Optimisation of BMW Group Standardised Load Units via the Pallet Loading Problem

Anja Heinze
Titel
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Sammanfattning
Abstract

The BMW Group uses load units for the transportation of assembly parts from the suppliers to the plants and for the internal material flow. This thesis analyses the advantageousness of introducing a load unit with a new size. There are three reasons why the current choice of containers is not sufficient. Firstly, there is a certain range of assembly parts that does not fit very well into the existing standard load units. Secondly, the average measurements of the parts have grown in the last years and thirdly, several of the existing containers leave unused space in the transportation vehicles. For this the relevant costs and other, more qualitative aspects like the placing at the assembly line are considered. A container size is identified that offers a significant savings potential. For this potential the handling and transportation costs are identified as the relevant leverages. These costs are found to depend mainly on the utilisation degree of the load units.

To calculate the different utilisation degrees, a packing-algorithm in form of a four-block heuristic is applied and its results are extrapolated on the basis of existing BMW packing information. Thus, several assembly parts are identified that fit better into the suggested load unit than in the existing ones. These results are assessed using BMW’s expense ratios for handling and transportation. 80 parts are determined for which the migration to the new size would result in savings of more than 5,000 EUR for each per year in Dingolfing. Together, these parts offer a savings potential of about 0.9 million Euro.

Nyckelord
Keyword
Logistics, Packing Problem, Load Unit, Container, Material Flow Analysis, Cost Analysis
Preface

This study has been conducted at BMW in Dingolfing, Germany in order to complete my Master of Manufacturing Management at the University of Linköping in Sweden as well as my Diploma of Wirtschaftsingenieurwesen at the University of Karlsruhe (TH) in Germany.
Abstract

The BMW Group uses load units for the transportation of assembly parts from the suppliers to the plants and for the internal material flow. This thesis analyses the advantageousness of introducing a load unit with a new size. There are three reasons why the current choice of containers is not sufficient. Firstly, there is a certain range of assembly parts that does not fit very well into the existing standard load units. Secondly, the average measurements of the parts have grown in the last years and thirdly, several of the existing containers leave unused space in the transportation vehicles.

For this the relevant costs and other, more qualitative aspects like the placing at the assembly line are considered. A container size is identified that offers a significant savings potential. For this potential the handling and transportation costs are identified as the relevant leverages. These costs are found to depend mainly on the utilisation degree of the load units.

To calculate the different utilisation degrees, a packing-algorithm in form of a four-block heuristic is applied and its results are extrapolated on the basis of existing BMW packing information. Thus, several assembly parts are identified that fit better into the suggested load unit than in the existing ones. These results are assessed using BMW’s expense ratios for handling and transportation. 80 parts are determined for which the migration to the new size would result in savings of more than 5,000 EUR for each per year in Dingolfing. Together, these parts offer a savings potential of about 0.9 million Euro.
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1 Introduction

The first chapter gives an overview over the topic of this thesis. It informs the reader about the background and the purpose. Furthermore, the problem is split up into sub-problems and references are given how they should be approached.

1.1 Background

In this part, the context that leads to the problem is presented. This is necessary in order to understand the purpose.

The BMW Group uses load units for the transportation of assembly parts from the suppliers to the plants and for the internal material flow. For this several standardised load units in different sizes are in use. Due to three reasons, BMW\textsuperscript{1} thinks about implementing an additional, larger standardised container\textsuperscript{2}:

Firstly, there is a certain range of assembly parts that does not fit very well into the existing standard load units. Secondly, the average measurements of the parts have grown in the last years and thirdly, several of the existing containers leave significant unused space in the transportation vehicles.

The standardised containers have influence on several types of the costs for the inbound logistics. The main influence of these containers lies on the transportation and handling costs of the assembly parts because they are strongly affected by the design of the containers. These costs are affected through the containers’ measurements as they determine how many parts they can carry and how many load units fit into a transportation vehicle. Other relevant expenses are the costs for purchasing, maintaining and disposing of the load units. These costs depend mostly on the load units’ material as this determines the costs for the raw materials, the effort in manufacturing, their durability and the rules for disposal.

The BMW Group as an international company purchases parts from many suppliers from all over the world. For the German plants the suppliers are mostly from Europe. Within the scope of the globalisation the range of suppliers has become significantly larger and in the search of the cheapest purchase price the suppliers from Eastern and Southern Europe are getting more and more attractive. Besides important aspects like quality and service level, both the purchasing price and the transportation costs are relevant when choosing a

\textsuperscript{1} In the following, the terms BMW group and BMW are used as synonyms.

\textsuperscript{2} In this thesis the terms load unit and container are used equivalently even though there might be technical differences between these terms.
supplier. Although the transportation costs for sourcing from Eastern Europe are higher due to the greater distance the low purchasing prices often compensate this negative effect and therefore in total lower costs follow. From this it follows that BMW has significant transportation costs although the transportation of parts on its own does not add value for the company. This constellation of high transportation costs and low prices leads to a strong potential for cost savings through increased transportation efficiency. One lever to increase this efficiency is a space saving packing of the assembly parts into the load units.

All containers are reused which means that their transportation takes place in both directions. Due to this, an important aspect of the transportation process is the fact that most of the currently used standardised load units cannot be folded nor staked together. This means that empty units need the same space in a vehicle as full ones. Therefore, the number of trips delivering parts to the plants is the same as the number of trips returning the empties to the suppliers. The transportation of parts to the BMW plants and back takes place mainly by truck and in few cases by train. This strong focus on one type of transportation allows big potential for cost savings as the load units can be tailored well to satisfy the requirements of truck-transportation. Nevertheless, currently there are some load units with a measurement that does not fit very well into most trucks and consequently leaves unused space.

In all three relevant production sites the plants have been enlarged over the years and changes in the production equipment have been made. Therefore complex intraplant logistics have developed over time. In Dingolfing, for example, the production is allocated in two manufacturing halls and the production takes place on four levels in both halls. Many different means of transportation are in use. The most important one is the automatic integration system (AMA), which is a conveyor technique that automatically delivers the load units from the automatic high rack to the assembly line. A downside of this system is the fact that it is only capable for the delivery of load units with one special size, even though this is the most frequently used measurement at BMW. The second most important means of transportation are the tractors, which are little transporters pulling several trailers for the delivery of load units to the assembly area. Additionally, elevators are required to transport load units to the upper levels. At the receipt of goods in the warehouses and the assembly area there are forklifts in use for storing and removing from storage. Through the example of Dingolfing it should become obvious that there are many handling processes within the plants. The handling processes in Regensburg and Munich are similarly complex and therefore cost intensive. Thus, in all three
plants the handling causes high costs which – like transportation costs – do not add value. As there is no difference in time and effort for handling large or small containers, a larger load unit (with many parts) creates the same handling costs as a smaller load unit (with fewer parts).

As there is a variety of requirements concerning the load units due to the part’s needs, there are more than 500 different load units of which a small number are characterised as standardised load units. These load units can be used for different parts and are – unlike the specialised load units – not specifically tailored for one part. At the moment the BMW Group uses 20 different standardised load units with different construction types for internal and external suppliers. The company divides the standardised load units into small and large containers. The group of large containers consist of two different sizes, where the smaller one of them covers around seventy per cent of all large standardised load units. The gap between the two sizes of BMW is quite large as the ground space of the smaller container is only half as big as that of the larger one. Therefore there are parts, which are too big for the smaller container and too small for the larger one. Many other automobile manufacturers use standardised load units with a square measure between these two measurements of BMW.

BMW presumes that the parts for car assembling have been growing during the last years. This development can be traced back to the fact that the cars have been growing too over the last year because of safety and luxury requirements. Another reason can be the fact that more and more parts are delivered as already assembled modules. Through this it could be that the number of parts that do not really fit into the main load unit is increasing.

