Skogmo Bruk - five lengths

The data used from Skogmo Bruk came from their annual sales report of 2020 and a document showing the total amount of sold meters of product per month. The whole data-set can be viewed in appendix A1 and A2. For the calculations done in Excel, view appendix B3.1, B3.2, and B3.3.

To get this data-set ready for this model a few adjustments and modifications have been made from the data-set in section 5.4.2. The six products used in the previous run of the model stays the same. The major change is in the lengths of the products; instead of having nine different lengths as Skogmo Bruk currently have, the number has been reduced to five. This idea of reducing the number of lengths came about in discussion with the manager at Skogmo Bruk; they are looking into reducing the number of SKUs they sell. So, for this data-set the lengths will be 3,00 m, 3,60 m, 4,20 m, 4,80 m, and 5,40 m. This data-set also assumes that the total amount of meters is evenly distributed over the five different lengths, that the calculations will be made for the month that has the highest sales for each product, and that the warehouse should be able to store half of the products that are sold in the most selling month of the year.

Step 1 - Define the product data input

The first step is to define the data input. Table 5.15 shows the six different products with their respective SKU number. In table 5.16 and 5.17 the different SKUs of the general data-set is defined by number i, length L, width W, height H, quantity q, and stackability

z. The warehouse space of Skogmo Bruk is vast, so accounting for the warehouse length and width in this calculation was neglected. The width of the aisles within the warehouse is set to 10 m to accommodate moving the longest products with some clearance. The maximum storage row length is set to 42 m, and the minimum storage row length is set to 21 m (without accounting for the clearance between the slots).

Table 5.15: The products from Skogmo Bruk used in this model.

Product name	SKU i
F 28×120 TERRASSEBORD CU IMP AB	1-5
F 48×148 K-VIRKE JUSTERT CU IMP AB	6-10
F 48×198 K-VIRKE JUSTERT CU IMP AB	11-15
F 48×098 K-VIRKE JUSTERT CU IMP AB	16-20
F 75×200 SKURLAST UHVL CU IMP A	21-25
F 50×150 SKURLAST UHVL CU IMP A	26-30

Table 5.16: Data-set Skogmo Bruk - part 1.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
1	3,00	1,00	0,5	38	6
2	3,60	1,00	0,5	31	6
3	4,20	1,00	0,5	27	6
4	4,80	1,00	0,5	24	6
5	5,40	1,00	0,5	21	6
6	3,00	1,00	0,5	25	6
7	3,60	1,00	0,5	21	6
8	4,20	1,00	0,5	18	6
9	4,80	1,00	0,5	15	6
10	5,40	1,00	0,5	14	6
11	3,00	1,00	0,5	12	6
12	3,60	1,00	0,5	10	6
13	4,20	1,00	0,5	9	6
14	4,80	1,00	0,5	8	6
15	5,40	1,00	0,5	7	6

Table 5.17: Data-set Skogmo Bruk - part 2.

SKU i	Length L [m]	Width W [m]	Height H [m]	Quantity q [pallets]	Stackability z [pallets]
16	3,00	1,00	0,5	12	6
17	3,60	1,00	0,5	10	6
18	4,20	1,00	0,5	9	6
19	4,80	1,00	0,5	8	6
20	5,40	1,00	0,5	7	6
21	3,00	1,00	0,5	6	6
22	3,60	1,00	0,5	5	6
23	4,20	1,00	0,5	4	6
24	4,80	1,00	0,5	4	6
25	5,40	1,00	0,5	3	6
26	3,00	1,00	0,5	6	6
27	3,60	1,00	0,5	5	6
28	4,20	1,00	0,5	4	6
29	4,80	1,00	0,5	4	6
30	5,40	1,00	0,5	3	6

Step 2 - Determine the lane depths

For the next step of determining the lane depth for the SKUs of the data-set of Skogmo Bruk, the SKUs were sorted from low to high in terms of quantity q and then grouped into two groups based on the amount of product they have. Then lane depth equation 5.2 were used to determine the common lane depths for all of the SKUs. The results of the calculations can be viewed in table 5.18, showing both the exact lane depth and the round-up lane depth that is used for further calculations.

Table 5.18: Common lane depths for the two groups of SKUs.

Group	Lane depth	Round-up lane depth
1	4,71	5
2	2,58	3

After determining the lane depth for the two groups of SKUs, the next step is to determine the number of lanes that each SKU will need to store all of its product. Determining the number of lanes is done with equation 5.3, this is done to each SKU i and not as a group. The total number of lanes N of slot length x can be viewed in table 5.19. Another important measurement that is highlighted in table 5.19 is the total length of one group, which is the minimum requirement to be able to store all of the product.

Table 5.19: Total number of lanes N of slot length x.

Slot Length x	Group 1 N	Group 2 N
3,00	4	8
3,60	4	8
4,20	2	10
4,80	2	10
5,40	2	10
$\sum x_i N_i$	52,2	198,8

Step 3 - Determine the tiers profile

The next step in the model is to distribute the total amount of slots into equal storage rows. This is done by computing the decision variables, objective function, and constraints that are described in section 5.3 into Excel Solver. The results of the calculation can be viewed in table 5.20, showing the number of slots for each storage row, the number of rows required, and the total length for each group, respectively.

Table 5.20: Tiers profile of each group and the number of rows required.

Slot Length x	Group 1 n	Group 2 n
3,00	2	2
3,60	2	2
4,20	1	2
4,80	1	2
5,40	1	2
Nr. rows	2	5
$\sum x_i n_i \times R$	55,2	210,0

Step 4 - Design of the warehouse

Now that the product has been distributed into storage rows and the lane depth has been calculated for the storage rows, the process of arranging the storage rows into a suitable layout for the warehouse can begin. Before making the layout, some slight adjustments to the lengths of the storage rows need to be done; there is a need for a bit of clearance between the slots in the storage row. Table 5.21 show the different groups with their number of slots, the clearance added between the slots, the total length of the storage row, the width (or lane depth), and the number of rows that are required.

Table 5.21: Final dimensions for the storage rows

	Nr. slots	Clearance	Length	Width	Rows
Group 1	7	0,1m	28,2m	5	2
Group 2	10	0,1m	42,9m	3	5

Given the dimensions in table 5.21, an aisle width of 10 m, and that the input/output are to be located at the middle of the top side of the warehouse, the process of making a layout that facilitates access to the SKUs can begin. Figure 5.5 shows two different alternatives to how the storage rows might be configured. The blue blocks represent the storage rows of group 1, and the yellow blocks represent the storage rows of group 2, and the striped green area represent the aisles. The alternatives should be evaluated based on some criteria like distance to travel, but this is outside of the scope of this thesis.

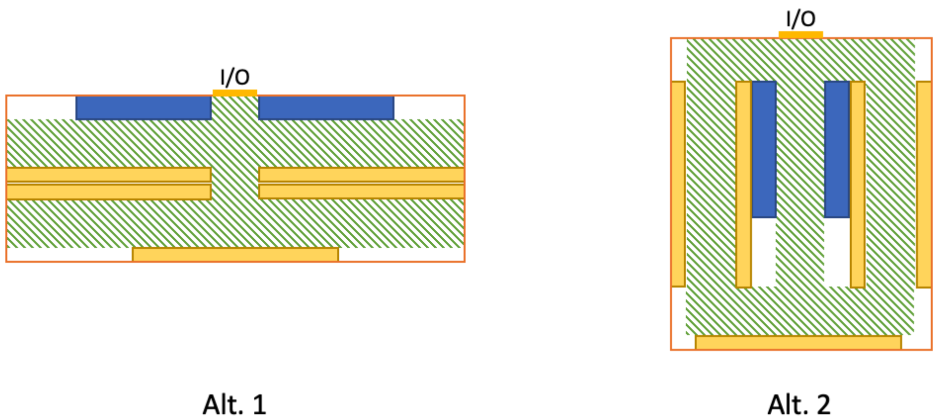

Figure 5.5: Figure showing two different alternatives for the layout of the warehouse.

5.5 Discussion of the model

The data sets that this model uses from Skogmo Bruk are not the most optimal. A few calculations and assumptions might make the data sets give an unrealistic picture of the actual situation. The major challenge is that Skogmo Bruk does not have a record of how many meters they sell of a specific length of a product; they only have a record of the total amount of meters they sell of a product. This means that to find the quantities of each specific length of each product, a calculation and an assumption has to be made for how the quantities are distributed among the different lengths.

Determining the suitable aisle width to use in the model should be based on the products that are to be stored in the warehouse and the equipment that is used to store and retrieve the products, instead of just being based on the length of the longest product with a bit of extra clearance. So, for an improved model, the aisle width should be determined by the longest product, the specification listed for the equipment used for storing and retrieving (for example, the turning radius of a forklift or truck loader), and a bit of clearance should also be added to make sure that the products can move efficiently throughout the warehouse.

Determining the optimal clearance between the products in the storage row should also be paid attention to. If the clearance is too small, it might not be possible to get the product in or out of the storage lane. On the other hand, if the clearance is too big, the storage row will be longer than it needs to be and waste storage space. This is, of course, a minor problem, but it is worth mentioning as it will have a slight impact on the warehouse.

The maximum and minimum storage row length were necessary constraints to make the model work properly; without the two constraints, the model struggled to find a solution. The two constraints give the model room to decide on a storage row length best suited for the number of storage slots necessary to store all of the product. Determining the two constraints have been loosely based on the total length of all the storage slots and human judgement to find the minimum and maximum length of the storage row. Ideally, these two constraints should be based on the dimensions of the warehouse following guidelines and criteria. Another approach would be to have a fixed length of the storage row, but then other changes to the model would be necessary to make it possible to find a solution.

The procedure of how the SKUs in this model is divided is not the most optimal way. It is based on quantity, but too much of the decision making is left to human judgement. The process of dividing the SKUs into groups should be done consistently, systematically, and structured based on specified criteria like quantity or turnover. There should be a protocol that drives this and not just human judgement.

For further development of the model, minimizing wasted storage space and accounting for honeycombing should be applied to the model. Including these aspects will allow for a much more optimized warehouse in terms of space utilization. The model should also be tested on a much larger scale, preferably on the entire assortment of a company. Testing the model on several companies that deal with different lengths SKUs will also be a great way to find aspects that need improvement.

6 Findings and Discussion

In this chapter, main findings from the literature study, case study, and mathematical modelling are presented and connected, then the findings are discussed. The chapter is structured with a section dedicated to each research question, where the theoretical and empirical findings provide a base for discussion. The chapter ends with a section that states the contribution of this thesis, the limitations of the thesis, and lastly, covering the areas for further research.

6.1 Research question 1

How can block stacking be applied for warehousing of SKUs with different lengths?

6.1.1 Theoretical and empirical findings

The first research question aimed to combine the theoretical and empirical findings from the literature study and case study, as well as the findings from the mathematical modelling, to explore the factors that are essential for the block stacking method and investigate how the factors can be applied or adjusted to handle SKUs of different lengths.

The prerequisite of the block stacking method is to have a detailed description of the SKUs that are to be stored in the warehouse along with the quantities. However, the case study of Skogmo Bruk showed that having complete control over all the different SKUs and their quantities might not be the case for companies that deal with a high variety of SKUs in many different lengths. In addition, findings from the mathematical model showed that not having sufficient and reliable input data lead to assumptions and estimates having to be made to get the necessary input data for the model. This again leads to less accurate and reliable output from the mathematical model.

From the literature study, accessibility was found to be a key factor for making a block stacking warehouse function efficiently. Accessibility concentrates on aisles, cross-aisles, and blockage, as specified in chapter three. Aisles create more storage lanes and make them accessible; cross-aisles connects the different aisles and reduce the travel distance (Derhami et al., 2019). A blockage is when a storage lane is filled up with more than one SKU type, meaning that to access a specific SKU re-handling would be required. According to Yang and Kim (2006) having to relocate SKUs due to a lack of access is one of the foremost reasons for decreased efficiency in material handling.

