MULTI-LEVEL OPTIMIZATION-HEURISTIC FRAMEWORK FOR THREE-DIMENSIONAL BIN PACKING PROBLEM WITH ITEM UPGRADING AND OUTSOURCING OPTIONS

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Preface

Before you lie my master thesis "Multi-level optimization-heuristic framework for three-dimensional bin packing problem with item upgrading and outsourcing options". This report marks the end of my studies, of which the last 2.5 years were at the University of Twente. After completing my bachelor's degree in Mechanical Engineering at Saxion University of Applied Science, I continued with the pre-master and master in Industrial Engineering & Management, with a specialization in Production & Logistics Management. The decision to combine my interest in engineering and optimization of production environments proved to be a wise choice.

During this thesis, I challenged myself with a subject that I had no knowledge of, namely the three-dimensional bin packing problem. Although I had knowledge of several heuristics on different applications, I had to work hard to master this problem. I learned that struggling is part of the process. Sometimes you have to start with the solution without knowing exactly how you will solve all the obstacles. Therefore, this thesis has taught me valuable lessons, both professionally and personally.

I would like to express my gratitude to my supervisors, Dr. Derya Demirtas and Dr. Alessio Trivella, for their guidance and support throughout this process. They are both very driven, and despite being busy, I often had feedback within days after submitting. I would also like to thank my company supervisors, Gijs Karsten and Mike Mansveld. When I started the literature study, a new challenge arose for Mike, so he handed over the supervision to Gijs. This transfer went very smoothly. I am very grateful to Gijs for his flexibility and contribution to the data collection for this study. I am grateful to Mike for the excellent kick-off of my thesis; his input gave me a clear assignment with enough depth.

Finally, I would like to thank my family and friends for being there for me. They ensured that I could entirely focus on my thesis. I also want to thank you, my reader: I wish you a pleasant reading.

Luc Stoverink
Rijssen, March 2023

Management Summary

Voortman Steel Machinery (VSM) designs and develops Computer Numerical Controlled (CNC) machines and solutions for the steel construction and manufacturing industry for over 50 years. VSM assembles machines and handling equipment, such as roller conveyors, cross transports, and cutting tables, at two locations in Rijssen, the Netherlands. VSM's customers are located worldwide, so the equipment is transported in collis from VSM to the customer's location and then assembled on-site.

The logistics employees determine the required number of each transport type based on their experience. It is unclear how the collis will be positioned in the transports and whether the ordered transport composition is feasible until loading is completed. They often order entire transports, while partial transports are also possible. Given a loading list, it is unknown which transport composition is most cost-effective. In addition, the machines and handling are prepared, loaded, and transported separately because it is easier not to transport a finished product by road to another location. How much could be saved by fully integrating the two locations' preparation, loading, and transport is unclear. Making non-stackable collis stackable by building wooden boxes around them may save transport costs, but it is uncertain when this would be cost-effective. Finally, all purchased parts are delivered in Rijssen, so they do not consider when purchasing parts directly on location is beneficial. The rising transport costs against the same (non-optimal) way of working have created the need to improve the transportation process, from which the following research objective has been defined:

"Research and propose a solution to automatically create a loading proposal, where the solution covers which collis to make stackable and which collis to purchase abroad (colli composition), the required number of each transport type (transport composition) and how to position the collis in the transports (transport layout)."

To improve the current situation, we must first understand it. We have collected all loading lists of the projects from recent years. The transport costs per project are, on average, 20.1% more than budgeted, and the number of transports per project is, on average, 4.0% more than budgeted. On average, 35.8 collis are shipped per project, and the average weight of collis per project is 30.4 metric tons. Each project requires an average number of 3.0 transports, with an average fill rate of 56.4%. Machine and handling collis are seldom transported together, as only 21.6% of all transports include both types of collis.

We have developed a decision support tool (DST) to create a loading proposal automatically. The solution covers which collis to make stackable and which collis to purchase abroad (colli composition), the required number of each transport type (transport composition) and how to position the collis in the transports (transport layout). The DST consists of a two-stage heuristic to solve the three-dimensional bin packing problem with item upgrading and outsourcing options. It is a combinatorial optimization to get the cheapest colli and transport composition with the best transport layout. The combinatorial optimisation decides what to purchase abroad, what to make stackable, and the number of each transport type while ensuring feasibility for the colli composition. Once the colli and transport composition have been chosen, we strive to create the best transport layout. We do this by maximizing the number of collis from the same machine and location in the same transport. The objective is ensured by minimizing the number of groups of machines and locations in the different transports. A group consists of at least one colli of a machine and location in a transport. We consider various restrictions such as weight limit, weight distribution, orientation, stacking, stability and loading.

The model is divided into two stages: the first stage determines the colli and transport composition using simulated annealing (SA) to escape local optima, and the second stage determines the transport layout using a randomized constructive heuristic. The two stages are intertwined because the first stage uses the heuristics of the second stage to check for feasibility. If in the second stage, it turns out that purchasing abroad, making it stackable, or some transports are unnecessary, these will be removed.

The colli and transport composition are initialized using a greedy heuristic that assigns each colli to the cheapest transport per volume unit in which the colli may be placed. In the initial solution, we do not purchase anything from abroad or make anything stackable. Feasibility is checked in three phases: first, we check whether the solution has already been checked, then we roughly check the solution, and if it meets the rough requirements, then the solution is checked exactly. To improve the colli and transport composition, we employ operators such as add, delete, and move with a certain probability to generate neighbour solutions. The cooling scheme consists of a starting temperature based on the maximum costs of purchasing abroad, making items stackable and the transport types, fixed length of the Markov Chain, and a maximum number of iterations as stopping criterion with a decrease factor for temperature cooling.

The randomized constructive heuristic for determining the transport layout consists of several phases for each transport, including filtering, pre-processing, sorting, randomization, and constructive packing. After all the transports have been filled, we evaluate the solution and start the next iteration. We found the randomized constructive heuristic in the literature. Unfortunately, the code was unavailable, so we re-implemented it using the paper. We adapted it to VSM's case: the objective is changed, constraints are added and removed, it is extended for packing multiple transports of different transport types, and it is extended with the ability to pre-process irregular collis manually.

The DST has created a new loading proposal for each project in recent years. The DST can find an equally good or better solution for all projects compared to the current situation. The total shipping costs of all projects of recent years are €10,032,537 in the current situation and €8,393,573 with the DST. Consequently, the implementation of the DST would result in a significant cost reduction of 16.3% (€1,638,964) if the projects were reshipped again using today's prices. To provide a more accurate savings estimate, we adjusted the transport and purchasing abroad costs in both situations with a correction factor to account for the variability of transport costs over time. Considering the correction factor, the DST saves 16.5% compared to the current situation.

The average number of groups is 4.08 in the current situation and 5.65 with the DST, which is an increase of 38.7% (+1.58). This increase is logical because the number of transports in the current solution is higher than with the DST, so collis from different machines and locations must be mixed less over the different transports to get a feasible solution. As a result, the DST uses a smaller number of transports, so the collis of the same machine and location are more spread over the different transports to get a feasible solution, which results in a higher number of groups.

The option to purchase abroad is not popular and is only used in 17.9% (19 out of 106 projects) where purchasing abroad is possible. Disabling this option would result in a cost increase of 0.5% (€42,576). Similarly, the option to make items stackable is also infrequently used: only 2.2% (8 out of 366 projects) use it. Disabling this option would result in a cost increase of 0.1% (€9,060). Disabling both options would result in a cost increase of 0.6% (€52,942).

The second stage of the algorithm checks if the transport composition is feasible without purchasing items from abroad or making them stackable. If the composition is feasible, the outsourcing and upgrading options are removed. While the algorithm in the first stage chooses to purchase an item from abroad or make an item stackable, it may turn out to be unnecessary in the second stage. However, in some cases, a larger transport composition may be selected because a smaller one is not feasible in the number of iterations of the feasibility check. Changing the parameters may lead to even better solutions, but that also further increases the computational time.

In order to use the DST, we recommend VSM to (1) reconsider whether the DST should decide to purchase items abroad and make them stackable, (2) consider applying for an overweight permit for projects to the USA or weighing up the risk of overloading, (3) connect the other software systems to the DST, (4) assess and supplement all the data, (5) eliminate the uncertainty of the dimensions and weight of some collis that are not standardized, (6) use the transport management functionality in the ERP system and finally (7) professionalize the DST through a user interface.

Although the DST shows promising performances, this research still contains some limitations. First, not all manual pre-processing collis are known. The pre-processing sets indicate which regular and irregular collis together form a larger regular colli. The irregular collis are considered as regular, causing empty space to be lost. As a result, the savings could have been even more significant. Second, not all manual pre-processing sets may be optimal for every situation. The manual pre-processing sets are built up per machine and are optimal for transporting that machine. However, there may be better manual pre-processing sets for a combination of machines. Third, we have not considered a restriction that allows collis to be fixed with ratchet straps to the hooks of the transport. We have considered this limitation by adjusting the dimensions of the collis and by manual pre-processing. However, solutions may have been generated that cannot be fixed. Fourth, not all input data, such as the dimensions and weight of the collis, may be correct. Finally, we have assumed that all collis of a project, except backorders, may be included in each transport of the project. In reality, it may be possible that certain machines were deliberately packed together in the transports, for example, because they were shipped earlier or later.

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Glossary

3DBBP	Three-Dimensional Bin Packing Problem
3DKP	Three-Dimensional Knapsack Problem
3DODP	Three-Dimensional Open Dimension Problem
AWF	Almost Worst-Fit
BBL	Back-Bottom-Left
BF	Best-Fit
BRKGA	Biased Random Key Genetic Algorithm
BSG	Beam Search with Greedy-based function
CLP	Container Loading Problem
CNC	Computer Numerical Control
CO	Combinatorial Optimization
Colli	The minor packaging unit of a consignment of goods
Collo	The individual packaging unit
CP	Corner Point
DST	Decision Support Tool
EMS	Empty Maximum Spaces
EP	Extreme Point
ERP	Enterprise Resource Planning
FBX	Freightos Baltic Container Index
FCL	Full Container Load
FF	First-Fit
FTL	Full Truck Load
GA	(hybrid) Genetic Algorithm
GRASP	Greedy Randomized Adaptive Search Procedure
HQ	Headquarter
ILP	Integer Linear Program

ILS	Iterated Local Search
LCL	Less than Container Load
LTL	Less than Trailer Load
MCL	Multiple Container Loading
MIP	Mixed Integer linear Program
Module	One of a set of separate parts that, when combined, form a complete whole
MSI	Multi System Integration
MSLS	Multi-Start Local Search
NF	Next-Fit
NkF	Next-k-Fit
RCH	Randomised Constructive Heuristic
SA	Simulated Annealing
SBSAA	Sub-volume-Based Simulated Annealing Algorithm
SCL	Single Container Loading
TS	Tabu Search
VNS	Variable Neighbourhood Search
VPM	Voortman Parts Manufacturing
VSG	Voortman Steel Group
VSM	Voortman Steel Machinery
WF	Worst-Fit

1 Introduction

This research improves the transportation process at Voortman Steel Machinery from the production facility to the customer. In this chapter, we introduce the research design. After the company's introduction in Section 1.1, Section 1.2 describes the project. We define in Section 1.3 the motivation and objective of the research. Section 1.4 discusses the scope, and Section 1.5 presents the research questions and the methodology used to answer the research questions. Finally, Section 1.6 offers the deliverables, and in Section 1.7, we conclude the chapter with a summary.

1.1 Introduction to Voortman

The Voortman Steel Group (VSG) consists of two divisions, each with its own strengths and specialisms, namely Voortman Steel Machinery (VSM) and Voortman Steel Construction (VSC). VSM designs and develops Computer Numerical Controlled (CNC) machines and solutions for the steel construction and manufacturing industry for over 50 years. VSC designs, produces, and delivers high-quality steel projects (Voortman Steel Group, 2022). Figure 1.1 shows the locations of VSG in Rijssen.

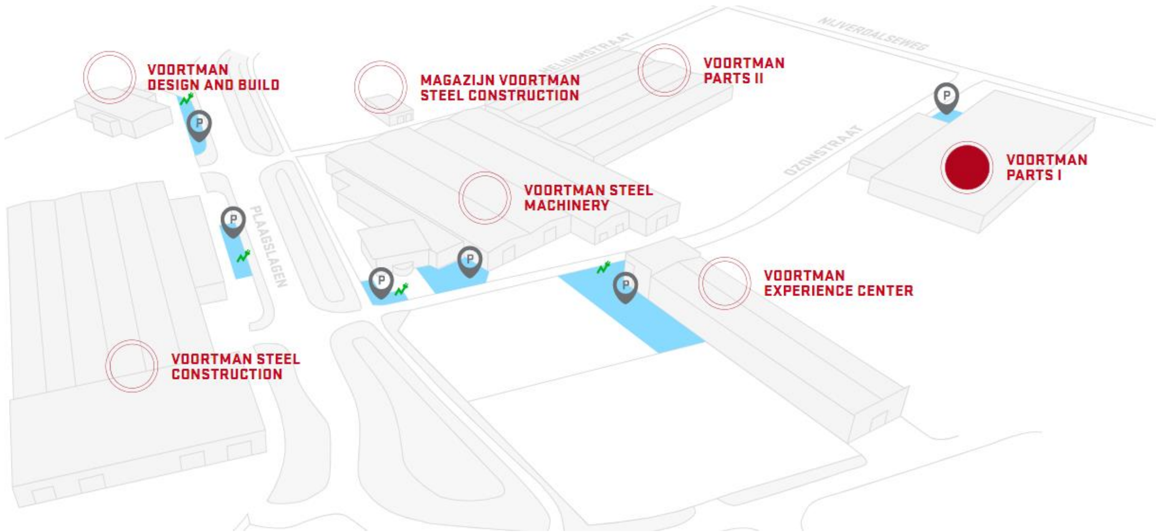

Figure 1.1 Locations of VSG in Rijssen (Voortman Steel Group, 2022)

The research is conducted at VSM, which has four locations in the Netherlands: the headquarters (HQ), the Experience Center and Parts I and II (VPM). The machines are designed, developed, and assembled in the HQ. The Experience Center is a beautiful showroom and high-tech academy for engineers and machine operators. VPM produces machine parts, such as frames and handling (roller conveyors, cross transports and cutting tables). At the time of authoring the thesis, VSM is building an Engineering Center, which ensures that the organisation can continue to grow and develop (Voortman Steel Group, 2022).

VSM manufactures machines for various processes, such as beam processing, plate processing, flat and angle processing, and surface treatment. Figure 1.2 shows the VSM portfolio.

Figure 1.2 VSM portfolio (Voortman Steel Machinery, 2022)

In addition to the stand-alone machines, VSM also offers MSI, also known as Multi System Integration. MSI makes it possible to fully automate production by connecting machines with cross transports, roller conveyors, product buffers and material sensors. However, the production data only needs to be imported once, and then MSI automatically distributes the data to all machines integrated into the production system. Manually transporting materials through the production line is made redundant by creating one integrated production system. Figure 1.3 shows the layout and configuration of a medium-sized steel fabricator (Voortman Steel Machinery, 2022).

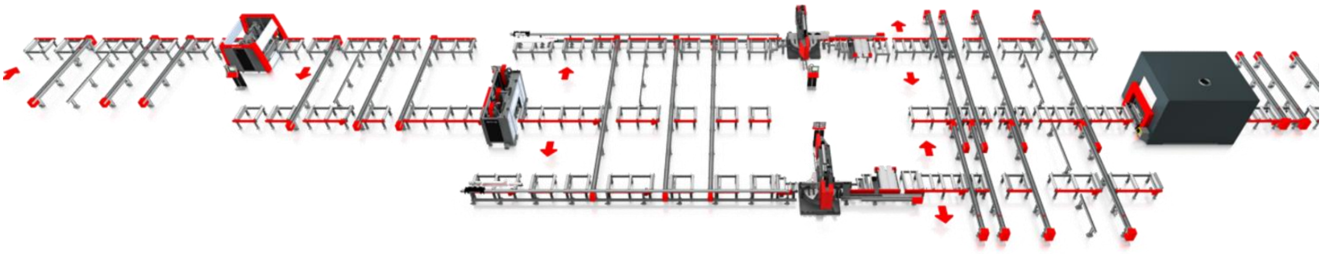

Figure 1.3 Example of MSI at a medium-sized steel fabricator (Voortman Steel Machinery, 2022)

1.2 Problem identification

VSM produces all equipment (machines and handling) in Rijssen in the Netherlands, while customers are located worldwide. Therefore, the equipment is transported from VSM to the customer in sub-assemblies and assembled at the customer's site. The different sub-assemblies in which the equipment is shipped are called collis. A colli designates the most minor packaging units of a consignment of goods. The individual packaging unit is a collo (LIS, 2022). A colli is, for example, a part of the machine or handling or multiple collo on a pallet.

The collis are transported in containers or semi-trailers, depending on the customer's location. When a project is released, a list with all the collis the customer needs is automatically generated based on the project DNA. The project DNA indicates what the customer has ordered. The logistics employees from the HQ (machines) and VPM (handling) decide, based on experience, the transport composition to be ordered. They make a puzzle on paper or in their mind about how it should fit and the required number of each transport type they need for this. The transport coordinators order the transports and prepare the transport template. In the week before loading, the logistics employees indicate which collis go in which transport in the template. The transport coordinators use this to create a loading list per transport and arrange the loading documents, such as CMR (delivery note) and export documents. During loading, it becomes clear whether the ordered transport composition is feasible. The loading documents must be adjusted if a colli is loaded in another transport. Since the loading is shortly before departure, this is not very pleasant for the transport coordinators. If not all collis fit in the transport composition, the transport coordinators urgently order an additional transport. Ordering a transport urgently is more expensive, costs extra effort and there is no guarantee that this transport will arrive on time. Mansveld (2022) estimates that the transport coordinators spend about 10 to 15 per cent of their time on ad hoc adjustments. The disadvantage of ad hoc is that, at that moment, it is no longer a matter of how it gets to the customer as cheaply as possible, but it arrives on time so that the chain disrupts as little as possible. An additional disadvantage is that the transport coordinators experience that if the export documents are adjusted, there is a greater chance that customs will carry out a check. The check slows down the process.

The logistic employees usually use entire transports, although partial transports are also possible. Partial transports are a few loading meters of an entire transport and usually cost less than a full transport. However, the positioning of collis in the transports prior to loading is unclear, which means that it is difficult to determine the exact loading meters required.

Machines at the HQ and handling at VPM are prepared, loaded and transported separately because it is easier not to transport a finished product by road to the other location. The logistic employees of both locations communicate to the transport coordinators about the required number of each transport type they expect to need and the space they expect to have left or short. For example, the logistics employee of VPM (handling) indicates that he expects a container and 2 "loading meters". The logistics employee of VSM (machinery) checks whether he can include these 2 "loading meters" in his calculation. VSM expects to save transport costs by fully integrating these two departments. A handling transport sometimes meets the maximum weight but still has much space left. However, there is almost no communication with each other at this micro level, so this transport volume is mainly lost.

Not all collis are stackable. Collis could be made stackable by building a wooden box around them. By making them stackable, perhaps transport costs can be saved. However, there is no insight into which collis are stackable, the costs to make a non-stackable colli stackable and whether this can save transport costs.

In addition to producing parts itself, VSM also purchases collis. The buyer can purchase these collis most cheaply through the standard supplier who delivers them to the HQ in Rijssen. An example of this is the exhaust unit. They can also purchase these collis in the customer's country, which is probably more expensive, but it saves perhaps transport costs. At this moment, there is no clear insight into what can be bought in the customer's country, what the costs are and if this can save transport costs.

Container freight rates have risen significantly over the past two years on most trade lanes during the COVID-19 pandemic. The Freightos Baltic Container Index (FBX) reflects spot rates for 40' containers on 12 trade routes. Figure 1.4 shows the FBX in recent years. Shipping a 40' container in August 2022 costs approximately US$6,000, more than six times more than just two years earlier. However, the price peaked in September 2021, when shipping a 40' container cost about US$11,100 (Freightos Ltd, 2022). At the same time, freight rates could rise further in the coming weeks and months due to the ongoing war between Russia and Ukraine (Placek, 2022).

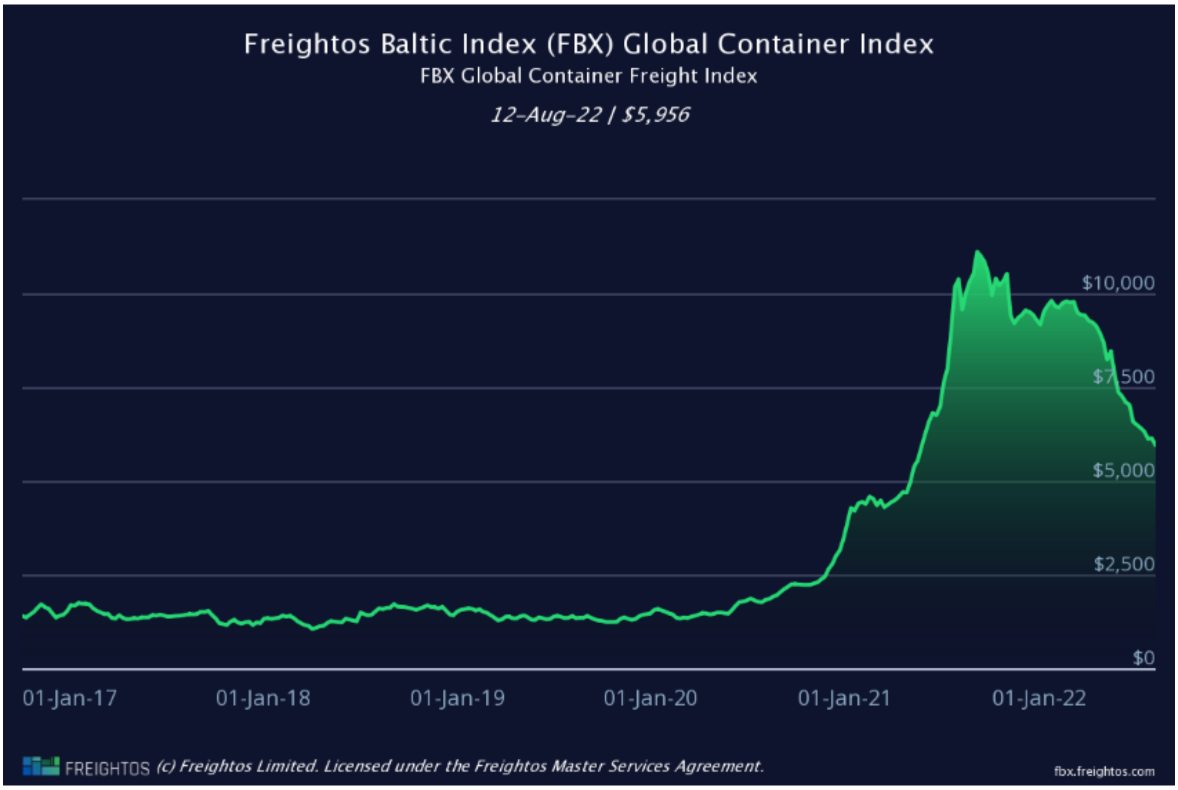

Figure 1.4 Freightos Baltic Container Index in recent years (Freightos Ltd, 2022)

The rising transport costs against the same (non-optimal) way of working have created the need to improve the transportation process. In June and July of 2022, VSM manually looked at how transport costs could be saved on projects sent in those months, with which significant savings were achieved. Therefore, the following action problem is defined:

"The transportation process from the production facility to the customer lacks strategy and (costs) efficiency."

1.3 Motivation and objective

The previous section described the action problem and the causes of the action problem. Appendix A shows the problem cluster, where we work from the action problem to the core problems and the consequences. This results in the following core problems:

- It is unclear:
  … if and how the collis will be positioned in the transports before loading.
  … which transport composition for a given loading list is the most cost-effective.
  … how much can be saved by fully integrating the loading and transporting of the machines and handling.
  … which non-stackable collis should be made stackable to be the most cost-effective.
- No consideration is made when purchasing procurement parts in the customer's country is beneficial.

The core problems give the following core consequences:

- Uncertainty whether the ordered transport composition is feasible.
- Collis arrive too late for more costs and effort than necessary at the customer.

The core consequences define the problem statement, which reads:

"The current way of creating the loading proposal results in uncertainty whether the ordered transport composition is feasible and collis arrive too late for more cost and effort than necessary. "

To improve the transportation process, we need to research and propose a solution to automatically create a loading proposal. The solution covers which collis to make stackable and which collis to purchase abroad (colli composition), the required number of each transport type (transport composition) and how to position the collis in the transports (transport layout). The solution considers all restrictions, such as maximum weight and dimensions. As a result, there is no longer any uncertainty about whether the ordered transport composition is feasible and all collis arrive on time for the lowest cost and least effort. Therefore, we define the following research objective:

"Research and propose a solution to automatically create a loading proposal, where the solution covers which collis to make stackable and which collis to purchase abroad (colli composition), the required number of each transport type (transport composition) and how to position the collis in the transports (transport layout)."

1.4 Research scope

The start point of the research is a list with all the required collis for the customer, which is automatically generated from the project DNA. The list holds all the needed information for the solution, such as the dimensions and weight of each colli. The data from the list is retrieved from a database. We assume that this database is complete and correct. We will add more information to the database if we need more information than is currently available.

We do not investigate whether the collis should be defined differently, for example, by adding a collo to another colli, which makes loading more efficient. Therefore, we use the collis as they are currently defined. The fluctuating currency exchange rate can make purchasing the procurement parts abroad more interesting. In the solution, we only work with EUR; therefore, the exchange rate is not considered. Finally, we are improving the transport process from VSM to one customer and are not considering combining the transport of multiple customers.

The endpoint of the assignment is a decision support tool (DST) that creates a loading proposal, which indicates which collis to make stackable, which collis to purchase abroad, the required number of each transport type and how to position the collis in the transports. In other words, a tool that determines the cheapest colli and transport composition with the best transport layout.

1.5 Research questions

The research objective in Section 1.3 leads to the following main research question:

"How can the way of creating a loading proposal be improved to remove the uncertainty whether the ordered transport composition is feasible and to ensure that all the collis arrive on time for the lowest cost?"

The main research question results in several sub-questions, which are structured in 6 phases: current situation, literature research, solution design, experiment design, analysis of the results and implementation plan. First, the research question is presented for each phase, followed by the sub-questions and the research design.

Current situation

Question 1. What is the current way of creating a loading proposal?

- 1.1 What does the current transportation process of VSM look like?
- 1.2 Which transport types does VSM use, and what are the characteristics?
- 1.3 How are the collis defined, and what are the characteristics of the collis?
- 1.4 What is the objective when making the loading proposal?
- 1.5 Which constraints are considered when making the loading proposal?
- 1.6 What is the performance if we look at the past years?

Before we improve the current situation, we should first understand the current situation. To know how much the current situation has improved, it is also essential to know its performance. We investigate this through the first research question. Chapter 2 describes the current situation of creating the loading proposal and its performance.