For storing these load units there are two different storages at BMW in Dingolfing, Regensburg and Munich. One is an automatic high rack and the other one is a conventional block storage. The way of storing the containers depends on their size. The automatic high rack is aligned for the main container, while the conventional block storage is capable to store every size, i.e. the rest of the large load units and excessive units of the main size. The costs for delivering parts from an automatic high rack to the assembly line are lower than those of the conventional block storage because almost no manual handling is needed. Currently, the capacity of the automatic high rack in Dingolfing is at its limit while the conventional block storage has excessive capacity.
The above background shows that there seems to be potential for cost savings with respect to the standardised load units. Concluding, the purpose stated in the following subchapter can be derived.

1.2 Purpose

The purpose of this thesis is as follows.

“Evaluate to which amount costs can be saved by introducing a new standardised load unit and which size would be recommendable.”

1.3 Delimitations

This chapter presents the delimitation BMW made concerning this thesis.

- BMW limited the scope of this thesis to only the automobile producing plants in Dingolfing, Munich and Regensburg because this selection covers all German plants for which the cost structures are available. Due to internal confidentiality reasons, the production site in Leipzig was not to be included. Furthermore, all plants that produce assembly parts and modules are also not to be included. The restriction to only German locations was made to keep the effort on a level that is manageable in six months.

- Concerning the costs which should be included, BMW recommended a focus on the regular costs. These include especially the transportation and handling. The purchasing costs for the new load unit should not be considered as they are strongly depended on the material and this material has not yet been chosen. To support this choice BMW requests an analysis of the advantages and disadvantages of different materials and their prices.

- Only the base measurement (length and width) of the load unit shall be part of the investigation. The height shall explicitly not be considered, because otherwise there would be too many different options for the analysis.

- The advantageousness of a new container shall be compared to only a certain selection of existing load units, which are given by BMW.

- The expense ratios for transportation, handling, and any other sort are not allowed to be published

All these issues need to be considered in the analyses of this thesis.
1.4 BMW History

This section gives a brief overview over the history of BMW.

In 1916 the Bayrische Flugzeug-Werke (BFW) is founded and in the same year the company incorporates Otto-Werke. One year later the Bayrische Motorenwerke (BMW) GmbH is founded and the production of the motor IIa for airplanes starts. Until 1918 the company builds engines for army planes. In 1922 BMW acquires the BFW plant and dates its origins back to the foundation of BFW. The war strongly drives the company’s growths. In purpose of expansion the firm builds a plant right next to the Oberwiesenfeld airfield in Munich. In 1923 BMW initiates the production of the motorcycle R32. By purchasing the automotive plant Eisenach BMW enters into the car industry.

After World War II BMW commences to built up again after destruction and disassembling. In 1948 the first post-war BMW motorcycle R24 is raffled to the employees. It is the first standard-production model and sells spectacularly in Germany after the war. Already in 1950 around 18 per cent of all BMW machines are exported abroad. Saved by a small car of Italian design, the BMW 700, BMW stays independent after a big crisis and nearly being bought. In the 70th the exterior of the BMW head office is finished in a time of continuing growth. In 1990 the Research and Innovation Centre (FIZ), which consists of design, construction and test facilities as well as a prototype construction unit and pilot plant, is officially opened.

With the brands BMW, MINI and Rolls-Royce Motor Cars, the BMW Group has been focusing on selected premium segments in the international automobile market since 2000. Today the BMW Group is present on every important world market with automobiles and motorcycles. Its annual sales account for 44.3 billion Euro in 2004 and around 1.2 million automobiles were produced. Figure 1 presents the production sites of the BMW group within Europe. It becomes obvious that still the main production sites are place in Germany and some in Great Britain due to the acquisition of the brands MINI and Rolls-Royce.
In 1967 the BMW Group acquires the Hans Glas GmbH in Dingolfing. Afterwards parts of the production have been shifted from Munich to Dingolfing. The first car produced in Dingolfing is finished in 1973. Nowadays the brands BMW 5, 6, 7 series and Rolls-Royce are produced in Dingolfing. Per day nearly 1,250 cars are finished in the production and some 270,000 cars are produced per year. The area of the plan is around 2.3 millions square meters. The plant is the biggest production site within BMW worldwide. There are more than 20,000 workers employed.

1.5 Problem Discussion and Specification

*In this chapter it is analysed and discussed what needs to be done to answer the purpose of this thesis. For this, the main problems are identified and broken down into sub-problems. This is necessary to ensure that all relevant aspects are included in the analyses.*

This purpose is to evaluate to which amount costs can be saved by introducing a new standardised load unit and which size would be recommendable. In detail, the purpose is to find an economically advantageous alternative size for a standardised load unit in the category of the large load units. Its size should be between the two measurements currently used by BMW in order to fill the gap of having several parts that do not fit very well into either of the existing containers. For this, several aspects need to be considered. To identify these aspects, in the remainder of this chapter, the problem is discussed along the following structure.
At first, the studied system is discussed and the relevant parts are identified. Afterwards for these parts all types of costs concerning the load units are identified and the relevant parameters among them are determined. This is necessary to understand the basis on which the further discussion can be made. Based on these insights, fundamentals for possible designs for the new container are identified because such designs are necessary for a cost comparison. Finally, steps are discussed to evaluate the potential cost savings necessary to create a basis on which recommendations can be made. The following discussion aims to identify the aspects which are required in the further analyses and which can already be factored out.

### 1.5.1 Studied system

BMW runs several different production sites all over the world. As explained in Chapter 1.3, this thesis considers the automobile producing plants in Dingolfing, Regensburg and Munich. As only those plants are included which actually produce cars (and not modules or assembly parts) the load units are only used for the inbound logistics in these locations. The flow of load units starts at the supplier from where it is transported to the manufacturing plants. In the plants the load units are stored and handled to the assembly area. Finally the load units are delivered back from the assembly line to the suppliers.

As the suppliers have to use the load units to make their deliveries to BMW, the introduction of a new container will affect them, too. Nevertheless, in the following different reasons are presented why the analysis can exclude the suppliers. For BMW, only the influence of a new load unit on their own costs is relevant because this is what decides about their profit. Therefore, it is only necessary to consider those effects of a new load unit on the suppliers that reflect to BMW. Such effects can arise if a supplier has problems introducing the new size. The number of suppliers who could face problems should be rather low because nearly all suppliers handle different sizes of load units to deliver parts to different purchasers. Therefore, their internal structure can be expected to be adaptable to different sizes of load units. In these cases, a different size for the deliveries to BMW would not matter to the suppliers. Nevertheless, it is likely that there are cases in which the introduction of new load units can affect the suppliers. An example for this is that a supplier delivers exclusively to BMW and has aligned his conveyor system to the current load unit size. A new measurement would force him to adapt his structure in order to be capable to handle the new size. Thus, costs arise for him. Depending on the scale of the necessary adaptations they might affect the costs of the assembly
parts for BMW. The question to what extent extra costs for a supplier can be handed on to BMW certainly depends on the dimension of the extra costs and the bargaining power of both parties. Due to BMW's size it can be expected that generally the supplier will have to deal with these costs alone. As the cases in which a supplier cannot adapt to the new size should occur only seldom the analysis can exclude the influences on the supplier. Nevertheless, if the new load unit is introduced for a certain assembly part BMW should check in advance with the supplier if there might be problems and how they might affect the costs.