The literature study also found space utilization to be a key factor for making a block stacking warehouse operate efficiently. Space utilization is a measurement of how much of the storage space available that is used for the storage of products. Aisles and cross-aisles can be regarded as a waste of storage space since it is not directly used for storage (Derhami et al., 2020). Waste of storage space can occur in the storage lanes in the form of vacant slots being created as products are taken out; this is referred to as honeycombing (Venkitasubramony and Adil, 2019b). Space utilization is found to be an area where the case company could benefit from some improvements. Having a large outdoor warehouse with a high variety of SKUs in many different lengths makes it challenging to utilize the space in the most effective way when there are few rules and policies for how the warehouse should be structured.

The trade-off between accessibility and space utilization is an intricate problem with many variable factors to consider. To reduce the honeycombing effect within the lanes, shallower lanes can be used instead of having deep storage lanes (Bartholdi and Hackman, 2014). Reducing the depth of the storage lanes will reduce the waste of space within the lanes, but it will result in more storage lanes being added to the warehouse, adding more aisle space. Therefore, finding the optimal lane depth that considers both the storage lane and the aisle space required for the storage lane is critical. Much research has been devoted to find the best model to determine the optimal lane depth for single and multiple SKUs. Derhami et al. (2017) develop mathematical models to find the optimal lane depth that maximizes volume utilization for single and multiple SKUs. When they evaluated the models against the existing models in the extant literature, the results showed that the lane depths ended up being up to twice as deep as they should be. Another important aspect that Derhami et al. (2017) brings up is that to dedicating an entire storage lane to a single SKU, the inventory needs to be sufficient enough to justify the space it consumes. If this can't be justified, then the lane should be shared by multiple SKUs.

Applying one of the lane depth models of Derhami et al. (2017) (the lane depth model is presented and described in both chapter three and five) to the mathematical model in this thesis on the data sets of Skogmo Bruk gave expected results regarding the lane depth for the different SKUs. On the other hand, when assessing the number of storage lanes required to store the product for the case when there were nine different lengths, every SKU needed a little less than one storage lane, resulting in waste of storage space. Similar results were found in the case of Skogmo Bruk when the number of lengths was reduced to five. Two factors can contribute to this result. The first, most apparent, that there is not a sufficient inventory level. The second possibility is that the width of the aisle affects the lane depth model.

6.1.2 Discussion

The aisle's width plays an important role in the accessibility of the SKUs and to the overall space utilization of the warehouse. The aisle needs to be wide enough to accommodate the longest SKU that will be stored in a storage lane that the aisle connects, and it also needs to be wide enough for the material handling equipment. Taking the case of Skogmo Bruk into consideration, they have products ranging from 3 meters to 11 meters. Making all of the aisles and cross-aisles at Skogmo Bruk facilitate the longest product may not be the best option as it will result in lots of wasted storage space. One option could be to allocate the longest products in one specific area of the warehouse and the smaller products in another area so that the warehouse can have different aisle widths in different parts of the warehouse.

The lane depth models are also heavily affected by the aisle width due to the models being designed to find the best balance between honeycomb loss and down-aisle space loss. When the aisle width increases, the lane depth also increases, and vice versa. The effects that this will have, if any, on a storage row that has SKUs of different lengths and share a common lane depth is unknown to the researcher. Logical reasoning may suggest that if the aisle width is wider than optimal for the specific SKU, the lane depth model will give deeper lanes than what is best for the SKU.

Another important aspect to mention about the lane depth models is that they usually give the lane depth in a number of pallet positions and not in meters. This could potentially be a conflict if the SKUs are different in more than one dimension, assuming that a common lane depth is given.

In conclusion, research question one aimed to answer how block stacking can be applied for warehousing of SKUs with different lengths and what key factors contributes to the method. From the findings presented in the previous section, detailed product descriptions, accessibility, and space utilization is considered as the key factors that contribute to the method. The mathematical model in chapter five shows one way to apply the method of block stacking to different lengths SKUs.

6.2 Research question 2

What is a suitable placement of different length SKUs in a block stacking warehouse?

6.2.1 Theoretical and empirical findings

The second research question aimed to combine the theoretical and empirical findings from the literature study, case study, and mathematical modelling to identify a placement for the different length SKUs that are structured, accessible, and less time-consuming.

The literature findings concentrate around two methods proposed by Cardona and Gue (2020) that could be adjusted for making a suitable storage row configuration for the different length SKUs in a block stacking warehouse. The first method, design by tiers, configure storage rows that are equal in the number and length of the slots and adjust the number of storage rows to make enough room to store every SKU. The second method, design by cutting stock, configure storage rows that are unique in the number and length of the slots. From the results and recommendation of Cardona and Gue (2020), as described in the literature findings in section 3.4.2, the choice of design by tiers seemed to be the best option as the two methods became similar in their results when the number of slots exceeded five, and that the design by tiers was a more manageable method to operate.

Findings from the case study suggest that the block stacking warehouse for different length SKUs should be well structured to facilitate accessibility to the SKUs and be less time-consuming to store and retrieve products. This comes as a result of observation of the case company and interviews with the manager. The current situation of the outdoor warehouse at Skogmo Bruk lacks structure in how the products are placed in the warehouse. Without a proper structure and system to where the different products are located, the time spent searching for the correct product can be tedious.

In the mathematical model, the configuration of storage rows was done with the tiers approach following the same overall idea as the one presented in the article by Cardona and Gue (2020). In the three problems that the model was tested on, all provided storage rows that accommodated the SKUs that were to be stored in the warehouse.

The storage rows for the group of SKUs that go through the tiers method will all be equal in the number and lengths of the slots. With this strict policy, there will be a few extra slots than needed. Having a few extra storage slots is not necessarily a bad thing; this adds some flexibility into the design that can facilitate fluctuations in the inventory and make the stock rotation process a bit easier.

6.2.2 Discussion

Structuring the storage rows to facilitate SKUs of different lengths could have been approached in many different ways. However, this thesis focus on the two methods presented by Cardona and Gue (2020). With the findings from the case study and the objective of the research question, the tiers method were selected as the most appropriate to facilitate structure and accessibility. Following the tiers approach gives the possibility to group SKUs based on criteria and place the SKUs in equal storage rows. Allocating specific SKUs to the storage rows will give control over where the products are placed in the warehouse, and the workers can find the products faster. The storage rows are also designed so that every SKU gets its own storage lane within the storage row allowing good access to the SKUs.

The design by tiers method used in the mathematical method on the two cases, section 5.4.2 and 5.4.3, of Skogmo Bruk did not work quite the way that it was intended. The expected result was that there should be a bit more variations in the number of slots in the storage row designs. But, instead, the storage rows ended up having one or two of each type of storage slot. There are two logical reasons for this; the first is the assumption that the sale of the different lengths of the products is relatively equal. The second is that there are not enough pallets of product for each of the different lengths.

In conclusion, research question two aimed to find a suitable placement of different length SKUs in a block stacking warehouse, with the objective of the placement to be structured, accessible, and less time-consuming. The design by tiers method was selected over the cutting stock method due to it being easier to implement and for providing similar results when the number of slots exceeds five. The design by tiers method also falls well in line with the objectives of the research question. Applying the method in the mathematical model in chapter five showed that it did what it was intended to do; however, the results weren't as good as first intended due to a lack of enough pallets to store.

6.3 Research question 3

What is a suitable storage policy for different length SKUs in a block stacking warehouse?

6.3.1 Theoretical and empirical findings

The third research question aimed to combine the theoretical and empirical findings from the literature study and the case study to identify the differences between the storage policies and evaluate the most suitable option for storage of different length SKUs in a block stacking warehouse. The findings of research question one and two also contribute to answering research question three in view of the block stacking method itself and how it is structured and organized to accommodate SKUs of different lengths.

Findings from the literature study on the topic of storage policies can be viewed in chapter three, section 3.4.3, table 3.3 shows the main characteristics of the three storage policies. Further, the findings from the case study can be viewed in chapter four, section 4.3.

6.3.2 Discussion

From the very definition of the three storage policies, a major challenge reveals itself in storage of different length SKUs. The dedicated storage policy is defined as a storage policy where every SKU gets a dedicated location within the warehouse, and that is the only SKU that can be stored in that location (Bartholdi and Hackman, 2014). The shared storage policy is defined as a storage policy where one SKU can have multiple storage locations within the warehouse (Bartholdi and Hackman, 2014). And the class-based storage policy is defined as a storage policy where the SKUs are grouped into multiple groups based on some form of criteria (de Koster et al., 2007), the classes are assigned dedicated spots within the warehouse, and the SKUs within the class can share the storage slots within the class among them (Kay, 2015). In light of different length SKUs, the challenge will then be that not all SKUs can share the same storage locations due to their difference in length. For example, there is not possible to store a SKU with a greater length than the width of the storage lane. Turning the problem the other way, it is possible to store a SKU that is shorter in length than the width of the storage lane, but this will imply poor space utilization. Using the dedicated storage policy for storing SKUs of different lengths will not inflict the challenge of not having enough room in the storage location to fit the SKU. Each SKU has their dedicated storage location. Using the shared storage policy for storing SKUs of different lengths will potentially inflict the challenge of not having a storage location appropriate for the SKU at some point. To minimize the chances of this, additional rules should be added to the policy: there should always be enough slots of the appropriate size to accommodate the SKUs, and slots should only be shared among the same size SKUs. Lastly, using the class-based storage policy for storing SKUs of different lengths faces the same challenge as the shared policy, although it depends a bit on the criteria that the classes are formed from.

Another important aspect to consider when choosing the most suitable storage policy for different length SKUs is whether or not to allow blockage. Allowing blockage more than one SKU can be stored in the same storage lane, making the process of storing and retrieving the SKUs considerably more complex, and it brings up the problem of relocation. According to Derhami et al. (2017), when there is a high number of SKUs with a low level of inventory, dedicating an entire lane to a single SKU cannot be justified due to the waste of storage space. On the other hand, if the inventory levels of the SKUs are sufficient to justify assigning them to dedicated lanes, the policy of allowing blockage will not be necessary and the problem of relocation will not occur (Derhami et al., 2017). Considering the findings from the case of Skogmo Bruk with respect to this, Skogmo Bruk should consider facilitating, at least for some of the SKUs, opening up to the possibility of letting multiple SKUs share one lane.

For choosing which storage policy is best suitable for storage of different length SKUs, choices have to be made in terms of the level of complexity that is suitable for the company. The dedicated storage policy operates with strict rules, making the process of having control over the warehouse much easier compared to the two other storage policies. With the dedicated policy, keeping track of where the different products are located within the warehouse is not hard, as the locations do not change and can be marked with a permanent label. The policy also allows the popular products to be placed in more convenient locations (Bartholdi and Hackman, 2014; Kay, 2015). Based on this, it's fair to say that the dedicated storage policy is less complex and can be performed with relative ease; the primary thing to keep track of would be the inventory levels. The shared storage policy, on the other hand, will only work efficiently if the warehouse is in a computer-controlled environment (de Koster et al., 2007), as the locations for the products are under constant change. Viewing the shared storage policy in light of different length SKUs the warehouse management software would need to be able to allocate the SKUs to a suitable location in terms of length of the product, keep track of where all of the product is located in the warehouse, and keep track of the inventory levels. Lastly, the class-based storage policy operates under many of the same conditions as the shared storage policy, but it allows for a little more control of the warehouse and where the products are located without checking with the warehouse management software.

Making a generalized conclusion of the most suitable storage policy for different length SKUs in a block stacking warehouse is challenging due to the lack of cases to compare against and draw patterns from. But, from Skogmo Bruk´s point of view, the class-based storage policy seems to be a good fit, facilitating good structure and flexibility in the warehouse. With Skogmo Bruk having a high variety of SKUs with many different lengths and huge variations in sales of the different products, classes could be created so that the top products get the best location in the warehouse and the less popular products can be placed further back. Another thing that should be considered for the less popular products is to allow blockage to minimize the space loss for the products that don't have a big enough inventory level to fill an entire storage lane.

6.4 Limitations, contribution and further research

The generalizability of the results is limited by only having a single case company. Having several cases allows patterns to be studied across the different cases, opening up the possibility of gaining more insight and knowledge about using block stacking to store SKUs of different lengths. If the cases were to be from various industries, then the potential of identifying other essential factors and contributions increase.