Literature research

Question 2. Which methods for solving the problem, suggested in the literature, best apply to VSM?

- 2.1 How is the packing problem of VSM known in the literature?
- 2.2 What is the formal statement of the packing problem of VSM?
- 2.3 Which packing methods are proposed in the literature, and which is best applicable to the problem of VSM?
- 2.4 What is the research gap between the chosen packing method and the problem of VSM?
- 2.5 How can the research gap between the chosen packing method and the problem of VSM be closed?

Once the current situation is clear, we explore the existing knowledge in this specific field. Keller (2022) once said: *"Alone we can do so little; together we can do so much."*. We leverage multiple parties' work and expertise through the literature review, saving us from reinventing the wheel. Next, we choose the most suitable method from the literature study to solve the packing problem. Chapter 3 describes the literature that can be applied to VSM's case.

Solution design

Question 3. What should be the decision support tool's design?

- 3.1 What is the formal statement of the problem at VSM?
- 3.2 What input data does the decision support tool use?
- 3.3 What does the decision support tool look like?
- 3.4 How can the data be initialized?
- 3.5 How can the cheapest feasible colli and transport composition be determined?
- 3.6 How can the best transport layout be determined?

Chapter 4 describes the DST, discussing which problem it solves, how it works, and what data is needed.

Experiment design

Question 4. What does the experimental design look like?

- 4.1 How can we prove that the decision support tool works?
- 4.2 How can the test instances be created?
- 4.3 How can the parameters of the decision support tool be calibrated?

Chapter 5 describes the experimental design for the experiments performed to test the performance of the DST.

Analysis of the results

Question 5. What is the performance of the decision support tool?

- 5.1 What are the results of the experiments in comparison with the current situation?
- 5.2 What are the consequences of adjusting the input data and constraints?
- 5.3 What is the quality of the solution of the decision support tool?

Chapter 6 analyses the experiment results of the DST. The experiments test the DST's performance and examine the consequences of adjusting input variables and constraints. Besides, the quality of the tool is evaluated.

Implementation plan

Question 6. How can the decision support tool be implemented in practice?

Chapter 7 describes how the DST can be implemented at VSM. Chapter 8 presents the research findings and provides recommendations and conclusions. Additionally, limitations and potential areas for future research are discussed.

1.6 Deliverables

This project will research and develop a decision support tool that, given a list with all collis, automatically creates a loading proposal. In addition, we propose a roadmap on how to implement the tool.

1.7 Conclusion

Voortman Steel Machinery (VSM) designs and develops CNC-controlled machines and solutions for the steel construction and manufacturing industry. The equipment (machines and handling) that a customer purchases from VSM is transported to the customer in collis and assembled at the customer's site. This transport process lacks strategy and (costs) efficiency. This results in uncertainty about whether the ordered transport composition is feasible and collis arrive too late and for more costs and effort than necessary. From this, the objective arises to research and propose a solution to automatically create a loading proposal. The solution covers which collis to make stackable and which collis to purchase abroad (colli composition), the required number of each transport type (transport composition) and how to position the collis in the transports (transport layout).

2 Current situation

This chapter describes the current situation at VSM by answering the first research question: *"What is the current way of creating a loading proposal?"*. In Section 2.1, we describe the current way of working. Section 2.2 describes the transport types and their characteristics. Afterwards, in Section 2.3, we describe the various collis transported in these transports and their characteristics. Section 2.4 describes the objective function, and Section 2.5 explains the considered restrictions. Section 2.6 looks at the performance in recent years. Finally, in Section 2.7, we conclude the chapter with a summary.

In this chapter, we use data from VSM in recent years. First, we collected data about the transported collis. The transport coordinators save the loading list per project in a folder on the file explorer. The loading lists are merged using a script in VBA. However, the format is not always used and correctly filled in. All the projects are manually checked to see whether the data have been transferred correctly. The data is validated with the ERP (Enterprise Resource Planning) system to check whether all customers and transports have been processed in the database. The result is a database with about 400 projects consisting of 13,000 collis sent to customers worldwide. Second, the budgeted and the actual transport costs are collected, which are both logged in the ERP system. This data is exported from the same time frame as the loading lists. Finally, the budgeted number of transports is collected, which is displayed in the quotations. All quotations are imported as PDFs into Power BI, after which Power BI extracted the budgeted number of transports.

2.1 Process overview

Figure 2.1 shows the current transportation process of VSM from the sale to the completion at the customer. After the flowchart, we zoom in on various steps of the process and look at what is involved in that step.

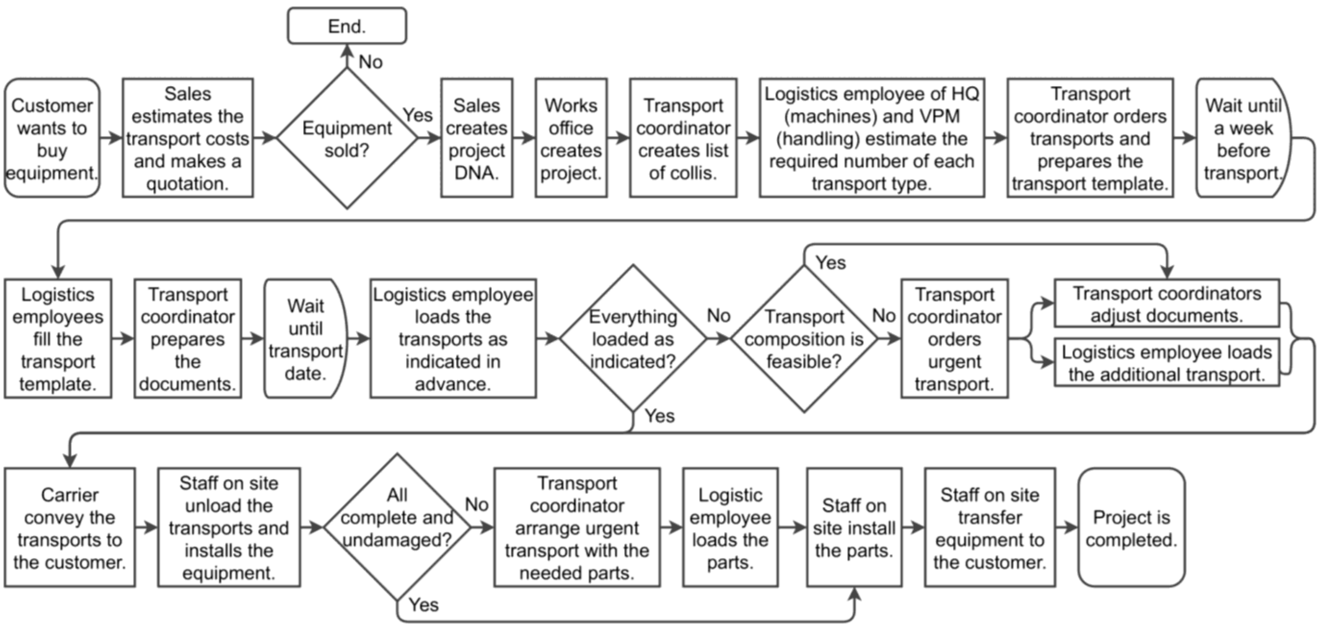

Figure 2.1 Overview of the current transportation process of VSM

2.1.1 Estimation of the transport costs

The sales department budgets the transport costs per project based on a certain fill level. A machine consists of several modules. A module is one of a set of separate parts that, when combined, form a complete whole (Cambridge Dictionary, 2022). For each module, the fill level for a container and semi-trailer is known, and for some modules also for a pallet. The fill level is based on volume, weight, and shape. VSM uses several containers and semi-trailers, as we will discuss in Section 2.2. However, the fill levels are based on one type of container (40' high cube hard top) and one type of trailer (curtain side). The only exception is the shot blasting machine with a width of 2.5 meters (VSB2500). Some collis of this machine do not fit in a container or semi-trailer and are transported on a low loader or flat rack. The filling degrees of all modules that the customer wants to purchase are summed up, which is rounded up to heal.

VSM uses a "country table" database for all country-specific calculations and quotations. This table shows per country, and in some countries also per state, the transport costs for a container/semi-trailer, low loader/flat rack and pallet. The country table also describes whether the collis are transported by container or truck. The transport budget is calculated by multiplying the budgeted number of transports by the transport costs from the country table. If the transport coordinators exceed the transport budget, they must report this to the project leader, which is responsible for the transport budget. Sometimes customers arrange the transport. In this case, the number of each transport type would still be budgeted, but no transport budget would be determined.

The budgeted and actual transport costs are subtracted to determine how often the budget exceeds. Figure 2.2 and Figure 2.3 show the difference in respectively euros and percentages. In 62.6% of the cases, the budget is exceeded. The transport costs per project are, on average, 20.1% (€2,613) more than budgeted. The actual transport costs can deviate from the budgeted transport costs because of several reasons, namely:

- The actual transport costs deviate from the country table.
- The used number of transports deviates from the budgeted.
- There are demurrage costs, which are costs for storing a loaded container at the terminal for longer than initially agreed (Shypple, 2022).

The budgeted and actual number of transports are subtracted to determine how often the number of transports exceeds. Figure 2.4 and Figure 2.5 shows the difference in containers/semi-trailers and percentages. In 33.0% of the cases, the budgeted number of transports is exceeded. On average, the number of transports per project is 4.0% (0.11) more than budgeted. The actual corresponds to the budgeted number of transports in 44.9% of the cases. In 25.3%, it deviates by half a transport, in 22.3% by one transport, and in 7.5%, more than one transport.

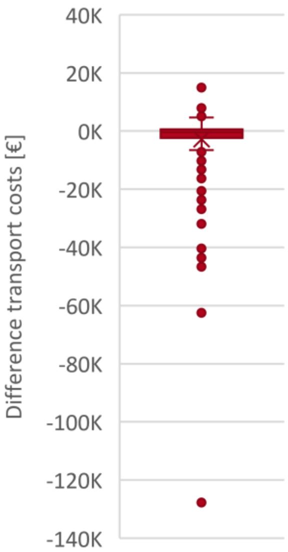

Figure 2.2 Budgeted – actual transport costs (in EUR)

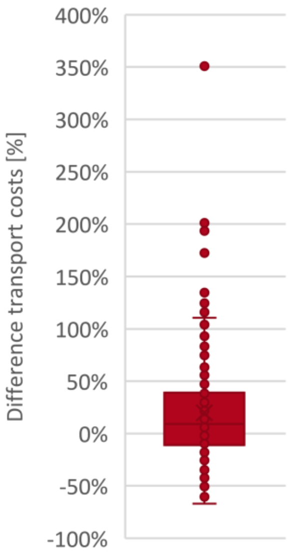

Figure 2.3 Budgeted – actual transport costs (in percentage)

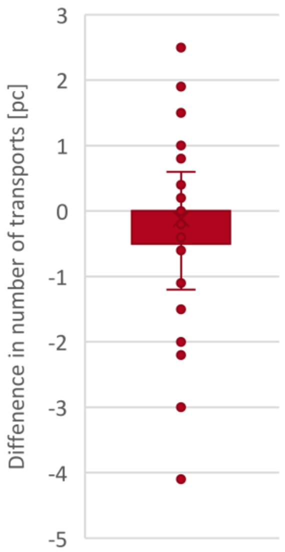

Figure 2.4 Budgeted – actual number of transports (in containers/semi-trailers)

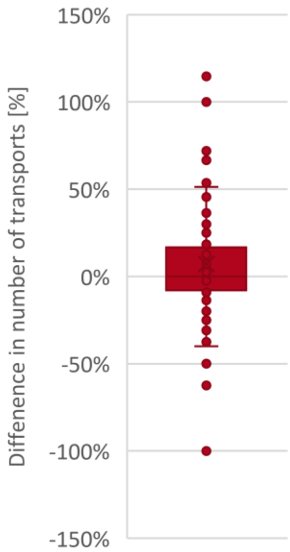

Figure 2.5 Budgeted – actual number of transports (in percentage of actual)

A project can consist of one or more machines, with or without handling. Figure 2.6 and Figure 2.7 show the distribution of single and multiple machines, respectively. We conclude that the budgeted number of transports is proportionally more likely to deviate in a project with multiple machines than a single one.

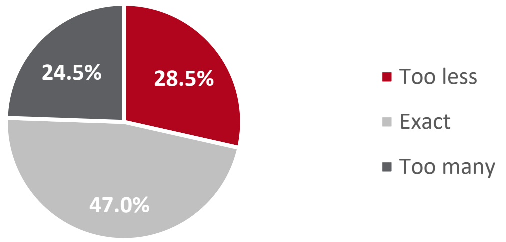

Figure 2.6 Difference between budgeted and actual number of transports for single-machine projects

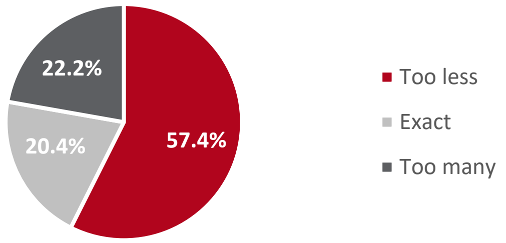

Figure 2.7 Difference between budgeted and actual number of transports for multiple machine projects

2.1.2 Project DNA

The sales department completes a configurator together with the customer. The configurator contains a set of rules that allow the user to tailor a solution while respecting current standards. The configurator creates the project DNA, describing what the customer bought. The load list generator, a functionality of the content generator, can automatically create the loading list based on the project DNA. Appendix B shows an overview of the different functionalities of the content generator.

A sales order is sometimes divided into several phases due to its enormous size. Each phase has its project number. The separate phases of a sales order are seen as independent projects from start to finish. An individual project DNA is created for each phase, and the entire process is individually completed. Therefore, the collis of the separate phases are also transported separately, even though the loading dates can be pretty close. Sometimes a project is sold in one go, but they agreed that a part of the sales order will be delivered later, for example, because the factory must still be built. In this case, the loading dates are far apart. Most sales orders, precisely 92.1%, consist of a single phase, while 7.0%, 0.6%, and 0.3% have two, three, and four phases, respectively.

2.1.3 Estimate the required number of each transport type

The logistics employees from the HQ (machines) and VPM (handling) decide, based on experience, the transport composition to be ordered. They make a puzzle on paper or in their mind about how it should fit and the required number of each transport type they need for this. Appendix C shows a sketch of a loading proposal. The transport coordinators order the required transport composition.

2.1.4 Transport template

The transport template is one of the functionalities of the project DNA. The transport template is filled by loading the project DNA. After loading the DNA, a list is created with all collis that must be sent to the customer. There is a database in which all collis for each machine and each option are defined. The following data is stored for each colli:

- Amount
- Colli type
- Machine
- Description
- Pieces per colli
- Length
- Width
- Height
- Weight
- Transport type

The transport type indicates under which condition the colli is transported. For example, the saw's frame will be transported in two pieces (two collis) if transported in a container and in one piece (one colli) if transported in a semi-trailer due to its size. In addition, there is a separate database for each machine that indicates which colli must be transported for a particular machine configuration. No more data is known than the rectangular shape (length, width, height); this data must be collected if necessary.

After loading the DNA into the load list generator, the transport coordinator fills in the required number of each transport type. The load list generator creates a column for each transport, in which the logistics employees can indicate through a cross that the colli in that row goes into that transport. When all collis have been assigned to a transport, the packing lists, CMR files and folder labels are generated automatically. The other transport documents can also be arranged afterwards; Appendix D describes all required transport documents per country.

The logistics employees currently complete the load list generator one week before transport because the collis does not always have a fixed width, length, height, and weight. Therefore, they must enter these sizes. An employee is currently eliminating this variation. In addition, they have most collis ready for transport a week before loading. Because this makes the collis tangible, dividing them over the different transports is more manageable.

2.1.5 Loading the transport

On the transport day, the transporter arrives with a truck with a container or semi-trailer. The logistics employees load the transport. The collis are loaded from the front by hand or forklift or from the top with an overhead crane, depending on the transport type. Ratchet straps fix the collis, which are attached to the hooks of the transport. Fixing is essential because the transport can receive strong shocks, especially the containers transported by sea. The logistics employees decide how many ratchet straps they need and how to tie them. Collis have fallen over in the past, which leads to transport damage. Figure 2.8 and Figure 2.9 show a container loaded with machinery and handling collis, respectively. It is impossible to fill the container 100 per cent based on volume because there must be room on the side to attach and tighten the ratchet straps.

Figure 2.8 Container loaded with machinery collis

Figure 2.9 Container loaded with handling collis

2.1.6 Additional transports and the loading documents

The required number of each transport type is estimated and ordered in the 8th week after the kick-off. In week 14, the collis are distributed over transports and loaded in week 15. During loading, it becomes clear whether the ordered transport composition is feasible. If the collis are loaded differently than indicated in the load list generator, the transport coordinator must adjust the loading documents. Since the loading is shortly before departure, this is not very pleasant for the transport coordinators. If not all collis fit in the transport composition, the transport coordinator urgently orders an additional transport. Ordering a transport urgently is more expensive, takes extra effort and there is no guarantee that this transport will arrive on time. Appendix E calculates the extra time per country for deviating from the loading proposal, which varies between ¾ and 4 hours.

The loading documents usually are printed a few days before transport. The number of times the loading documents are reprinted on the day of transport indicates how often the logistics employees deviate from the loading proposal. Appendix F determines that, of the transports for which the print date is not overwritten, the loading documents of the transport have been (re)printed on the day of transport in 45.1% of the cases.

Deviating from the loading proposal will be a thing of the past because a good estimate of the required number of each transport type can be made immediately after the kick-off. The transport coordinators, therefore, have more time to sort things out, which can save even more. Appendix G shows the current and future timeline from kick-off to the start of the installation.

If collis are shipped later, additional transports will be necessary. In certain projects, one or more collis are dispatched later for various reasons such as backorders, forgotten, and warranty. Appendix H presents a detailed analysis of all collis sent later.

2.2 Transport types

VSM uses various transport modes to convey the collis to the customer. All European countries and the Eastern Bloc are transported by truck and beyond by container. Collies shipped later than the container freight are mainly transported by aeroplane, which is much faster. Figure 2.10 shows the distribution of the various transport modes. Section 2.2.1 describes truck transport, followed by container transport in Section 2.2.2 and aeroplane transport in Section 2.2.3. Section 2.2.4 describes the characteristics of the transport types.

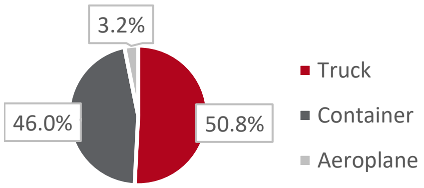

Figure 2.10 Distribution of the transport modes

2.2.1 Truck transport

If the collis are transported by truck, the collis are loaded on a semi-trailer. A semi-trailer is a freight trailer that, when attached, is supported at the front end by the fifth wheel of the truck tractor (Merriam-Webster, 2022). VSM uses several diverse types of semi-trailers, namely:

- FTL Curtain side
- FTL MEGA
- FTL Low loader
- Less than Truck Load (LTL)

The curtain side, MEGA and low loader are all FTL, standing for a Full Truck Load. A curtain side trailer (Figure 2.11) combines a dry van and a flatbed trailer. The sides are open for loading access, and the swing doors allow loading from the dock, like a dry van. Curtains hang from the roof on either side of the trailer, sliding open and closed to create a closed trailer (Utility Keystone, 2022). A curtain side trailer is the default truck transport at VSM. A MEGA trailer has the same characteristics as the curtain side trailer but is about 30 centimetres higher (DSV, 2022). A MEGA trailer is used when the collis are too high for the curtain side trailer. Four collis of the shot blasting machine (VSB2500-6) do not fit on the default trailer: the brush blow-off, inspection platform, shot blaster cabinet and the covers. These four collis are transported by a low loader (Figure 2.12), which fits on two low loaders. Due to the increased risk of damage, these are also the only collis allowed on a low loader. Finally, transporting a colli with LTL is possible. LTL is used if an entire curtain side cannot be filled. LTL can be ordered between 1 and 8 meters in whole meters. Above 8 meters, it is no longer cheaper to order a partial trailer.

Figure 2.11 Curtain side trailer (Pultrum, 2022)

Figure 2.12 Low loader trailer (Pultrum, 2022)

Figure 2.13 and Figure 2.14 show, respectively, the distribution of truck and LTL transport. We conclude that a curtain side is the most used truck transport type, and LTL is most used when a single loading meter is short.

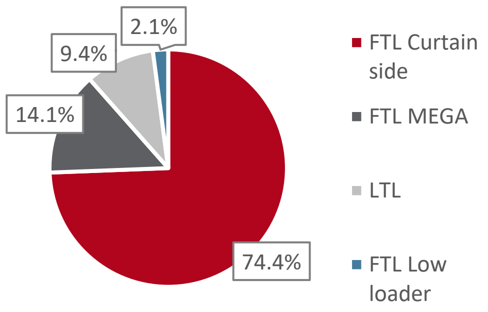

Figure 2.13 Distribution of the transport types of truck transport

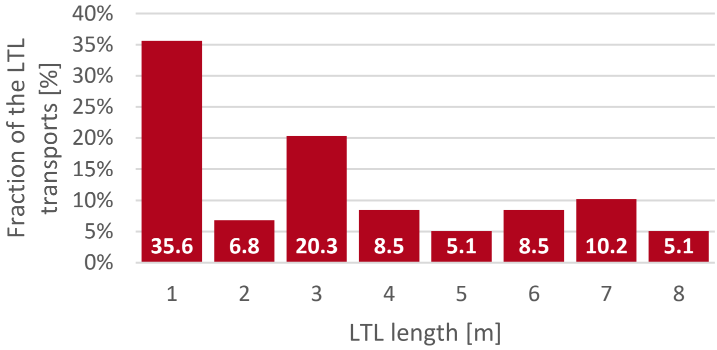

Figure 2.14 Distribution of LTL transport

2.2.2 Container transport

A container is any receptacle or enclosure containing a product used in packaging and shipping (Soroka, 2008). VSM uses diverse types of containers, namely:

- 20’ and 40’ Standard container
- 20’ Hardtop container
- 40’ Standard high cube container
- 40’ Hardtop high cube container
- 40’ High cube flat rack
- Less than Container Load (LCL)

The standard containers are used if all collis can be loaded with a forklift from the front doors. A container with a hardtop is chosen if the collis must be loaded with an overhead crane. The overhead crane can remove the hardtop of the container, allowing loading from the top. The 40’ hard top is a high cube container because this type is more common. The 40’ high cube flat rack for container transport is used for the same case as the low loader for truck transport. LCL can be used when the collis do not fill the entire container. The logistic employees load the collis then into a wooden box. A transport company collects the wooden box and combines the collis from customers who want to ship to the same port. The collis are loaded out of the container at the destination port and are delivered to the locations. LCL is currently little used. Recently, the legs of the roller conveyors have been shipped with LCL for three projects of customers in the USA. This change saved three times a 20’ container. In all cases, the 20’ container cost about €10,000, while the LCL costs about €2,500 (Morsinkhof, 2022). Figure 2.15 shows the distribution of container transport. We conclude that a 40’ hard top high cube is the most used container.

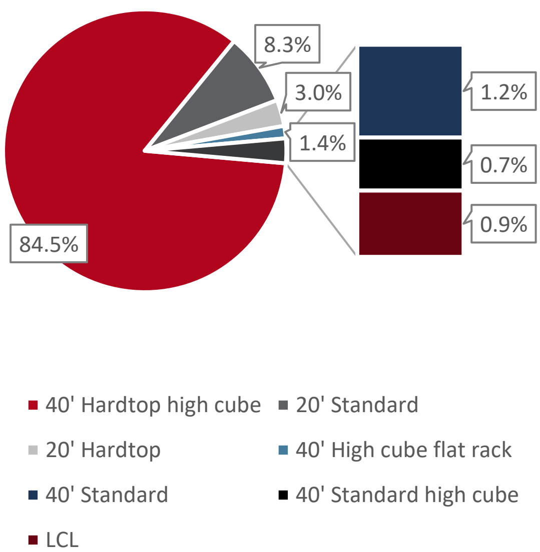

Figure 2.15 Distribution of the transport types of container transport

2.2.3 Aeroplane transport

If collis are sent by aeroplanes, the collis are not packed in a transport but collected by a parcel delivery service. The decision support tool does not need to consider aeroplanes as it only sends an individual colli. If an individual colli needs to be transported, the transport coordinators determine how it should be transported.

2.2.4 Characteristics

All transport types have their restrictions, namely:

- **Inside dimensions**: length, width, height
- **Door opening dimensions**: width, height
- **Roof opening**: length, width
- **Weight**: max gross, tare, max payload

Since all collis can fit in at least one of the transport types, the door opening and roof opening are not considered. The maximum payload in the USA depends on the truck, chassis, container, and driven states. Each state has their own rules, so in one state, the road may charge heavier than the other. The containers for a specific state do not always arrive in the same port because when booking the transports, it is also checked which port is busy and which port is not. In addition, it is not known in advance which type of truck with chassis is available for transporting the containers in the USA. Therefore, containers for the USA are always loaded with a maximum payload of 14.5 metric tons. There are also states in the USA where an overweight permit can be applied for, increasing the maximum payload to 18 metric tons. This permission must be requested in time. In other countries is the maximum payload according to the sea carrier leading.

The actual transport costs are variable per day and are only known once they are requested from the carrier. The country table shows per country, and in some countries also per state, the transport costs for a default semi-trailer (curtain side)/container (40' high cube hard top), low-loader/flat rack and pallet. However, there are also other types of semi-trailers and containers. By questioning the carrier, we found the ratios between the different semi-trailer and container prices. For example, transporting a MEGA to Berlin, Germany, currently costs 1.13 times a curtain side. The proportions for each transport type have been added to the country table so they can be changed just like the transport prices. Ultimately, we have a transport price for each semi-trailer and container type based on the default semi-trailer/container and low loader/flat rack price.

2.3 Collis

This section describes all information related to the collis. Section 2.3.1 describes the diverse types of collis. In Section 2.3.2, we analyse the characteristics. Section 2.3.3 describes the shapes and outstanding parts of the collis. Section 2.3.4 describes the stability of the collis, after which we describe in Section 2.3.5 which collis can be purchased abroad.

2.3.1 Diverse types of collis

The collis sent to the customer can be divided into five types: carton box, pallet, wooden box, tool container and package. We discuss the types in the sections below.

Carton box

Carton boxes store small loose parts that can be lifted into the transport by hand, such as manuals, consumables, and installation tools. The maximum weight is 25 kilograms, and the maximum dimensions are 0.80 by 0.60 by 0.70 meters.

Pallet

Pallets store more significant loose parts that are too heavy or too large to lift into the transport by hand, such as covers and sub-assemblies (Figure 2.16). The maximum weight is about 8 metric tons, with maximum dimensions of 6.6 by 2.4 by 3.0 meters.

Figure 2.16 Pallets with covers and weldment parts

Wooden box

Parts can be in a wooden box because the supplier supplies it, it is a loose delivery, or to make it stackable (Section 2.3.4). The maximum weight is 4650 kilograms, and the maximum dimensions are 7.5 by 2.2 by 2.6 meters.