The actual process of storing the assembly parts can also be excluded from the analysis. This is due to the fact that the number of parts in the storage will remain equal no matter which size the load unit has because the inventory depends on BMW's order policy. Thus, the bound capital for assembly parts does not change. A marginal effect on the storage costs could be that the same number of parts requires less space in the warehouse due to better packing. Nevertheless, these savings are difficult to measure and no data is available from BMW. Furthermore, as the space of storage cannot be adapted easily and as the effect should be insignificantly small the storage costs per part can be assumed independent from the load unit size.

The studied system therefore starts with the transportation of the load units from the supplier to the plants. This is followed by the handling of load units to the assembly line and the transportation back from there to the supplier. In this thesis, these processes in the system are referred to as the inbound logistics of BMW. They are influenced by the size of the load unit in terms of costs, which are discussed in the next chapter.

1.5.2 Cost Structure

According to Pfohl (2004) logistics deal with “the process of planning, realising and controlling the efficient and cost-effective flow and storage of raw materials, semi-finished and finished products and the related information from the origin to the final destination according to the requirements of the customer”. From this very embracing definition, only certain aspects are relevant for the purpose of this thesis. Only those activities are important that are affected by the load units and as described in the background, these activities completely belong to the inbound logistics. The term inbound logistics refers to the processes from the purchasing of the assembly parts to their transportation and their placing at the production (Wikipedia 2005). To identify these activities, the flow of the load units needs to be examined. As stated in the purpose, the final recommendation
concerning a new load unit should be based on the potential cost savings. To determine the cost savings, cost parameters have to be assigned to the different activities and the reaction of the costs on the introduction of a new load unit has to be determined.

In the following, the respective steps necessary to handle the tasks stated above need to become more detailed. For such a detailed problem discussion those cost parameters that are influenced the most through the load units need to be known. To identify the relevant cost parameters, a total cost model is advisable and should be applied before the further problem discussion (Abrahamson and Aronsson 2003). Otherwise, the problem discussion can only be done on a very general and generic level.

The so-called total cost concept is a state-of-the-art concept for the optimisation of logistics costs. According to Bowersox et al. (2002) the total cost concept was introduced in 1956 and provided a new perspective concerning logistical costs. The main idea of this concept is to consider the effect of a decision on all types of costs for the company. A total cost model can be used not only to identify the net effects of decisions on the total costs but also to determine the interrelation of different cost parameters. This allows a more comprehensive understanding of the logistics costs. As Ballou (1992) states this interrelation is usually a conflict between some costs which are decreasing and others which are rising. Without such an embracing approach it can happen that changes in the system do not lead to cost savings but only to cost trade-offs.

An important aspect of a total cost model is to decide which categories and cost parameters to include. From an extreme point of view, all activities of a whole economy are related to the costs of a respective firm. If all this were to be considered in the cost parameters, this would certainly mean that a problem is unsolvable. According to Ballou (1992), the judgment of the management – or in this case of the author of this thesis – is required in order to decide which factors are to be considered.

As stated above, the actual application of this concept requires knowledge about the activities in the inbound logistics. At BMW, the assembly parts are either produced in own plants or purchased from external suppliers. In both cases, they are packed in load units and transported to the three considered plants. There, the load units are stored in different warehouses until their content is demanded at the assembly area. Then they are internally transported by different kinds of handling equipment to the assembly lines where the workers remove the parts. Afterwards the empties are transferred back to the
suppliers. The purchasing, scheduling and management of the containers is planned, executed and supervised by different divisions at BMW. Damaged load units are either repaired by BMW or by external contractors, depending on the damage. This brief overview is sufficient to determine the cost parameters of a total cost model. Nevertheless, in order to actually calculate the impact of a new container on the costs, a more detailed understanding of the current situation at BMW is necessary.

Based on the above process information two major categories in the total cost model for the load units can be identified. The first category contains all costs that are directly related to the load units while the second one includes those costs that are indirectly influenced by them. Table 1 shows which costs are assigned to which category.

**Table 1  Cost parameters related to the load units**

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<td>Direct influence</td>
<td>Administrative costs</td>
<td>Overhead costs for planning, scheduling and management of the load units</td>
</tr>
<tr>
<td></td>
<td>Maintenance costs</td>
<td>Purchasing, Maintaining and Disposing of the load units</td>
</tr>
<tr>
<td>Indirect influence</td>
<td>Handling costs</td>
<td>Intraplant transportation, premises and personnel for warehousing</td>
</tr>
<tr>
<td></td>
<td>Transportation costs</td>
<td>Inbound transportation from suppliers and other BMW plants, including packaging for transportation</td>
</tr>
</tbody>
</table>

Although these cost parameters are of different relevance with respect to the standardised load units they all need to be discussed in order to ensure that no important aspects have been missed. The areas highlighted in grey are the three most important cost parameters and this choice is explained in the following.

The administrative costs cover all overhead activities related to the load units. The number of load units and how many different types of load units there are affect these costs. Therefore, an additional type of container should increase them. Nevertheless, as stated in the background, there are more than 500 different kinds of containers which is why the increase should be insignificantly small. Therefore, this cost parameter should not be considered any further.

The term maintenance costs includes the costs for purchasing, maintaining and disposing of the load units. This parameter depends mostly on two aspects. On the one hand, it depends on the material the load units are made of as this
determines the costs for the raw materials, the effort in manufacturing, their durability and the rules for disposal. On the other hand the specific contracts with the suppliers of the load units have an important influence on these costs because it e.g. contains agreements about the price and the warranty. Due to the large number of containers that BMW uses, these kinds of costs are relevant. For this, the different materials available should be examined with respect to their price and technical characteristics. To determine the exact maintenance costs of the load units, the design of the contract with their supplier is necessary. For this it is problematic that BMW will initiate negotiations for this contract only after having evaluated the recommendation of this thesis. Thus, it is not possible to quantitatively consider the maintenance costs in a model. However, to support BMW's final choice as good as possible the question of the right choice of material should be covered on a more qualitative level in this paper.

The handling costs cover the whole movement of the containers within a production site. The total costs of this category for BMW are high considering that these activities do not add value to the firm. Although the aim of the handling is to make available the parts these costs are allocated per load unit. Aside from the question whether the AMA can be used, it does not matter how large the respective container is or how many parts it holds. The design of the load units has a significant influence on these costs because it determines how many parts it can carry. Thus, a “better” design can reduce the handling costs per part. To examine this effect of a new load unit on the handling costs, the possibility to pack parts into it needs to be analysed. Furthermore, a sound understanding of the composition of the expense ratios for handling is required.

Similar to the handling, the transportation actually deals with the movement of the parts and the load units are only tools for this. This is the reason, why these two cost parameters are classified to only have an “indirect influence”. The transportation costs cover the transfer of the assembly parts from the suppliers to the production sites and from one plant to another. Furthermore, they contain the returning of the empties back to the sources. They are generally allocated with respect to the volume. These costs are also strongly affected by the design of the containers as this determines how many parts they can carry and how many load units fit into a transportation vehicle. To analyse the savings potential through lower transportation costs, two steps should be taken. At first, the composition of the expense ratios for transportation needs to be understood and secondly, the possible number of parts per volume in a new load unit has to be compared with the performance of the existing ones.
From this discussion it follows that there are two types of costs that should receive the main attention of this thesis: Handling costs and transportation costs. Furthermore, the choice of material needs to be discussed on a qualitatively level. Such a simplification is not without risk. If some cost categories were missed in the model or falsely sorted out, the results of the analysis might be not reliable. In order to minimise this risk, the above cost model has been discussed and agreed on with the supervisors at BMW.

Based on these results, the remainder of the problem discussion focuses on identifying concrete sub-problems to answer the purpose (see Figure 2).