Due to a lack of data on the quantities of the different length products from Skogmo Bruk, the results from the mathematical model will not provide an accurate representation of the actual situation. From the data available, calculations and assumptions were made to get the necessary input data for the mathematical model.

The main contribution to knowledge of this thesis is an extension of the scope that research on the block stacking method has focused on in the currently available literature. There is no mention of utilizing the block stacking method to store different length SKUs in a warehouse in the extant literature on block stacking to the researcher's knowledge. Instead, the literature addresses block stacking applied to SKUs of the same size (e.g. euro-pallets or shipping containers), focusing on optimizing lane depth, space utilization, and reducing the number of relocations. This thesis provides a mathematical model that determines the lane depth for the different length SKUs and arranges them into storage rows. This thesis also provides guidelines and recommendations to practitioners who want to use the block stacking method for SKUs of different lengths to decide on a suitable storage policy.

Further research is needed to determine the effects of wide aisles in a block stacking warehouse with SKUs of different lengths. With the storage rows being filled with SKUs of varying lengths, the width of the aisle may become wider than necessary for most of the SKUs in the storage row. The lane depth models are based on a balance between the honeycomb loss in the storage lane and the down-aisle space loss. Too wide aisles may affect the lane depth of the shorter SKUs to a large degree in terms of honeycomb loss.

Further work on the problem of applying the block stacking method to SKUs of different lengths should consider investigating the aspect of space utilization to a higher degree. For instance, by examining the actual footprint that the SKUs take up in the warehouse and how that may affect the lane depths.

The mathematical model of this thesis should be refined and extended to encompass finite production rate and take factors like demand into consideration. Enabling this will allow for more realistic results that are closer to the real-life situations.

7 Conclusion

This thesis aimed to explore how the block stacking method could be applied to SKUs of different lengths, identifying the key factors, suitable storage row configuration, and a suitable storage policy that accommodates the different length SKUs. Findings from the literature study related to the first research question identified two factors; the accessibility to the SKUs in the warehouse and the space utilization in terms of maximizing the storage space used for the SKUs. Furthermore, the case study of Skogmo Bruk identified control and structure to be essential for the warehouse to function effectively, contributing to the third factor of detailed product description that includes dimensions and quantities.

To determine a suitable storage row configuration for different length SKUs, two methods, tiers and cutting stock, were evaluated against the case study's findings to select the method that was structured, facilitated accessibility, and were less time-consuming. The design by tiers was selected over the cutting stock method due to it being easier to implement and for providing similar results when the number of slots exceeds five.

Findings from the literature study and the case study of Skogmo Bruk contributed to the development of a mathematical model that applies the block stacking method to SKUs of different lengths. The model provides the lane depths and number of lanes for each SKU and arranges the SKUs into suitable storage rows. The mathematical model delivers acceptable results in terms of lane depth. However, in the configuration of storage rows using the tiers method, the model provides results but not the best in terms of space utilization due to a lack of enough SKUs in inventory. Nevertheless, the mathematical model in this thesis shows one way that the block stacking method can be applied to SKUs of different lengths and with that reach the overall scientific goal of this thesis.

The third research question aimed to combine the findings from the literature study related to the storage policies with the findings from the case study of Skogmo Bruk to find a suitable storage policy that accommodates different length SKUs. Generalizing a conclusion based on findings for a single case is challenging; therefore, the conclusion is drawn in light of Skogmo Bruk. Evaluating the different storage policies characteristics against the current situation at Skogmo Bruk, found the class-based storage policy as the best fit, facilitating good structure and flexibility in the warehouse.

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Appendix

A Data collected from Skogmo Bruk

A1 Sales report 2020

This section provides a part of the sales report from Skogmo Bruk.

Radetiketter	Summer av Totalt
101128120 - FURU 28X120 TERRASSEBORD CU IMPREGNERT AB	-7 058 949
101048148 - FURU 48X148 K-VIRKE JUSTERT CU IMPREGNERT AB	-3 901 815
101048198 - FURU 48X198 K-VIRKE JUSTERT CU IMPREGNERT AB	-2 295 493
101048098 - FURU 48X098 K-VIRKE JUSTERT CU IMPREGNERT AB	-2 005 238
111275200 - FURU 75X200 SKURLAST UHVL CU IMPREGNERT A	-1 170 827
111250150 - FURU 50X150 SKURLAST UHVL CU IMPREGNERT A	-1 118 872
101436048 - FURU 36X048 REKKE JUSTERT CU IMPREGNERT AB	-775 366
DIV UIMPR TRE - (Ingen verdi)	-766 473
151522148 - FURU 22X148 REKT KLEDN FS CU IMPREGNERT AB	-689 410
111250200 - FURU 50X200 SKURLAST UHVL CU IMPREGNERT A	-677 300
111275150 - FURU 75X150 SKURLAST UHVL CU IMPREGNERT A	-617 344
1423150500 - FURU 150X5000 STOLPE KONISK KREOSOT KL M	-597 064
101519148 - FURU 19X148 REKT KLEDNING CU IMPREGNERT AB	-485 402
101036148 - FURU 36X148 K-VIRKE JUSTERT CU IMPREGNERT AB	-484 641
1127140200 - FURU 140X2000MM STOLPE AUTOVERN CU IMPREG A	-477 653
1112100200 - FURU 100X200 SKURLAST UHVL CU IMPREGNERT A	-462 743
111275175 - FURU 75X175 SKURLAST UHVL CU IMPREGNERT A	-445 850
151522173 - FURU 22X173 REKT KLEDN FS CU IMPREGNERT AB	-423 781
1423150120 - FURU 150X12000 STOLPE KONISK KREOSOT KL M	-370 540
111238150 - FURU 38X150 SKURLAST UHVL CU IMPREGNERT A	-358 560
1112150200 - FURU 150X200 SKURLAST UHVL CU IMPREGNERT A	-347 125
101448048 - FURU 48X048 REKKE JUSTERT CU IMPREGNERT AB	-317 155
101519123 - FURU 19X123 REKT KLEDNING CU IMPREGNERT AB	-314 415
111048148 - FURU 48X148 K-VIRKE JUSTERT CU IMPREGNERT A C24	-298 405
101436073 - FURU 36X073 REKKE JUSTERT CU IMPREGNERT AB	-295 263
101121095 - FURU 21X095 TERRASSEBORD CU IMPREGNERT AB	-284 211
111232150 - FURU 32X150 SKURLAST UHVL CU IMPREGNERT A	-272 479
101519098 - FURU 19X098 REKT KLEDNING CU IMPREGNERT AB	-262 692
103128120 - FURU 28X120 TERRASSEBORD RILLET CU IMPREGNERT AB	-253 291
1423150100 - FURU 150X10000 STOLPE KONISK KREOSOT KL M	-237 819
1423150600 - FURU 150X6000 STOLPE KONISK KREOSOT KL M	-236 164
101430048 - FURU 30X048 REKKE JUSTERT CU IMPREGNERT AB	-229 549
151522198 - FURU 22X198 REKT KLEDN FS CU IMPREGNERT AB	-226 925
101448073 - FURU 48X073 REKKE JUSTERT CU IMPREGNERT AB	-214 085
111128120 - FURU 28X120 TERRASSEBORD CU IMPREGNERT A	-213 693
1423150700 - FURU 150X7000 STOLPE KONISK KREOSOT KL M	-206 867
101423048 - FURU 23X048 REKKE JUSTERT CU IMPREGNERT AB	-206 030
183010023 - FRAKT	-205 572
DIV FINGERSKJ - (Ingen verdi)	-198 768
1128100600 - FURU 100X6000MM STOLPE CU IMPREGNERT A	-191 551
1124060175 - FURU 60X1750MM GJERDESTOLPE CU IMPREGNERT A	-191 145
111048198 - FURU 48X198 K-VIRKE JUSTERT CU IMPREGNERT A C24	-185 987
111263150 - FURU 63X150 SKURLAST UHVL CU IMPREGNERT A	-184 885

151522123 - FURU 22X123 REKT KLEDN FS CU IMPREGNERT AB	-180 322
101834145 - FURU 34X145 ALTANREKKE CU IMPREGNERT AB	-159 403
101098098 - FURU 98X098 K-VIRKE JUSTERT CU IMPREGNERT AB	-156 920
1128140500 - FURU 140X5000MM STOLPE CU IMPREGNERT A	-156 869
111275225 - FURU 75X225 SKURLAST UHVL CU IMPREGNERT A	-155 642
1124070175 - FURU 70X1750MM GJERDESTOLPE CU IMPREGNERT A	-152 803
103219148 - FURU 19X148 DOBBEL-FALS 28 GR CU IMPREGNERT AB	-150 927
112010008 - FURU VANNBRETT PROF CU IMPREGNERT AB SPS	-149 727
111048098 - FURU 48X098 K-VIRKE JUSTERT CU IMPREGNERT A C24	-147 361
1423150900 - FURU 150X9000 STOLPE KONISK KREOSOT KL M	-144 933
101522148 - FURU 22X148 REKT KLEDNING CU IMPREGNERT AB	-143 064
111210002 - FURU SKURLAST UHVL CU IMPREGNERT A SPS	-140 463
102122148 - FURU 22X148 TAKBORD CU IMPREGNERT A	-137 408
101522198 - FURU 22X198 REKT KLEDNING CU IMPREGNERT AB	-131 198
161048148 - FURU 48X148 K-VIRKE FS CU IMPREGNERT A C24	-130 379
1423150800 - FURU 150X8000 STOLPE KONISK KREOSOT KL M	-130 315
1128160500 - FURU 160X5000MM STOLPE CU IMPREGNERT A	-125 744
101048223 - FURU 48X223 K-VIRKE JUSTERT CU IMPREGNERT AB	-125 367
161048198 - FURU 48X198 K-VIRKE FS CU IMPREGNERT A C24	-124 706
1128120500 - FURU 120X5000MM STOLPE CU IMPREGNERT A	-120 341
101128145 - FURU 28X145 TERRASSEBORD CU IMPREGNERT AB	-105 632
101036098 - FURU 36X098 K-VIRKE JUSTERT CU IMPREGNERT AB	-103 029
1128140400 - FURU 140X4000MM STOLPE CU IMPREGNERT A	-101 995
101834120 - FURU 34X120 ALTANREKKE CU IMPREGNERT AB	-96 928
171048198 - GRAN 48X198 K-VIRKE FINGERSKJ C 24	-92 288
171048148 - GRAN 48X148 K-VIRKE FINGERSKJ C 24	-92 047
1128200400 - FURU 200X4000MM STOLPE CU IMPREGNERT A	-90 874
1423150110 - FURU 150X11000 STOLPE KONISK KREOSOT KL M	-87 455
DIV IMTREL - (Ingen verdi)	-86 678
1124080175 - FURU 80X1750MM GJERDESTOLPE CU IMPREGNERT A	-83 539
173548048 - GRAN 48X048 TREKANTLEKT JUSTERT	-78 839
183010026 - KUTTERSPON	-77 068
171519148 - GRAN 19X148 REKT KLEDNING	-74 686
1128140600 - FURU 140X6000MM STOLPE CU IMPREGNERT A	-73 512
1123150900 - FURU 150X9000 STOLPE KONISK CU IMPREG A	-72 501
171519123 - GRAN 19X123 REKT KLEDNING	-70 977
111098098 - FURU 98X098 K-VIRKE JUSTERT CU IMPREGNERT A C24	-70 661
111250175 - FURU 50X175 SKURLAST UHVL CU IMPREGNERT A	-68 475
1123150100 - FURU 150X10000 STOLPE KONISK CU IMPREG A	-64 534
111275125 - FURU 75X125 SKURLAST UHVL CU IMPREGNERT A	-64 530
1128120400 - FURU 120X4000MM STOLPE CU IMPREGNERT A	-64 351
1112100150 - FURU 100X150 SKURLAST UHVL CU IMPREGNERT A	-64 288
101128095 - FURU 28X095 TERRASSEBORD CU IMPREGNERT AB	-62 277
111225125 - FURU 25X125 SKURLAST UHVL CU IMPREGNERT A	-56 840