Tool container

A small container with tools is sent along for projects within Europe where the installation technicians do not drive a service bus. The tool container is sent from customer to customer and sometimes with a stop at VSM. In that case, the tool container is on the loading list since it is transported along with the machines. Outside Europe, VSM makes agreements with the customer about tools. In the USA, tool containers are circulated from customer to customer, but these never go through VSM and are, therefore, never on the loading list. The tool containers are 2.4 by 1.0 by 2.0 meters and weigh 1600 kilograms.

Package

Packages are anything that is not in any of the other categories. Packages come in small and large sizes and can be anything: small parts of a machine, large parts of a machine (Figure 2.17), roller conveyors and cross transports (Figure 2.18). The maximum weight is 22 metric tons, with maximum dimensions of 15.0 by 3.50 by 3.46 meters.

Figure 2.17 Examples of large packages

Figure 2.18 Cross transport, each transport is a package

2.3.2 Analysis of the characteristics

VSM transports collis of diverse types, dimensions, and weights. Figure 2.19 shows the distribution of the diverse types of collis. We conclude that the majority is a package (70.5%).

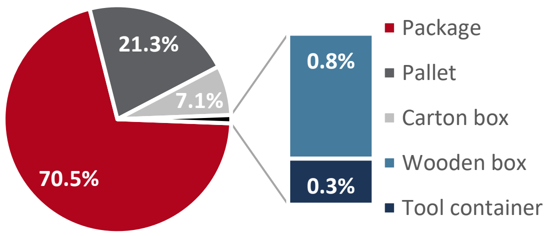

Figure 2.19 Distribution of the packing methods

Each colli has a length, width, and height. The collis can be rotated so the length can become the width and vice versa. We define the length as the longest side and the width as the shortest side of a colli. Most collis cannot be tilted, so we do not swap heights with lengths and widths. Figure 2.20 shows the distribution of the collis lengths. We conclude that the collis have a wide range of lengths. A length between 1 and 1.5 meters is the most popular (14.5%), followed by a length between 2.5 and 3 meters (10.9%) and 1.5 and 2 meters (10.4%).

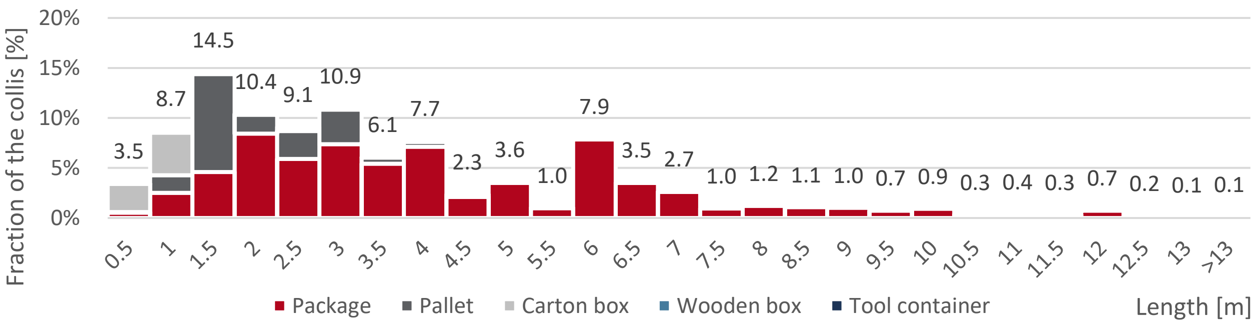

Figure 2.20 Distribution of the length of the collis

Figure 2.21 and Figure 2.22 show the distribution of the width and height of the collis, respectively. The collis have a smaller range of widths and heights, which makes sense because the transports are less wide and high than long. A colli is a maximum of 3.5 meters wide and high. Almost half of the collis is between 0.5 and 1 meter wide (46.7%). Second, length up to and including 0.5 meters is the most popular (30.0%). The popularity is the same for the heights; 41.8% of the collis is between 0.5 and 1 meter high, followed by 26.8% up to 0.5 meters high.

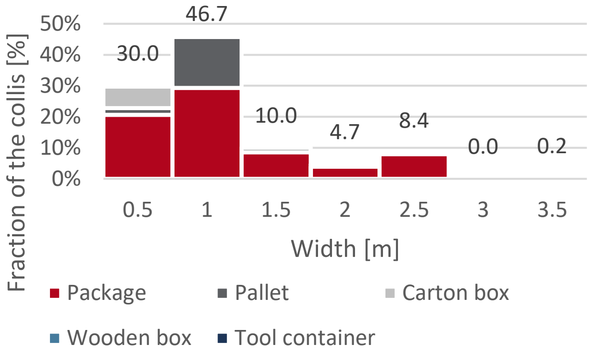

Figure 2.21 Distribution of the width of the collis

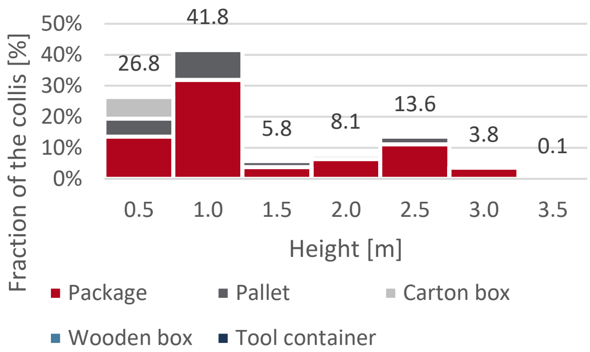

Figure 2.22 Distribution of the height of the collis

Figure 2.23 shows the distribution of the weight of the collis. Most collis weigh up to 250 kg (35.6%), followed by the collis between 250 and 500 kg (18.9%) and the collis between 500 and 750 kg (16.4%). The weight varies greatly and reaches almost 14 metric tons (short blaster cabinet).

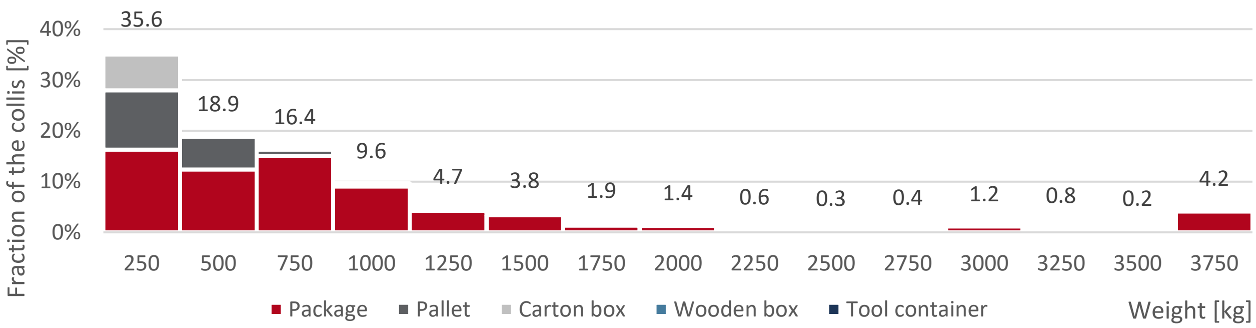

Figure 2.23 Distribution of the weight of the collis

Collis that cannot be loaded by hand or forklift must be loaded with an overhead crane. Collis can only be loaded with an overhead crane if the transport roof is removable. It is unknown for each colli whether it can be loaded by hand or forklift; this data needs to be collected.

2.3.3 Shapes and outstanding parts

The outer dimensions (l x w x h) of each colli are available. However, with some collis, much space is lost when approximated as rectangular. Some collis can be intertwined, and some have empty spaces where other collis can be put.

Collis intertwined

Cross transports can be positioned intertwined, which provides an advantage over non-intertwined positioning. Figure 2.24 shows cross transports positioned as rectangles (top) and intertwined (bottom).

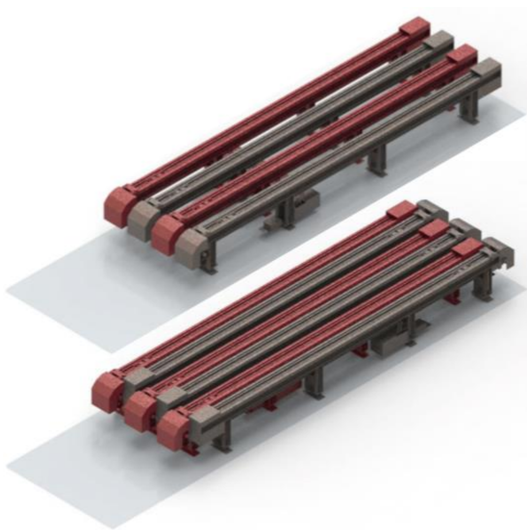

Figure 2.24 Non-intertwined vs intertwined

By positioning them intertwined, six cross transports will fit next to each other in a 40' container, and by not doing this, only 4. Figure 2.25 and Figure 2.26 show the top views of non-intertwined and intertwined positioned, respectively. On average, if a project contains cross transports, there are 12 of them.

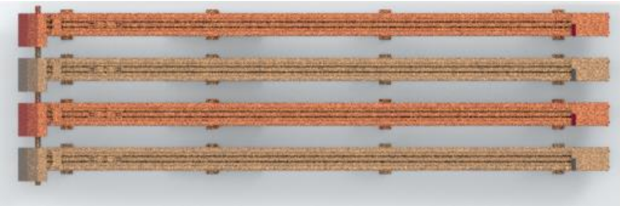

Figure 2.25 Top view of cross-transport non-intertwined

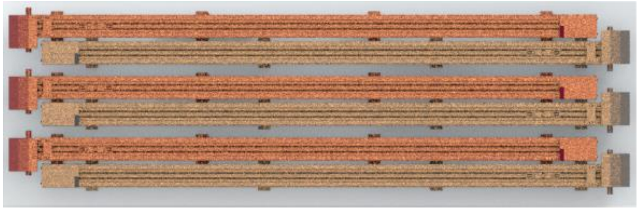

Figure 2.26 Top view of cross-transport intertwined

Empty space
Some collis contain empty space, which is lost when approaching as rectangular. Figure 2.27 to Figure 2.29 show examples of collis that cannot be approximated as rectangular.

Figure 2.27 Outstanding part

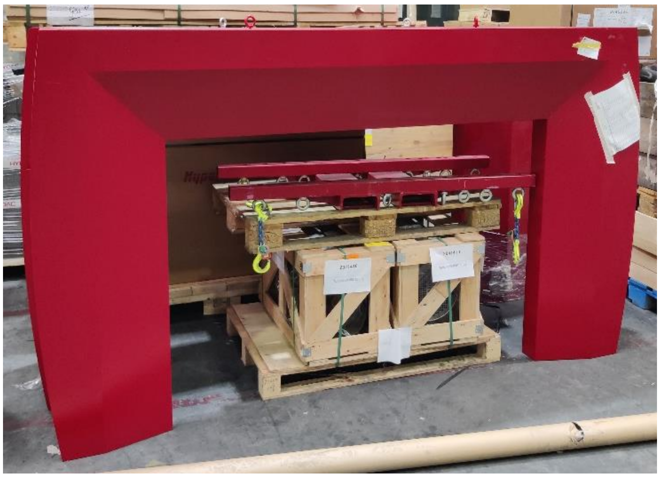

Figure 2.28 Empty space under colli

Figure 2.29 Empty corner

2.3.4 Stackability

A colli is stackable if it can be loaded with the weight of the stacked colli(s) without damaging the colli. The weight that a colli can carry differs per colli. A colli can, for example, be not stackable because the top compartment is not horizontal, which is approached as a colli that can carry 0 kg weight. In addition, the entire surface of a colli is not always suitable for stacking. It is unknown which collis and on which surfaces can be stacked; this data needs to be collected.

If a colli is not stackable, it can be made stackable, which is done by using wooden boxes. Wooden boxes are currently not standardised and can be ordered in any dimension. Making it stackable using a wooden box ensures that the colli becomes 10 cm longer and wider and 12 cm higher. The weight and the cost of a wooden box can be calculated by multiplying the area of the outer dimensions of the collis by constants for respectively the weight and the price per square meter, which are currently $c_{weight} = 9.5\ kg/m^2$ and $c_{costs} = €30/m^2$. Equations 2.1 and 2.2 show the weight and cost formula for making a colli stackable. For example, making a colli of 1 by 1 by 1 meter stackable costs €180, gives an additional weight of 57 kg, and the new dimensions are 1.1 by 1.1 by 1.12 meters.

$$Additional\ weight = A_{colli} * c_{weight} = 2 * (w * l + l * h + h * w) * c_{weight} \quad \textbf{2.1}$$

$$Costs\ making\ stackable = A_{colli} * c_{costs} = 2 * (w * l + l * h + h * w) * c_{costs} \quad \textbf{2.2}$$

2.3.5 Purchasing abroad

At the moment, almost all purchased parts are delivered at the HQ in Rijssen. These parts are then loaded into the transports and shipped to the customer. Sometimes parts are delivered on location if they cannot be provided on time in Rijssen. The purchase parts for which it must be considered whether they should be purchased at the HQ in Rijssen or abroad must meet the following characteristics:

- VSM does not modify the purchase part (standard product).
- The purchase part should not be needed when testing the machines.
- The purchase part must be able to be delivered abroad (on time).

After intensive consultation with various departments, we conclude that the power supply, exhaust unit, and safety fences meet these requirements. There are more candidates, such as the cable ducts and the machine covers. However, finding a suitable supplier, ensuring the connection of the replacement component to the machines, and making delivery requirements and price agreements take much time. Therefore, we first focus on these three components. In addition, the USA is a highly concentrated country of VSM's sales, located on the ocean's other side. We, therefore, first focus on purchasing in the USA.

Power supply

The power supply is supplied with every plasma cutting machine. There are plasma cutting machines for processing plates and processing beams. The supplier of the power supply is located in the USA and imports this product from the Netherlands all over Europe. The product is therefore delivered free of charge to HQ in Rijssen. The supplier can provide this product on location in the USA for a particular additional cost per state. Diverse types of power supplies are used for various kinds of machines. However, the outer shape of each power supply is the same, and therefore the additional cost is the same for each type. Purchasing abroad saves a colli of 1300 by 950 by 1560 mm, weighing 650 kg. In recent years, 180 of these collis have been transported, of which, based on the floor area, approximately 8 full 40' containers to the USA.

Exhaust unit

The exhaust unit is also supplied with every plasma cutting and painting machine. The supplier of the exhaust unit is located in Europe. The exhaust unit is always delivered on location for European customers without additional cost. So, this colli is, by default, not on the loading list for customers within Europe. The supplier is not represented in the USA, so we found a similar supplier in the USA.

In the past, the exhaust unit has been transported to the customer in various ways. The exhaust unit consists of 1 and 8 collis, with dimensions between 0.22 and 4.3 meters with weights between 15 and 2200 kg. If it is decided to purchase the exhaust unit abroad for a project, all collis are purchased there. In recent years, 187 collis related to the exhaust unit have been transported, of which, based on the floor area, approximately 35 full 40' containers to the USA.

Safety fences

Fences protect almost every machine for the safety of the operators. A European supplier currently supplies the fencing through a Dutch broker. However, the supplier or the broker cannot deliver it on location. In addition, both parties are not active in the USA, so we have also found a similar supplier in the USA. The fencing differs per project and consists of posts and mesh panels of different heights and widths. The dimensions of the collis are variable per project. The fencing is usually packed in one colli per project, but this can differ. The average length, width, height, and weight of the fencing collis in recent years were respectively 2060 by 615 by 1933 mm, with 289 kg. In recent years, 708 collis related to safety fences were transported, of which, based on the floor area, approximately 31 full 40' containers to the USA.

2.4 Objective

The objective is that all collis arrive at the customer for the lowest possible costs, which gives the objective to get the lowest feasible composition of transport, purchasing abroad and making stackable costs, as Equation 2.3 represents.

$$Total\ shipping\ costs = Transport\ costs + Purchasing\ abroad\ costs + Making\ stackable\ costs \quad (2.3)$$

Currently, the purchasing abroad and making stackable options are scarcely utilized, so only the transport (standard freight) costs are incurred. As the exact costs at any given time are unknown, we compute the optimal composition for each project given the current costs. In other words, what would be the optimal composition if we resend the projects?

In addition, the future situation gives more cost advantages that are not included in the cost comparison. First, there are no urgent freight and change loading lists costs because it is evident in advance what the required number of each transport type is and how the collis are divided among the transports. Second, personnel costs for preparation will be reduced by automating and optimizing the loading plan; no time is spent making the plan, no mistakes, and no reloading. However, the personnel costs for loading transports will probably be higher because the transports are loaded more thoroughly and there is more cooperation between machines and handling. Third, back order costs will likely decrease as loading is more structured.

2.5 Constraints

When creating the loading proposal, the logistic employees consider various conditions. These conditions can be translated into constraints. There are two types of constraints, namely hard and soft constraints. First, hard constraints are constraints that must always be satisfied. A soft constraint is a want to be satisfied as much as possible if the costs for doing are not so high (Kendall, 1975). The hard constraints are:

- **Weight limit:** the weight of the collis in the transport does not exceed the maximal payload of the transport type.
- **Weight distribution and load balancing:** the load inside the transport is distributed as evenly as possible along the longitudinal and horizontal axles.
- **Loadable:** the colli can only be loaded in a suitable transport type. Not all collis can be positioned in transport by hand or forklift. For this collis, it is essential that the top of the transport can be removed so that the collis can be positioned in the transport using an overhead crane. In addition, some collis may only be packed on a low loader/flat rack, and all other collis may not be packed on these transports.
- **Positionable:** the colli is entirely positioned in the transport and does not overlap with other collis. The collis are positioned on the ground or on top of another colli and can rotate and tilt based on their properties.
- **Stackable:** the weight placed on a colli is less than the maximum weight that can be placed on the colli, where the weight is placed on the loadable surface. The surfaces should have at least 80% overlap to create enough stability.
- **Fixable:** the collis can be fixed with ratchet straps on the hooks of the transport.
- **(Project separation):** the collis of separate phases (other projects of the same sales order) are not loaded on the same transports. The production process must be adjusted if this is changed into a soft constraint. This constraint is met in any case because each phase has its loading list.

If the hard constraints are met, the wishes can be met. The more these wishes are fulfilled, the better the solution is preferred over another (provided the hard constraints are met). The soft constraints are:

- **Machine grouping:** the collis of the same machine (or its handling) are loaded in the same transport, which is desirable because machine-by-machine is built on-site.
- **Location grouping**: the collis from the same location are loaded in the same transport, which is desirable, so that as few collis as possible must be transported by road between the different locations.

2.6 Current performance

In this section, we analyse the current performance, of which Figure 2.30 supplies an overview. The numbers are calculated without the backorder transports.

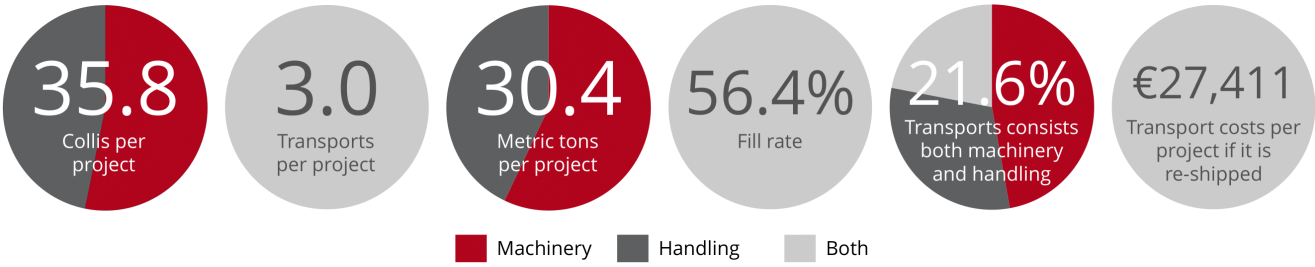

Figure 2.30 Current performance

The transports can be loaded to the maximum in terms of volume or weight. The highest filling degree of these two typifies the fill rate of the transport. Although not all collis can be approached as rectangular, we calculate the volume by multiplying the length, width, and height. The filling degree based on volume is, therefore, lower in reality. Figure 2.31 shows a histogram with the filling level of the transported semi-trailers, containers, and low loaders/flat racks. Several transports were sent almost empty. However, the transports were much cheaper a few years ago, so there was less focus on minimising the number of transports. Containers are better packed than semi-trailers, which makes sense because container transport has always been more expensive than semi-trailer transport, making this slightly more important. In addition, a semi-trailer is larger/longer, which means there is a greater chance of space being left. Several transports are also more than 100 per cent full because more weight was loaded than was allowed. The reasons are that they weigh up the risk of a fine against a bigger transport composition or did not realise it. In addition, while creating the database, we found out that the collis' weight was not consistently multiplied by the amount, so the weight in transport was more than what was stated in the loading documents.

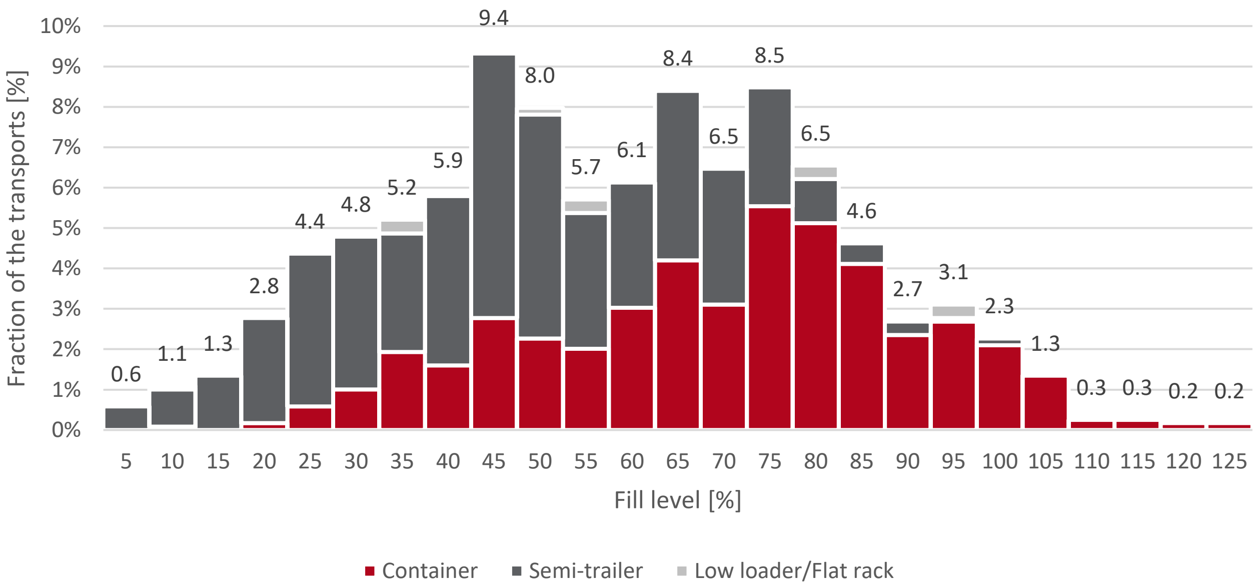

Figure 2.31 Fill rate of all transports

Appendix I shows per country/state the fraction of the number of transports and the costs of these transports if they were shipped using today's prices. It is clear from the figure that the USA plays a significant role in both the number of transports and associated costs. Therefore, the focus should be on the USA in terms of addressing these issues.

2.7 Conclusion

Sales budget the transportation costs based on a filling level. The transport costs per project are, on average, 20.1% (€2,613) more than budgeted, and the number of transports per project is, on average, 4.0% (0.11) more than budgeted. The budgeted transports are proportionally more likely to deviate in a project with multiple machines than a single one. The DNA contains all the information about what the customer has purchased. The logistic employees must fill in how many containers are required and what goes in which. The logistics employees load the transports; if the transports are loaded differently, the documents must be adjusted. Of the transports about which the print date is not overwritten, loading documents were (re)printed on 45.1% on the day of transport.

The collis are transported to the customer by trucks, containers, and aeroplanes. Of all transports, 50.8% is by truck, 46.0% by container and 3.2% by aeroplane. The Full Container Load (FCL) transports are 20' standard and hardtop containers and 40' standard, standard high cube, hard top high cube, and high cube flat rack. The Full Truck Load (FTL) transports are curtain side, MEGA and low loader. Besides, Less than Container/Truck Load (LCL/LTL) are also possible.

The collis can be packages (70.5%), pallets (21.3%), carton boxes (7.1%), wooden boxes (0.8%) and tool containers (0.3%). The lengths vary between 0.1 and 15 meters, and the widths and heights are between 0.03 and 3.5 meters. The weight varies between 0.5 kg and 22 metric tons. With some collis, much space is lost when approached as rectangular. These collis can be intertwined or have empty spaces where other collis can be positioned. A colli is stackable if it can be loaded with the weight of the stacked colli(s) without damaging the colli and can be made stackable using a wooden box. VSM can also purchase the power supply, exhaust unit and safety fences in the USA and deliver them to the customer.

The objective is to get the lowest feasible composition of transport, purchasing abroad and making stackable costs. When creating the loading proposal, the logistic employees consider various conditions, which are translated into constraints. When looking at the fill level, some transports have been sent almost empty, and containers are better packed than semi-trailers. We conclude that the focus is on the USA because that is where a significant part of the number of transports and costs come from.

3 Literature review

This chapter reviews the literature by answering the second research question: *"Which methods for solving the problem, suggested in the literature, best applies to VSM?"*. The chapter starts by positioning the packing problem of VSM in Section 3.1, followed by the formal packing statement in Section 3.2. Section 3.3 describes the solution methods for the packing problem proposed in the literature, after which we choose the most suitable method for VSM. Section 3.4 describes the research gap between the chosen solution method and the problem of VSM, and in Section 3.5, we describe how we can close the research gap. Finally, in Section 3.6, we conclude the chapter with a summary.

3.1 Packing positioning

The packing problem falls in the literature under the class Cutting & Packing problems. Cutting & Packing problems have identical structures in which (part of) a set of small items is packed into a set of large objects. The items and objects are defined in one, two, three or an even greater number (n) of geometric dimensions; only 3D is researched since this is also the case in the problem of VSM (Wäscher, Haußner, & Schumann, 2007). Martello, Pisinger, & Vigo (2000) prove that the problem is strongly NP-hard and challenging to solve in practice. The problem has many real-world applications in packing and freight forwarding industries, such as container loading (Gajda, Trivella, Mansini, & Pisinger, 2022), air-cargo loading (Chan, Bhagwat, Kumar, Tiwari, & Lam, 2006) and pallet loading (Gzara, Elhedhli, & Yildiz, 2020).