<table>
<thead>
<tr>
<th>Cost Model</th>
<th>Load Unit Design</th>
<th>Savings Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Create total cost model</td>
<td>• Identify relevant cost parameters</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2** Sub-problems of cost model

### 1.5.3 Design of the New Load Unit

Before it is possible to determine potential designs for the new load unit, the processes in which they are used have to be examined in detail. While in the previous chapter, a simplified presentation was sufficient to create a basic cost model for the detailed analysis of the measurements of the containers this is not enough. This is due to the reason that there are several factors which have to be considered as is shown in the rest of this section.

It has to be decided which measurements of new load units shall be considered in the model. In the current situation there are no load units with floor space between 1240mmx800mm and 1600mmx1200mm. Nevertheless, BMW purchases more and more parts, which are too large for the 1240mmx800mm and too small for the 1600mmx1200mm load units. Among others, a measurement of 1200mmx1000mm would be an agreeable possibility as many other automobile manufacturers use this dimension. Therefore, experience already exists with this measurement and products in this size are already on the market available, which might lead to lower purchasing prices than for a completely new development. An alternative could be an even larger load unit, for example with a measurement of 1200mmx1200mm. It has to be tested whether it is economically advantageous to bring into action one of these load unit designs.
units or even one of a different size. For this, it is important to analyse both the suitability of the container regarding the parts and the loading area of the means of transportation.

The automatic high rack can only store containers with the size 1240mmx800mm while all other load units need to be taken to the conventional block storage. Any new container will have to be stored in the latter warehouse. Therefore, it needs to be checked how many of the new load units fit into this warehouse as this will be a natural upper bound to determine the maximal number of new load units.

It seems that the geometry of parts within the BMW group has been growing in the last years as many whole systems are delivered and the cars are getting larger. Due to larger parts the available load units may not fulfil the requirements like size any more. This might further increase the importance of the question concerning the gap between the two large standardised load units currently in use. The potential growth of parts therefore has to be considered and evaluated using the measurements of the parts introduced in the last years. If there is indeed a growth, this would support the introduction of a new container.

Probably the most important aspect of the new container is its ability to carry as many parts as possible. To gain results with respect to the number of parts per load unit, investigations have to be made, how economically the new load unit can be packed, especially in comparison to the old one. For this comparison the utilisation\(^3\) degree of the new container has to be calculated. This is not necessary for the existing load units as their utilisation is already known to BMW. For this a fast and reliable tool for calculation needs to be implemented. A similar consideration has to be made concerning the packing of the load units into the associated means of transportation. Therefore evaluations of the most common means of transportation and their measurements and restrictions have to be made.

Another aspect for the design of the new container is the service level. Generally, the term service level describes the possibility for stockouts. In this case, stockouts means the unavailability of the load units themselves. This can have negative effects on the logistics costs of BMW because it can either force the suppliers to use other, less efficient containers or might even lead to delays

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\(^3\) Note that for BMW (and thus in this thesis) the term “utilization” refers to the absolute number of parts within a container and not to a relative value.
in the deliveries because the suppliers cannot ship their goods. Especially the latter problem can have significant consequences but is not very likely to occur. Generally, the demand for load units is easily predictable and the use of backup load units in different sizes should be possible. Nevertheless, in order to further ensure that the service levels remain constant a gradual introduction of the new load unit can make the demand even more predictable. Also part of this aspect is the ability of the suppliers to handle the container well enough. This could be problematic in situations where a supplier adopted his whole production to a certain type of load unit and who would then be forced to use a different size. To avoid these problems, BMW needs to discuss the migration of a part to a new container with the part’s supplier. Although it is very likely, that the demand power of BMW is strong enough to enforce changes in the standard load units there might be situations in which it is advantageous not to do so. Nevertheless, this aspect should only be problematic for a few exceptions and does not pose a problem to the general question whether a new load unit makes sense.

It is also crucial that the load unit allows the transportation, handling and storing of the assembly parts without risks for their quality. Currently, there are situations in which fewer assembly parts than theoretically possible are packed into one load unit because otherwise they would cause damage to another. Similar to the service level, this does not pose too great a problem for two reasons. Firstly, those items which are damageable are not packed into standard containers but into specialised load units. Secondly it is no problem to adapt the packing plans for the new container like those for the existing ones if there seem to be quality problems.

If the measurements for a new load unit are defined and the calculations result in cost savings for transportation and handling the material for construction has to be evaluated. This decision has significant influence both on the purchasing price as well as on the durability and maintainability of the boxes. Currently, all standardised load units from BMW are made of steel. Besides steel, it is also possible to construct them using plastic or combination of both materials. The prices for both raw materials have generally risen and fluctuated quite often. Especially the price for plastics has been rising because of the climbing oil prices, but also the steel prices have been varying a lot over the last months. The prices of these two materials have to be surveyed and predictions for the future have to be made in order to decide on the new material. Due to issues of stability, durability and maintenance not only the price for the raw materials but also more qualitative factors need to be considered. In the past there have been problems with the handling and maintaining of containers made of steel.
because of bad construction or issues with the material. The characteristics of these two materials differ in terms of weight, stability, foldability, payload, and maintenance.

All sub-problems for the new load unit are displayed in Figure 3.

<table>
<thead>
<tr>
<th>Cost Model</th>
<th>Load Unit Design</th>
<th>Savings Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Create total cost model</td>
<td>• Analyse current situation</td>
<td></td>
</tr>
<tr>
<td>• Identify relevant cost parameters</td>
<td>• Decide on measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– Consider warehouse compatibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– Consider geometry of parts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Calculate utilisation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Consider service level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Consider quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Choose material</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 Sub-problem for the design of a new load unit

1.5.4 Cost Savings through the New Load Unit

As stated above, the cost savings through the introduction of a new standard load unit will mainly result from reductions in the transportation and handling costs. The choice of material can only be considered on a more quantitative level. To identify the positive effects of a new load unit with respect to the transportation costs, firstly the transportation network of BMW has to be analysed. For this, the distances between the different suppliers and plants as well as the expense ratios per cubic metre are relevant. Through this it is possible to calculate the transportation costs per part depending on the respective load unit. A better utilisation of the vehicles leads to lower transportation costs per part. The utilisation of a vehicle can be described through the term “parts per vehicle” and depends on two aspects, which are the number of parts per container and the number of containers per load. Subsequently, the costs per part can only drop if the combination of these two ratios can be improved. Thus, it has to be determined how these ratios react on the new size.
When it comes to determining the handling costs, at first the material flow of the load units within the plants has to be analysed. A complete picture of the intraplant material flow should show all instances in which handling is necessary. This approach ensures that all relevant handling costs are included in the analysis. Expense ratios for the handling of a load unit have to be associated with the relevant processes and steps. These expense ratios need to reflect the different means of handling of a respective load unit. Concretely, this means that it has to be considered which load units can be handled by the automatic integration system (AMA) and which not.

In order to compare the costs of the old load unit with the new one, the costs for every process have to be calculated and summed up for all examined load units. As the handling costs are independent of the size and utilisation of a load unit, it is necessary to calculate the costs per part for each container in order to be able to directly identify the cost differences. This means that a smaller load unit will always result in higher costs per part. Similar to the analysis of the transportation costs, for this the utilisation degrees of the old and new containers have to be known. Thus, the results from the packing tool are relevant for both aspects.