103319148 - FURU 19X148 DOBBEL-FALS RETT CU IMPREGNERT AB	-53 659
DIV IMSTOLPER - (Ingen verdi)	-53 653
101928095 - FURU 28X095 GULVBORD TG CU IMPREGNERT A	-52 139
101048123 - FURU 48X123 K-VIRKE JUSTERT CU IMPREGNERT AB	-51 986
1125100175 - FURU 100X1750MM GJERDE HALVKL CU IMPREGERT A	-50 391
183010022 - LEIEARBEID	-49 966
1124080250 - FURU 80X2500MM GJERDESTOLPE CU IMPREGNERT A	-48 715
1128160600 - FURU 160X6000MM STOLPE CU IMPREGNERT A	-47 443
1128100400 - FURU 100X4000MM STOLPE CU IMPREGNERT A	-44 904
1123150800 - FURU 150X8000 STOLPE KONISK CU IMPREG A	-44 318
1112125125 - FURU 125X125 SKURLAST UHVL CU IMPREGNERT A	-44 261
1124080300 - FURU 80X3000MM GJERDESTOLPE CU IMPREGNERT A	-43 739
101522123 - FURU 22X123 REKT KLEDNING CU IMPREGNERT AB	-43 443
103219123 - FURU 19X123 DOBBEL-FALS 28 GR CU IMPREGNERT AB	-42 973
1423150400 - FURU 150X4000 STOLPE KONISK KREOSOT KL M	-42 478
103434045 - FURU 34X045 LEKTEKLEDNING CU IMPREGNERT AB	-42 208
101522098 - FURU 22X098 REKT KLEDNING CU IMPREGNERT AB	-40 858
1112150150 - FURU 150X150 SKURLAST UHVL CU IMPREGNERT A	-39 328
1128120600 - FURU 120X6000MM STOLPE CU IMPREGNERT A	-37 618
1112100100 - FURU 100X100 SKURLAST UHVL CU IMPREGNERT A	-36 264
1124060250 - FURU 60X2500MM GJERDESTOLPE CU IMPREGNERT A	-35 897
183010025 - ANBREKK/PLUKKTILLEGG	-35 850
1128160400 - FURU 160X4000MM STOLPE CU IMPREGNERT A	-35 006
1128100500 - FURU 100X5000MM STOLPE CU IMPREGNERT A	-34 654
1128180500 - FURU 180X5000MM STOLPE CU IMPREGNERT A	-33 194
101522173 - FURU 22X173 REKT KLEDNING CU IMPREGNERT AB	-32 534
101448068 - FURU 48X068 REKKE JUSTERT CU IMPREGNERT AB	-32 479
111263175 - FURU 63X175 SKURLAST UHVL CU IMPREGNERT A	-31 337
171048098 - GRAN 36X198 K-VIRKE FINGERSKJ C 24	-29 621
161010018 - FURU K-VIRKE FS CU IMPREGNERT A C24 SPS	-28 989
171522148 - GRAN 22X148 REKT KLEDNING	-28 635
101073148 - FURU 73X148 K-VIRKE JUSTERT CU IMPREGNERT AB	-27 875
151519148 - FURU 19X148 REKT KLEDN FS CU IMPREGNERT AB	-27 200
102258120 - FURU 58X120 TAKRENNE CU IMPREGNERT A	-27 152
1123150600 - FURU 150X6000 STOLPE KONISK CU IMPREG A	-26 611
111250100 - FURU 50X100 SKURLAST UHVL CU IMPREGNERT A	-26 307
101073198 - FURU 73X198 K-VIRKE JUSTERT CU IMPREGNERT AB	-26 145
150200FB - 150X200 MM UH. IMPR. CU KL. A	-24 466
101619148 - FURU 19X148 DOBBEL-FALS KLEDN CU IMPREGNERT AB	-23 552
1123150700 - FURU 150X7000 STOLPE KONISK CU IMPREG A	-23 350
111036148 - FURU 36X148 K-VIRKE JUSTERT CU IMPREGNERT A C24	-23 057
101410005 - FURU LEKT-REKKE JUSTERT CU IMPREGNERT AB SPS	-22 925
1128200600 - FURU 200X6000MM STOLPE CU IMPREGNERT A	-22 921
075200FB - 075X200 MM UH. IMPR. CU KL. A	-21 513

1124100175 - FURU 100X1750MM GJERDESTOLPE CU IMPREGNERT A	-21 310
183010021 - STAALBAND	-20 865
103128145 - FURU 28X145 TERRASSEBORD RILLET CU IMPREGNERT AB	-20 674
101516098 - FURU 16X098 REKT KLEDNING CU IMPREGNERT AB	-20 508
101719123 - FURU 19X123 SKRAA KLEDNING CU IMPREGNERT AB	-19 712
171010004 - GRAN K-VIRKE FINGERSKJ C 24 SPS	-19 442
075150FB - 075X150 MM UH. IMPR. CU KL. A	-19 141
183010024 - OMSTILLINGSTILLEGG	-18 600
1128200500 - FURU 200X5000MM STOLPE CU IMPREGNERT A	-18 586
111122095 - FURU 22X095 TERRASSEBORD CU IMPREGNERT A	-17 040
1126120400 - FURU 120X4000MM STOLPE SIDESKAARET CU IMPREG A	-16 395
1112200200 - FURU 200X200 SKURLAST UHVL CU IMPREGNERT A	-15 785
101519073 - FURU 19X073 REKT KLEDNING CU IMPREGNERT AB	-15 605
111128095 - FURU 28X095 TERRASSEBORD CU IMPREGNERT A	-15 564
1423150140 - FURU 150X14000 STOLPE KONISK KREOSOT KL M	-15 375
101121120 - FURU 21X120 TERRASSEBORD CU IMPREGNERT AB	-13 701
112810015 - FURU STOLPE CU IMPREGNERT A SPS	-13 238
1123150120 - FURU 150X12000 STOLPE KONISK CU IMPREG A	-13 128
111238100 - FURU 38X100 SKURLAST UHVL CU IMPREGNERT A	-12 919
101073073 - FURU 73X073 K-VIRKE JUSTERT CU IMPREGNERT AB	-12 883
111073198 - FURU 73X198 K-VIRKE JUSTERT CU IMPREGNERT A C24	-11 890
182910000 - TAKKROK FOR TRETAKRENNE GALVANISERT STAAL	-11 769
102045095 - FURU 45X095 VANNBRETT SPOR CU IMPREGNERT AB	-11 365
101036198 - FURU 36X198 K-VIRKE JUSTERT CU IMPREGNERT AB	-10 975
1127140250 - FURU 140X2500MM STOLPE AUTOVERN CU IMPREG A	-10 629
111910012 - FURU GULVBORD TG CU IMPREGNERT KLASSE A SPS	-10 508
171510006 - GRAN REKT KLEDNING SPS	-10 071
101036123 - FURU 36X123 K-VIRKE JUSTERT CU IMPREGNERT AB	-9 995
111263200 - FURU 63X200 SKURLAST UHVL CU IMPREGNERT A	-8 910
1128180600 - FURU 180X6000MM STOLPE CU IMPREGNERT A	-8 757
100200FB - 100X200 MM UH. IMPR. CU KL. A	-8 675
171519098 - GRAN 19X098 REKT KLEDNING	-8 084
101529198 - FURU 29X198 REKT KLEDNING CU IMPREGNERT AB	-7 912
101719148 - FURU 19X148 SKRAA KLEDNING CU IMPREGNERT AB	-7 430
101921095 - FURU 21X095 GULVBORD TG CU IMPREGNERT A	-7 358
111225150 - FURU 25X150 SKURLAST UHVL CU IMPREGNERT A	-7 055
171522198 - GRAN 22X198 REKT KLEDNING	-7 009
100100FB - 100X100 MM UH. IMPR. CU KL. A	-6 831
101519173 - FURU 19X173 REKT KLEDNING CU IMPREGNERT AB	-6 524
171036198 - GRAN 36X198 K-VIRKE FINGERSKJ C 24	-6 443
111238125 - FURU 38X125 SKURLAST UHVL CU IMPREGNERT A	-6 402

FRAKT - FRAKT	-6 250
1123150500 - FURU 150X5000 STOLPE KONISK CU IMPREG A	-5 427
102045145 - FURU 45X145 VANNBRETT PROF CU IMPREGNERT AB	-5 313
1423150130 - FURU 150X13000 STOLPE KONISK KREOSOT KL M	-4 510
111250225 - FURU 50X225 SKURLAST UHVL CU IMPREGNERT A	-4 233
1128180400 - FURU 180X4000MM STOLPE CU IMPREGNERT A	-3 660
101411036 - FURU 11X036 LEKT JUSTERT CU IMPREGNERT AB	-3 630
111250125 - FURU 50X125 SKURLAST UHVL CU IMPREGNERT A	-3 400
1123150110 - FURU 150X11000 STOLPE KONISK CU IMPREG A	-3 150
111098198 - FURU 98X198 K-VIRKE JUSTERT CU IMPREGNERT A C24	-3 101
171048223 - GRAN 48X223 K-VIRKE FINGERSKJ C 24	-3 014
101516073 - FURU 16X073 REKT KLEDNING CU IMPREGNERT AB	-2 809
101010003 - FURU K-VIRKE JUSTERT CU IMPREGNERT AB SPS	-2 496
151519123 - FURU 19X123 REKT KLEDN FS CU IMPREGNERT AB	-2 483
171036148 - GRAN 36X148 K-VIRKE FINGERSKJ C 24	-2 009
101510007 - FURU REKT KLEDNING CU IMPREGNERT AB SPS	-1 985
111232125 - FURU 32X125 SKURLAST UHVL CU IMPREGNERT A	-1 677
028095TB - 028X095 MM TG IMPR. CU KL. A	-1 579
101522073 - FURU 22X073 REKT KLEDNING CU IMPREGNERT AB	-1 284
KROKER - TAKRENNEKROKER	-1 273
101411048 - FURU 11X048 LEKT JUSTERT CU IMPREGNERT AB	-1 249
1112125200 - FURU 125X200 SKURLAST UHVL CU IMPREGNERT A	-1 238
101529173 - FURU 29X173 REKT KLEDNING CU IMPREGNERT AB	-1 195
111263125 - FURU 63X125 SKURLAST UHVL CU IMPREGNERT A	-983
111275100 - FURU 75X100 SKURLAST UHVL CU IMPREGNERT A	-772
111073148 - FURU 73X148 K-VIRKE JUSTERT CU IMPREGNERT A C24	-732
101036173 - FURU 36X173 K-VIRKE JUSTERT CU IMPREGNERT AB	-510
1126120300 - FURU 120X3000MM STOLPE SIDESKAARET CU IMPREG A	-280
101516148 - FURU 16X148 REKT KLEDNING CU IMPREGNERT AB	-174
101516123 - FURU 16X123 REKT KLEDNING CU IMPREGNERT AB	-100
(tom)	
DIVERSE - (Ingen verdi)	81 529
Totalsum	**-37 630 957**

A2 Sales data for each product

This section provides the sales of each product in meters distributed over the months of 2020.