The problem can be approached as regular and irregular. Irregular packing problems are also known as nesting problems. The problems consist of assigning a set of regular and irregular items to larger regular or irregular containers while minimising the waste of material or space. These problems combine the combinatorial hardness with the computational difficulty of enforcing the geometric non-overlap and containment constraints (Leao, Toledo, Oliveira, Carravilla, & Alvarez-Valdés, 2020). Egeblad, Garavelli, Lisi, & Pisinger (2010) and Chekanin (2020) propose examples in the literature that work with irregular shapes. Egeblad et al. (2010) propose a heuristic for loading containers with furniture using a triangle-mesh structure. Chekanin (2020) proposes a heuristic in which the shapes are divided into orthogonal polyhedrons. The irregular approach is much more complex than the regular approach. According to Leao, Toledo, Oliveira, Carravilla, & Alvarez-Valdés (2020), three-dimensional packing problems involving irregular shapes are less studied. Most VSM collis are approachable as regular, and VSM currently only knows the length, width, and height of each colli. Therefore, we will review only the regular (heterogeneous) approach.

The problem contains an online and offline variant. The algorithm knows all the collis and containers in the offline variant before deciding. The online algorithm makes decisions immediately and irrevocably based only on the part of the input without any knowledge of the future (Ha, Nguyen, Bui, & Wang, 2017). In the case of VSM, we know all collis and shipping options in advance, so we will only review the offline variant.

Cutting & Packing problems can be solved by maximising the output and minimising the input. The basic type of problems for offline packing of three-dimensional strongly heterogeneous items are (Wäscher, Haußner, & Schumann, 2007):

- **Container loading problem (CLP) / Knapsack problem (3DKP)**: assigning a part of a set of items to a limited set of objects, where the availability of the objects is limited, so not all items can be assigned. The value of the assigned items should be maximised.
- **Bin packing problem (3DBPP)**: assigning a set of items to a set of identical objects. The required objects' value, number or total size should be minimised.
- **Open dimension problem (3DODP)**: assigning a set of items to a set of objects. The objects are given, but their extension in at least one dimension can be considered variable. The value of the input (or a corresponding auxiliary measure like length, size, or volume) should be minimised.

3.2 Formal statement

Baldi, Perboli, & Tadei (2012) give a basic formulation of CLP, which is more clearly rewritten by Gajda, Trivella, Mansini, & Pisinger (2022). The basic CLP aims to select and orthogonally load the subset of items that maximise the total value or profit in a container. We have a container with a length, width, and height equal to $(L, W, H) \in \mathbb{R}^3_+$ and a set $\mathcal{B}$ of boxes, where box $i \in \mathcal{B}$ has size $(l_i, w_i, h_i) \in \mathbb{R}^3_+$ in its original orientation, weight $q_i > 0$, and value $\pi_i > 0$. Figure 3.1 introduces the orientation and dimensions of an empty container, where the eight corners are identified by a sequence of three letters: (i) "F" front of "R" rear, (ii) "L" left or "R" right, and (iii) "B" bottom or "T" top. The rear corresponds to the rear doors of the container from which unloading is usually carried out. A box can be positioned in the container in any direction, keeping the surfaces parallel to the container surfaces. Each box has six different spatial rotations, as shown in Figure 3.2 (Gajda et al., 2022)

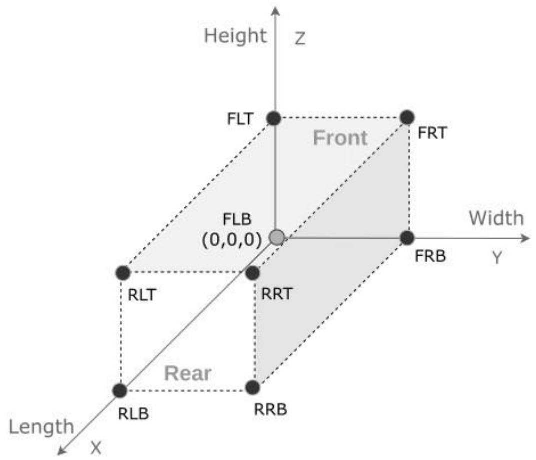

Figure 3.1 Container dimensions and orientations (Gajda et al., 2022).

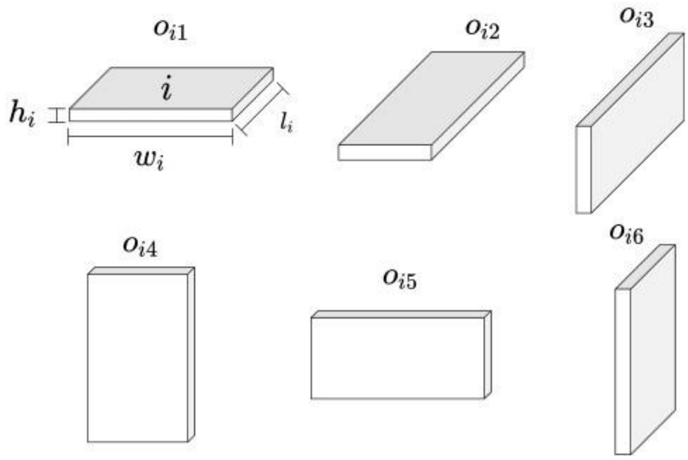

Figure 3.2 Six orthogonal item orientations (Gajda et al., 2022).

Gajda et al. (2022) rewrite the CLP with rotation as the following mixed integer linear program (MIP):

$$\max \sum_{i \in \mathcal{B}} \pi_i t_i \qquad (3.1)$$

s.t. :

$$f_{ij} + f_{ji} + b_{ij} + b_{ji} + u_{ij} + u_{ji} + (1 - t_i) + (1 - t_j) \geq 1 \qquad \forall i, j \in \mathcal{B} \quad i < j \qquad (3.2)$$

$$x_i + w_i(o_{i2} + o_{i4}) + l_i(o_{i1} + o_{i6}) + h_i(o_{i3} + o_{i5}) - x_j \leq L(1 - b_{ij}) \qquad \forall i, j \in \mathcal{B} \qquad (3.3)$$

$$y_i + w_i(o_{i1} + o_3) + l_i(o_{i2} + o_{i5}) + h_i(o_{i4} + o_{i6}) - y_j \leq W(1 - f_{ij}) \qquad \forall i, j \in \mathcal{B} \qquad (3.4)$$

$$z_i + w_i(o_{i5} + o_6) + l_i(o_{i3} + o_{i4}) + h_i(o_{i1} + o_{i2}) - z_j \leq H(1 - u_{ij}) \qquad \forall i, j \in \mathcal{B} \qquad (3.5)$$

$$x_i + w_i(o_{i2} + o_{i4}) + l_i(o_{i1} + o_{i6}) + h_i(o_{i3} + o_{i5}) \leq L \qquad \forall i \in \mathcal{B} \qquad (3.6)$$

$$y_i + w_i(o_{i1} + o_3) + l_i(o_{i2} + o_{i5}) + h_i(o_{i4} + o_{i6}) \leq W \qquad \forall i \in \mathcal{B} \qquad (3.7)$$

$$z_i + w_i(o_{i5} + o_6) + l_i(o_{i3} + o_{i4}) + h_i(o_{i1} + o_{i2}) \leq H \qquad \forall i \in \mathcal{B} \qquad (3.8)$$

$$o_{i1} + o_{i2} + o_{i3} + o_{i4} + o_{i5} + o_{i6} = 1 \qquad \forall i \in \mathcal{B} \qquad (3.9)$$

var. :

$f_{ij}, b_{ij}, u_{ij}, t_i, o_{i1}, o_{i2}, o_{i3}, o_{i4}, o_{i5}, o_{i6} \in \{0,1\}$ $\forall i, j \in \mathcal{B}$ **3.10**

$x_i, y_i, z_i \geq 0$ $\forall i \in \mathcal{B}$ **3.11**

The decision variables (x_i, y_i, z_i) represent the coordinates of the front-left-bottom corner of box i concerning the origin of the axes defined by the FLB corner of the container. Binary variables o_{i1}, o_{i2}, o_{i3}, o_{i4}, o_{i5}, o_{i6} determine the six possible orientations (see Figure 3.2), while variables (f_{ij}, b_{ij}, u_{ij}) indicate the relative position (left, behind and under) of box i with respect to box j and are used to model overlapping. Finally, variables t_i establish whether boxes are selected or not (Gajda et al., 2022).

The objective function maximises the profit of the loaded boxes (see Equation 3.1). Constraint set 3.2 enforce no overlap between each pair of packed items, Constraint sets 3.3 to 3.5 define the overlapping conditions, Constraint sets 3.6 and 3.7 ensure that the loaded items are entirely inside the container, and Constraint set 3.9 enforces boxes to only have one orientation. Finally, Constraint sets 3.10 to 3.11 define the domain of the variables (Gajda et al., 2022).

The model contains $\mathcal{O}(|\mathcal{B}|^2)$ binary variables and $\mathcal{O}(|\mathcal{B}|^2)$ big-M constraints, which makes it complicated to solve to optimality for large instances (Gajda et al., 2022).

3.3 Solution methods

This section shows the appropriate solution methods proposed in the literature. Section 3.3.1 describes the different methods for determining the placement locations, and Section 3.3.2 describes the different strategies for selecting one. Section 3.3.3 describes the relevant algorithms that can be applied to solve the problem of VSM, and Section 3.3.4 describes how to deal with the irregular bins. Finally, in Section 3.3.5, we weigh the different solution methods and choose the most suitable one.

3.3.1 Placement locations

The solution methods need information about the locations where the next item can be placed; in the literature known as placement locations. First, we introduce corner points. We continue with extreme points, for which corner points are the basis. Finally, we discuss potential points.

Corner points

Martello, Pisinger, & Vigo (2000) define corner points (CPs) as the non-dominated locations where an item can be placed in an existing bin. CPs in a two-dimensional envelope are defined where the envelope of the items in the bin changes from vertical to horizontal (green dots in Figure 3.3(b)). CPs in the three-dimensional envelope can be found by applying the two-dimensional algorithm for each value of the bin height defined by each item's lower and upper end lines. Figure 3.3(a) shows the concept of CPs in 3D, which we made on the inspiration of Crainic, Perboli, & Tadei (2008).

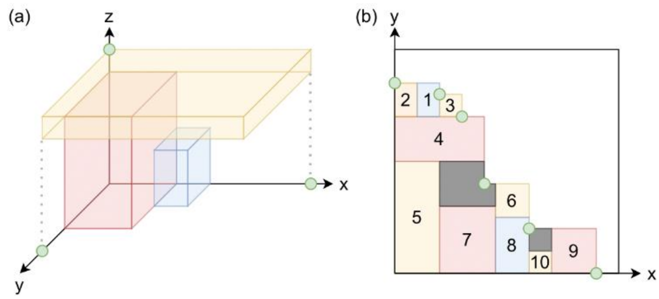

Figure 3.3 Corner points in 3D (a) and 2D (b) (Crainic, Perboli, & Tadei, 2008)

Extreme points

Extreme points (EPs) extend on corner points. EPs provide the means to utilize the free space within a bin through the shapes of the items already in the bin. The basic idea of the EPs is that when an item is added to a bin, it generates a series of new extreme points, the EPs, where additional items can be accommodated. For example, the space under item 4 cannot be used with corner points (no green dot between items 5 and 7 in Figure 3.3(b)), while this is possible with extreme points (green dot between items 5 and 7 in Figure 3.4(b)). Figure 3.4(a) shows the concept of extreme points in 3D, which we made on the inspiration of Crainic, Perboli, & Tadei (2008).

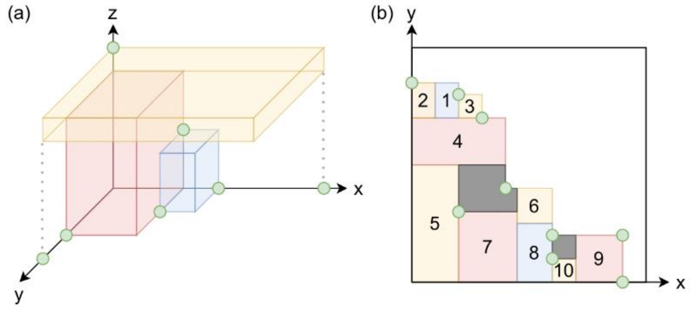

Figure 3.4 Extreme points in 3D (a) and 2D (b) (Crainic, Perboli, & Tadei, 2008)

Potential points

Potential points (PPs) reduce on EPs; PPs are a subset of EPs. The PPs, like EPs, are updated after each item is added. Each iteration adds a maximum of four PPs. The difference between EPs and PPs is that on some EPs, it is already a bad idea to locate the next item here, for example, the top right corner of item 9 in Figure 3.4(b). This point is not a PP, as there is no dot in the top right corner of item 9 in Figure 3.5(b). Figure 3.5(a) shows the concept of potential points in 3D (Feng, Moon, & Shin, 2015).

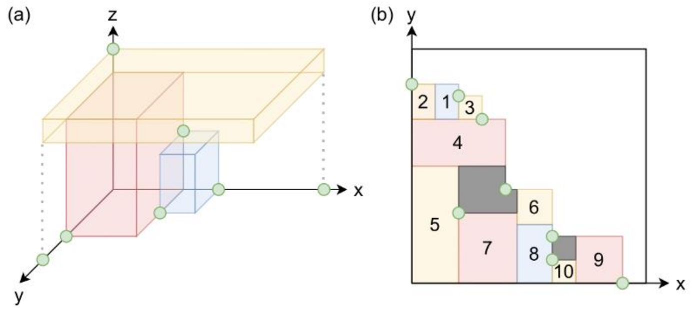

Figure 3.5 Potential points in 3D (a) and 2D (b)

3.3.2 Placement strategies

The solution method needs a strategy to determine where to place the next item; in the literature known as placement strategies. We start with the classical strategies, followed by empty maximum spaces. Then we describe the back-bottom-left strategy. Finally, we describe layer building.

Classical strategies

The classical placement selections are (Coffman Jr., Csirik, Galambos, Martello, & Vigo, 2013):

- **Next-fit (NF)**: after the first item is placed, NF packs each subsequent item into the bin with the last item to be placed, if it fits in that bin; if it does not fit, NF closes that bin and places the item into an empty bin.
- **Next-k-fit (NkF)**: a variant of NF, but instead of keeping only one bin open, NkF keeps the last k bins open and chooses the first bin in which the item fits.

- **First-fit (FF)**: the item is placed into the lowest-indexed non-empty bin where it will fit, assuming such a bin exists. The item is placed in an empty bin if no such bin exists.
- **Best-fit (BF)**: if there is no open bin in which the item fits, the item is placed in an empty bin. Otherwise, the item is placed into an open bin of the largest content in which it fits; if there is more than one such bin, BF chooses the lowest indexed one.
- **Worst-fit (WF):** if there is no open bin to fit the item, the item is placed into an empty bin. Otherwise, the item is placed into an open bin with the smallest content it will fit; if there is more than one such bin, WF chooses the lowest indexed bin.
- **Almost worst-fit (AWF)**: tries to place the item in the second most empty bin or the emptiest bin if there are two or more such empty bins. If it does not fit, AWF tries in the emptiest bin, and if this also does not fit, AWF places the item into an empty bin.

Empty maximal spaces (EMS)

Empty maximum spaces (EMS) is a method that tries to keep the empty rectangular spaces where the next items can be placed as large as possible. The empty rectangular spaces are represented by their vertices with minimum and maximum coordinates (Gonçalves & Resende, 2013). The difference process (DP) is used to generate and maintain EMS. Lai and Chan (1997) developed the DP process, which consists of the following three steps:

1. Place an item in an EMS;
2. Generate new EMSs as a result of the intersection of the item being placed with the existing EMSs and delete the intersected EMSs;
3. Eliminate the EMSs that are infinitely thin or that are fully enrolled by other EMSs.

Figure 3.6 shows an example of the application of the DP process: a) box to be packed and initial maximal space; b) box packed in the maximal space; and c) newly generated maximal spaces. We made the figure on the inspiration of Gonçalves & Resende (2013).

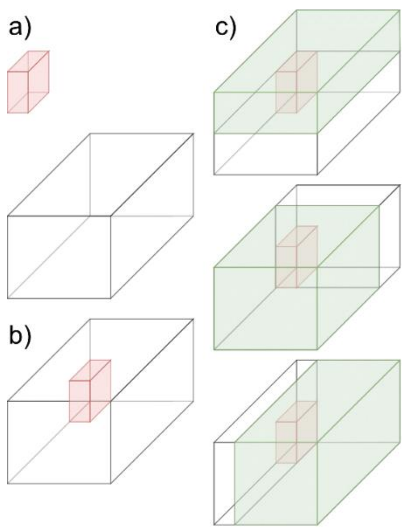

Figure 3.6 EMS strategy (Gonçalves & Resende, 2013)

Back-bottom-left (BBL)

Back-bottom-left (BBL) is a strategy that builds up from the left-back corner. The first item is placed in the lower left corner. Subsequent items are moved down and left as far as possible from the top right corner (Liu & Teng, 1999). Figure 3.7 shows the BBL strategy in 2D, which we made on the inspiration of Liu & Teng (1999).

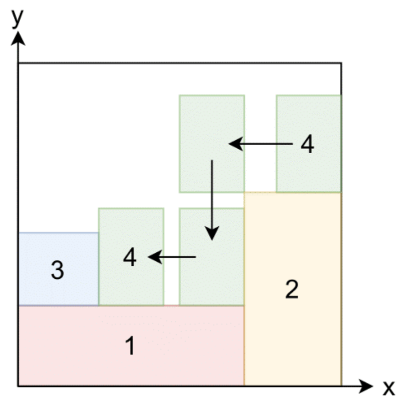

Figure 3.7 BBL strategy (Liu & Teng, 1999)

Layer building

Layer building is a strategy that fills a container with layers of items. The layer-building solution consists of several vertical, cubic, and non-overlapping layers parallel to the face walls of the container. The layers follow each other without gaps. Each layer contains one or more items that do not protrude into adjacent layers. The height and width of a layer is equal to its container dimensions. The layer's depth results from the layer-defining item's depth dimension (Gehring & Bortfeldt, 2001).

3.3.3 Algorithms

The literature tackles the CLP using exact methods, heuristics, and meta-heuristics. Most exact methods are mathematical formulations using mixed integer linear programming (MIP) solvers. Given the large number of constraints of VPM, it is almost impossible to solve this exactly in a reasonable time (Silva, Toffolo, & Wauters, 2019). Heuristics can be divided into construction (placement) and improvement heuristics. A construction heuristic decides how the items are placed in the empty bin. The outcome can be a first solution or an integral part of the approach. An improvement heuristic broadens the search space of the outcome of the construction heuristic, which can usually yield significant gains (Zhao, Bennell, Bektaş, & Dowsland, 2016). Meta-heuristics are more general algorithms that can be applied to a broader range of problems. This section describes the most relevant algorithms.

Exact methods

Integer linear programming (ILP)

Alonso, Alvarez-Valdes, Iori, & Parreño (2019) propose an integer linear programming (ILP) model for a company that serves its customers' orders by building pallets with the required products and loading them into trucks. A computational study is performed on many real instances with up to 44 trucks. From this study, Alonso et al. (2019) conclude that the model can find the optimal solution in most cases in minutes, and there are small gaps when optimality cannot be proven.

Heuristics

Beam search with greedy-based function (BSG)

Araya & Riff (2014) propose a beam-search-based algorithm that uses a greedy-based function (BSG) to evaluate states in the search graph. Beam search can be viewed as an adaption of the branch-and-bound search that expands only a subset of the most promising nodes at each level of the search graph. The competition between different states allows the algorithm to quickly discard worse states, opening the search for more promising states. Also, a simple mechanism for removing comparable states maintains a minimum required level of diversity between states. BSG works in minutes.

Randomised constructive heuristic (RCH)

Gajda, Trivella, Mansini, & Pisinger (2022) propose a randomised constructive heuristic (RCH) that (1) iteratively combines items in a pre-processing procedure, (2) sorts them based on multiple criteria, (3) uses randomisation to disrupt sorting partially, and finally (4) constructs the packing with taking into account all the restrictions. RCH produces different loading solutions by iterating between pre-processing, sorting, disrupting, and packing, from which a set of non-dominated solutions is chosen in terms of chargeable weight and the number of unloading obstacles. The solutions are visually represented in 3D, allowing warehouse personnel to select the preferred loading pattern to implement. Sometimes, slightly worse solutions may be easier to load, saving workers time and effort. On large-scale industry instances, RCH works in seconds.

Meta-heuristics

Biased random key genetic algorithm (BRKGA)

Gonçalves & Resende (2013) propose a biased random-key genetic algorithm (BRKGA). The approach uses empty maximum spaces to manage the free spaces in bins. The proposed algorithm hybridizes a novel placement procedure with a genetic algorithm based on random keys. The BRKGA evolves the order in which the items are packed in the bins and the parameters used by the placement procedure. A new placement heuristic has been used to determine the bin and the free maximum space where each bin is placed, namely the Distance to the Front-Top-Right Corner (DTFRC). This heuristic contains two versions, and each has its objective. Also, a new fitness function is used, namely the adjusted number of bins (aNB). The aNB combines the number of bins (NB) with a measure of the improvement potential of the bin packaging solution. The rationale is that if two solutions use the same number of bins, the one with the least loaded bin has more improvement potential. BRKGA works in seconds.

Hybrid genetic algorithm (GA)

Gehring & Bortfeldt (2001) propose a hybrid genetic algorithm (GA) that works in minutes. The algorithm uses layer building, as described in the previous section. Within the procedure, stowage plans are represented by complex data structures closely related to the problem. Offspring are generated using specific genetic operators based on an integrated greedy heuristic. GA works in minutes.

Sub-volume-based simulated annealing algorithm (SBSAA)

Jin, Ohno, & Du (2004) propose a sub-volume-based simulated annealing algorithm (SBSAA), which aims to generate flexible and efficient packing patterns and simultaneously provide a high degree of inherent stability. Simulated annealing is based on the simulation of the annealing of solids and applied to solving large-scale combinatorial optimization problems. SBSAA works within a minute. The SBSAA algorithm contains the following steps:

1. **Initial solution**: obtain the initial packing pattern by the heuristic algorithm (Jin, Ito, & Ohno, 2000) and reduce it to the initial packing order.
2. **Neighbour solution**: generate the neighbourhood by swapping the positions of two random items and randomly selecting a packing order.
3. **Objective function**: calculate the value of the objective function for the packing pattern.
4. **Accept/reject**: if the current solution is better than the best-found solution, overwrite the best and neighbour with the current solution. If the current solution is worse than the best solution but is better than the neighbour solution, overwrite only the neighbour with the current solution. If the current solution is worse than the best and the neighbour solution, then overwrite with a certain probability the neighbour with the current solution.
5. **Next iteration**: if the maximum number of iterations has not yet been executed, go back to step 2.
6. **Decrease temperature**: reduce the temperature; if the current temperature does not fall below the minimum temperature, reset the iteration counter and return to step 2.

3.3.4 Irregular bins

Some of VSM's collis lose much space when approached as rectangular (as described in Section 2.3.3). Gajda, Trivella, Mansini, & Pisinger (2022) and Parreño, Alvarez-Valdes, Oliveira, & Tamarit (2010) use automatic pre-processing of multiple items into a larger item, reducing the number of items to be processed in subsequent stages of the algorithm. Based on this principle, we came up with the idea of adding a manual pre-processing step. VSM's collis are standardized, meaning they always send the same collis. This standardization makes it possible to store in a database where regular and irregular collis form a larger rectangular. With this manual pre-processing (which has to be entered once per machine), we can deal with the irregular collis.

3.3.5 Choose solution method

From the proposed methods, we will choose the method that suits the problem of VSM the best. The best method has as much overlap as possible in the objective and constraints with the VSM problem and is as fast as possible. Table 3.1 shows the consideration of the various methods.

The objective of VSM is that all collis arrives at the customer for the least possible cost. The costs consist of transport, purchasing abroad and making stackable costs. No solution method can handle multiple transports of different transport types. The methods that pack one transport as fully as possible with collis can do this for any transport type. The methods that use as few transports as possible to send all collis can do this for one type of transport. No solution method has the option of purchasing abroad or making it stackable.

The solution methods contain practical constraints; some also contain constraints that do not apply to the problem of VSM. For example, in RCH, there is a constraint that flammable and generally dangerous goods are legally placed close to the unloading side. VSM's problem contains eight constraints (as described in Section 2.5), of which RCH satisfies six. GA satisfies four constraints, ILP satisfies three and BSG, BRKGA, and SBSAA satisfy only the positionable constraint.

The solution methods each have their performance. However, it is difficult to compare the performance of the different solution methods because not every method has been tested on the same instances, and some methods are more constrained than others. However, we can conclude that RCH performs very well; it achieves a high-volume utilization in less than 10 seconds on average.

We choose to adapt and extend RCH for the problem of VSM because this heuristic meets the most practical constraints and can generate a good solution quickly. In addition, it is a recent paper in which most previous methods have been considered.

Table 3.1 Balancing alternatives

Criteria \ Method	**Exact**	**Heuristic**		**Meta-heuristic**		
	ILP	BSG	RCH	BRKGA	GA	SBSAA
Objective						
Different transport types	No	Yes	Yes	No	Yes	Yes
Multiple transports of the same type	Yes	No	No	Yes	No	No
Purchasing abroad	No	No	No	No	No	No
Making stackable	No	No	No	No	No	No
Constraints						
Weight limit	Yes	No	Yes	No	Yes	No
Weight distribution and load balancing	Yes	No	Yes	No	Yes	No
Loadable	No	No	No	No	No	No
Positionable	Yes	Yes	Yes	Yes	Yes	Yes
Stackable	No	No	Yes	No	Yes	No
Fixable	No	No	No	No	No	No
Machine grouping	No	No	Yes[1]	No	No	No
Location grouping	No	No	Yes	No	No	No

[1] In the paper, machine grouping is not grouping machines but customers; the principle is the same.

3.4 Research gap

The scientific contribution of this thesis is to solve a new variant of the three-dimensional bin packing problem, namely an extension with item upgrading and outsourcing options. It is a combinatorial optimization to get the cheapest colli and transport composition with the best transport layout. The combinatorial optimization chooses:

- What to purchase abroad (Purchasing abroad costs)
- What to make stackable (Making stackable costs)
- The number of each transport type (Transport costs)

The combinatorial optimization has the objective of minimizing the total shipping costs. The best transport layout can be determined with RCH. Given several practical constraints, RCH tries to pack the given collis in the transports. RCH aims to meet the two soft constraints as much as possible: collis of the same machine and location in the same transport.

RCH will be adapted to VSM's case: the objective will be changed, constraints will be added and removed, it will be extended for multiple transports of different transport types, and it will be extended with the ability to pre-process irregular collis manually. The constraint that will be added is the loadable constraint that ensures that a colli can only be packed in a suitable transport type. The constraint that ensures that collis can be fixed with ratchet straps on the hooks of the transport is very vague; there are currently no standardizations for this either; the logistic employees fix it how it suits the best at that moment. This constraint will be considered by adjusting collis' dimensions and manually pre-processing.