<table>
<thead>
<tr>
<th>Cost Model</th>
<th>Load Unit Design</th>
<th>Savings Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Create total cost model</td>
<td>• Analyse current situation</td>
<td>• Determine expense ratios</td>
</tr>
<tr>
<td>• Identify relevant cost parameters</td>
<td>• Decide on measurement</td>
<td>• Decide on basis for cost comparison</td>
</tr>
<tr>
<td></td>
<td>– Consider warehouse compatibility</td>
<td>• Assign and compare costs</td>
</tr>
<tr>
<td></td>
<td>– Consider geometry of parts</td>
<td>• Make recommendation</td>
</tr>
<tr>
<td></td>
<td>• Calculate utilisation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Consider service level</td>
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<td></td>
<td>• Consider quality</td>
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<tr>
<td></td>
<td>• Choose material</td>
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</tbody>
</table>

Figure 4 Structure of the problem

The above discussion shows how the problem of this thesis can be broken down to solvable sub-problems. Figure 4 illustrates this decomposition.
1.6 Methodology

In this part, the methodology is discussed with which the different problems are addressed. For this, appropriate theoretical references are given.

The procedure of this thesis is divided into seven steps, which are displayed in Figure 5.

At first the background of the situation at BMW was examined, which led to the purpose. To solve the purpose in a structured manner the studied system and problems were identified and discussed. Within this discussion the problems were broken down to sub-problems and boundaries concerning the studied system were drawn. Thus, it was possible to structure the tasks which have to be done to answer the purpose. Now, in the methodology relevant literature for the identified problems is examined and selected for the further analysis. Within this step the theoretical framework is built up. This is initiated by reviewing books and journals concerning this context leading to further reading. High level journals in general offer articles concerning a specific with a high quality due to the so-called "double blind review". A double blind review means that both the author does not know the reviewer and the reviewer does not know the author. Through this anonymity a high objectivity can be assumed. The journals "Operations Research" and "Journal of Operational Research Society" and to some extent "Management Science" offer a wide range of publications concerning the packing problem. Articles in these journals concerning the packing problem often refer to the textbooks of Exeler (1988) and Nelißen (1993), what makes these books also a reliable source. Thus, they were chosen as standard literature for this thesis. While some articles from the journals are rather old they are nevertheless a good source for the understanding of the problem. They discuss the basic setup and characteristics of the packing
problem and offer solutions which are still up-to-date. This is due to the fact that the more recent research on this subject generally deals with rather specific and complex types of the packing problem. Such academic approaches are difficult to apply in real situations because the available data in practice is usually insufficient. The further reading is examined and, thus, relevant literature is selected, which can be applied to the problems in this study. Finally, the analysis leads to the recommendation and to the conclusion of this thesis. In the following problems are addressed with regard to theoretical references.

To achieve a detailed analysis of the relevant processes at BMW several tools can be applied. A common tool is the graphic representation of processes which can be a helpful tool to advance efficiency and help to improve operations (Keller 1999). The so-called process mapping is such an approach. Process mapping analyses the connectivity, controls, impacts, and results among the processes, i.e. it determines whether processes achieve the originally followed objectives. Soliman (1998) suggests to perform process mapping is in the following three steps:

1) Identification of products and their related processes, i.e. the starting point, finishing points and the processes in between are identified.
2) Collection and preparing of data.
3) Graphical representation with the gathered data in order to identify bottlenecks, wasted activities, delays and duplication of efforts.

Usually the first level of process mapping represents an overall view of the core process. However, if more detailed information is needed for the analysis, the core processes need to be broken up into sub-processes. This must be done until the segmentation of the process does not offer additional information. Detailed information is required to find out where the process starts, finishes, and to identify any overlapping processes or processes which influence one another. According to Curtis et al. (1992) the accuracy of results obtained from a process and the level of details of that process are linked, i.e. a bad defined process would produce poor results.

Youngblood (1994) suggests the following information, which can be included in the mapping process:

- Operations descriptions
- Cost/resources consumed
- Activity times
• Frequencies
• Material and information inputs and outputs of each operation
• Volume measure

But of course the detail of the description will depend on the level of mapping required for the study.

Depending on the levels of detail, there are different ways to display the process. Arnold (2003) suggests different possibilities to represent especially material flow systems. Arnold describes

• Flowcharts, the material flows from the starting point (source) to the finishing point (sink). Information about capacity, strategies of the consolidation, etc. are not available from this type of representation.
• Draft Layouts, information about the technical realisations are available, which makes it possible to shed light on information like capacity.
• Directed Graphs, which have one source and one sink and in between nodes, which represent e.g. machining centres. The arc can represent capacities, distances, etc.
• Matrices display structures and directions of flow for the graphs via number schemata.

The level of detail of the representation of the process depends on the requirements of the analysis. For the process mapping the risk of errors is rather small. The only reason for mistakes could be that this analysis lacked accuracy or that the information gathered in interviews is not correct. While this is unlikely, this could be due to a misperception of the processes from the point of view of some interviewees. To understand the processes at BMW, such an analysis is applied in Chapter 3.1

Potential for cost savings exist in the holistic packing optimisation. In a holistic approach the matching of product packing and transportation packing is regarded as high potential for the improvement of the utilisation degree of the pallet and the vehicle. Isermann (1998) says that already by a marginal adjustment of the load unit improvements of the utilisation within the loading space of the container and the utilisation within the transportation vehicle with load units can be achieved. Thus sustained success in form of reduced costs per product can be achieved. Bischoff and Dowsland (1982) identified two factors which directly affect packing and handling costs, as well as the efficiency
of transport and warehousing operations. These factors are the geometrical characteristics of the products and the load units in their distribution. As the geometrical characteristics of the product cannot be influenced the leverage in this case are the dimensions of the load unit.

There is a broad range of literature addressing the choice of the right measurements of load units. The question concerning the size of the new container has to be analysed against the background of the possibility of introducing no new container at all. The costs induced by this solution should be seen as a lower limit, i.e. it would not make sense to choose an alternative that leads to higher costs than that. According to Wilson (1965) a certain diversity in the sizes of load units makes sense. Whether it would be advantageous to introduce a new container can only be decided with respect to a certain measurement. Therefore several different sizes for the new load unit have to be chosen and their financial consequences have to be compared to the current situation. It is important that the load unit’s size fits well both into the transportation vehicle and for the items. In the following, it will be referred to the issue of loading the transportation vehicles as the “truck-loading problem” and to the issue of packing the items in the container as “pallet-loading problem”. With respect to the available data and the required computation time it needs to be decided whether both problems can be solved in an integrated approach or whether they should be decomposed into two steps.

Both aspects of the problem can be characterised as so-called packing problems. These problems deal with the question how to pack as many items into containers as possible. This topic has been discussed in the literature quite intensely and Sweeney and Paternoster (1992) offer a broad overview over existing work. The packing problem is generally very wide because different specifications in several areas are possible, e.g. the dimensions or the shape of the items. Probably most important is the number of considered dimensions which can range from one to more than three. The one-dimensional packing problem (cf. Exeler 1988) is of low theoretical use for this thesis. The two- and three-dimensional ones are much more suitable for the identification of fitting container sizes. Well-known sources for the solution of two-dimensional problems are Bischoff and Dowsland (1982) and Smith and de Cani (1980) while Martello et al. (2000) present a solution to the three-dimensional case. In the following it is necessary to identify to which extent the truck-loading and the pallet-loading problem require complex approaches or allow more simple solutions. In this context the specific restrictions and prerequisites of BMW need to be considered. As the packing problem is quite complex and as exact
solutions are generally very time consuming it is important to select an approach that works fast while delivering a sufficient quality of the solution. This trade-off between computation time and quality is discussed by Exeler (1988) who compared the two-dimensional approaches of the literature presented above. To create an appropriate tool to calculate packing plans as described in the problem discussion, it is necessary to have a very good understanding of these packing problems. Therefore, the whole Chapter 2 deals with the characteristics and possible approaches of the packing problem.