Artikkel - salg 2020 antall meter pr. mnd	Januar	Februar	Mars	April	Mai	Juni	Juli	August	September	Oktober	November	Desember	Totalt
028095TB - 028X095 MM TG IMPR. CU KL. A	-	67	-	-	-	-	-	-	-	-	-	-	67
075150FB - 075X150 MM UH. IMPR. CU KL. A	-	-	-	-	504	-	-	-	-	-	-	-	504
075200FB - 075X200 MM UH. IMPR. CU KL. A	-	-	-	-	426	-	-	-	-	-	-	-	426
100100FB - 100X100 MM UH. IMPR. CU KL. A	-	-	-	-	-	132	-	-	-	-	-	-	132
100200FB - 100X200 MM UH. IMPR. CU KL. A	-	-	-	-	71	-	-	-	-	-	-	-	71
101010003 - FURU K-VIRKE JUST CU IMP KL AB SPS	-	120	-	-	-	-	-	-	-	-	-	-	120
101036098 - FURU 36X098 K-VIRKE JUST CUIMP AB	-	-	-	1 972	1 470	1 091	544	309	987	759	26	-	7 158
101036123 - FURU 36X123 K-VIRKE JUST CUIMP AB	-	-	-	-	198	52	15	280	-	-	8	66	618
101036148 - FURU 36X148 K-VIRKE JUST CUIMP AB	-	461	379	553	198	1 855	7 305	12 333	1 553	1 202	54	378	26 272
101036173 - FURU 36X173 K-VIRKE JUST CUIMP AB	-	-	-	-	-	-	-	-	12	-	-	-	12
101036198 - FURU 36X198 K-VIRKE JUST CUIMP AB	-	197	12	-	5	-	68	23	32	10	-	-	347
101048098 - FURU 48X098 K-VIRKE JUST CUIMP AB	2 165	3 262	4 151	6 628	19 186	10 872	38 829	20 021	17 939	19 339	1 015	1 207	144 613
101048123 - FURU 48X123 K-VIRKE JUST CUIMP AB	338	-	-	-	1 420	14	405	-	165	-	3 228	66	5 637
101048148 - FURU 48X148 K-VIRKE JUST CUIMP AB	1 479	3 171	1 999	5 653	24 896	27 456	52 099	28 518	17 605	7 737	1 079	1 262	172 954
101048198 - FURU 48X198 K-VIRKE JUST CUIMP AB	1 362	1 614	2 684	3 266	13 370	7 233	11 939	19 633	9 326	3 553	989	1 889	76 859
101048223 - FURU 48X223 K-VIRKE JUST CUIMP AB	-	400	-	205	99	1 040	355	561	-	-	599	122	3 380
101073073 - FURU 73X073 K-VIRKE JUST CUIMP AB	-	-	-	209	-	42	259	5	-	-	-	-	515
101073148 - FURU 73X148 K-VIRKE JUST CUIMP AB	-	-	-	-	73	-	28	122	367	-	-	-	590
101073198 - FURU 73X198 K-VIRKE JUST CUIMP AB	-	-	-	85	-	187	97	-	18	85	-	-	472
101098098 - FURU 98X098 K-VIRKE JUST CUIMP AB	120	-	7	343	934	270	504	964	120	15	108	32	3 417
101121095 - FURU 21X095 TERRASSE CU IMP KL AB	-	857	-	6 245	6 375	4 830	15 298	1 728	30	832	2 140	-	38 334
101121120 - FURU 21X120 TERRASSE CU IMP KL AB	-	-	-	-	-	35	727	717	100	-	-	-	1 579
101128095 - FURU 28X095 TERRASSE CU IMP KL AB	723	-	-	667	520	693	3 468	37	-	-	-	-	6 108
101128120 - FURU 28X120 TERRASSE CU IMP KL AB	1 739	12 205	10 788	37 041	116 091	123 878	168 074	70 517	50 406	26 288	6 264	2 716	626 007
101128145 - FURU 28X145 TERRASSE CU IMP KL AB	-	-	-	1 152	1 003	1 141	806	2 954	74	856	1 040	-	9 025
101410005 - FURU LEKT-REKKE JUST CU IMP AB SPS	864	-	-	-	118	-	-	-	-	612	-	-	1 594
101411036 - FURU 11X036 LEKT JUST CU IMP AB	-	-	-	-	-	-	787	214	-	-	-	-	1 001
101411048 - FURU 11X048 LEKT JUST CU IMP AB	88	-	-	-	8	-	-	-	167	-	103	-	366
101423048 - FURU 23X048 REKKE JUST CU IMP AB	1 017	2 760	-	978	2 332	6 032	5 173	5 554	13 943	-	428	908	39 124
101423073 - FURU 23X073 REKKE JUST CU IMP AB	-	-	-	-	-	-	-	-	-	66	-	-	66
101430048 - FURU 30X048 REKKE JUST CU IMP AB	-	-	370	2 580	2 872	2 054	15 219	4 432	8 984	2 903	2 756	-	42 170
101436048 - FURU 36X048 REKKE JUST CU IMP AB	3 585	2 482	4 442	6 099	10 855	17 949	42 145	11 526	15 274	10 581	2 376	-	127 315
101436073 - FURU 36X073 REKKE JUST CU IMP AB	1 536	111	1 520	2 370	4 596	2 980	8 564	4 536	3 309	1 782	-	-	31 303
101448048 - FURU 48X048 REKKE JUST CU IMP AB	1 735	6 365	1 124	861	1 963	5 798	6 049	3 995	5 833	3 928	3 342	1 120	42 111
101448068 - FURU 48X068 REKKE JUST CU IMP AB	-	-	-	-	361	321	1 265	321	-	-	311	-	2 578
101448073 - FURU 48X073 REKKE JUST CU IMP AB	-	2 205	-	70	2 719	1 116	7 245	953	1 700	2 723	-	63	18 794
101510007 - FURU REKT KLEDNING CUIMP AB SPS	-	-	113	-	-	-	-	-	-	-	3 073	-	3 187
101516073 - FURU 16X073 REKT KLEDNING CUIMP AB	-	-	-	-	49	-	420	-	-	-	-	-	469
101516098 - FURU 16X098 REKT KLEDNING CUIMP AB	-	619	-	520	105	76	685	513	-	2 078	-	-	4 597
101516123 - FURU 16X123 REKT KLEDNING CUIMP AB	-	-	-	-	-	-	8	-	-	-	-	-	8
101516148 - FURU 16X148 REKT KLEDNING CUIMP AB	-	-	-	-	15	-	-	-	-	-	-	-	15
101519073 - FURU 19X073 REKT KLEDNING CUIMP AB	-	-	201	512	380	-	-	-	487	-	-	158	1 738
101519098 - FURU 19X098 REKT KLEDNING CUIMP AB	-	1 851	-	893	535	10 676	9 415	4 109	4 320	1 513	965	21	34 296
101519123 - FURU 19X123 REKT KLEDNING CUIMP AB	829	787	2 633	2 803	5 353	3 541	5 527	5 793	3 463	6 920	991	810	39 449
101519148 - FURU 19X148 REKT KLEDNING CUIMP AB	1 216	3 222	1 519	1 961	2 829	4 420	14 165	3 292	6 613	7 241	980	677	48 133
101519173 - FURU 19X173 REKT KLEDNING CUIMP AB	-	-	-	-	246	14	-	-	32	38	-	56	386
101522073 - FURU 22X073 REKT KLEDNING CUIMP AB	-	-	-	-	-	-	156	-	-	-	-	-	156
101522098 - FURU 22X098 REKT KLEDNING CUIMP AB	862	-	-	153	835	29	1 844	-	-	4	1 615	-	5 341
101522123 - FURU 22X123 REKT KLEDNING CUIMP AB	297	-	19	513	-	1 104	1 150	-	31	1 499	43	851	5 507
101522148 - FURU 22X148 REKT KLEDNING CUIMP AB	1 170	477	1 361	867	16	1 146	265	1 331	3 358	1 109	1 519	237	12 854
101522173 - FURU 22X173 REKT KLEDNING CUIMP AB	269	11	-	10	29	595	295	33	268	190	-	-	1 700
101522198 - FURU 22X198 REKT KLEDNING CUIMP AB	883	236	158	828	768	583	586	1 314	636	730	-	479	7 201
101529148 - FURU 29X148 REKT KLEDNING CUIMP AB	-	-	-	-	-	-	-	-	-	104	101	-	205
101529173 - FURU 29X173 REKT KLEDNING CUIMP AB	-	-	-	38	-	-	-	-	-	-	-	-	38
101529198 - FURU 29X198 REKT KLEDNING CUIMP AB	-	144	-	-	24	-	-	-	-	-	34	-	202
101619148 - FURU 19X148 D-FALS KLEDN CUIMP AB	-	-	-	-	1 134	-	-	516	-	-	-	-	1 650
101719123 - FURU 19X123 SKRÃ... KLEDNING CUIMP AB	-	-	-	-	-	224	701	-	218	-	-	211	1 355
101719148 - FURU 19X148 SKRÃ... KLEDNING CUIMP AB	-	-	-	-	-	110	136	-	88	-	-	18	351
101834120 - FURU 34X120 ALTANREKKE CU IMP KL AB	-	-	51	922	491	453	968	1 646	-	-	435	447	5 412
101834145 - FURU 34X145 ALTANREKKE CU IMP KL AB	322	-	324	673	1 468	1 023	857	1 154	-	1 783	-	-	7 604
101921095 - FURU 21X095 GULV TG CU IMP KLASS AB	293	-	-	-	-	17	-	63	8	137	-	163	681
101928095 - FURU 28X095 GULV TG CU IMP KLASS AB	48	1 219	170	106	250	384	-	-	22	198	113	-	2 509
102045095 - FURU 45X095 VANNBRETT SPOR CUIMP AB	-	-	-	4	-	29	-	36	178	-	-	-	248
102045145 - FURU 45X145 VANNBRETT PROF CUIMP AB	-	-	-	-	29	-	-	-	61	28	18	-	137
102122148 - FURU 22X148 TAKBORD CU IMP KL AB	-	-	892	1 124	268	1 279 -	139	180	518	10	-	-	4 132
102258120 - FURU 58X120 TAKRENNE CU IMP KL AB	-	-	14	-	63	107	35	-	40	-	12	-	270
103128120 - FURU 28X120 TERRASSE RILL CUIMP AB	-	1 335	-	2 569	3 835	5 299	2 201	1 463	3 551	85	-	-	20 337
103128145 - FURU 28X145 TERRASSE RILL CUIMP AB	-	-	-	-	330	111	81	36	889	-	-	-	1 447
103219123 - FURU 19X123 D-FALS 28 GR CUIMP AB	-	840	-	922	32	405	1 225	22	202	-	-	205	3 852
103219148 - FURU 19X148 D-FALS 28 GR CUIMP AB	993	-	725	1 744	3 045	1 828	2 213	864	1 296	2 256	1 925	1 050	17 939
103319148 - FURU 19X148 D-FALS RETT CUIMP AB	-	528	-	1 196	605	510	-	-	525	1 835	-	1 353	6 552
103434045 - FURU 34X045 LEKTEKLEDNING CUIMP AB	-	-	-	604	-	614	-	1 324	-	-	-	-	2 543