3.5 Closing the research gap

We do not need additional literature to adapt RCH to VSM's case. However, we do need this for solving the combinatorial optimization (CO). The CO of the problem of VSM is not a common problem in the literature. Therefore, the CO can be solved with a meta-heuristic: a more general algorithm that can be applied to a broader range of problems. More specifically, we need trajectory methods: a class of meta-heuristics that works with a single solution. In this section, we describe the most well-known methods.

3.5.1 Basic local search

Basic local search is also known as iterative improvement because any move will only be performed if the resulting solution is better than the current solution. Algorithm 3.1 outlines basic local search on high-level. The local search stops at the local optimum, making implementing CO problems usually unsatisfactory. Therefore, several techniques have been developed to prevent algorithms from getting stuck in local minima, which is done by adding mechanisms that allow them to escape local minima (Blum & Roli, 2003).

Algorithm 3.1 Basic local search (Blum & Roli, 2003)

$s \leftarrow$ GenerateInitialSolution()
repeat until no improvement is possible
  $s \leftarrow$ Improve($\mathcal{N}(s)$)

3.5.2 Simulated annealing (SA)

Simulated annealing (SA) has the idea to allow moves resulting in solutions of worse quality than the current solution (uphill move) to escape from the local minima. The probability of making such a move is decreased during the search. Algorithm 3.2 outlines the SA algorithm on a high level (Blum & Roli, 2003).

Algorithm 3.2 Simulated annealing (Blum & Roli, 2003)

$s \leftarrow$ GenerateInitialSolution()
$T \leftarrow T_0$
while terminate conditions not met **do**
  $s' \leftarrow$ PickAtRandom($\mathcal{N}(s)$)
  if ($f(s') < f(s)$) **then**
    $s \leftarrow s'$ % s' replaces s
  else
    Accept s' as new solution with probability $p(T, s', s)$
  Update(T)

3.5.3 Tabu search (TS)

Tabu search (TS) explicitly uses the history of the search, both to escape from local minima and to implement an explorative strategy. The simple TS algorithm applies a local search with the best enhancement and uses short-term memory to escape the local optimum. Short-term memory is implemented as a tabu list that keeps track of the most recently visited solutions and prohibits movement towards them. The neighbourhood of the current solution is thus limited to the solution that does not belong to the tabu list. Algorithm 3.3 represents the TS algorithm at a high level (Blum & Roli, 2003).

Algorithm 3.3 Simple tabu search (Blum & Roli, 2003)

$s \leftarrow$ GenerateInitialSolution()
$TabuList \leftarrow \emptyset$
while terminate conditions not met **do**
  $s' \leftarrow$ ChooseBestOf($\mathcal{N}(s) \setminus TabuList$)
  Update($TabuList$)

3.5.4 Explorative local search methods

The general exploratory algorithms that can incorporate other trajectory methods as components are:

- **Greedy randomized adaptive search procedure (GRASP)**: generates greedy randomized solutions using constructive heuristics and then searches for improvements through local search (Blum & Roli, 2003).
- **Variable neighbourhood search (VNS)**: explores distant neighbourhoods of existing solutions and moves there to a new one if and only if improvements are made (Blum & Roli, 2003).
- **Guided local search (GLS)**: helps the search to gradually move away from local minima by changing the search landscape (Blum & Roli, 2003).

- **Iterated local search (ILS)**: applies local search to an initial solution until it finds a local optimum; then, it perturbs the solution and restarts local search (Blum & Roli, 2003).
- **Multi-start local search (MSLS):** applies local search to an initial solution until it finds a local optimum; then, it creates a new initial solution and restarts the local search. It is possible to use a new random or the same initial solution every iteration.

3.6 Conclusion

The problem of VSM falls into the class of Cutting & Packing problems, in which strongly heterogeneous items are offline packed in a three-dimensional environment. The problem can be solved as Container Loading Problem (CLP) / Knapsack Problem (3DKP), Bin Packing Problem (3DBPP) and Open Dimension Problem (3DODP).

The formal statement of CLP has been given. The objective is to select and orthogonally load the subset of items that maximise the total value or profit in a container. The statement ensures that the items do not overlap and are fully positioned in the container. Solving the model for large instances is complex.

Placement locations are the available locations where the next items can be placed; the best known are corner points, extreme points, and potential points. Placement strategies represent the strategies that determine on which placement location the following items should be placed. There are classic strategies, such as next-fit, next-k-fit, first-fit, best-fit, worst-fit, and almost worst-fit. There are also more innovative strategies, such as empty maximum spaces (EMS), back-bottom-left (BBL) and layer building. EMS is a method that tries to keep the empty rectangular spaces in which the next items can be placed as large as possible, BBL is a strategy that builds up from the left back corner, and layer building is a strategy that fills a container with layers or items.

The literature tackles the CLP using exact methods, heuristics, and meta-heuristics. The proposed exact method is an integer linear programming (ILP) model. The proposed heuristics are beam search with greedy-based function (BSG) and randomized constructive heuristic (RCH). The proposed metaheuristics are biased random key genetic algorithm (BRKGA), hybrid genetic algorithm (GA), and sub-volume based simulated annealing algorithm (SBSAA). We handle irregular collis by manual pre-processing. We choose to adapt and extend the RCH heuristic for the problem of VSM because this heuristic meets the most practical constraints and can generate a good solution quickly. In addition, it is a recent paper in which most previous methods have been considered.

The scientific contribution of this thesis is to solve a new variant of the three-dimensional bin packing problem, namely an extension with item upgrading and outsourcing options. It is a combinatorial optimization to get the cheapest colli and transport composition with the best transport layout. The combinatorial optimization chooses what to purchase abroad and make stackable and the number of each transport type. The transport layout will be determined with the RCH heuristic. RCH will be adapted to VSM's case: the objective will be changed, constraints will be added and removed, it will be extended for multiple transports of different transport types, and it will be extended with the ability to pre-process irregular collis manually.

We can solve combinatorial optimization with meta-heuristics. The most well-known are basic local search, simulated annealing (SA) and tabu search (TS). Explorative local search methods are greedy randomized adaptive search procedure (GRASP), variable neighbourhood search (VNS), guided local search (GLS), iterated local search (ILS) and multi-start local search (MSLS).

4 Solution design

This chapter describes the decision support tool by answering the third research question: *"What should be the decision support tool's design?"*. The chapter starts with a brief description of the optimization problem we propose to solve in Section 4.1, followed by a description of all the input data required by the decision support tool in Section 4.2. Section 4.3 shows an overview of the model. Section 4.4 describes how we initialize the customer data. Afterwards, Section 4.5 describes how we determine the transport and colli composition. Section 4.6 describes how we determine the transport layout. Finally, in Section 4.7, we conclude the chapter with a summary.

4.1 Problem definition

We propose to solve the three-dimensional bin packing problem with item upgrading and outsourcing options. It is a combinatorial optimization to get the cheapest colli and transport composition with the best transport layout. First, we describe the constraints and objectives for determining the colli and transport composition. Next, we describe this for determining the transport layout.

4.1.1 Colli and transport composition

The goal is to determine the cheapest colli and transport composition. The colli and transport composition consist of making choices for:

- What to purchase abroad (Purchasing abroad costs)
- What to make stackable (Making stackable costs)
- The number of each transport type (Transport costs)

The objective is to minimize the total shipping costs, consisting of the purchasing abroad, making stackable and transport costs, as shown in Equation 2.3 (Section 2.4). The transport composition must be feasible for the colli composition. To purchase a set abroad, two conditions must be met: all collis of the set must appear in the colli list with the required quantity, and the set must be available for purchase in the customer's country. A colli can only be made stackable if it is not yet stackable and if it is not purchased abroad. Each country has its transport mode, indicating whether the collis are sent to the customer by truck or ship. A transport type can be used if the mode of the transport type matches the transport mode of the customer's country and if it is available for the customer's country.

4.1.2 Transport layout

The goal is to determine the best transport layout, which includes as many collis from the same machine and location in the transport type. For each colli, we must determine in which transport and on which position in the transport it will be placed.

Objective

The objective is ensured by minimizing the number of groups of machines and locations in the different transports. A group consists of at least one colli of a machine and location in a transport. If a group of colli(s) of machine m and location l exists in transport t, is indicated by the Boolean variable $Group_{m,l,t}$, as Equation 4.1 shows. The total number of groups can be obtained by summing up all the true values, as shown in Equation 4.2. The minimum number of groups is equal to the maximum of the number of transports and the number of machines and locations.

$$Group_{m,l,t} = \begin{cases} 1, If\ at\ least\ one\ colli\ of\ Machine\ m\ and\ Location\ l\ is\ in\ Transport\ t \\ 0, Otherwise \end{cases} \quad (4.1)$$

$$Total\ groups = \sum_{t=1}^{T} \sum_{l=1}^{L} \sum_{m=1}^{M} Group_{m,l,t} \quad (4.2)$$

Constraints

In this section, we indicate how we consider all the logisticians' constraints of Section 2.5 in the solution model. We rely on the notation introduced in Section 3.2. Constraints C1-C5 are derived from Gajda, Trivella, Mansini, & Pisinger (2022).

C1. Weight limit

The total weight of the items in the transport must not exceed the maximum payload Q^{MAX}, which depends on the transport type and the customer's country. The customer's country may result in an additional payload restriction, as described in Section 2.2.4 (Gajda et al., 2022).

C2. Weight distribution and load balancing

The load inside the transport is distributed as evenly as possible along the longitudinal and horizontal axles. In the longitudinal direction, the transport is divided into different zones (Figure 4.1), where each zone can carry maximum weight. Each transport type has its number of zones, size, and maximum weight per zone. Since zones are not physically separated in the transport, an item can be in multiple zones. To calculate the contribution of the weight of the item q_i to a zone Z, we assume that each item has a homogeneous density. If item i is positioned directly above the floor of the transport (i.e. there are no items below it), then this contribution is $y^Z * q_i$, where y^Z is the portion of base area of i ($w_i * l_i$) that overlies zone Z. Otherwise, the weight will be evenly distributed on the items below in proportion to the size of the contact area. Horizontal load balancing requires that the centre of gravity of the loaded transport does not exceed a maximum displacement from the horizontal centre. Figure 4.2 shows an acceptance zone around the horizontal midpoint where the balance is considered feasible, which can differ for each transport type. Longitudinal and horizontal load balancing are hard constraints, which we hereafter refer to as $C2^L$ and $C2^H$, respectively (Gajda et al., 2022).

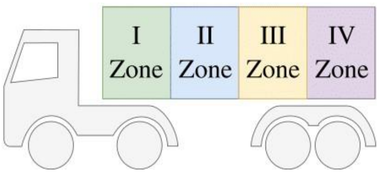

Figure 4.1 Longitudinal zone separation (Gajda et al., 2022).

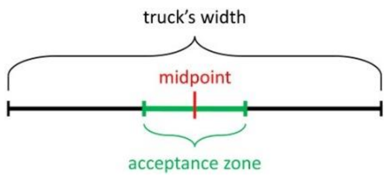

Figure 4.2 Horizontal acceptance zone (Gajda et al., 2022).

C3. Orientation constraints

Each item i is provided with an initial orientation (without loss of generality, o_{i1}) and a subset of the six orthogonal orientations $\{o_{i1}, o_{i2}, o_{i3}, o_{i4}, o_{i5}, o_{i6}\}$, as Figure 3.2 shows, in which the item can be feasibly rotated when packing it. Each item has the characteristics "rotatable" and "tiltable". If both are false, then only o_{i1} is true. If an item is rotatable, then o_{i2} is also true and if tiltable, then o_{i5} and o_{i6} are also true. If an item is rotatable and tiltable, then all orientations are true (Gajda et al., 2022).

C4. Stacking constraint

Each item has a stacking characteristic of true (resp. false), which indicates that the item can (resp. cannot) support the weight of other items on top of it. In other words, fragile items get the value false and non-fragile items get the value true. We assume that stackable items have no maximal payload restriction (Gajda et al., 2022).

C5. Stability constraint

The support factor approach ensures that a packaging solution is vertically stable. We model this by ensuring that each item is supported by at least a minimum portion of the ground surface by underlying items. In other words, the cantilever portion of an item cannot exceed a certain percentage. Figure 4.3 illustrates this concept, showing an item's supported and exceeding area (cantilever portion) (Gajda et al., 2022).

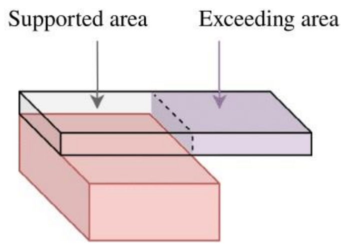

Figure 4.3 Stability constraint via support area (Gajda et al., 2022)

C6. Loadable constraint

An item can only be positioned in the transport types that are suitable for that item. Transport types with removable roofs must be used for items that cannot be positioned in the transport by hand or forklift. If the roof can be removed, the item can be positioned in the transport by the overhead crane. Items that can be positioned in the transport by hand or forklift can be positioned in any transport type. In addition, some items only fit on a low loader or flat rack. Items are extra vulnerable on low loaders and flat racks, so other items cannot be positioned on them. We ensure both restrictions with variables for the items and the transport types.

In addition to the practical constraints of the logisticians, we also consider the standard knapsack constraints of Section 3.2: the item does not overlap with other items, nor it exceeds the boundaries of the transport.

4.2 Input data

This section outlines all the data required by the decision support tool. The data is divided into two categories: customer data and general data. The customer data consists of the colli(s) the customer needs and the country. Figure 4.4 details all the necessary colli characteristics, with green icons indicating known characteristics and red icons indicating unknown ones. The notation for dimensions is provided in Figure 3.1 (Section 3.2). The data for each colli is stored in a database, and the load list generator determines which collis should be exported (see Section 2.1.4). Any unknown characteristics must be added to the database in order to be exported automatically.

Figure 4.4 Needed characteristics of the collis

In addition, the algorithm uses general data. The general data consists of the manual pre-processing sets, purchase abroad sets, transport characteristics, country characteristics and stacking characteristics. The pre-processing sets indicate which regular and irregular collis together form a larger regular colli. Figure 4.5 shows an example of a colli set. For each set, we have determined which collis and quantities the set consists of and what the characteristics of the set are. The same characteristics as the collis are collected, except that the amount, machine, and location do not have to be saved. These three follow from the colli list. In addition, a photo is taken of each set as it is loaded onto the transport. This is important because the set appears as one rectangular colli in the visual representation.

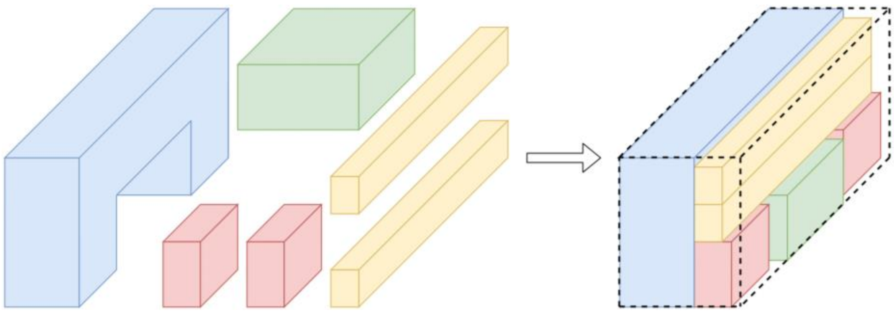

Figure 4.5 Example of manual pre-processing; the regular and irregular collis (left) that together form a regular colli (right)

The purchase abroad sets indicate which sets can be purchased abroad. For each set, we have determined its specific collis and the quantities. For each transport type, we know the transport ID, the dimensions, the maximum load capacity, whether the transport can only be loaded by forklift, whether it concerns a low loader/flat rack, the zones for longitudinal load balancing, the acceptance zone for vertical load balancing and the maximum quantity. The notation from Figure 3.1 (Section 3.2) is also used for the transport dimensions. Each transport type has its number of zones, size, maximum weight per zone and acceptance zone. The country characteristics indicate per country the costs for each set to purchase abroad, the costs for each transport type, the transport mode (truck/ship) and optional an additional payload limitation. The stacking characteristics consist of the additional dimensions, weight, and cost of making them stackable, as described in Section 2.3.4.

4.3 Model overview

Figure 4.6 shows an overview of the solution approach, which consists of two stages: the first stage determines the colli and transport composition, and the second stage determines the transport layout. The two stages are intertwined because the first stage uses the heuristics of the second stage to check a solution for feasibility. To determine the colli and transport composition, we proposed several metaheuristics in Section 3.5. We started with a completely random heuristic, concluding that finding a good solution takes a long time. We then expanded this with a local search, resulting in a multi-start local search (MSLS) with an initial randomized solution. This already worked better, but because there are many solutions to check for feasibility, reaching a local optimum takes a long time. Therefore, we created a good initial solution instead of a random one. The local optima are very similar, and local search often returns to the same local optima. Therefore, we chose to eventually use simulated annealing (SA) because SA accepts moves that result in worse solutions to escape local optima. As agreed in Section 3.3, we determine the transport layout with a randomized constructive heuristic, which is proposed for a single transport by Gajda, Trivella, Mansini, & Pisinger (2022).

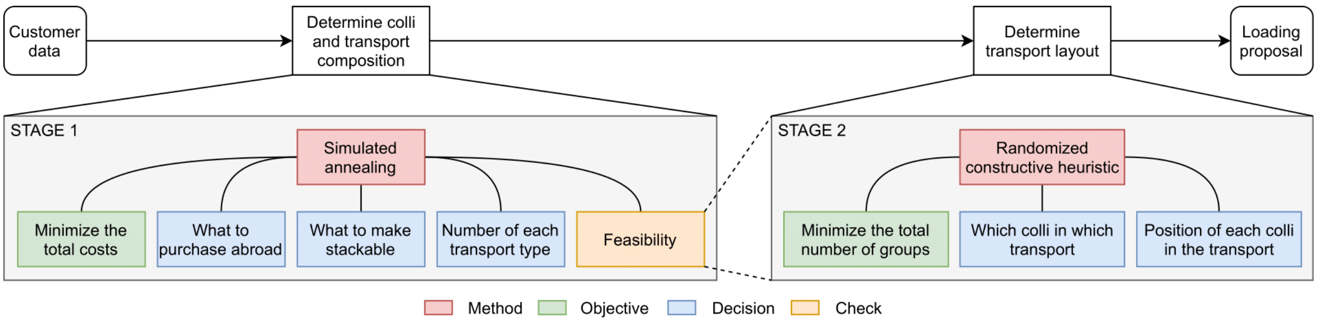

Figure 4.6 Model overview

The framework is also presented as a pseudo-code in Algorithm 4.1. We initialise the customer data, after which we create an initial solution. If there are collis for which no suitable transport type can be found, then no feasible solution exists, and the algorithm stops. Otherwise, the initial solution is saved as the current and best solution. Next, we iterate until the stop criteria are reached. We perform a certain number of iterations for each iteration, defined as the Markov chain length. In these iterations, we create neighbour solutions. After each Markov chain length, the temperature is decreased. We perform a feasibility check only if the neighbour solution is cheaper than the current solution. If feasible, the neighbour solution is saved as the current solution. If the neighbour solution is also cheaper than the best solution, then the neighbour solution is also saved as the best solution. Suppose the neighbour solution is more expensive than the current solution. In that case, the neighbour solution is accepted as the current solution if the probability is true and the solution is feasible. This acceptance probability is high initially and becomes smaller as the temperature decreases. The feasibility check is performed if the solution is accepted because the feasibility check takes more computational effort than comparing costs. By doing the feasibility check last, it needs to be performed as little as possible. If the initial solution is feasible, the transport layout is determined after reaching the stop criteria (stage 2). We check whether the composition is also feasible without purchasing abroad and making stackable options. If true, we remove the upgrades. If, after determining the transport layout, a transport is unused or there is nothing on an item that has been made stackable, we also remove it. Initially, it would not be possible that fewer resources or upgrades are needed than determined in the first stage. However, the randomized constructive heuristic of the second stage is performed less extensively in the first stage.

Algorithm 4.1 Model overview (Henderson, Jacobson, & Johnson, 2003)

Input: Colli list; manual pre-processing sets; purchase abroad sets; transport types; customer characteristics; SA parameters

Initialize customer data
Initialize Temperature with Start Temperature
Determine Initial Solution: what to purchase abroad and make stackable; number of each transport type; total costs

if Feasible Initial Solution **then**
    Save Initial Solution as Current Solution and as Best Solution
    while Stop criteria are not reached **do**
        for m = 1 to Markov Chain Length **do**
            Find Neighbour Solution: what to purchase abroad and make stackable, number of each transport type; total costs
            if Costs Neighbour Solution < Costs Current Solution **then**
                if Feasible Solution **then**
                    Save Neighbour Solution as Current Solution
                    if Costs Neighbour Solution < Costs Best Solution **then**
                        Save Neighbour Solution as Best Solution
            elseif Random Number ≤ e^((Costs Best Solution - Costs Neighbour Solution) / Temperature) **then**
                if Feasible Solution **then**
                    Save Neighbour Solution as Current Solution
        Decrease Temperature
    Determine the transport layout and remove purchasing abroad, stackability and transports if it is also feasible without it

Output: What to purchase abroad and make stackable, number of each transport type, total costs, transport layout

4.4 Initialize customer data

In this section, we describe how to initialize the customer data. We pre-calculate as much as possible so that we have to recalculate as little as possible each iteration.

Pre-process regular and irregular collis

Based on the colli list and the manual pre-processing sets, we merge all regular and irregular collis, forming a larger regular colli. The condition is that all collis with the required quantity appears in the colli list. The collis are removed from the colli list, and the larger regular colli is added to the colli list with its characteristics. In addition, we adjust the dimensions of some collis because otherwise, it is no longer possible to fix it in the transport.

Purchase abroad, stackable and transport types

Based on the input data, we list the sets that can be purchased abroad with their costs, the collis that can be made stackable and the suitable transport types. Section 4.1.1 describes the conditions for appearing on the lists.

Loading possible

For each colli and suitable transport type, we check whether the colli fits into the transport type. We check whether the weight of the colli is smaller than the maximum payload of the transport type (C1), whether the dimensions of the colli are smaller than the dimensions of the transport type in at least one of the feasible orientations (standard knapsack constraint and C3) and whether the loadable constraint is met (C6). This variable is, for example, used to quickly filter all candidate collis when a single transport needs to be filled.

Chargeable weight

For each colli and suitable transport type, we calculate the chargeable weight of the colli for the transport type. The chargeable weight π_{it} of an item $i \in B$ for a transport type $t \in T$ is defined as the maximum between its weight q_i $[kg]$ and a volumetric weight computed as the product of its volume $v_i = l_i * w_i * h_i$ $[m^3]$ and the density ρ_t $[kg/m^3]$, that is $\pi_{it} = \max\{q_i, \rho_t v_i\}$. The density of a transport type ρ_t can be determined by dividing the maximum payload q_t^{MAX} $[kg]$ by its volume $v_t = l_t * w_t * h_t$ $[m^3]$, that is $\rho_t = q_t^{MAX}/v_t$. This means that the chargeable weight of high-density items (e.g. weldments) corresponds to their weight, while the load capacity of light and bulky items is determined by their volume (Gajda, Trivella, Mansini, & Pisinger, 2022).

4.5 Colli and transport composition

This section describes how we determine the colli and transport composition. In Section 4.5.1, we describe how we create the initial solution. Section 4.5.2 describes how we check whether a solution is feasible. Section 4.5.3 describes how we create the neighbour solutions. Finally, in Section 4.5.4, we describe the cooling scheme.

4.5.1 Initial solution

In the initial solution, we do not purchase anything abroad or make anything stackable. We determine the transport composition with a greedy algorithm. We assign each item to the transport type which is the cheapest per volume unit ($costs_t/v_t$) in which the item can be placed. Per transport type, we sum the chargeable weight of all items added to that transport type. We divide the total chargeable weight by the maximum payload of the transport type and round this up to a whole number. Since it is crucial to have a feasible initial solution, we check this. If this is not the case, we randomly add a transport in which at least one colli fits until the solution is feasible. Our findings indicate that this is an effective method for generating an initial solution. Due to the high density of VSM collis, the chargeable weight is typically determined by weight rather than volumetric weight. As a result, the first proposed transport composition without adding random transports is often already feasible.

4.5.2 Feasibility check

The solutions are checked in three phases: first, we check whether the solution has already been checked, then we roughly check the solution, and if it meets the rough requirements, it is checked exactly. If the solution has already been checked, it no longer needs to be roughly or exactly checked. If the exact solution is not feasible, we check if the solution is feasible when we make all items to be shipped stackable without adjusting the size or weight of the items. If the solution is still not feasible, we save this in the already-checked solutions. If we know that making everything stackable still does not fit, we do not have to try to make a single item stackable. Figure 4.7 shows the flow of the feasibility check. We already reject many solutions using the two stages before they are checked exactly. This reduces computation time because the exact check takes the most time for each iteration. The exact check takes up to a few seconds, depending on the number of iterations before a feasible solution and the number of collis and transports.

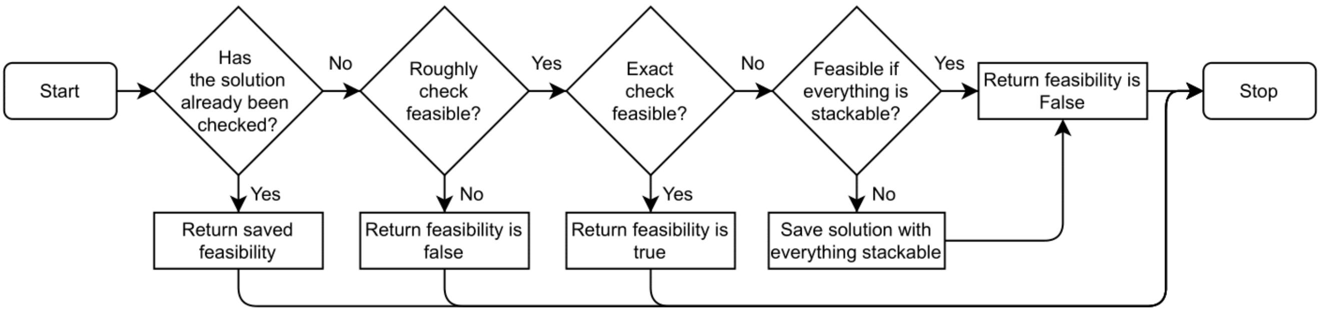

Figure 4.7 Flowchart to determine the feasibility

The feasibility of each checked solution is stored so that it does not have to be rechecked. For a solution, it is stored which sets are purchased abroad, what is made stackable and the number of each transport type. If the solution to be checked is the same or more (e.g. everything the same and one extra 40' container or another additional item stackable) as already a checked feasible solution, then the solution is also feasible. If the solution to be checked is the same or less than a checked non-feasible solution, then the solution is also not feasible. The stackability of an object results in a slight increase in dimensions and weight, as described in Section 2.3.4. We assume that these differences do not have an impact on the feasibility. However, even if this assumption is inaccurate, it is not a problem, as making more items stackable means higher total shipping costs. Due to the higher total costs, the solution can only be saved as a neighbour and not as the best solution, so we cannot get an infeasible best solution.