For the actual calculation of the packing problems the measurements of all relevant parts of BMW are necessary. For this thesis the first hand data of the assembly parts from BMW can be used. While it is always good to use such primary data, some risks remain. As there is a vast amount of data and as the sizes of the parts were measured and recorded manually by BMW, it is likely that at least some mistakes cannot be avoided. This is the only source for errors concerning this data source and therefore their reliability should be high. To validate the results of this thesis a sample of an adequate number of parts should be selected and tested before the actual implementation of a new load unit.

The question whether the measurements of the parts used by BMW have increased in the last years requires a statistical analysis. Eßbach (2005) conducted such an analysis with positive results. Furthermore, he identified reasons for the growth. These results are used in this thesis and his approach is discussed in chapter 3.3. Here, the risk for errors is higher than in the previous aspects because Eßbach’s diploma thesis only offers secondary data. Nevertheless, the impact of errors in his work on the results of this thesis is very low. This is due to the fact that the potential growth of parts would only be a supporting factor of the results and not a prerequisite, as the analysis is based on the current sizes and not on their development over time. This means that if there is no growth of the parts, the results of this thesis are still valid.

To compare the performance of two load units, it is necessary to allocate costs to them. To allocate these costs, expense ratios for transportation and handling are required. In order to make recommendations for BMW these expense ratios have to be determined with their methodology. Unfortunately, the approach BMW uses to assign the overhead costs is strictly confidential and it was neither possible to gather enough information about this topic nor to present the actual expense ratios in this thesis. Thus, the expense ratios could only be applied in order to calculate the cost savings. The major disadvantage of this situation for
this thesis is that the “blind application” of the cost parameters increases the possibility of errors in the analysis. In order to reduce this risk and to ensure that the ratios are correctly applied, the responsible controller was interviewed several times. Nevertheless, to gain a better understanding of potential risks of a new load unit, the effects of possible mistakes are discussed further in Chapter 5.2.

A detailed theoretical framework for the packing problem is given in Chapter 2. In Chapter 2 the current situation at BMW is presented in more detail with special focus on the material flow, the load units and the assembly parts. Chapter 4 deals with the analyses that were conducted. For this, at first the collected data is presented and afterwards the optimal measurements for the new load unit are determined. Subsequently, in Chapter 4.3 a tool to calculate the utilisation of the new load unit is applied on all available assembly parts. Based on these results and the identified expense ratios, in Chapter 4.4 the cost savings are determined. Subsequently, several aspects for the choice of material are discussed. The thesis closes in Chapter 5 with a recommendation and risk analysis.
2 Theoretical Framework for the Packing Problem

In the following part, a theoretical framework for the packing problem is given. The packing problem can be analysed with respect to many different situations and has been focus for scientific work in the last decades.

2.1 Introduction to the Packing Problem

A better utilisation of the loading space of load units, like containers or pallets, and means of transportation, like trucks or trains, results in the decrease of product-related and order-related logistic costs (cp. Isermann 1998). In the supply chain of BMW a large number of load units with standardised length, width and height are used in order to simplify the processing the processing of transportation and storing. By improving the utilisation of these load units additional potential for cost reduction exists which can be realised without deep changes in the processes. If it is possible to pack more items than before into a given space the logistics cost can be allocated on a greater amount of parts and the product- and order-related costs decrease. For this optimisation of the utilisation the packing problem is an appropriate concept.

In Exeler (1988) the packaging problem is defined as the problem of packing smaller units (parts) into a larger one (container) with regard to a specified objective. The packing problem is closely related to the cutting problem. Here it is the objective to cut items with given shapes from a source of material with minimal waste or by using a minimal amount of the material. These two problems are similar because in both cases it is required to identify the best way to place the parts on or into the source. According to Watson and Tobias (1999) such problems were already in the focus of seventeenth century scientists’ like Johannes Kepler – even though from a very mathematical point of view. In the 1950s this question started to become popular and the work of Gilmore and Gomory\(^4\) presented the first techniques which could be practically applied to difficult real-world problems. A very extensive bibliography with a useful categorisation for the work until 1992 can be found in Sweeney and Paternoster (1992).

They suggest a categorisation of the different approaches with respect to two criteria. The first criterion is the dimensionality of the problem and the second one is the employed solution methodology. According to the first criteria, the general packing problem can be categorised into one-, two- and three-

dimensional problems. Theoretically, it is also possible to create n-dimensional problems for $n>3$, if for example the factor time is considered as well. Nevertheless, the relevance of such high-dimensional questions is too low for this thesis in order to consider them any further. For the employed solution methodology there care the following three categories:

- Sequential assignment heuristics
- Single-pattern generating procedures
- Multiple-pattern generating procedures

Sequential heuristics can be described as the application of a certain assignment rule for the placing of items into a cutting or packing pattern. An example for this approach is given in Eilon and Christofides (1971) where all items are considered consecutively and stored into the containers according to a penalty function that increases with the number of used boxes. The single-pattern procedures, for which the four-block heuristic of Smith and de Cani (1980) is an example, start with the generation of a single optimal pattern which can be used once or several times. However, the procedure does not consider subsequent patterns for residual demand items. The multiple-pattern procedures, which for example are linear-programming-based algorithms, identify optimal patterns with respect to the interactions between different patterns for different parts of the pallet.

In the following, the one-, two- and three-dimensional packing problems are discussed in more detail and some approaches for their solution are presented.

### 2.2 One-Dimensional Packing Problems

Since 1957 one-, two- and three-dimensional packing problems have been extensively studied by operational workers (Smith and De Cani 1980). Exeler (1988) defines the one-dimensional problem in the following way:

“There are $m$ units with a capacity demand of $I_i$ ($i = 1, \ldots, m$) and $n$ containers with a fixed capacity of $L_j$ ($j = 1, \ldots, n$). The units shall be packed into the container without exceeding the capacity limit while the given objective function is optimised.”

An example for the one-dimensional question is the cutting of ropes with certain lengths from different reels or a packing problem where only the weight of the parts (and not their size) is relevant. According to Eilon and Christofides (1971) two possible situations for such problems can be distinguished. The first
situation is that the total capacity of the containers is at least as big as the sum of the capacity demand of all units and that all units can be accommodated in the array of boxes. The second situation is that the accommodation of all parts is not possible. This can be due to two reasons: Either the capacity of the containers is large enough but the parts do not fit into the array of boxes because they would have to be divided. Or the total capacity of the containers is smaller than the total demand of capacity of the units. In this case, it is obvious that some parts will be left over.

Especially for those cases, in which not all parts can be stored, it is useful to base the decision on an objective function in order to identify the solution with the highest utility. Possible objectives could be the minimisation of the total number of containers (which is also useful for the case in which all items can be accommodated), the minimisation of the unused space in the filled container or the minimisation of the number of not accommodated units. The last minimisation is quite equal to the so called knapsack-problem. Further references to this problem can be found for example in Neumann and Morlock (2002). Finally, it is also possible to introduce a combined objective that considers a weighted combination of used boxes and stored items. These or similar objective functions are also valid for certain more-dimensional problems. Nevertheless, as the problem of optimally packing the new BMW standard load unit cannot be answered with regard to only one dimension, this topic is not presented in any more detail here.

2.3 Two-Dimensional Packing Problems

The two-dimensional packing problem has the highest importance for this thesis because it is significantly less complex than the three-dimensional one while being able to provide very applicable solutions for the packing of standard load units.

2.3.1 General Aspects

The two-dimensional packing problem solves the task of packing a two-dimensional base with smaller two-dimensional units. There are two possibilities for the two-dimensionality: It can mean that either items with two dependent characteristics, like length and a width, (which is the more important case) or items with two independent characteristics, like volume and weight, are considered. Eilon and Christofides (1971) state that the latter case can be solved quite similar to one-dimensional packing problems, e.g. through the stepwise consideration of the dimensions. The former possibility, on the other
hand, leads to a problem which is much more complex. Here, the relation between the length and the width of the parts needs to be considered, which means that their orientation and exact position within the container is important. A statement like “with the current packing plan there are 30cm of the width and 25cm of the length left” cannot be made because the container’s width has to be tracked for every centimetre of the container’s length and vice versa. As this thesis deals with the sizes of the containers and parts only these more complex two-dimensional settings are considered in the following.