103548048 - FURU 48X048 TREKANTLEKT CU IMP AB	-	-	-	-	-	-	-	-	-	-	-	112	112
111036148 - FURU 36X148 K-VIRKE CUIMP A C24	-	415	-	-	-	403	360	-	-	454	2 923	-	4 554
111048098 - FURU 48X098 K-VIRKE CUIMP A C24	-	-	-	2 306	761	3 049	-	1 296	832	1 010	416	-	9 669
111048148 - FURU 48X148 K-VIRKE CUIMP A C24	-	302	1 278	1 785	348	4 384	853	2 022	368	964	1 021	-	13 326
111048198 - FURU 48X198 K-VIRKE CUIMP A C24	120	-	50	1 349	306	1 963	419	189	744	243	446	-	5 828
111073148 - FURU 73X148 K-VIRKE CUIMP A C24	-	-	10	-	-	-	-	-	-	-	-	-	10
111073198 - FURU 73X198 K-VIRKE CUIMP A C24	-	-	-	-	86	-	86	-	-	-	-	-	173
111098098 - FURU 98X098 K-VIRKE CUIMP A C24	-	128	-	120	215	254	117	88	470	163	-	-	1 555
111098198 - FURU 98X198 K-VIRKE CUIMP A C24	-	-	-	-	46	-	-	-	-	-	-	-	46
111122095 - FURU 22X095 TERRASSE CU IMP KL A	-	-	-	-	210	863	886	-	-	840	-	-	2 799
111128095 - FURU 28X095 TERRASSE CU IMP KL A	-	-	-	-	1 390	-	-	-	-	-	-	-	1 390
111128120 - FURU 28X120 TERRASSE CU IMP KL A	-	-	-	5 508	-	5 468	1 537	-	2 754	729	2 074	-	18 069
111210002 - FURU SKURLAST CU IMP KL A SPS	1 817	-	29	16	-	-	-	-	-	-	-	-	1 862
1112100100 - FURU 100X100 SKURLAST CUIMP A	-	52	185	209	12	122	82	52	-	-	97	-	810
1112100150 - FURU 100X150 SKURLAST CUIMP A	16	-	-	-	514	30	-	22	74	-	441	618	1 715
1112100200 - FURU 100X200 SKURLAST CUIMP A	-	91	2 127	2 690	-	-	-	36	26	323	363	357	6 012
1112125125 - FURU 125X125 SKURLAST CUIMP A	-	-	15	155	22	57	28	105	46	7	-	-	435
1112125200 - FURU 125X200 SKURLAST CU IMP A	-	-	-	-	8	-	-	-	-	-	-	-	8
1112150150 - FURU 150X150 SKURLAST CU IMP A	33	-	-	16	89	52	67	10	8	335	151	45	805
1112150200 - FURU 150X200 SKURLAST CU IMP A	-	-	-	257	803	625	-	581	254	225	800	321	3 865
1112200200 - FURU 200X200 SKURLAST CU IMP A	-	-	-	-	-	-	-	-	66	131	211	-	409
111225100 - FURU 25X100 SKURLAST CU IMP A	-	-	-	-	-	-	-	-	-	-	63	-	63
111225125 - FURU 25X125 SKURLAST CU IMP A	-	-	1 512	878	3 096	-	-	-	-	2 034	-	-	7 520
111225150 - FURU 25X150 SKURLAST CU IMP A	-	-	-	-	126	-	-	-	302	-	-	-	428
111232125 - FURU 32X125 SKURLAST CU IMP A	-	-	-	-	-	36	-	-	62	-	-	4 122	4 220
111232150 - FURU 32X150 SKURLAST CU IMP A	352	-	890	3 449	5 527	903	-	1 006	358	1 000	739	1 180	15 403
111238100 - FURU 38X100 SKURLAST CU IMP A	-	-	-	-	1 025	-	-	-	-	-	-	-	1 025
111238125 - FURU 38X125 SKURLAST CUIMP A	-	-	-	-	374	-	-	-	-	620	-	-	995
111238150 - FURU 38X150 SKURLAST CU IMP A	-	-	565	3 904	7 805	738	717	-	2 375	2 567	5 378	-	24 049
111250100 - FURU 50X100 SKURLAST CU IMP A	15	-	107	-	316	247	354	-	420	884	241	851	3 433
111250125 - FURU 50X125 SKURLAST CU IMP A	-	-	-	-	93	-	-	-	27	2 168	207	-	2 495
111250150 - FURU 50X150 SKURLAST CU IMP A	2 698	2 630	3 467	630	7 938	6 299	2 424	4 242	11 245	3 485	3 783	3 144	51 984
111250175 - FURU 50X175 SKURLAST CU IMP A	-	-	-	1 134	-	-	567	32	-	-	240	-	1 973
111250200 - FURU 50X200 SKURLAST CU IMP A	3 553	2 252	1 248	2 772	1 242	1 815	2 349	708	2 408	3 143	2 752	938	25 179
111250225 - FURU 50X225 SKURLAST CU IMP A	-	-	-	-	-	-	21	-	71	-	-	-	92
111263125 - FURU 63X125 SKURLAST CU IMP A	-	-	19	-	-	-	-	-	-	-	-	-	19
111263150 - FURU 63X150 SKURLAST CU IMP A	-	-	510	2 023	523	-	-	1 182	98	874	876	-	6 086
111263175 - FURU 63X175 SKURLAST CU IMP A	-	-	-	-	50	-	405	80	-	-	-	-	536
111263200 - FURU 63X200 SKURLAST CU IMP A	-	-	-	-	-	-	-	108	-	277	-	-	385
111275100 - FURU 75X100 SKURLAST CU IMP A	- 1	-	-	-	8	51	-	-	-	-	-	-	58
111275125 - FURU 75X125 SKURLAST CU IMP A	-	-	-	-	-	1 256	-	244	-	-	-	-	1 499
111275150 - FURU 75X150 SKURLAST CU IMP A	491	466	1 369	603	2 773	1 796	334	1 654	1 948	1 150	1 393	6 530	20 507
111275175 - FURU 75X175 SKURLAST CU IMP KL A	-	437	108	495	1 163	1 101	127	473	4 131	5 002	801	3 960	17 797
111275200 - FURU 75X200 SKURLAST CU IMP KL A	446	1 243	3 449	2 191	2 987	230	384	3 742	2 267	1 002	6 293	3 640	27 872
111275225 - FURU 75X225 SKURLAST CU IMP KL A	217	172	-	-	4	1 081	105	17	372	216	54	253	2 489
111910012 - FURU GULV TG CU IMP KLASSE A SPS	-	-	-	-	-	-	-	-	701	-	-	-	701
112010008 - FURU VANNBRETT PROF CUIMP AB SPS	789	931	212	-	-	452	-	154	1 952	-	130	-	4 620
1123150100 - FURU 150X10000 STOLPE KON CU KL A	-	-	-	16	4	-	6	-	-	-	-	-	26
1123150110 - FURU 150X11000 STOLPE KON CU KL A	-	-	-	-	-	1	-	-	-	-	-	-	1
1123150120 - FURU 150X12000 STOLPE KON CU KL A	-	1	-	1	-	2	-	-	-	16	-	-	20
1123150140 - FURU 150X14000 STOLPE KON CU KL A	-	-	-	-	-	-	-	-	-	6	-	-	6
1123150500 - FURU 150X5000 STOLPE KON CU KL A	-	-	-	-	2	3	-	-	-	-	-	-	5
1123150600 - FURU 150X6000 STOLPE KON CU KL A	-	12	-	5	3	-	-	3	-	-	-	-	23
1123150700 - FURU 150X7000 STOLPE KON CU KL A	-	-	-	7	-	-	-	6	4	-	35	-	52
1123150800 - FURU 150X8000 STOLPE KON CU KL A	-	-	-	10	4	-	10	-	-	3	-	-	27
1123150900 - FURU 150X9000 STOLPE KON CU KL A	-	-	-	24	4	6	1	-	6	6	-	-	47
1124060175 - FURU 60X1750MM GJERDESTOLPE CU IMP	-	504	-	1 780	1 236	2 234	756	1 108	156	252	504	282	8 812
1124060250 - FURU 60X2500MM GJERDESTOLPE CU IMP	-	100	-	414	50	150	91	26	2	50	-	-	883
1124070175 - FURU 70X1750MM GJERDESTOLPE CU IMP	-	-	180	1 080	1 102	1 848	312	457	230	90	90	-	5 389
1124080175 - FURU 80X1750MM GJERDESTOLPE CU IMP	-	84	-	840	252	238	728	196	-	238	154	-	2 730
1124080250 - FURU 80X2500MM GJERDESTOLPE CU IMP	-	-	-	180	89	346	42	-	149	-	-	-	806
1124080300 - FURU 80X3000MM GJERDESTOLPE CU IMP	-	-	-	-	-	627	60	-	-	1	5	50	743
1124100175 - FURU 100X1750MM GJERDESTOLPE CU IMP	-	-	-	200	60	110	-	12	-	-	10	-	392
1125100175 - FURU 100X1750 GJERDE HALV CU KL A	-	14	-	160	668	678	338	47	-	-	-	198	2 103
1126120300 - FURU 120X3000MM STOLPE SIDESK CU A	-	-	-	-	-	1	-	-	-	-	-	-	1
1126120400 - FURU 120X4000MM STOLPE SIDESK CU A	-	-	-	-	27	21	-	-	-	-	-	-	48
1127140200 - FURU 140X2000MM STOLPE AUTOV CU A	1 203	-	150	45	200	1 207	108	1 350	150	53	-	50	4 516
1127140250 - FURU 140X2500MM STOLPE AUTOV CU A	-	-	-	-	-	-	37	-	26	-	-	-	63
112810015 - FURU STOLPE CU IMP KL A SPS	-	80	1	-	6	-	-	14	3	-	-	-	104
1128100400 - FURU 100X4000MM STOLPE CU IMP KL A	4	-	-	46	113	64	18	46	10	6	6	-	313
1128100500 - FURU 100X5000MM STOLPE CU IMP KL A	-	-	-	15	1	31	4	11	98	16	-	-	176
1128100600 - FURU 100X6000MM STOLPE CU IMP KL A	-	400	-	10	-	-	-	4	400	-	-	-	814
1128120400 - FURU 120X4000MM STOLPE CU IMP KL A	66	-	-	50	65	46	39	22	11	-	96	144	539