The rough check performs a liquid lower bound check on volume and weight: is the volume (resp. weight) of the items smaller than or equal to the volume (resp. maximal payload) of the transport composition? If both criteria are valid, then the solution is roughly feasible; otherwise, it is not. If the rough feasibility is satisfactory, we will check the solution exactly. We use the randomized constructive heuristic described in the next section (4.6). The heuristic is slightly different for the feasibility check and to determine the best transport layout, which we will explain in the next section.

4.5.3 Neighbour solution

In order to improve the composition of purchasing abroad, making items stackable, and the number of each transport type, several techniques can be employed to generate neighbour solutions. These techniques involve the add, delete, and move operators, which we apply with a certain probability.

When adjusting the composition of purchasing abroad, the add operator randomly adds a set of items that is currently not being purchased abroad. The delete operator randomly removes a set of items that is currently being purchased abroad, and the move operator removes a random set of items and adds a different set.

Similarly, to adjust the composition of making stackable, the add operator randomly makes a colli stackable that is currently not stackable (made) and is not being purchased abroad. The delete operator randomly removes the stackability of an item that has been made stackable. The move operator removes the stackability of a random colli and makes a different random colli stackable.

Finally, to adjust the transport composition, the add operator randomly adds a random transport that accommodates at least one of the collis. The delete operator randomly removes one of the transports that cannot accommodate any collis if such transports exist; otherwise, it removes a random transport. The move operator removes a random transport and adds a different random transport. In order to eliminate solutions that are not cost-effective, we establish a maximum number for each transport type. This maximum number is 1 or infinite, depending on the availability of a multiple of 2 of the same transport type. For instance, the maximum number for a 20ft standard container is 1, as a 40ft standard container is also available. Using two 20ft standard containers would never be more cost-efficient than one 40ft standard container.

The probabilities of changing the composition of purchasing abroad, making items stackable, and the number of each transport type are equal for all iterations except for the last iteration. Significant changes, such as entirely different transports, are desired in the initial iterations. However, as the process progresses, the focus shifts towards making small-scale improvements, such as reducing the number of stackable collis. Therefore, we set the probability of changing the composition depending on the iteration. In addition, the probability that the transport composition changes depends on whether the composition of purchasing abroad or making it stackable has changed.

4.5.4 Cooling scheme

The cooling scheme is a crucial component of the algorithm, which includes the starting temperature, the length of the Markov chain, the temperature decrease rule, and the stopping criterion. The starting temperature should be chosen in a way that allows for a high level of diversification at the beginning of the algorithm. The acceptance ratio, which is the ratio of accepted worse solutions divided by proposed worse solutions, should be approximately equal to 1 at the start of the algorithm and approach 0 at the end. Due to the high differences between the (transportation) costs close to the Netherlands and the other side of the world, the starting temperature must be chosen differently for each scenario to avoid an overly high or low acceptance ratio for an extended period. We use a start temperature that is a factor times the highest purchase abroad, making items stackable and transport costs. The Markov chain length is fixed, and a stopping criterion is a maximum number of iterations. The temperature decreases using the cooling scheme $T_{k+1} = \alpha T_k$. The algorithm proceeds to the last iteration if no better solution is found in a certain number of consecutive iterations. Before the final iteration begins, the best solution is saved as the current solution. In the last iteration, the algorithm attempts to make further cost reductions through minor adjustments to the current solution.

4.6 Transport layout

In this section, we describe how we determine the transport layout. In Section 4.6.1, we give an overview of the model. Section 4.6.2 explains how pre-processing works, followed by sorting and controlled perturbation in Section 4.6.3. Finally, in Section 4.6.4, we discuss constructive packing.

4.6.1 Model overview

Figure 4.8 shows an overview of the multiple container loading (MCL) algorithm, which we made on the inspiration of Gajda, Trivella, Mansini, & Pisinger (2022). MCL is a randomized constructive heuristic that, for every iteration n, loops over all transports. The transports are sorted from cheapest to most expensive cost density (cost/volume). For each transport, m attempts are made to fill this transport using a single container loading (SCL) algorithm. Each row in the overview within the braces (filtering, pre-processing, sorting and perturbation and packing) represents a separate invocation of the SCL algorithm. If the packing solution of SCL is feasible, it moves to the next transport; if it is not feasible, another attempt is made with the SCL algorithm. If there is no feasible attempt after M trials, then iteration n is infeasible. If all transports are filled, but not all items are packed, then iteration n is also infeasible. If all items are packed, then the number of groups of machines and locations in the different transports is calculated (with Equation 4.2). If the number of groups is less than the best number found, then the solution is saved as the best solution. If the algorithm is used to check whether the combinatorial solution is exactly feasible, it stops as soon as a feasible solution is found; otherwise, all iterations N are executed to find the smallest number of groups.

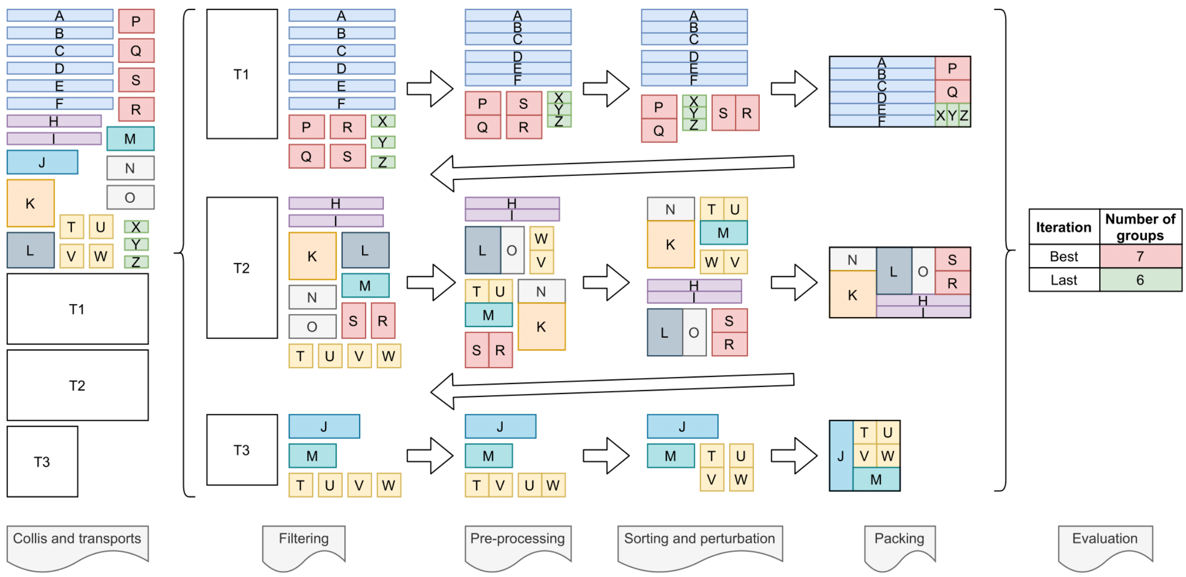

Figure 4.8 Overview MCL algorithm (Gajda et al., 2022)

The SCL algorithm is also presented as a pseudo-code in Algorithm 4.2, which we derived from Gajda et al. (2022). Unfortunately, the code was unavailable, so we re-implemented the SCL algorithm using the paper. First, we filter all items that have not yet been packed in other transports and which can be packed in this transport. Second, the items are pre-processed, where items are combined based on their dimensions to construct larger blocks. Then the items are sorted into a partially randomized list and packed using a constructive method. The construction phase takes as input an ordered list of items and inserts them sequentially into the transport, starting from the first item in the list, using specific candidate locations inside the transport. Because the order of the items is essential during packing, we initially sort into a list of functions that make packing easier or more profitable afterwards. Controlled perturbation can be seen as a diversification phase in which the initial list order is partially disrupted. This generates different lists that ultimately lead to different loading patterns. With each iteration, all constraints, except horizontal load balancing ($C2^H$), are explicitly enforced at the packing phase. After the packing phase, we check the horizontal load balancing and whether all items left can still be packed in another transport. The packaging solution is only feasible if both are met. Horizontal load balancing is only checked if more than one item is loaded. Otherwise, the solution is often invalid because the item is packed in one of the two corners, causing the centre of gravity to be too far from the centre. The algorithm's output is a packing solution, where the solution encodes which items to load, the orientation, and the placement coordinates in the transport (Gajda et al., 2022).

Algorithm 4.2 SCL algorithm (Gajda et al., 2022)

Input: CLP instance with a set of items; transport characteristics

Filter all items that are not packed yet and can be packed in this transport
Pre-process the items by combining them into larger blocks [▷Section~4.6.2]
Sort and randomize the items [▷Section~4.6.3]
Construct solution that satisfies weight limit (C1), longitudinal load balancing ($C2^L$), orientation (C3), stacking (C4), stability (C5) and loadable (C6) [▷Section~4.6.4]
if Horizontal load balancing is not respected ($C2^H$) **or** There are collis left that do not fit in the next transports **then**
  Mark single packing solution as infeasible

Output: If single packing solution is feasible; single packing solution

4.6.2 Pre-processing

The pre-processing phase combines items with specific characteristics into larger blocks to handle large-scale instances more efficiently. Such pre-processing is helpful to fill the transport volume better and facilitates the subsequent stages of the algorithm by reducing the number of items to be packed (Gajda et al., 2022). We use the same pre-processing method as in the paper of Gajda et al. (2022), which consists of combining items sharing two or all three dimensions or keeping the items as they are (i.e. the pre-processing phase has been skipped). We add the restriction that items can only be merged from the same machine and location.

4.6.3 Items sorting and controlled perturbation

The order in which items are packed into a transport can significantly impact the success of the process. We attempt to generate lists of "promising" items to achieve optimal packaging based on specific sorting criteria. We implemented two sorting rules. The first rule is derived from Gadja et al. (2022), who describe that sorting the items by descending chargeable weight yields solutions with higher objective values. We have extended this sorting rule with the function that if this is the last transport the item fits in, the item will be at the top of the list. This maximizes the chance of creating a feasible packaging solution. The second sorting rule first puts the items that only fit in this transport at the top. Second, we prioritize the machine and location items that still have the most chargeable weight. The items are then sorted by machine, location and chargeable weight. The way of sorting differs for the exact checking of a solution and for determining the best transport layout. If we sort the items for exact solution checking, the probability for the first and second sorting rule is 2/3 and 1/3, respectively. If we want to determine the best transport layout, the probability for the first and second sorting rule is 1/3 and 2/3, respectively. In addition to sorting the items, we disrupt the sorted list in each iteration of the algorithm to diversify the loading procedure. We use the same disrupting methods as in the paper of Gajda et al. (2022), which consists of two probabilistic rules to rotate the items and perturb the loading sequence. Rotating the items is done by choosing a random orientation for each item or choosing the same one for the items that share all dimensions. The perturbation of the loading sequence is done by swapping items based on the volume of weight with a randomized probability.

4.6.4 Constructive packing

The packaging method is initially proposed by Gajda et al. (2022), which sequentially packs the items in the transport from the first item in the list while complying with several constraints. We have modified the way items from the retry list are handled. Instead of trying to pack these items in a single random direction, as the original method suggests, we suggest trying to pack them in all possible directions. We decided this based on the observation that most items can only rotate. The computational time, therefore, hardly increases, while the chance of a feasible packing solution is greater. Furthermore, we attempted to load all items from the retry list as separate rather than pre-processed items. However, we found that this did not result in a significant improvement in the solution. This is likely because pre-processed items, which have a higher chargeable weight, are rarely placed on the retry list because they have a higher packing priority.

4.7 Conclusion

We propose a heuristic to solve the three-dimensional bin packing problem with item upgrading and outsourcing options. It is a combinatorial optimization to get the cheapest colli and transport composition with the best transport layout. The combinatorial optimisation decides what to purchase abroad, what to make stackable, and the number of each transport type while ensuring feasibility for the colli composition. Once the colli and transport composition have been chosen, we strive to create the best transport layout. We do this by maximizing the number of collis from the same machine and location in the same transport. We consider various restrictions such as weight limit, weight distribution, orientation, stacking, stability and loading.

The data required by the decision support tool can be divided into customer data and general data. Customer data includes the collis to be sent and the customer's country. General data includes manual pre-processing and purchase abroad sets and transport, country and making stackable characteristics. The model is divided into two stages: the first stage determines the colli and transport composition using simulated annealing (SA) to escape local optima, and the second stage determines the transport layout using a randomized constructive heuristic. The two stages are intertwined because the first stage uses the heuristics of the second stage to check for feasibility. If in the second stage, it turns out that purchasing abroad, making it stackable, or some transports are unnecessary, these will be removed.

The colli and transport composition are initialized using a greedy heuristic that assigns each colli to the cheapest transport per volume unit in which the colli may be placed. In the initial solution, we do not purchase anything from abroad or make anything stackable. Feasibility is checked in three phases: first, we check whether the solution has already been checked, then we roughly check the solution, and if it meets the rough requirements, then the solution is checked exactly. To improve colli and transport composition, we employ operators such as add, delete, and move with a certain probability to generate neighbour solutions. The cooling scheme consists of a starting temperature based on the maximum costs of purchasing abroad, making items stackable and the transport types, fixed length of the Markov Chain, and a maximum number of iterations as stopping criterion with a decrease factor for temperature cooling.

The randomized constructive heuristic for determining the transport layout consists of several phases for each transport, including filtering, pre-processing, sorting, randomization, and constructive packing. After all the transports have been filled, we evaluate the solution and start the next iteration.

5 Experiment design

This chapter describes the experimental design by answering the fourth research question: *"What does the experimental design look like?"*. The chapter starts by describing the experiments in Section 5.1. Section 5.2 validates the existing data and completes the missing data from the test instances. Afterwards, in Section 5.3, we calibrate the parameters of the decision support tool. Finally, in Section 5.4, we conclude the chapter with a summary.

5.1 Experiments

We want to demonstrate that the decision support tool (DST) works by making a new loading proposal for every transported project in recent years. The DST is implemented in Python and runs on a PC with an Intel Core i7 processor and 16 GB RAM. The total shipping costs and the number of groups will be compared with the current situation. We calculate everything with the current prices; it is possible that the cost ratios between the transport types were different in the past, making this the best combination at the time. In addition, we want to examine the consequences of adjusting input variables and constraints and assess the quality of the DST.

5.2 Data collection

In this section, we describe how we created the test instances. For the test instances, we use the database of all the transported projects of recent years, which we have built up when describing the current situation (Chapter 2). We have a total of 366 test instances, consisting of a total of 13,353 collis.

The data from the built-up database is incomplete: we are missing several characteristics of the collis, namely: rotatable, tiltable, stackable, forklift possible and low loader (Section 4.2). In addition, the pre-processing sets are unknown, indicating which regular and irregular colli together form a regular colli. Checking and updating the available data from the collis and adding new data is time-consuming. So, we focused on verifying and updating the data of three machines and all handling, which we selected based on their high sales volume and their frequent use in combination. We have made the data accurate by manually checking and supplementing all data with a logistics work preparator, i.e. measuring and weighing each colli and filling and checking the other characteristics.

We also want to test the DST on machines from other projects. We make this possible by filling in the missing characteristics of the collis as accurately as possible without assessing each colli individually. We assume that each colli is rotatable. In addition, we assume that only the fences are tiltable. The logistics work preparator has named all collis that are stackable from memory. In addition, we have devised several ways to assume that a colli can be loaded into a standard container by hand or forklift. First of all, all collis that have been loaded in a standard container in the past. Secondly, all collis that were packed on pallets or wooden or carton boxes. Third, all collis weighing 20 kg or less. Finally, several collis that the logistics work preparator knew by heart. All collis loaded on a low loader in the past may be loaded on a low loader. We also made the dimensions as accurate as possible by looking at the outliers in dimensions of the same colli.

By making the data from the three machines and all handling accurate, we can compare the results with the current situation for 30.9% of the projects. We can also generate a loading proposal for the remaining 69.1% of the projects, but we cannot compare it accurately with the current situation as we lack knowledge of the manual pre-processing sets for those collis. Consequently, we consider each colli as regular, and the DST may give a higher total shipping cost than the current situation. Moreover, the DST may yield results that cannot be fixed with ratchet straps. In conclusion, we have an accurate and approximate set of test instances, and Table 5.1 shows the characteristics of each.

Table 5.1 Characteristics of all test instances

	Accurate set				Approximate set			
	μ	σ	min	max	μ	σ	min	max
Number of unique machines and locations	2.04	0.50	1	4	2.13	1.12	1	9
Number of items	37.0	16.5	9	139	32.0	29.3	1	186
Different item types	33.4	12.7	9	93	26.7	24.3	1	130
Volume per item [m^3]	3.36	5.05	0.01	31.67	3.88	6.83	0.001	99.00
Weight per item [kg]	896	1,580	1	11,800	938	1,675	1	22,000
Making stackable options	25.5	10.4	4	88	20.5	20.6	1	126
Purchase abroad options, resp. 0; 1; 2; 3; 4 sets	44.2%; 4.4%; 11.5%; 39.8%; 0%				83.0%; 5.9%; 8.3%; 2.4%; 0.4%			
Transport type options, resp. 11 (truck); 9 (ship)	32.7% ; 67.3%				73.5% ; 26.5%			

In addition to the customer data, the general data, consisting of purchase abroad sets, transport characteristics, country characteristics and stacking characteristics, must also be filled in. The purchase abroad sets are defined in Section 2.3.5. The purchase abroad sets contain an average of 2.9 collis, with an average total volume of 10.4 m^3 and weight of 1181 kg. The costs of each set purchased abroad are determined per country in consultation with the strategic buyer and are, on average, €5012. The transport types are defined in Section 2.2. The characteristics of the transports and derived from Hapag-Lloyd (2022) and obtained in consultation with the transporter. In addition to the costs, the transport mode is stored in the country characteristics. Finally, the stacking characteristics are defined in Section 2.3.4.

5.3 Parameter calibration

In this section, we describe how to calibrate all parameters. Section 5.3.1 describes the representative test instance we use to calibrate the parameters. Section 5.3.2 describes how we calibrate the parameters of the cooling scheme, followed by the probabilities of different operators for creating the neighbour solutions in Section 5.3.3. Finally, in Section 5.3.4, we describe how to calibrate the parameters of the randomized constructive heuristic.

5.3.1 Representative test instance

To calibrate the parameters of simulated annealing and the randomized constructive heuristic, we use a representative test instance of the data set defined in the previous section. Of the past years, this test instance is the most complex and largest in terms of total weight and number of collis shipped. We have made this test instance more challenging by increasing the number of options for purchasing abroad and making stackable. Table 5.2 shows the characteristics of the representative test instance.

Table 5.2 Characteristics of the representative test instance

Number of unique machines and locations	6
Number of items	189
Different item types	98
Volume per item [m^3]	μ = 3.11 ; σ = 4.29 ; min = 0.03 ; max = 27.64
Weight per item [kg]	μ = 901 ; σ = 1,333 ; min = 5 ; max = 11,800
Making stackable options	164
Purchase abroad options	5
Transport type options	9 (ship)

5.3.2 Cooling scheme

In this section, we determine the parameters of the cooling schedule of simulated annealing, consisting of the temperature factor, the stop criteria, the decrease factor and the length of the Markov Chain. Table 5.3 gives an overview of the values we use for the parameters. We determine these values empirically after several experiments. Appendix J shows the results of the experiments.

Table 5.3 Cooling scheme

Parameter	Value	Explanation
Temperature factor	35	This temperature factor gives an acceptance ratio of approximately 1 in the first Markov Chain. By using a higher temperature factor, worse solutions are accepted for too long, requiring much computational time to check all these solutions for feasibility. By using a lower temperature factor, too few worse solutions are accepted, resulting in a high probability that it will not be possible to get out of the local optimum.
Maximum number of iterations	50	This stop criterion ensures that the computational time remains within limits, but this stopping criterion is rarely decisive.
Number of iterations no change	30	This stopping criterion is usually decisive. We have established through experiments that if no better solution has been found after 30 consecutive iterations, the chance that a better solution will be found is small.
Decrease factor	0.6	This decrease factor causes the temperature to drop so that the probability of accepting a worse solution in the last iteration is approximately equal to 0.
Markov Chain Length	80	This Markov chain length ensures that enough neighbour solutions are created in each iteration.

5.3.3 Neighbour solution

In this section, we describe the probabilities of the compositions being changed with the probabilities of the different operators. Table 5.4 provides an overview of the various probabilities. We determine these probabilities empirically after extensive experimentation.

The probability that the transport composition changes depends on whether the purchase abroad and stackable composition has changed. If both have not changed, the probability is 0.80 in iteration 1…N-1 and 0.1 in iteration N. If one of the two compositions changes, the probability is 0.05 higher; if both compositions change, the probability is 0.10 higher.

Table 5.4 Probabilities of compositions being changed with the probabilities of the different operators

	Iteration 1…N-1	Iteration N
Purchase abroad	0.05	0.7
Add	0.2	0.1
Delete	0.2	0.3
Move	0.6	0.6
Making stackable	0.05	0.7
Add	0.2	0.1
Delete	0.2	0.3
Move	0.6	0.6
Transport	0.8 / 0.85 / 0.9	0.2 / 0.25 / 0.3
Add	0.2	0.1
Delete	0.2	0.1
Move	0.6	0.8

5.3.4 Randomized constructive heuristic

The number of iterations to find a feasible packaging solution and the best packaging solution is equal to $N = 100$ and $N = 500$, respectively. We found that after this number of iterations, the probability of finding a feasible packing solution or better transport layout is minimal. The number of iterations of a single transport is equal to $M = 25$. We found that after this number of iterations, the probability of finding a feasible solution is minimal.

5.4 Conclusion

We want to demonstrate that the decision support tool works by making a new loading proposal for every transported project of recent years. The total shipping costs and the number of groups will be compared with the current situation. The test instances are the transported projects, of which we have checked and updated the data of three machines and all handling. We filled the data with a rough method for all other machines, resulting in an accurate and approximate set of test instances, which are 30.9% and 69.1% of the whole. Finally, we calibrated the parameters of simulated annealing and the randomized constructive heuristic by performing experiments.

6 Analysis of the results

This chapter aims to analyse the experiments' results to answer the fifth research question: *"What is the performance of the decision support tool?"*. The chapter starts with the presentation of the results of the decision support tool and the comparison with the current situation in Section 6.1. Section 6.2 examines the consequences of adjusting input variables and constraints. Section 6.3 assess the quality of the decision support tool. Finally, in Section 6.4, we conclude the chapter with a summary.

6.1 Comparison company's solutions

In this section, we present the results of the decision support tool (DST) and compare them with the current situation. We start with an overview, after which we zoom in on several aspects.

6.1.1 Overview results

The DST has created a new loading proposal for each project in recent years. Figure 6.1 shows the packing solution for a single transport determined by the DST, and Figure 6.2 shows how the transport is packed in real life. The logistics employee packs it slightly differently than the tool has devised by starting with the cross transports (elongated collis) instead of the roller conveyors and legs (high collis). However, repositioning within a transport is not a problem as long as the distribution of the collis over the transports remains the same.

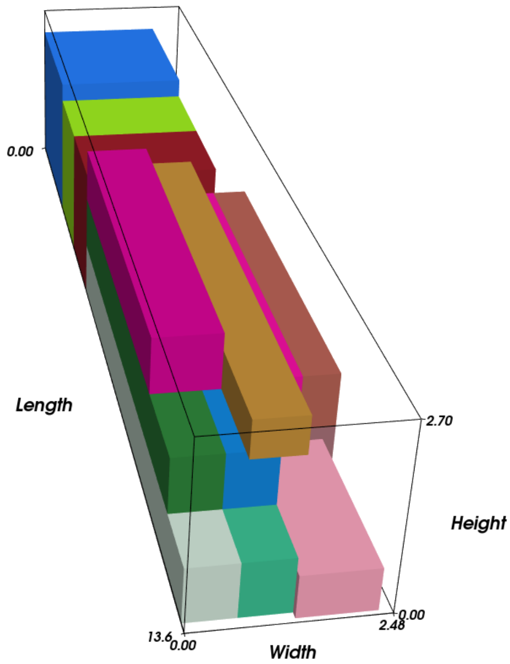

Figure 6.1 Packing solution determined with DST

Figure 6.2 Packing solution in real life

Table 6.1 compares the average costs and the number of groups per project for the current situation and the DST, as well as the difference between them. The DST can find an equally good or better solution for all exact and approximate projects compared to the current situation, with substantial cost savings of 18.2% and 15.3%, respectively. Although there were initially certain projects where the DST was not effective, we were able to use the photos for insurance purposes to identify and correct inaccuracies in the input data. The current situation does not include purchasing abroad and making stackable costs, so these are higher in the DST's solution. On the other hand, the transport costs are lower, meaning the total shipping costs are lower. The savings are higher with the accurate dataset than with the approximate dataset; this makes sense because the machines' manual pre-processing sets are unknown in the approximate set. The irregular items are considered as regular, causing empty space to be lost. The number of groups is higher for the DST's solution, which makes sense because, in the current solution, the average number of transports is higher. Hence, collis from different machines and locations must be mixed less over the different transports to get a feasible solution. The DST uses fewer number of transports, so the collis of the same machine and location are more spread over the transports to get a feasible solution, which results in a higher number of groups.

Table 6.1 Average costs and number of groups per project

	Accurate data set				Approximate data set			
	Current	DST	Difference		Current	DST	Difference	
Costs	€32,004	€26,168	€-5,835	-18.2%	€25,360	€21,488	€-3,872	-15.3%
Purchase abroad	€0	€605	€605	+100%	€0	€66	€66	+100%
Making stackable	€0	€6	€6	+100%	€0	€14	€14	+100%
Transport	€32,004	€25,577	€-6,447	-20.1%	€25,360	€21,409	€-3,951	-15.6%
Number of groups	3.90	4.83	0.93	+23.8%	4.15	6.02	1.87	+44.9%

In the rest of the chapter, we use the entire data set, i.e. the combination of the accurate and approximate data set.

6.1.2 Purchase abroad

The purchase abroad option is unpopular: it is only used in 17.9% (19 out of 106 projects) where purchasing abroad is possible. Among these 19 projects, 57.9% purchased one set abroad, while the remaining 42.1% purchased two. Within these projects, Figure 6.3 shows the distribution of the use of the different purchasing abroad options. The average volume of items purchased abroad is 5.9 m^3, while the average volume of all items that can be purchased abroad for all projects is 10.4 m^3. This makes sense because the larger the set to be purchased, the higher the likelihood that a larger transport composition will be more economical than smaller ones with the set purchased abroad.