Due to practical issues, it makes sense to distinguish the container’s form as well as the parts’ form into either rectangular or so-called irregular shapes, which cover all other shapes. The reason for this approach is the fact, that the fitting of rectangles into a larger rectangle can be described with relatively low effort and is most common for the practical use. For irregular forms the problem becomes more complex due to the fact that it no longer has to be the case that the parts can be placed next to each other without leaving any gaps unused. Grünbaum and Shephard (1987) show that only convex polygons with fewer than five edges always tile the plane and that there are only few pentagons and hexagons with the same ability. Non-convex shapes, for example L-shaped items, generally cannot be accommodated in a way that leaves any uncovered gaps (although exceptions exist). Irregular forms cannot be described by the two values length and width, but require a more complex description. To deal with this problem, it is possible to either ignore the special shapes of the parts or to apply complex methods that are able to consider them. In practice the former approach is the most common solution (Exeler 1988). Thus, I concentrate on this in my thesis, too. For this, the parts’ length and width is taken from the smallest containing rectangle that can be laid around it (Watson and Tobias 1999). While this approach obviously causes a loss of information and thus will most likely not allow an optimal solution it is very practical and can provide good results.

Considering only rectangular items, two packing possibilities can be identified. The first possibility is the orthogonal packing. The orthogonality-condition says that the sites of the parts have to be parallel towards the sites of the container. The second possibility is the non-orthogonal arrangement in which the parts may be stored in any orientation. There are situations in which the orthogonality-condition does not allow any feasible arrangement or that the optimal arrangement cannot be found. An example for this is a part that is longer than the length of the container and which subsequently can only be stored diagonally. In this case the non orthogonal arrangements on rectangular
spaces are useful. Even though in a practical situation these cases are easily identified and solved, the diagonal arrangement of objects is formally much more complex. Furthermore, it is obvious that generally unused spaces result, which means that this approach is of less importance for my work. Therefore, this thesis concentrates on the assumption of orthogonal arrangements. With this, the definition of Smith and de Cani (1980) follows who ask the question how to “pack as many inside rectangles as possible into a containing rectangle, allowing orthogonal layouts only.”

The orthogonal packaging problem can again be divided into two subtypes called the homogeneous and the heterogeneous packaging problem. The homogenous problem makes the assumption that all units are congruent, i.e. the parts have the same length and the same width. This is for example the case, if only one type of items is stored in a container or if all items are previously packed into small boxes of the same size. In the heterogeneous problem different units are packed in the same box. The heterogeneous problem is more complex than the homogeneous one because it is necessary to identify patterns with regard to the different sizes. At BMW only one type of items is stored in a container. Therefore the thesis is focusing on homogeneous problems.

In the following, procedures for the homogeneous two-dimensional packing problem are introduced. To formulate a method of resolution it is important that it is possible to characterise the problem accurately, completely and consistent. An additional requirement is that the algorithm attains in finite steps to a solution and that in an economically arguable complexity. For the two-dimensional packing problem these requirements of the formulation are fulfilled but the long calculation time needed for exact procedures require other proceedings, i.e.

“In order to solve such problems in practice, one is forced to use approximate, heuristic algorithms which hopefully compute good solutions in an acceptable amount of computing time. Thus, instead of seeking the fastest algorithm from the set of exact optimisation algorithms, one seeks the best approximation algorithm from the set of ‘sufficiently fast’ algorithms” (Johnson et al. 1974).

Heuristics cannot guarantee that the optimal solution is found. In general the adoption of heuristically solution procedures cannot offer a conclusion about the quality of a calculated solution as long as the optimal solution is not known. For the two-dimensional homogeneous procedure the quality can be approximated by a theoretical upper bound. Naujoks (1995) gives a good review about the calculation of ‘good’ upper bounds. These upper bounds are especially
important for the reduction of iterations both for heuristics and exact procedures. The advantage of heuristics is that they offer a “good” solution in an arguable amount of time. According to Meissner (1978) heuristics can be divided into the transformation of the initial condition into a given final condition and the problems which offer just some characteristics about the final condition. The homogeneous packing problem belongs to the latter case.

In the following some heuristics and afterwards an exact procedure are presented.

2.3.2 One-, Two- and Three-Block Heuristics

For the packing problem many heuristics have been developed since 1979. Mainly these heuristics are the so-called block heuristics. All these approaches are just a suboptimal solution and not an optimal one due to their heuristic character. The one-, two- and three-block heuristics are a basic and simple procedure to solve the packing problem. The proceeding of block heuristics is to separate the base of the container into blocks. The definition of a block is according to Nelißen (1993) the following:

“A block is a rectangle which contains a number of boxes of the same orientation.”

The simplest block heuristic is the one-block heuristic. The whole rectangle plane, which shall be packed, is equal to the one block, i.e. in the whole plan just one orientation of the boxes is possible. Therefore two solutions to this problem exist. The boxes can be packed with their length parallel to the plane’s length or with their width parallel to the plane’s length. According to Nelißen (1993) the formulation of this problem is the following:

$$\left\{ \begin{array}{l}
\text{If } \frac{X}{a} \times \frac{Y}{b} > \frac{Y}{a} \times \frac{X}{b}, \text{ then place } \frac{Y}{b} \text{ rows of } \frac{X}{a} \text{ H-boxes on the base,} \\
\text{else place } \frac{X}{b} \text{ columns of } \frac{Y}{a} \text{ V-boxes on it,} 
\end{array} \right.$$  

where,

$$X = \text{length of base}, \ Y = \text{width of base}, \ a = \text{length of box}, \ b = \text{width of box}, \ \text{and} \ H\text{-boxes} = \text{horizontal boxes}, \ V\text{-Boxes} = \text{vertical boxes}.$$
The one-block heuristic is exemplified in Figure 6. It just has to be decided if more boxes fit on the base lengthways or sideways.

The two- and three block heuristics are an extension of the one-block heuristic with an introduction of a second and third block, respectively. The two-block heuristics proceed in the following way. It arranges $n$ columns of $\left\lfloor \frac{Y}{b} \right\rfloor$ H-boxes and right of these $m$ columns of $\left\lfloor \frac{Y}{a} \right\rfloor$ V-boxes for an efficient X-partition. Additionally, the three-block heuristic tries after this step to fill the gap at the top of the $m$ columns with some more H-boxes. These steps are carried out for each efficient X-partition. Analogously, this is done for each Y-partition. Afterwards, the best solution is selected. Figure 7 shows examples for the two- and three-block heuristic. The blocks can be distinguished by the different colours.
Advantages of these heuristics are the simplicity and, therefore, the low computation time and the easiness of understanding. The solutions of these heuristics are easy to implement and to pack for the worker. The packing structures are easy to comprehend, because there are no changes of orientation in one block. The disadvantages of these heuristics are that they do not offer optimal solutions for every problem. More efficient computers make it possible to implement more complex algorithms. The next, more complex block heuristic offers better solutions.

### 2.3.3 Four-Block Heuristics

A four-block heuristic divides the base into four blocks which are positioned in the four corners of the rectangular base. Several approaches exist to identify good solutions and two of them will be presented in the following. The first approach originates from Steudel (1979) and the second one from Smith and De Cani (1980). While Steudel’s heuristic starts with the recursive optimisation at the four edges of the base and creates the blocks on this way, Smith and De Cani start with one block and the optimisation is done by generating enumeratively all efficient arrangements of the four blocks.