1128120500 - FURU 120X5000MM STOLPE CU IMP KL A	15	10	10	-	44	161	32	16	273	515	-	32	1 108
1128120600 - FURU 120X6000MM STOLPE CU IMP KL A	10	35	42	4	2	-	-	12	-	100	290	346	841
1128140400 - FURU 140X4000MM STOLPE CU IMP KL A	25	-	5	43	33	94	50	28	49	10	50	4	391
1128140500 - FURU 140X5000MM STOLPE CU IMP KL A	-	66	-	-	112	47	68	46	96	83	71	28	617
1128140600 - FURU 140X6000MM STOLPE CU IMP KL A	-	-	-	-	-	1	3	19	106	13	1	6	149
1128160400 - FURU 160X4000MM STOLPE CU IMP KL A	-	-	42	-	4	25	-	-	-	-	-	1	72
1128160500 - FURU 160X5000MM STOLPE CU IMP KL A	-	70	3	-	-	-	35	34	121	50	35	70	418
1128160600 - FURU 160X6000MM STOLPE CU IMP KL A	-	-	26	11	7	14	-	5	2	90	-	-	155
1128180400 - FURU 180X4000MM STOLPE CU IMP KL A	-	-	-	6	-	-	-	-	-	10	-	-	16
1128180500 - FURU 180X5000MM STOLPE CU IMP KL A	-	1	-	-	19	-	18	4	18	7	-	16	83
1128180600 - FURU 180X6000MM STOLPE CU IMP KL A	-	-	8	-	1	-	-	-	-	5	-	-	14
1128200400 - FURU 200X4000MM STOLPE CU IMP KL A	16	100	-	-	4	5	-	10	-	26	-	1	162
1128200500 - FURU 200X5000MM STOLPE CU IMP KL A	9	-	-	3	1	5	-	-	-	2	6	-	26
1128200600 - FURU 200X6000MM STOLPE CU IMP KL A	6	-	-	-	1	1	6	3	3	-	-	-	20
113128120 - FURU 28X120 TERRASSE RILL CUIMP A	-	-	-	-	-	-	-	-	-	643	-	-	643
1423150100 - FURU 150X10000 STOLPE KON KREOSOT	-	2	-	13	8	35	10	4	2	5	-	52	131
1423150110 - FURU 150X11000 STOLPE KON KREOSOT	-	-	-	7	7	-	-	15	-	14	47	81	171
1423150120 - FURU 150X12000 STOLPE KON KREOSOT	10	-	-	19	15	-	20	15	10	7	15	74	185
1423150130 - FURU 150X13000 STOLPE KON KREOSOT	-	-	-	-	1	-	-	-	-	-	-	12	13
1423150140 - FURU 150X14000 STOLPE KON KREOSOT	-	-	-	-	3	-	-	-	-	-	5	-	8
1423150400 - FURU 150X4000 STOLPE KON KREOSOT	-	-	-	2	15	-	10	4	-	9	-	-	40
1423150500 - FURU 150X5000 STOLPE KON KREOSOT	-	7	340	105	30	2	23	-	7	10	6	12	542
1423150600 - FURU 150X6000 STOLPE KON KREOSOT	16	6	-	16	45	30	14	8	2	48	6	47	238
1423150700 - FURU 150X7000 STOLPE KON KREOSOT	8	6	2	1	53	-	-	8	35	2	-	11	126
1423150800 - FURU 150X8000 STOLPE KON KREOSOT	6	5	-	23	9	2	-	14	-	22	1	22	104
1423150900 - FURU 150X9000 STOLPE KON KREOSOT	6	3	-	2	13	5	15	-	10	1	-	37	92
150200FB - 150X200 MM UH. IMPR. CU KL. A	-	-	-	-	202	-	-	-	-	-	-	-	202
151519123 - FURU 19X123 REKT KLEDN FS CUIMP AB	-	-	-	-	39	-	96	30	-	25	750	78	1 018
151519148 - FURU 19X148 REKT KLEDN FS CUIMP AB	-	-	-	-	-	341	1 076	298	-	-	-	-	1 715
151522123 - FURU 22X123 REKT KLEDN FS CUIMP AB	3 456	-	3 456	4 095	-	480	857	28	3 963	468	2 304	33	19 139
151522148 - FURU 22X148 REKT KLEDN FS CUIMP AB	3 900	208	8 942	1 200	5 494	3 556	13 373	2 547	2 886	2 366	12 180	1 229	57 881
151522173 - FURU 22X173 REKT KLEDN FS CUIMP AB	2 592	100	3 756	8 083	1 138	186	3 698	133	6 619	5 131	56	723	32 214
151522198 - FURU 22X198 REKT KLEDN FS CUIMP AB	-	26	3 048	2 428	12	28	2 160	810	3 712	3 642	1 228	325	17 419
161010018 - FURU K-VIRKE FS CU A C24 SPS	-	-	542	-	-	-	-	-	-	-	-	-	542
161048148 - FURU 48X148 K-VIRKE FS CU A C24	180	88	84	221	1 425	431	421	722	216	-	360	-	4 148
161048198 - FURU 48X198 K-VIRKE FS CU A C24	-	-	286	16	962	567	40	278	753	218	132	6	3 259
171010004 - GRAN K-VIRKE C 24 SPS	1 519	-	-	-	224	-	-	-	-	-	-	-	1 743
171036148 - GRAN 36X148 K-VIRKE C 24	-	-	-	-	-	-	-	-	72	-	-	-	72
171036198 - GRAN 36X198 K-VIRKE C 24	-	-	-	120	-	52	-	-	-	-	-	-	172
171048098 - GRAN 48X098 K-VIRKE C 24	-	600	-	-	-	-	-	742	-	-	65	-	1 407
171048148 - GRAN 48X148 K-VIRKE C 24	351	171	108	-	-	510	149	1 426	45	-	-	-	2 759
171048198 - GRAN 48X198 K-VIRKE C 24	599	232	-	-	150	91	204	637	150	87	97	-	2 246
171048223 - GRAN 48X223 K-VIRKE C 24	-	-	-	-	-	-	-	-	53	72	-	-	126
171510006 - GRAN KLEDNING REKTANGULÃ†R SPS	952	-	-	-	-	-	58	-	196	-	-	-	1 206
171519098 - GRAN 19X098 KLEDNING REKTANGULÃ†R	-	-	208	-	-	-	1 004	-	-	-	-	-	1 212
171519123 - GRAN 19X123 KLEDNING REKTANGULÃ†R	415	1 664	665	-	2 039	2 039	286	443	312	-	-	-	7 863
171519148 - GRAN 19X148 KLEDNING REKTANGULÃ†R	952	-	416	1 788	300	456	1 163	201	1 356	175	-	201	7 008
171522148 - GRAN 22X148 KLEDNING REKTANGULÃ†R	-	600	-	2 002	-	-	-	50	-	6 468	1 960	-	11 080
171522173 - GRAN 22X173 KLEDNING REKTANGULÃ†R	-	-	-	-	-	-	-	-	-	192	-	-	192
171522198 - GRAN 22X198 KLEDNING REKTANGULÃ†R	323	-	-	-	-	-	-	-	-	-	600	-	923
173548048 - GRAN 48X048 TREKANTLEKT JUST	-	-	1 974	-	2 907	41	958	-	510	1 236	10	-	7 636
182910000 - TAKKROK FOR TRETAKRENNE GALV	-	-	18	-	-	106	-	-	39	3	-	-	166
183010020 - VED/KAPP	-	-	-	-	-	-	-	-	-	-	36	3	39
183010021 - STAALBAND	-	100	-	700	200	50	-	-	300	-	-	642	1 992
183010022 - LEIEARBEID	13	-	17	4	1	-	2	-	7	7	4	2	57
183010023 - FRAKT	3	2 490	4 453	2 169	27	23	26	15	14	13	10	9	9 253
183010024 - OMSTILLINGSTILLEGG	1	-	5	2	4	2	11	5	12	4	8	10	64
183010025 - ANBREKK/PLUKKTILLEGG	2	2	19	6	7	27	10	16	12	12	20	14	147
183010026 - KUTTERSPON	-	-	188	-	-	-	195	33	-	328	-	210	953
DIV FINGERSKJ - (Ingen verdi)	-	-	-	-	-	6 056	1 342	713	396	14	452	-	8 973
DIV IMSTOLPER - (Ingen verdi)	-	-	-	-	-	105	1	22	66	6	15	170	385
DIV IMTREL - (Ingen verdi)	318	-	-	3	108	804	428	3	2 481	-	1 042	179	5 365
DIV UIMPR TRE - (Ingen verdi)	940	2 441	8 255	3 663	578	524	6 581	444	2 181	1 969	779	8 799	37 154
DIVERSE - (Ingen verdi)	- -	1	99 -	1	-	52	1	1 138	2	1	- -	1	1 291
FRAKT - FRAKT	-	1	-	-	2	-	-	-	-	1	-	-	4
KROKER - TAKRENNEKROKER	-	-	-	-	-	-	-	19	-	-	-	-	19
Totalt	52 393	66 889	90 153	160 061	295 387	309 485	479 272	246 280	237 457	165 721	93 120	56 843	2 253 060

B Mathematical model

B1 General data set

B1.1 Lane depth

SKU i	Length L	Width W	Height H	Quantity q	Stackability z	Lane depth	Nr. Lanes
36	3,50	1,00	0,50	30	6	4	2
18	2,50	1,00	0,50	32	6	4	2
26	2,50	1,00	0,50	36	6	4	2
8	1,50	1,00	0,50	37	6	4	2
13	2,00	1,00	0,50	39	6	4	2
16	2,50	1,00	0,50	44	6	4	2
22	2,50	1,00	0,50	45	6	4	2
31	3,00	1,00	0,50	48	6	4	2
24	2,50	1,00	0,50	49	6	4	3
39	4,00	1,00	0,50	49	6	4	3
14	2,00	1,00	0,50	50	6	5	2
37	3,50	1,00	0,50	52	6	5	2
11	2,00	1,00	0,50	56	6	5	2
5	1,50	1,00	0,50	60	6	5	2
6	1,50	1,00	0,50	60	6	5	2
25	2,50	1,00	0,50	62	6	5	3
29	3,00	1,00	0,50	63	6	5	3
4	1,50	1,00	0,50	65	6	5	3
12	2,00	1,00	0,50	67	6	5	3
23	2,50	1,00	0,50	67	6	5	3
33	3,50	1,00	0,50	67	6	6	2
40	4,00	1,00	0,50	68	6	6	2
17	2,50	1,00	0,50	69	6	6	2
7	1,50	1,00	0,50	78	6	6	3
2	1,50	1,00	0,50	80	6	6	3
30	3,00	1,00	0,50	87	6	6	3
9	2,00	1,00	0,50	89	6	6	3
34	3,50	1,00	0,50	89	6	6	3
35	3,50	1,00	0,50	90	6	6	3
27	3,00	1,00	0,50	98	6	6	3
1	1,50	1,00	0,50	100	6	7	3
28	3,00	1,00	0,50	102	6	7	3
3	1,50	1,00	0,50	110	6	7	3
32	3,50	1,00	0,50	113	6	7	3
19	2,50	1,00	0,50	120	6	7	3
15	2,50	1,00	0,50	130	6	7	4
20	2,50	1,00	0,50	130	6	7	4
38	4,00	1,00	0,50	135	6	7	4
10	2,00	1,00	0,50	140	6	7	4
21	2,50	1,00	0,50	154	6	7	4

Aisle width	Clear height
4,5	6

Lane depth 1	Lane depth 2	Lane depth 3	lane depth 4
3,91631204	4,75131561	5,5283361	6,80257305

x	n
1,5	2
2	2
2,5	11
3	2
3,5	2
4	3
59,5	

x	n
1,5	7
2	7
2,5	6
3	3
3,5	2
4	0
55,5	

x	n
1,5	6
2	3
2,5	2
3	6
3,5	8
4	2
74	

x	n
1,5	6
2	4
2,5	15
3	3
3,5	3
4	4
90	

B1.2 Tiers

Decision variables

	n1	n2	n3	n4	n5	n6	Nr. Rows
Number	2	1	4	2	1	1	3

Objective function

	n1	n2	n3	n4	n5	n6
Number	2	1	4	2	1	1
	x1	**x2**	**x3**	**x4**	**x5**	**x6**
Length	1,5	2	2,5	3	3,5	4
X_Row	28,5					
Nr. Rows	3					
X_tot	85,5					

Constraints

	Totals		
N1	6	>=	2
N2	3	>=	2
N3	12	>=	11
N4	6	>=	2
N5	3	>=	2
N6	3	>=	3
X_Row	28,5	<=	30
X_Row 2	28,5	>=	28,5
Nr. Rows	3	>=	1
X_tot	85,5	>=	59,5

Decision variables

	n1	n2	n3	n4	n5	n6	Nr. Rows
Number	4	4	2	2	1	0	3

Objective function

	n1	n2	n3	n4	n5	n6
Number	4	4	2	2	1	0
	x1	x2	x3	x4	x5	x6
Length	1,5	2	2,5	3	3,5	4
X_Row	28,5					
Nr. Rows	3					
X_tot	85,5					

Constraints

	Totals		
N1	12	>=	7
N2	12	>=	7
N3	6	>=	6
N4	6	>=	3
N5	3	>=	2
N6	0	>=	0
X_Row	28,5	<=	30
X_Row 2	28,5	>=	28,5
Nr. Rows	3	>=	1
X_tot	85,5	>=	55,5

Decision variables

	n1	n2	n3	n4	n5	n6	Nr. Rows
Number	3	1	1	2	3	1	3

Objective function

	n1	n2	n3	n4	n5	n6
Number	3	1	1	2	3	1
	x1	**x2**	**x3**	**x4**	**x5**	**x6**
Length	1,5	2	2,5	3	3,5	4
X_Row	29,5					
Nr. Rows	3					
X_tot	88,5					

Constraints

	Totals		
N1	9	>=	6
N2	3	>=	3
N3	3	>=	2
N4	6	>=	6
N5	9	>=	8
N6	3	>=	2
X_Row	29,5	<=	30
X_Row 2	29,5	>=	28,5
Nr. Rows	3	>=	1
X_tot	88,5	>=	74

Decision variables

	n1	n2	n3	n4	n5	n6	Nr. Rows
Number	4	1	4	1	1	1	4

Objective function

	n1	n2	n3	n4	n5	n6
Number	4	1	4	1	1	1
	x1	**x2**	**x3**	**x4**	**x5**	**x6**
Length	1,5	2	2,5	3	3,5	4
X_Row	28,5					
Nr. Rows	4					
X_tot	114					

Constraints

	Totals		
N1	16	>=	6
N2	4	>=	4
N3	16	>=	15
N4	4	>=	3
N5	4	>=	3
N6	4	>=	4
X_Row	28,5	<=	30
X_Row 2	28,5	>=	28,5
Nr. Rows	4	>=	1
X_tot	114	>=	90