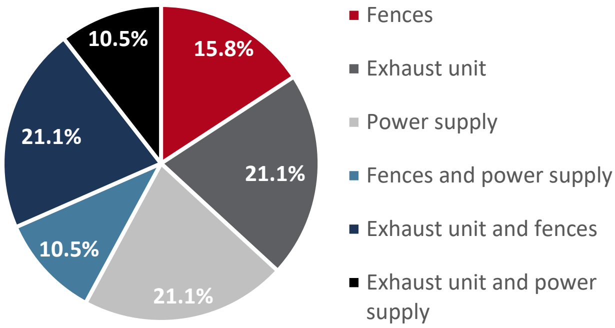

Figure 6.3 Distribution of the use of the purchasing abroad options

We observed no significant relationship between a project's total weight and volume and the decision to purchase items from abroad. However, we observed a relationship between the transport composition and whether something is purchased abroad. The option is mainly used if the transport composition comprises only 40' containers. This insight makes sense because purchasing abroad is expensive, so it is only used if the item that can be purchased abroad does not fit into the transport composition. For example, if a transport composition of 2 containers and 3 loading meters is not feasible, it is often cheaper to order 2.5 containers and purchase nothing abroad.

6.1.3 Making stackable

The option to make items stackable is not widely used, with only 2.2% (8 out of 366 projects) utilizing this option. It is possible to make items stackable in every project as each contains at least one colli that is currently not stackable. In 7 projects (87.5%), one item is made stackable, while in 1 project (12.5%), two items are made stackable. The items are made stackable with an average volume of 3.0 m^3, which is considerably smaller than the average volume of non-stackable items (4.08 m^3). This is logical as smaller items are less expensive to make stackable. Thus, the smallest items that ensure everything fits in transport composition are made stackable. The smallest items are often not made stackable because they are often placed on top of a stackable item. The largest items are also not made stackable due to the high costs involved. For larger items, expanding the transport composition is often cheaper than making the item stackable. The average cost of items made stackable is €460.

The less frequent use of making stackable is logical because 34.3% of all collis are already stackable. Additionally, there is no intermediate size between 8 loading meters and a full trailer of 13.62 meters for truck transport, nor between 20' and 40' containers for container transport. For example, if something can fit in 10 loading meters by making a colli stackable, this would be less cost-effective than using an entire semi-trailer since 10 loading meters is not an option.

In projects that utilize the making stackable option, 62.5% are transported via containers, while 37.5% are transported via trucks. Container transport is more expensive than truck transport, making it more cost-effective to make items stackable rather than expanding the transport composition. No significant correlation exists between a project's total weight and volume and the decision to make items stackable.

6.1.4 Transport types

The DST has lower transport costs than the current situation by better packing items in the transports. The DST makes it possible to fit items accurately, so more single loading meters (LTL/LCL) are needed instead of entire transport. Assessing the required loading meters is hard in the current situation, which makes ordering complete transports a safe solution. Besides, fewer transports are required because items are purchased abroad and made stackable. Figure 6.4 shows the difference between the current situation and the DST. By applying the DST, the number of curtain side trailers required for truck transport has been reduced by 43.4% (-201), and the number of single loading meters is increased by 230% (+92). The DST can pack the items more efficiently and has the option to make items stackable, reducing the need for an extra loading meter (1m LTL) compared to the current situation. In addition, MEGA trailers, 30 cm higher and slightly more expensive than curtain side trailers, are used 5.7% more in the DST (+5), reducing the need for other transport types. The number of low loaders remains the same because it is used for a few collis, and saving on this limited number is impossible. We can draw similar conclusions for container transport; the DST requires 20.9% fewer 40' hardtop high cube containers (-100). The DST uses instead 950% more 40' standard high cube containers (+38) and 42.9% more standard containers (+3), which are cheaper because the roof cannot be removed. The DST also reduces the need for 20' hardtop and standard containers by 47.1% (-8) and 80.9% (-38), respectively, by making 475% more use of single loading meters (+19). The number of 40' high cube flat racks remains the same for the same reason as with low loaders for truck transport.

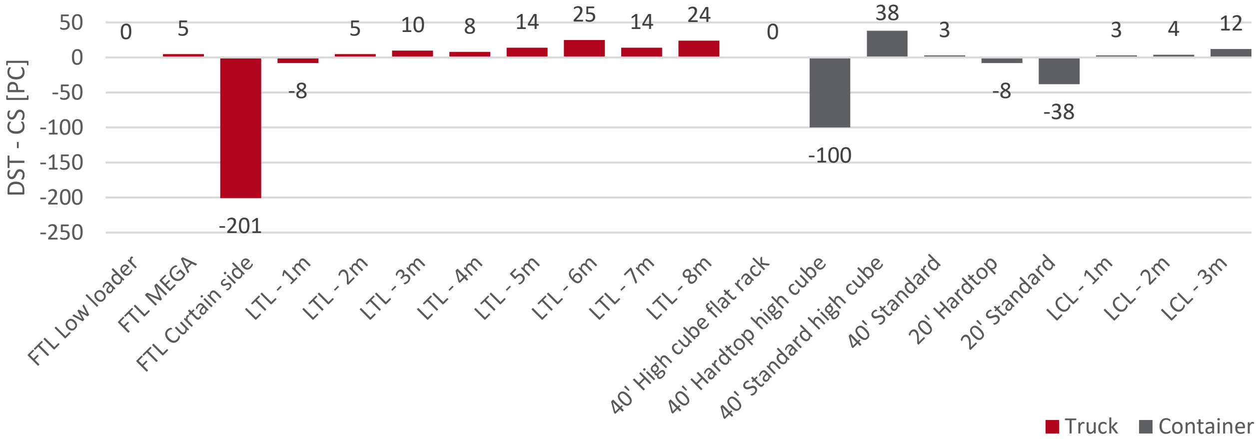

Figure 6.4 Difference between the current situation (CS) and the decision support tool (DST)

6.1.5 Total shipping costs

The total shipping costs of all projects of recent years are €10,032,537 in the current situation and €8,393,573 with the DST. Consequently, the implementation of the DST would result in a significant cost reduction of 16.3% (€1,638,964) if the projects were reshipped again using today's prices.

To provide a more accurate estimate of the savings, we adjusted the transport and purchasing abroad costs in both situations with a correction factor. This factor corrects for the variation in transport prices over time, which we have determined in cooperation with the transporter. However, we have not applied the correction factor to the making stackable costs, as we assume these costs have remained constant in recent years. Considering the correction factor, the total shipping costs for the current situation are €6,748,356. For completed projects where customers did not arrange the transports themselves, we compared the total transport costs of the current situation with the correction factor with the total shipping costs in the ERP system and found that they were almost identical. Despite the cost variation, we also assume that each project's colli and transport composition is still optimal. With this correction factor, the total shipping costs for the DST amount to €5,632,813, resulting in a cost saving of 16.5% (€1,115,543).

6.1.6 Fill rate

Although maximizing the fill rate was not an objective, the fill rate is related to the total shipping costs. The higher the degree of filling, the fewer transports are required to send the collis, and the lower the costs. Section 2.6 defines the fill rate as the highest filling level based on the volume and weight of the collis. Figure 6.5 shows the fill rate of the DST vs the current situation. The average fill rate for the DST is 69.3%, while the average fill rate of the current situation is 56.4% (Section 2.6). For container transport, the fill rate is determined by weight for 85% of all transports and by volume for 15%. For truck transport, the fill rate is determined by weight for 37% and volume for 63%. This discrepancy is due to containers transported to the USA having a maximum payload of 14,500 kg, whereas truck transport can be loaded more than twice as heavy, making weight restrictions less significant. The fill rate of the DST falls between 95-100% in 24.2% of all container transports due to VSM transporting heavy cargo and the low maximum payload for container transport. In the current situation, 25 containers (4.4% of all containers) were overloaded. In the DST, the weight limit is a hard constraint, meaning this is impossible. However, an equally expensive or cheaper solution has always been found with DST, meaning that overloading was never necessary to find a feasible packing solution for the current transport costs. The weight limit has always been kept by better distributing the items over the transports.

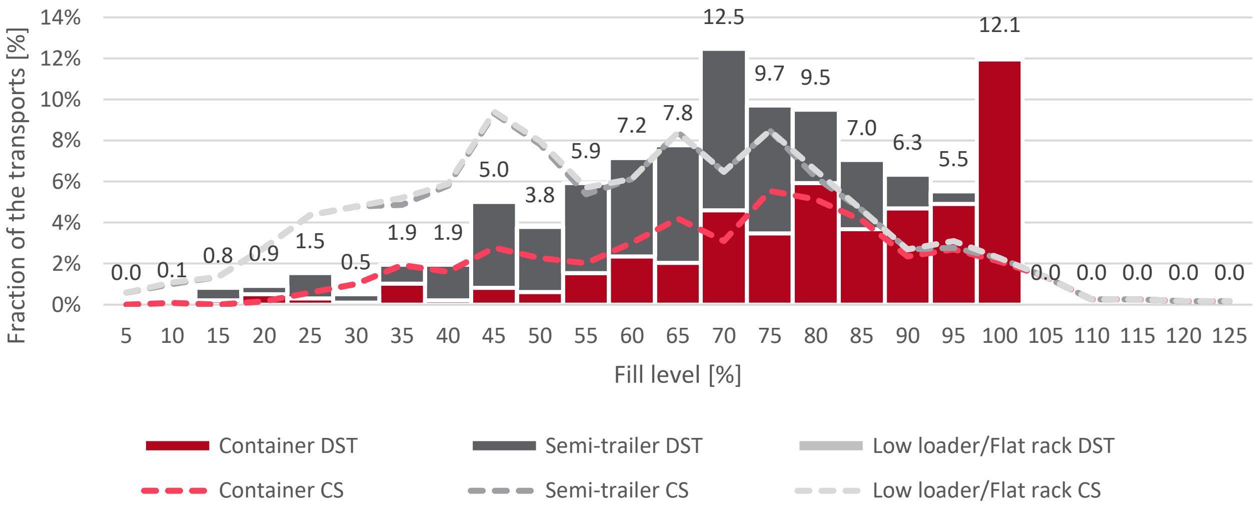

Figure 6.5 Fill rate of all transports of the decision support tool (DST) vs the current situation (CS)

6.2 Adjusting input variables and constraints

In this section, we examine the consequences of adjusting input variables and constraints. We start by investigating the additional costs incurred when disabling the purchasing abroad and making stackable options. Subsequently, we examine the potential cost savings from permitting overloading and merging the phases of a sales order.

6.2.1 Disabling purchasing abroad and making stackable

As described in the previous section, the options to purchase abroad and make stackable are not widely favoured. To explore the financial impact of disabling these options, projects that utilized these options were recalculated with the options disabled. Disabling purchase abroad results in a cost increase of 0.5% (€42,576) and disabling making stackable results in a cost increase of 0.1% (€9,060). Disabling both options incurs an additional cost of 0.6% (€52,942). This is not a sum of disabling either option, as some projects use both options. We can conclude that, while these options are unpopular, their implementation can result in cost savings for projects that require them.

6.2.2 Permitting overloading

As described in Section 2.6, previous cases of overloading transports sometimes led to fines, but most cases had no consequences. In addition, transports are often full based on weight, while there is still room for additional items. We recalculate all projects with an infinite maximum payload restriction. Allowing overloading can result in cost savings of 1.7% (€145,577). Only 40' containers with an extra weight restriction of 14,500 kg are overloaded. Of the projects where savings are possible, 68 containers are overloaded, which varies between 0.4 and 71.9%. We can conclude that overloading transports can save costs, making it interesting to find out whether a permit for overweight or taking the gamble is cost-effective for projects to the USA.

6.2.3 Merging phases

As indicated in Section 2.1.2, because of their considerable size, sales orders are sometimes split into separate phases that are considered as separate projects. As a result, collis cannot be exchanged between phases. To evaluate the potential savings of combining phases within sales orders, we examined 27 sales orders of multiple phases, totalling 58 project numbers. Merging phases can result in cost savings of 0.4% (€36,479). We can conclude that the sales orders are well divided into phases because minimal cost savings can be achieved by merging the phases.

6.3 Evaluate solution quality

In this section, we assess the quality of the DST. We start by evaluating the computational time, followed by a comparison with a less advanced method. Finally, we evaluate the parameters of the DST.

6.3.1 Computational time

A short computation time is essential for the practical usability of the DST. Figure 6.6 shows the number of items versus the total computational time of each project. On average, the total computational time is 10 minutes, which consists of initializing the customer data, determining the cheapest colli and transport composition and determining the best transport layout. Initializing the customer data takes a few seconds, and determining the best transport format takes tens of seconds. Therefore, determining the cheapest colli and transport composition is the most time-consuming. The DST completes within 5 minutes in 39.1% of the projects, between 5 and 10 minutes in 30.3%, and between 10 and 20 minutes in 19.7%. The DST takes longer than 20 minutes in 10.9%, with a maximum of 110 minutes. We think these times are reasonable, as a few projects need to be calculated every week.

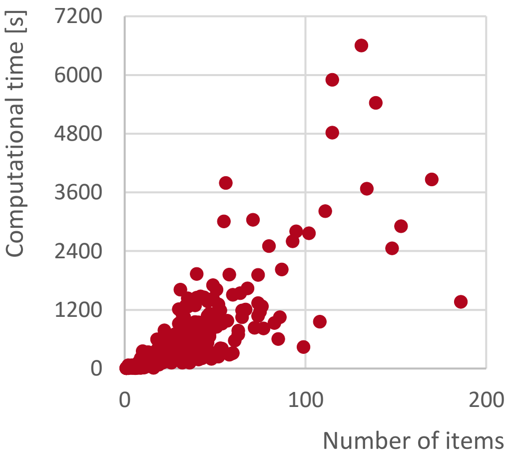

Figure 6.6 Number of items vs computational time

6.3.2 Comparison with less advanced method

The optimization framework proposed in this study is a complex multi-level approach that requires much computational power to determine the solution. To demonstrate the superior performance of this algorithm, we compare it with a less advanced method which employs a single stage. First, we sort the items by prioritizing the machine and location items with the most chargeable weight. The items are then sorted by machine, location and chargeable weight. Second, we pack the items according to the constructive packing heuristic as described in Section 4.6.4. Depending on the requirements, we pack items in either a MEGA trailer or a low loader for truck transport and a 40' hardtop high cube or a flat rack for container transport. All restrictions are considered when packing the items except horizontal load balancing ($C2^H$). We will have infeasible solutions if we reject solutions that do not meet this criterion since we get the same solution in every iteration.

The less advanced method can find a better solution than the DST for two projects (0.5%). In the first project, instead of 5 curtain sides, 1 MEGA and 2 low-loaders, the less advanced method uses 5 MEGAs and 2 low-loaders. The MEGA is slightly more expensive than a curtain side, but apparently, a transport can be saved by taking 5 of them. In the second project, instead of 2 curtain sides and 3 loading meters, 2 MEGAs were used. In the first project, simulated annealing probably did not thoroughly search the colli and transport composition. In the second project, probably no feasible solution could be found for this composition in the 100 iterations. These two projects show that the DST does not always come up with the best solution.

In addition, the less advanced method can find the same solution as the DST for six projects (1.6%) and finds a more expensive solution for the remaining 358 projects (97.8%). The total shipping costs incurred by the less advanced method is €10,557,459, which is 25.8% (€2,163,886) more than the advanced method. It is important to note that the advanced method also provides the flexibility to purchase items abroad and make them stackable, which the less advanced method lacks. When subtracting the additional costs incurred when these options are disabled, the less advanced method is still 25.0% (€2,040,329) more expensive than the DST. Additionally, the less advanced method meets only the horizontal load balancing in 90.3% of all filled transports, whereas the advanced method always ensures that all restrictions are met. However, the less advanced method provides a quick solution, taking only seconds to compute, and the advanced method takes 10 minutes to arrive at a solution.

We further compared the performance of the less advanced method with the current situation. We found that the less advanced method produces a better solution for only 15.3% of projects, produces an equally good solution for 9.8% of projects, and performs worse than the current situation in 74.9% of projects. The total shipping costs of the less advanced method are 5.2% (€524,922) more than the current solution. The less advanced method may find a better solution than the current situation because rough estimates were often made and ordered in the past because the transport costs were meagre.

In conclusion, the less advanced method does not perform as well as the advanced one, and the less advanced method is even worse than the current situation.

6.3.3 Evaluation parameters

The second stage of the algorithm checks if the transport composition is feasible without purchasing items from abroad or making them stackable. If the composition is feasible, the outsourcing and upgrading options are removed. Initially, it is not possible that fewer resources or upgrades are needed than determined in the first stage. However, in the first stage, the randomized constructive heuristic is performed with fewer iterations (100 instead of 500) to check for feasibility than in the second stage to improve the transport layout. The algorithm sometimes chooses to purchase an item from abroad or make an item stackable to achieve a feasible transport composition in the first stage, but this turns out unnecessary in the second stage. Occasionally, better solutions may exist but are not discovered, as evidenced by comparison with the less advanced method.

Using the upgrade or outsourcing option in the first stage and removing it in the second stage does not pose a problem. However, in some cases, a larger transport composition may be selected because a smaller one is not deemed feasible in the current number of iterations of the feasibility check. In the second stage, the transport composition is not adjusted unless an entire transport remains unused.

One possible solution to improve the exact check is to increase the number of iterations to find a feasible solution. However, this would further increase the computational time, which is already long (61 hours for all 366 projects). Alternatively, we could choose not to save the checked solutions, but this would lead to checking the same solution many times, which also increases the computational time. Therefore, allowing a higher computational time can solve this problem, but this is not desirable.

We conducted an experiment to determine how often a more expensive transport composition is chosen because a cheaper one is not feasible during the feasibility check or is not found because simulated annealing did not search thoroughly enough. We increased the number of iterations of the feasibility check from 100 to 200 and reduced the solution space by disabling purchasing abroad and making stackable options. This approach searches more thoroughly for the cheapest transport composition without increasing the computational time (59 hours for all 366 projects).

In 69.4% (254 out of 366) of all projects, this experiment yields the same solution as the original DST solutions. However, in 15.0% (55 out of 366) of the projects, this experiment finds a cheaper solution, which is, on average, €1,496 cheaper than the original DST solutions. This result confirms the hypothesis that a larger transport composition is sometimes chosen in the original DST solutions because a smaller one is not feasible in the iterations of the feasibility check or because simulated annealing did not search thoroughly enough.

On the other hand, in 15.6% (57 out of 366) of the projects, this experiment finds a more expensive solution, which is, on average, €1,525 more expensive than the original DST solutions. In 22 of these projects, the upgrading or outsourcing option is used in the original DST solutions, which explains the more expensive solution. However, in the remaining 35 projects, these options are not utilized. The original DST can probably find these better solutions by making something stackable or purchasing something abroad in the first stage to get a feasible solution for the transport composition. In the second phase, 500 iterations of the randomized constructive heuristic are performed, identifying a feasible solution without using the upgrading or outsourcing option. The upgrading and outsourcing option work as an aid to find the cheapest transport composition, whereby they are not necessary in the end. In this experiment, more iterations of the feasibility check are carried out (200 instead of 100), but this is apparently not enough to compensate for the aid in the original DST. The best transport composition must be found in the first stage because the transport composition is not adjusted in the second stage unless an entire transport remains unused. To achieve this, the number of iterations for the feasibility check must be high enough to identify a feasible solution if one exists. In this study, 200 iterations were insufficient, as we found worse solutions in some cases. However, increasing the number of iterations would exceed the available computational time.

In conclusion, changing the parameters may lead to even better solutions, but that also further increases the computational time. To ensure that the cheapest colli and transport composition that the DST can find is chosen, the number of iterations for the feasibility check must be high enough to always find a feasible solution, if there is one.

6.4 Conclusion

The DST has created a new loading proposal for each project in recent years. The DST can find an equally good or better solution for all exact and approximate projects compared to the current situation. The total shipping costs of all projects of recent years are €10,032,537 in the current situation and €8,393,573 with the DST. Consequently, the implementation of the DST would result in a significant cost reduction of 16.3% (€1,638,964) if the projects were reshipped again using today's prices. To provide a more accurate estimate of the savings, we adjusted the transport and purchasing abroad costs in both situations with a correction factor to account for the variability of transport costs over time. Considering the correction factor, the total shipping costs of the current situation are €6,748,356 and of the DST €5,632,813, resulting in a cost saving of 16.5% (€1,115,543).

The average number of groups is 4.08 in the current situation and 5.65 with the DST, which is an increase of 38.7% (+1.58). This increase is logical because the average number of transports in the current solution is higher than with the DST, so collis from different machines and locations must be mixed less over the different transports to get a feasible solution. As a result, the DST uses fewer transports, so the collis of the same machine and location are more spread over the different transports to get a feasible solution, which results in a higher number of groups.

The DST has lower transport costs than the current situation by better packaging items in the transports. The DST makes it possible to fit items accurately, so more single loading meters (LTL/LCL) are needed instead of entire transports. Assessing the required loading meters is hard in the current situation, which makes ordering complete transports a safe solution. Besides, fewer transports are required because items are purchased abroad and made stackable. For truck transport, the DST has reduced the number of curtain side trailers by 43.4% (-201), increased the number of MEGA trailers by 5.7% (+5) and increased the number of single loading meters by 230% (+92). For container transport, the DST requires 20.9% fewer 40' hardtop high cube containers (-100) and uses 950% more 40' standard high cube containers (+38) and 42.9% more standard containers (+3) instead. The DST also reduces the need for 20' hardtop and standard containers by 47.1% (-8) and 80.9% (-38), respectively, by making 475% more use of single loading meters (+19). The number of low loaders and flat racks remains because saving on this limited number is impossible.

The average fill rate of the DST is 69.3%, while the average filling level of the current situation is 56.4%. For container transport, the fill rate is determined by weight for 85% of all transports and by volume for 15%, whereas for truck transport, it is based on weight for 37% and based on volume for 63%. This difference is because containers transported to the USA have a maximum payload of 14,500 kg, while truck transport can be loaded more than twice as heavy, making weight restrictions less relevant. In 24.2% of all container transports, the filling level of DST is between 95-100% because VSM transports heavy cargo and the low maximum payload for container transport.

The option to purchase abroad is not popular and is only utilized in 17.9% (19 out of 106 projects) where possible. Disabling this option would result in a cost increase of 0.5% (€42,576). Similarly, the option to make items stackable is also infrequently used: only 2.2% (8 out of 366 projects) use it. Disabling this option would result in a cost increase of 0.1% (€9,060). Disabling both options would result in a cost increase of 0.6% (€52,942). When we allow overloading, we can save 1.7% (€145,577), making it interesting to find out whether a permit for overweight or taking the gamble is cost-effective for projects to the USA. Combining phases may result in a minor cost savings of 0.4% (€36,479), so we can conclude that the sales orders are well divided into phases.

The optimization framework proposed in this study is a complex multi-level approach that takes an average of 10 minutes per project to compute. In addition to this advanced method, we have devised a less advanced method, which packs all items until everything is packed. The less advanced method produces, in comparison to the DST, a better solution in 0.5% (2 out of 366 projects), the same solution in 1.6% (6 out of 366 projects) and a more expensive solution in the remaining 97.8% (358 out of 366 projects). The total shipping cost of the less advanced method is €10,557,459, which is 25.8% (€2,163,886) more than the advanced method and 5.2% (€524,922) more than the current solution.

In the second stage, the algorithm checks if the transport is possible without purchasing items from abroad or making them stackable. If so, the outsourcing and upgrading options are removed. While the algorithm in the first stage chooses to purchase an item from abroad or make an item stackable, it may turn out to be unnecessary in the second stage. However, in some cases, a larger transport composition may be selected because a smaller one is not feasible in the number of iterations of the feasibility check. Changing the parameters may lead to even better solutions, but that also further increases the computational time. Figure 6.7 shows a cost overview of all experiments.

Figure 6.7 Overview of the total shipping costs of all projects per experiment

7 Implementation plan

This chapter advises how the decision support tool can be implemented at VSM by answering the sixth research question: *"How can the decision support tool be implemented in practice?"*. We present a road map to get the full potential out of the decision support tool (DST). Figure 7.1 shows the step-by-step plan, consisting of (1) a reconsideration of the choices, (2) improving the data, (3) simplifying the use, and (4) extending the functionality. The steps are further explained in the sections below, after which we present the stakeholders and their responsibilities.

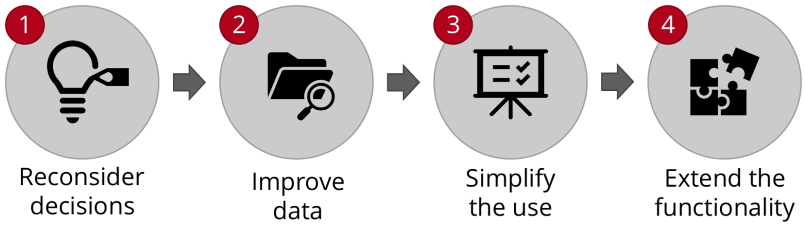

Figure 7.1 Road map

Step 1. Reconsider decisions

As discussed in the preceding chapter, the purchasing abroad and making stackable options are not commonly used. Therefore, it is crucial to initiate a meeting with the purchase manager, group leader works office, team leader logistics, and the DST owner to present the results and identify the options of the DST. When evaluating the options, it is essential to consider their consequences. If the purchasing abroad option will be used, the purchasing employee must ensure that the component is delivered directly to the site instead of VSM, and this should also be discussed with the suppliers. If the stackable option is chosen, someone needs to order the wooden boxes, and the logistic employees must know which box corresponds to which project and which colli should be placed in each box. If adjustments are necessary, the DST owner must modify this and recalibrate the parameters accordingly.

Step 2. Improve data

VSM uses a load list generator to determine which collis should be sent based on the project DNA. However, the database used by the load list generator is afflicted by incomplete and polluted data, which requires review and supplementation by the logistics work preparator for machines not yet covered by the study. Additionally, some collis do not conform to standard dimensions and weight, making what they entail uncertain. This uncertainty must be removed to enable the generation of a loading proposal early.

The new colli properties must also be exported by the load list generator. The load list generator's output format differs from the input format of the DST, requiring adjustments to either of them. The load list generator adjustments require the Configure to Order (CTO) engineer, while the DST adjustments necessitate the DST owner.

The logistics work preparator must have much contact with the logistics employees. The logistics employees have worked similarly for years, making them critical about using a tool. The logistics employees must indicate when impossible packing solutions have been generated so that the data can be modified or the DST itself. By showing that the logistics employees feel heard, they will provide more input, so we ultimately have a tool that works in practice.

Moreover, the transportation process occurs outside the Enterprise Resource Planning (ERP) system. The collis are a non-existent phase between the assembled modules in the factory and the fully assembled machine line at the customer site. Thus, it is unknown which module, and material numbers are associated with each colli, making it challenging to identify the contents of a lost or damaged shipment.

To address this issue, the ERP system has a transport management functionality that supports all activities related to the physical transportation of goods (SAP, 2023). This functionality enables the generation of a transport bill of materials, guaranteeing the traceability of each part. Moreover, it allows for easy export of sent collis, unlike the method used in this thesis of merging loading lists using VBA, which required a manual check due to inconsistent filling of lists. However, using this functionality requires an additional revision of the bill of material when changing a machine.

Step 3. Simplify the use

After the first two steps have been completed, the DST can be used by the logistics work preparator. The DST is programmed in Python, which is also free for commercial use (Python, 2023). The input data of the DST must be placed in a specific file location. By pressing run, all projects are processed, and the output is written to a different file location. This way of working is acceptable in the first phase, but it would be nice if the DST owner could create a user interface for this in the long term. The logistics work preparator can load projects in the input screen and see the results. The user interface makes the DST easier to use, which increases efficiency.

Step 4. Extend the functionality

After the DST has been implemented at the company and is working correctly, extending the functionality further is possible. For example, it is possible to generate loading lists, folder labels and CMRs automatically, so this does not have to be done with another tool. In addition, the valuation of transports, which is necessary for insurance purposes, is now done manually. This functionality can also be added.

Stakeholders and responsibilities

The implementation of the DST involves the participation of various stakeholders. The logistics work preparator is accountable for the correct input data and liaises between the logistics employees and the DST owner. The logistics work preparator also monitors the feasibility of solutions generated by the DST. The logistics employees use the loading proposals, report unfeasible solutions to the logistics work preparator and suggest other points for improvement. The logistics coordinators utilize the output of the DST to order the required number of each transport type. The team leader logistics is responsible for the logistics employees and contributes to the tool's choices. The purchasing manager and purchasing employee are also involved. The purchasing manager contributes to the choices the tool has to make, and the purchasing employee may have to ensure that the parts are purchased directly on-site instead of from VSM. The group leader works office supervises the logistics work preparator and transport coordinators, contributes to the tool's choices, and ensures smooth implementation. Finally, a CTO engineer and the DST owner are involved, with the coordinator CTO modifying the load list generator and the DST owner adjusting the DST as needed.

We use the RASCI model to indicate the roles and responsibilities of the various stakeholders. RASCI is an acronym derived from the five key criteria most typically used: Responsible (R), Accountable (A), Supporting (S), Consulted (C) and Informed (I) (Eltis, 2022). Table 7.1 shows the RASCI matrix, where the responsibilities of those involved are summarized for each step described in previous sections, with the steps described as rows.

Table 7.1 RASCI matrix

	Logistics work preparator	Logistics employees	Logistics coordinators	Logistics team leader	Purchase manager	Purchase employee	Group leader works office	CTO engineer	DST owner
S1	I	I	I	C	C	I	A		R
S2	R	C	I	I	I		A	S	R
S3	C		I	I			A		R
S4	I		C	I			A		R

8 Conclusion

This chapter aims to conclude this thesis by answering the main research question: *"How can the way of creating a loading proposal be improved to remove the uncertainty whether the ordered transport composition is feasible and to ensure that all the collis arrive on time for the lowest cost?"*. The chapter starts by answering the main question in Section 8.1. Section 8.2 discusses this study's limitations, and Section 8.3 provides suggestions for future research areas.

8.1 Conclusion and recommendations

We have developed a decision support tool (DST) to create a loading proposal automatically. The solution covers which collis to make stackable and which collis to purchase abroad (colli composition), the required number of each transport type (transport composition) and how to position the collis in the transports (transport layout). The DST consists of a two-stage heuristic to solve the three-dimensional bin packing problem with item upgrading and outsourcing options. It is a combinatorial optimization to get the cheapest colli and transport composition with the best transport layout. The combinatorial optimisation decides what to purchase abroad, what to make stackable, and the number of each transport type while ensuring feasibility for the colli composition. Once the colli and transport composition have been chosen, we strive to create the best transport layout. We do this by maximizing the number of collis from the same machine and location in the transport. The objective is ensured by minimizing the number of groups of machines and locations in the different transports. A group consists of at least one colli of a machine and location in a transport. We consider various restrictions such as weight limit, weight distribution, orientation, stacking, stability and loading.

The model is divided into two stages: the first stage determines the colli and transport composition using simulated annealing (SA) to escape local optima, and the second stage determines the transport layout using a randomized constructive heuristic. The two stages are intertwined because the first stage uses the heuristics of the second stage to check for feasibility. If it turns out in the second stage that purchasing abroad, making it stackable, or some transports are unnecessary, then these will be removed.

The DST has created a new loading proposal for each project in recent years. The DST can find an equally good or better solution for all projects compared to the current situation. The total shipping costs of all projects of recent years are €10,032,537 in the current situation and €8,393,573 with the DST. Consequently, the implementation of the DST would result in a significant cost reduction of 16.3% (€1,638,964) if the projects were reshipped again using today's prices. To provide a more accurate estimate of the savings, we adjusted the transport and purchasing abroad costs in both situations with a correction factor to account for the variability of transport costs over time. Considering the correction factor, the total shipping costs of the current situation are €6,748,356 and of the DST €5,632,813, resulting in a cost saving of 16.5% (€1,115,543).

The average number of groups is 4.08 in the current situation and 5.65 with the DST, which is an increase of 38.7% (+1.58). This increase is logical because the number of transports in the current solution is higher than with the DST, so collis from different machines and locations must be mixed less over the different transports to get a feasible solution. As a result, the DST uses fewer transports, so the collis of the same machine and location are more spread over the different transports to get a feasible solution, which results in a higher number of groups.

The option to purchase abroad is not popular and is only utilized in 17.9% (19 out of 106 projects) where possible. Disabling this option would result in a cost increase of 0.5% (€42,576). Similarly, the option to make items stackable is also infrequently used: only 2.2% (8 out of 366 projects) use it. Disabling this option would result in a cost increase of 0.1% (€9,060). Disabling both options would result in a cost increase of 0.6% (€52,942).

The purchase abroad option owes its unpopularity to the large size of the purchase abroad items. Due to the items' size, purchasing them abroad is relatively expensive. It is, therefore, only cheaper to use this option if the part to be purchased abroad no longer precisely fits in the 40' containers. This option can be valuable if smaller items can be purchased abroad. If the items are immense, for example, if the part already uses half a container, then with the current prices for purchasing abroad, it is often cheaper to transport it from VSM than to purchase it abroad.

The making stackable option owes its unpopularity to the fact that many items are already stackable, namely 34.3%. In addition, for truck transport, there is no intermediate size between 8 loading meters and a full trailer of 13.62 meters and for container transport, between 20' and 40' containers. For example, suppose it fits in 10 loading meters by making something stackable. In that case, this is less cost-effective than using a full trailer and not making anything stackable because 10 loading meters is not an option. Therefore, it is only used if it saves on the total costs. However, we think this option can be valuable if fewer items are stackable and there are more intermediate sizes for the transports.

The second stage of the algorithm checks if the transport composition is feasible without purchasing items from abroad or making them stackable. If the composition is feasible, the outsourcing and upgrading options are removed. While the algorithm in the first stage chooses to purchase an item from abroad or make an item stackable, it may turn out to be unnecessary in the second stage. However, in some cases, a larger transport composition may be selected because a smaller one is not feasible in the number of iterations of the feasibility check. Changing the parameters may lead to even better solutions, but that also further increases the computational time.

Given the little use of the purchasing abroad and making stackable option, we recommend reconsidering whether the DST should decide to purchase items abroad and make them stackable. Besides, we recommend considering applying for an overweight permit for projects to the USA or weighing up the risk of overloading because this can save costs in some cases.

In order to use the DST, it must be connected to the other software systems used by VSM. The input data of the DST is afflicted and suffers from incomplete and polluted data. Therefore, we recommend assessing and supplementing all data by the logistics work preparator for machines not covered in this study. In addition, some collis do not conform to standard dimensions and weights, making what they entail uncertain. Therefore, we recommend eliminating this uncertainty to generate a loading proposal early.

The transportation process occurs outside the Enterprise Resource Planning (ERP) system. The collis are a non-existent phase between the assembled modules in the factory and the fully assembled machine line at the customer. Thus, it is unknown which module, and material numbers are associated with each colli, making it challenging to identify the contents of a lost or damaged shipment. We recommend using the transportation management functionality in the ERP system, which supports all activities related to physical goods. With this functionality, a transport bill of materials can be generated, ensuring the traceability of each part. Finally, we recommend professionalizing the DST through a user interface, making it easier to use, which increases efficiency.

8.2 Discussion

Although the DST shows promising performances, this research still contains some limitations, which we discuss in this section.

First, not all manual pre-processing sets are known. The pre-processing sets indicate which regular and irregular collis together form a larger regular colli. The irregular collis are considered as regular, causing empty space to be lost. As a result, the savings could have been even more significant. The difference in savings between the accurate and approximate data sets underlines this hypothesis; in the accurate dataset, there is a saving of 18.2%, while in the approximate dataset, this is 15.3%.

Second, not all manual pre-processing sets may be optimal for every situation. The manual pre-processing sets are built up per machine and are optimal for transporting that machine. However, there may be better manual pre-processing sets for a combination of machines. Nevertheless, it is not preferable to create pre-processing sets from different machines. This method would result in combining collis from various machines in the same transportation beforehand, which should be avoided as much as possible.

Third, we have not considered a restriction that allows collis to be fixed with ratchet straps to the hooks of the transport. There are currently no standardizations for this; the logistics employees solve it as it suits them best at the time. We have considered this limitation by adjusting the dimensions of the collis and the manual pre-processing. However, solutions that cannot be fixed may have been generated.

Fourth, not all input data, such as the dimensions and weight of the collis, may be correct. This inaccuracy may have created solutions that are in reality infeasible or not the cheapest.

Finally, we have assumed that all collis of a project, except for backorders, may be included in each transport of the project. In reality, it may be possible that certain machines were deliberately packed together in a transport, for example, because they were shipped earlier or later. By splitting up the machines, more transports may be required than if all collis are allowed to be clustered.

8.3 Further research

In this section, we propose further research in several areas based on the findings and remarks gained in this research.

First, the algorithm packs transport by transport with a single container loading (SCL) algorithm. Filtering, pre-processing, sorting and perturbation and packing are completed for each transport. Any items that are not packed will be packed in one of the following transports. Another method is to pack the transports at the same time, whereby the algorithm determines for each item the best place in the best transport in the packing phase. The costs will probably not decrease, but the number of collis of the same machine and location in a transport will probably increase, or in other words, the number of groups will decrease. As an illustration, assume that there are two ideal transports, where the collis produced by machines A and B both fill a transport for 95%. When the transports are packed, all collis from machine A will be accommodated in the first transport. Afterwards, the algorithm will attempt to fit the collis from machine B into the remaining 5% of the first transport, while all collis of machine B fit entirely into the second transport. Therefore, it would be interesting to investigate a packing algorithm in which the items are packed over multiple transports.

Secondly, we have considered the restriction that allows the collis to be fixed with ratchet straps by adjusting the collis' dimensions and manual pre-processing. We have not found any literature on determining whether something can still be fixed, which is also logical because this has not (yet) been standardized and is quite specific. Therefore, it would be interesting to investigate how we can determine how the collis can be fixed automatically.

Third, we have now assumed that items, or multiple items together, are always rectangular. We have found literature about irregular nesting, but this is very complex. We think this level of detail is also irrelevant to the items that VSM transports. However, we have not found any literature on partial irregular nesting, where a shape is built up from several regular shapes. To keep this practically workable, we could, for example, choose several shapes, such as an L-shape. For each colli, we choose the shape and enter the desired sizes. In this way, we do not have to load step files, but it is possible to indicate more complexity than just a rectangle. Besides, we assume that a colli is always fully stackable or not. Often not the entire top surface is stackable, but only a part. By applying partial irregular nesting, it would be possible to indicate whether the part is stackable for each part of the shape. Therefore, it would be interesting to investigate partial irregular nesting, where it can be indicated per part of the colli, whether it is stackable or not.

Fourth, each item has a stacking characteristic of true (resp. false), which indicates that the item can (resp. cannot) support the weight of other items on top of it. In other words, fragile items get the value false and non-fragile items get the value true. We assume that stackable items have no maximal payload restriction. This method is appropriate for the VSM as steel items are generally stackable and can handle substantial weight, while other items cannot support any weight. Additionally, the colli composition usually consists of a limited number of lightweight boxes that can be stacked on top of all items. However, in other applications, an item may have a specific weight capacity, and a strict requirement may not give the best packaging solution (infeasible if the characteristic is true and too broad if the characteristic is false). Therefore, it would be interesting to investigate how stackability could be expressed in terms of weight limits rather than as a strict requirement.

Fifth, we are now optimizing on two levels: first, we try to minimize costs, and then we try to get as many collis as possible from the same machine and location in the same transport at these costs. A third level could be added, whereby the level tries to make the best possible layout for a single transport, given the items that must be packed in that transport. Therefore, it would be interesting to investigate how the quality of a layout within a transport can be measured.

Sixth, collis are always placed tightly next to each other, and the contact area is used to measure stability. In the current situation, sometimes several stackable items are placed next to each other with a space in between, with an item on top that is stacked on top of all items. The algorithm cannot create this packing solution, which can only be enforced through manual pre-processing. Therefore, it would be interesting to investigate how the algorithm can also create these packing solutions.

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Appendix

Appendix A Problem cluster

Figure 0.1 shows the problem cluster, where we work from the action problem to the core problems and the consequences.

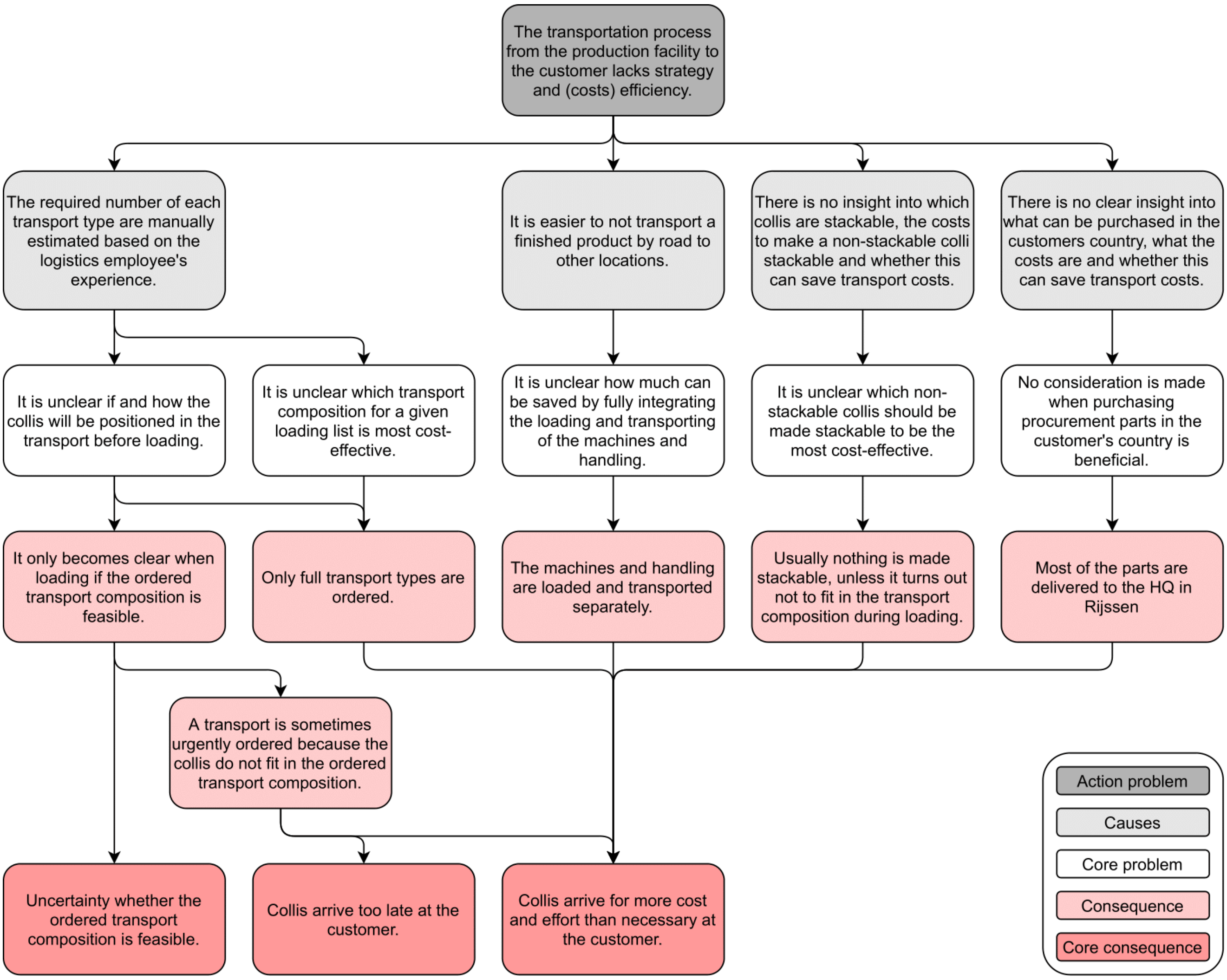

Figure 0.1 Problem cluster showing related causes, core problems and consequences of the current transportation process

Appendix B Functionalities content generator

Figure 0.2 shows an overview of the different functionalities of the content generator.

Figure 0.2 Overview of the different functionalities of the content generator (Visual Components, 2022), (Free Logo Vectors, 2022), (Voortman Steel Machinery, 2022), (Voortman Steel Machinery, 2022), (SMC, 2022)

Appendix C Sketch loading proposal

Figure 0.3 shows the sketch of the loading proposal for a curtain side trailer.

Figure 0.3 Loading proposal of a curtain side trailer

Appendix D Transport documents

After the distribution of the collis over the transports is known, the transport documents are generated. The load list generator generates the packing list, CMR and folder labels to stick on the collis. These are required for every transport. An invoice and export document is required for customers outside the European Union. The EFTA countries, four European states with a regional trade organisation and free trade zone consisting of Iceland, Liechtenstein, Norway, and Switzerland also need a EUR.1 document. With EUR.1, these countries receive a reduction or exemption from import duties, provided that the delivered goods are of preferential origin (van Hagen, 2022). Customs must physically sign the EUR.1 document by going to the customs post, which makes it very annoying if the colli distribution changes at the last minute. Finally, the customer can request a certificate of origin, which is not created by default. No insurance is taken out per project because there is continuous transport insurance. Table 0.1 shows the transport documents needed per country.

Table 0.1 Transport documents

Document	Country
Packing list	All
CMR	All
Folder labels	All
Invoice	Outside EU
Export document	Outside EU
EUR.1 document	EFTA
Certificate of origin	(All)

Appendix E Calculate the extra time due to deviating from the loading proposal

Table 0.2 shows the extra time it takes per action to deviate from the loading proposal, and Table 0.3 shows the sum of the extra time per country.

Table 0.2 Determining the extra time due to deviating from the loading proposal per action

Document	Activity	Time [hours]	Responsible	Country
Loading list generator	Adjust what is positioned in which container in the load list generator and report that changes have been made.	1/12	Logistic Employee	Each country
Packing list, CMR, Folder label	Regenerate and print packing lists, CMRs and folder labels for collis.	1/2	Transport Coordinator	Each country
Folder labels for collis	Stick labels on the collis.	1/6	Logistic Employee	Each country
Invoice	Adjust invoices.	1/2	Administration	Countries outside EU
Export document	Cancel and re-apply export documents.	1/4	Transport Coordinator	Countries outside EU
EUR.1 document	Withdraw and request the EUR.1 documents.	1/2	Transport Coordinator	EFTA countries
EUR.1 document	To the customs to sign the EUR.1 documents.	2	General Employee	EFTA countries
Certificate of origin	Cancel and re-apply the certificate of origin.	1/4	Transport Coordinator	(Each country)

Table 0.3 Extra time due to deviating from the loading proposal per country

Country	Extra time [hours]
Inside EU	3/4
EFTA	4
Other outside EU	1 ½

Appendix F Transport documents reprinted

The transport coordinators print the transport documents a few days before loading. Suppose the transport documents are printed on the day of transport. In that case, it is plausible that the logistics employees loaded the collis differently than the loading proposal, meaning the documents must be reprinted. Only the last print date of an Excel document is saved. A document can contain several transports with several loading dates, so we cannot conclude every transport. There are three scenarios:

1. **Last print date is earlier than loading date**: nothing has likely changed on the transports on this loading date.
2. **Last print date equals loading date**: it is plausible that the logistics employees loaded the collis differently than the loading proposal.
3. **Last print date is later than loading date**: we cannot conclude something about these transports because we do not know whether the print date is overwritten.

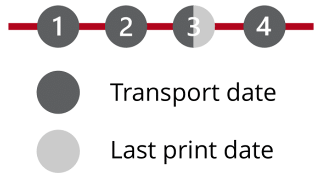

Figure 0.4 Example of transport and print date

Figure 0.4 shows the three scenarios, and Figure 0.5 shows the distribution of the three scenarios. Transport dates 1 and 2 are an example of scenario 3: the last print date is later than the transport date, so we cannot conclude something about these transports. In reality, this is 33.6% of the transports. Transport date 3 is an example of scenario 2: the print date is equal to the transport date, so it is plausible that the logistics employees loaded the collis differently than the loading proposal. In reality, this is 29.9% of the transports. Transport date 4 is an example of scenario 1: the print date is earlier than the loading date, so we cannot conclude something about these transports because we do not know whether the print date is overwritten. In reality, this is 36.4% of the transports. Of the transports about which the print date is not overwritten, loading documents were (re)printed on 45.1% on the day of transport.

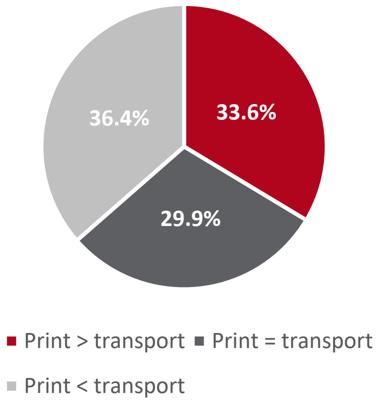

Figure 0.5 Transport vs print dates

Appendix G Timeline of the current and future situation

Figure 0.6 shows the timeline of the current and future situation.

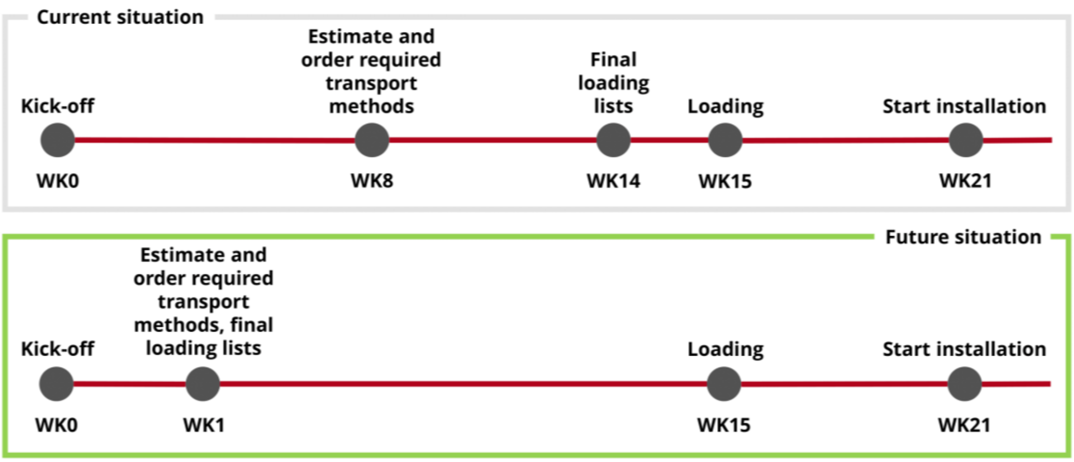

Figure 0.6 Current vs future situation

Appendix H Collis sent later

There are several reasons that something is sent later to the customer. The varied reasons are:

- **Backorder**: the collis are not delivered on time, or the colli is not finished on time.
- **Forgotten**: the colli has been forgotten to send.
- **Send the wrong**: the wrong collis has been sent.
- **Sold the wrong**: the DNA does not match the customer order, resulting in the wrong collis on the loading list.
- **Transport damage**: the collis are damaged during transport.
- **Unknown**: the reason the colli is transported later is unknown.
- **Warranty**: the parts do not work correctly and must therefore be replaced.

In <confidential>% of the projects, one or more collis were sent later. This value is obtained by adding the extra loading list, which is created for each back order, to the load list database. This document should be saved in the project folder, but there is a chance that it will not be saved correctly. Therefore, this percentage may be higher than calculated. Figure 0.7 shows the distribution of the varied reasons.

Figure 0.7 Distribution of the varied reasons why collis are sent later

Appendix I Distribution of the number of transports and total shipping costs

Figure 0.8 shows per country/state the fraction of the number of transports and the costs of these transports if they were shipped using today's prices. The larger the dot, the greater the share concerning the total number of transports and the total shipping costs.

Figure 0.8 Number of transports and the transport costs per country/state of the current situation

Appendix J Parameter calibration

For the calibration of the simulated annealing parameters we use the test instance described in Table 5.2 (Section 5.3). Figure 0.9 and Figure 0.10, respectively, show the temperature vs the acceptance ratio and temperature vs costs at a starting temperature 35 times higher than the highest purchase abroad, making items stackable and transport costs. The acceptance ratio equals 1 at the start of the algorithm and approaches 0 at the end. The cost also decreases as the temperature decreases. So we found neighbour solutions that are better than the best solution.

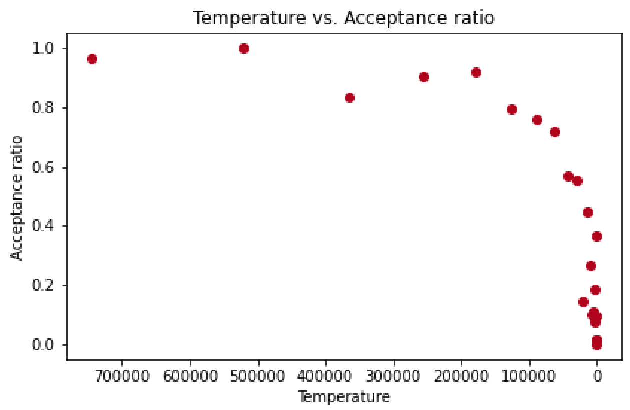

Figure 0.9 Temperature vs acceptance ratio

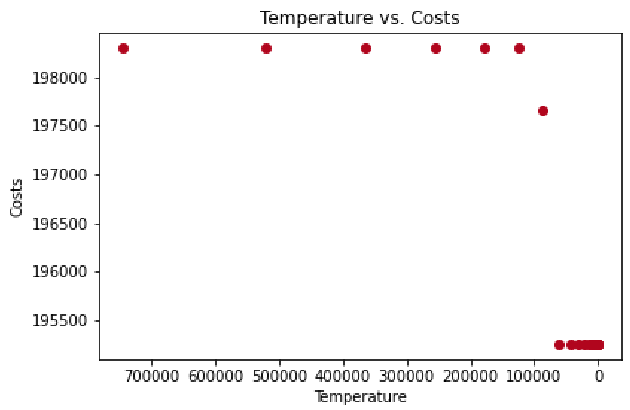

Figure 0.10 Temperature vs costs

After much experimentation, we concluded that a start temperature of 35, a stop criteria of a maximum number of iterations of 50, a stop if no change has occurred for 30 consecutive iterations, a Markov Chain (MC) length of 80 and a decrease factor or 0.6 gives the best results in a reasonable time.