B2 Skogmo Bruk - nine lengths

B2.1 Calculations for the quantities

m	m	m		m^3	
1	0,028	0,12	168074	564,72864	31,3738133
	3	1,5	21		
	3,3	1,65	19		
	3,6	1,8	17		
	3,9	1,95	16		
	4,2	2,1	15		
	4,5	2,25	14		
	4,8	2,4	13		
	5,1	2,55	12		
	5,4	2,7	12		

m	m	m		m^3	
2	0,048	0,148	52099	370,111296	20,5617387
	3	1,5	14		
	3,3	1,65	12		
	3,6	1,8	11		
	3,9	1,95	11		
	4,2	2,1	10		
	4,5	2,25	9		
	4,8	2,4	9		
	5,1	2,55	8		
	5,4	2,7	8		

m	m	m		m^3	
3	0,048	0,198	19633	186,592032	10,366224
	3	1,5	7		
	3,3	1,65	6		
	3,6	1,8	6		
	3,9	1,95	5		
	4,2	2,1	5		
	4,5	2,25	5		
	4,8	2,4	4		
	5,1	2,55	4		
	5,4	2,7	4		

m	m	m		m^3	
4	0,048	0,098	38829	182,651616	10,147312
	3	1,5	7		
	3,3	1,65	6		
	3,6	1,8	6		
	3,9	1,95	5		
	4,2	2,1	5		
	4,5	2,25	5		
	4,8	2,4	4		
	5,1	2,55	4		
	5,4	2,7	4		

m	m	m		m^3	
5	0,075	0,2	6293	94,395	5,24416667
	3	1,5	3		
	3,3	1,65	3		
	3,6	1,8	3		
	3,9	1,95	3		
	4,2	2,1	2		
	4,5	2,25	2		
	4,8	2,4	2		
	5,1	2,55	2		
	5,4	2,7	2		

m	m	m		m^3	
6	0,05	0,15	11245	84,3375	4,68541667
	3	1,5	3		
	3,3	1,65	3		
	3,6	1,8	3		
	3,9	1,95	2		
	4,2	2,1	2		
	4,5	2,25	2		
	4,8	2,4	2		
	5,1	2,55	2		
	5,4	2,7	2		

B2.2 Lane depth

SKU i	Length L	Width W	Height H	Quantity q	Stackability z	Clear height	Lane depth	Nr. Lanes
1	3,00	1,00	0,50	21	6	6	4	1
2	3,30	1,00	0,50	19	6	6	4	1
3	3,60	1,00	0,50	17	6	6	4	1
4	3,90	1,00	0,50	16	6	6	4	1
5	4,20	1,00	0,50	15	6	6	4	1
6	4,50	1,00	0,50	14	6	6	4	1
10	3,00	1,00	0,50	14	6	6	4	1
7	4,80	1,00	0,50	13	6	6	4	1
8	5,10	1,00	0,50	12	6	6	4	1
9	5,40	1,00	0,50	12	6	6	4	1
11	3,30	1,00	0,50	12	6	6	4	1
12	3,60	1,00	0,50	11	6	6	4	1
13	3,90	1,00	0,50	11	6	6	4	1
14	4,20	1,00	0,50	10	6	6	4	1
15	4,50	1,00	0,50	9	6	6	2	1
16	4,80	1,00	0,50	9	6	6	2	1
17	5,10	1,00	0,50	8	6	6	2	1
18	5,40	1,00	0,50	8	6	6	2	1
19	3,00	1,00	0,50	7	6	6	2	1
28	3,00	1,00	0,50	7	6	6	2	1
20	3,30	1,00	0,50	6	6	6	2	1
21	3,60	1,00	0,50	6	6	6	2	1
29	3,30	1,00	0,50	6	6	6	2	1
30	3,60	1,00	0,50	6	6	6	2	1
22	3,90	1,00	0,50	5	6	6	2	1
23	4,20	1,00	0,50	5	6	6	2	1
24	4,50	1,00	0,50	5	6	6	2	1
31	3,90	1,00	0,50	5	6	6	2	1
32	4,20	1,00	0,50	5	6	6	2	1
33	4,50	1,00	0,50	5	6	6	2	1
25	4,80	1,00	0,50	4	6	6	2	1
26	5,10	1,00	0,50	4	6	6	2	1
27	5,40	1,00	0,50	4	6	6	2	1
34	4,80	1,00	0,50	4	6	6	2	1
35	5,10	1,00	0,50	4	6	6	2	1
36	5,40	1,00	0,50	4	6	6	2	1
37	3,00	1,00	0,50	3	6	6	2	1
38	3,30	1,00	0,50	3	6	6	2	1
39	3,60	1,00	0,50	3	6	6	2	1
40	3,90	1,00	0,50	3	6	6	2	1
46	3,00	1,00	0,50	3	6	6	2	1
47	3,30	1,00	0,50	3	6	6	2	1
48	3,60	1,00	0,50	3	6	6	2	1
41	4,20	1,00	0,50	2	6	6	2	1
42	4,50	1,00	0,50	2	6	6	2	1
43	4,80	1,00	0,50	2	6	6	2	1
44	5,10	1,00	0,50	2	6	6	2	1
45	5,40	1,00	0,50	2	6	6	2	1
49	3,90	1,00	0,50	2	6	6	2	1
50	4,20	1,00	0,50	2	6	6	2	1
51	4,50	1,00	0,50	2	6	6	2	1
52	4,80	1,00	0,50	2	6	6	2	1
53	5,10	1,00	0,50	2	6	6	2	1
54	5,40	1,00	0,50	2	6	6	2	1

Aisle width	Clear height	Lane depth 1	Lane depth 2
10	6	3,42435256	1,87638837

x	n		x	n
3	2		3	4
3,3	2		3,3	4
3,6	2		3,6	4
3,9	2		3,9	4
4,2	2		4,2	4
4,5	1		4,5	5
4,8	1		4,8	5
5,1	1		5,1	5
5,4	1		5,4	5
55,8			171	

B2.3 Tiers

Decision variables

	n1	n2	n3	n4	n5	n6	n7	n8	n9	Nr. Rows
Number	1	1	1	1	1	1	1	1	1	2

Objective function

	n1	n2	n3	n4	n5	n6	n7	n8	n9
Number	1	1	1	1	1	1	1	1	1
	x1	**x2**	**x3**	**x4**	**x5**	**x6**	**x7**	**x8**	**x9**
Length	3	3,3	3,6	3,9	4,2	4,5	4,8	5,1	5,4
X_Row	37,8								
Nr. Rows	2								
X_tot	75,6								

Constraints

	Totals		
N1	2	>=	2
N2	2	>=	2
N3	2	>=	2
N4	2	>=	2
N5	2	>=	2
N6	2	>=	1
N7	2	>=	1
N8	2	>=	1
N9	2	>=	1
X_Row	37,8	<=	50
X_Row 2	37,8	>=	37,8
Nr. Rows	2	>=	1
X_tot	75,6	>=	55,8

Decision variables

	n1	n2	n3	n4	n5	n6	n7	n8	n9	Nr. Rows
Number	1	1	1	1	1	1	1	1	1	5

Objective function

	n1	n2	n3	n4	n5	n6	n7	n8	n9
Number	1	1	1	1	1	1	1	1	1
	x1	x2	x3	x4	x5	x6	x7	x8	x9
Length	3	3,3	3,6	3,9	4,2	4,5	4,8	5,1	5,4
X_Row	37,8								
Nr. Rows	5								
X_tot	189								

Constraints

	Totals		
N1	5	>=	4
N2	5	>=	4
N3	5	>=	4
N4	5	>=	4
N5	5	>=	4
N6	5	>=	5
N7	5	>=	5
N8	5	>=	5
N9	5	>=	5
X_Row	37,8	<=	50
X_Row 2	37,8	>=	37,8
Nr. Rows	5	>=	1
X_tot	189	>=	171

B3 Skogmo Bruk - five lengths

B3.1 Calculations for the quantities

m	m	m		m^3	
1	0,028	0,12	168074	564,72864	56,472864
	3	1,5	38		
	3,6	1,8	31		
	4,2	2,1	27		
	4,8	2,4	24		
	5,4	2,7	21		

m	m	m		m^3	
2	0,048	0,148	52099	370,111296	37,0111296
	3	1,5	25		
	3,6	1,8	21		
	4,2	2,1	18		
	4,8	2,4	15		
	5,4	2,7	14		

m	m	m		m^3	
3	0,048	0,198	19633	186,592032	18,6592032
	3	1,5	12		
	3,6	1,8	10		
	4,2	2,1	9		
	4,8	2,4	8		
	5,4	2,7	7		

m	m	m	m^3		
4	0,048	0,098	38829	182,651616	18,2651616
	3	1,5	12		
	3,6	1,8	10		
	4,2	2,1	9		
	4,8	2,4	8		
	5,4	2,7	7		

m	m	m	m^3		
5	0,075	0,2	6293	94,395	9,4395
	3	1,5	6		
	3,6	1,8	5		
	4,2	2,1	4		
	4,8	2,4	4		
	5,4	2,7	3		

m	m	m	m^3		
6	0,05	0,15	11245	84,3375	8,43375
	3	1,5	6		
	3,6	1,8	5		
	4,2	2,1	4		
	4,8	2,4	4		
	5,4	2,7	3		

B3.2 Lane depth

SKU i	Length L	Width W	Height H	Quantity q	Stackability z	Clear height	Lane depth	Nr. Lanes
1	3,00	1,00	0,50	38	6	6	5	2
2	3,60	1,00	0,50	31	6	6	5	2
3	4,20	1,00	0,50	27	6	6	5	1
6	3,00	1,00	0,50	25	6	6	5	1
4	4,80	1,00	0,50	24	6	6	5	1
5	5,40	1,00	0,50	21	6	6	5	1
7	3,60	1,00	0,50	21	6	6	5	1
8	4,20	1,00	0,50	18	6	6	3	1
9	4,80	1,00	0,50	15	6	6	3	1
10	5,40	1,00	0,50	14	6	6	3	1
11	3,00	1,00	0,50	12	6	6	3	1
16	3,00	1,00	0,50	12	6	6	3	1
12	3,60	1,00	0,50	10	6	6	3	1
17	3,60	1,00	0,50	10	6	6	3	1
13	4,20	1,00	0,50	9	6	6	3	1
18	4,20	1,00	0,50	9	6	6	3	1
14	4,80	1,00	0,50	8	6	6	3	1
19	4,80	1,00	0,50	8	6	6	3	1
15	5,40	1,00	0,50	7	6	6	3	1
20	5,40	1,00	0,50	7	6	6	3	1
21	3,00	1,00	0,50	6	6	6	3	1
26	3,00	1,00	0,50	6	6	6	3	1
22	3,60	1,00	0,50	5	6	6	3	1
27	3,60	1,00	0,50	5	6	6	3	1
23	4,20	1,00	0,50	4	6	6	3	1
24	4,80	1,00	0,50	4	6	6	3	1
25	5,40	1,00	0,50	4	6	6	3	1
28	4,20	1,00	0,50	4	6	6	3	1
29	4,80	1,00	0,50	4	6	6	3	1
30	5,40	1,00	0,50	3	6	6	3	1

Aisle width	Clear height
10	6

Lane depth 1	Lane depth 2
4,7182523	2,5819889

x	n
3,00	4
3,60	4
4,20	2
4,80	2
5,40	2
55,2	

x	n
3,00	8
3,60	8
4,20	10
4,80	10
5,40	10
196,8	

B3.3 Tiers

Decision variables

	n1	n2	n3	n4	n5	Nr. Rows
Number	2	2	1	1	1	2

Objective function

	n1	n2	n3	n4	n5
Number	2	2	1	1	1
	x1	**x2**	**x3**	**x4**	**x5**
Length	3	3,6	4,2	4,8	5,4
X_Row	27,6				
Nr. Rows	2				
X_tot	55,2				

Constraints

	Totals		
N1	4	>=	4
N2	4	>=	4
N3	2	>=	2
N4	2	>=	2
N5	2	>=	2
X_Row	27,6	<=	30
X_Row 2	27,6	>=	21
Nr. Rows	2	>=	1
X_tot	55,2	>=	55,2

Decision variables

	n1	n2	n3	n4	n5	Nr. Rows
Number	2	2	2	2	2	5

Objective function

	n1	n2	n3	n4	n5
Number	2	2	2	2	2
	x1	**x2**	**x3**	**x4**	**x5**
Length	3	3,6	4,2	4,8	5,4
X_Row	42				
Nr. Rows	5				
X_tot	210				

Constraints

	Totals		
N1	10	>=	8
N2	10	>=	8
N3	10	>=	10
N4	10	>=	10
N5	10	>=	10
X_Row	42	<=	42
X_Row 2	42	>=	21
Nr. Rows	5	>=	1
X_tot	210	>=	196,8

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