Steudel’s four-block heuristic is based on dynamic programming and is of a recursive nature. The heuristic starts with the calculation of four optimum sets of length and/or width placements of the boxes along the inside edges of the base. The objective function of this phase is to maximise the utilisation of the length of the perimeter of the base. In the second step the beforehand found optimal arrangements of boxes along the perimeter are expensed inward to fill the centre of the base. In this step the objective is to minimise the amount of unused area. Here, two problems can occur which are either the overlapping of the blocks or the remaining of free space in the centre of the base large enough for at least one more part. To identify the first problem additional conditions are checked. If this case is approved by the conditions, the blocks three and four are adjusted in order to avoid overlapping while the blocks one and two remain as they are. In case of the second problem it is checked if multiple optimum solutions to the recursion exist and returns to the beginning of step two. If not, the first two blocks remain fixed and the last two are adjusted.

The formulation of the problem according to Steudel (1997) is in step one the maximisation of the utilisation of the perimeter of the base. The recursive objective function is defined as follows:

\[
F_n(S_n) = \text{Max}[X_n \cdot l + Y_n \cdot w + F_{n-1}(S_{n-1})]
\]
The constraints in step one consider that the lengths of the edges of the base are not exceeded. The formulation looks like:

\[ X_n \cdot l + Y_n \cdot w \leq D_n, \quad n = 1, \ldots, 4, \]

where

\[ F_n (S_n) = \text{maximum value of the sum of the length and width placements through stage (edge) } n \text{ of the base with state variable } S_n \text{ entering that stage.} \]

\[ X_n = \text{number of boxes of length } l \text{ placed lengthwise along the edge } n. \]

\[ Y_n = \text{number of boxes of width } w \text{ placed widthwise along the edge } n. \]

\[ D_n = \text{dimensional size of edge } n \text{ for the container (either length } L \text{ or width } W). \]

\[ S_n = \text{state variable which defines the initial conditions for the edge } n. \text{ } S_n \text{ has three possible values:} \]

\[ S_n = X_n = Y_n = \text{Boxes are only placed lengthwise along edge } n. \]

\[ S_n = X_n = Y_n = \text{Boxes are only placed widthwise along edge } n. \]

\[ S_n = X_n = Y_n = \text{Boxes are placed length and widthwise along edge } n. \]

The four blocks are defined as the following patterns:

B1: the block of rectangles formed by \( X_1 \) and \( Y_4 \)

B2: the block of rectangles formed by \( X_2 \) and \( Y_1 \)

B3: the block of rectangles formed by \( X_3 \) and \( Y_2 \)

B4: the block of rectangles formed by \( X_4 \) and \( Y_3 \)

The objective function is an enumeration of every combination of the three values for all \( S_n \). Therefore for three states and four blocks in the first step \( 3^4 = 81 \) solutions are calculated and the best one is selected. Figure 8 shows the enumeration tree for the first step of the heuristic.
The formulation of the objective function $F_n(S_n)$ can be described as the maximisation of the distance along each edge, while for larger $n$ the results of the previous sides are taken into account as well. Thereby, $X_i$ is the distance created by $i$ boxes lengthwise and $Y_j$ is the distance created by $w$ boxes width-wise. It also could be described as the minimisation of unused space along the perimeter.

The steps one and two are displayed in Figure 9. Additionally, Figure 10 shows the two problems which can appear in step two and which require additional consideration. The red arrows show the way the problems are solved. The left case represents unused space in the middle of the base which is large enough for at least one more part. To solve this problem the blocks one and two remain unchanged (and thus also $X_1, X_2, Y_1, Y_4$) while the blocks three and four are...
adjusted. In the example in Figure 10a), $X_3$ is extended to $X_3'$ while $Y_3$ reduced to $Y_3'$, i.e. block 3 is enlarged while block 4 is decreased.

![Diagram of block adjustment](image)

In Figure 10b), the case of overlapping is presented and solved. The formulation of identifying overlapping is the following: If both

$$D_1 - X_1l < X_3l \text{ and } D_4 - X_4l < X_2l$$

hold, there is an overlapping of the blocks one and three. If, on the other hand, both

$$D_1 - Y_1w < Y_3w \text{ and } D_2 - X_2l < X_4l$$

can be observed, step two resulted in an overlapping of the blocks two and four. In case of overlapping, the proceeding is similar to the one of the unused-hole case. Block one and two remain equal while the blocks three and four are adjusted. In the example in Figure 10b), block four is increased to $Y_3'$ and block three is decreased to $X_3'$. Here, it needs to be checked in which way the blocks can be transformed in order to minimise the number of parts "sacrificed" to eliminate the overlapping.

The four-block heuristic developed by Smith and De Cani (1980) only considers the arrangements of the type displayed in Figure 11, i.e. four blocks with a defined orientation. Other than Steudel (1979) this heuristic examines all structurally different arrangements of this type. The procedure of the heuristic is to start with the determination of block one. Afterwards block two is defined to be higher than block one. Block three again has to be wider than block two. At
least block four just has to fit in. This is calculated for different starting solutions, what from the best solution is selected.

The formulation of the problem is introduced in the following. The length and width of the boxes are denoted by \( l \) and \( w \) respectively. Similarly, the container sides are denoted with \( L \) and \( W \).

The variables \( s, t, u, v, w, x, y \) and \( z \) have to be calculated so that the number of packed units is maximised with the orientations of the blocks shown in Figure 11 at the corners of the rectangle, i.e.

\[
Max \quad Z = a \cdot b + c \cdot d + e \cdot f + g \cdot h.
\]

The optimisation is done by generating enumeratively all efficient arrangements of the four blocks. While enumerating, the variables belonging to the best found solution are saved.

In Figure 11 it becomes clear that the values of the variables \( a \) and \( b \) cannot exceed \( b_{\text{max}}, a_{\text{max}} \) and \( b_{\text{max}} \), which are defined as

\[
a_{\text{max}} = \left\lfloor \frac{L}{l} \right\rfloor > a \quad \text{and} \quad b_{\text{max}} = \left\lfloor \frac{W}{w} \right\rfloor > b.
\]

Thus all combinations \( (a,b) \) with \( a = 1, \ldots, a_{\text{max}} \) and \( b = 1, \ldots, b_{\text{max}} \) are possible. The combination \( (a,b) \) defines the remaining section \( EH \) of \( AH \) and fills it with boxes. Thus, for each pair of values for the variables \( (a,b) \) the value \( c \) itself to
\[ c = \left\lfloor \frac{L - al}{w} \right\rfloor \]

Afterwards, block two is required to be higher than block one; otherwise unused space can occur above block two. This requirement is assured by

\[ d_{\text{min}} = \left\lfloor \frac{bw}{l} \right\rfloor \leq d. \]

The maximal value of \( d \) is

\[ d_{\text{max}} = \left\lfloor \frac{w}{l} \right\rfloor \geq d. \]

Every possible value of the variable \( d \) is considered concerning the current values of \( a, b \) and \( c \). Afterwards again for each value of \( d \) the variable \( f \) can be calculated by

\[ f = \left\lfloor \frac{W - dl}{w} \right\rfloor, \]

i.e. for the fixed value of \( d \) the remaining section \( LK \) of \( HK \) is filled with boxes. Block three is required to be wider than block two and smaller than \( e_{\text{max}} \). The formulations of these restrictions are

\[ e_{\text{min}} = \left\lfloor \frac{cw}{l} \right\rfloor \leq f \quad \text{and} \quad e_{\text{max}} = \left\lfloor \frac{L}{l} \right\rfloor \geq f. \]

For the current values \( a, b, c, d, e \) and \( f \), the variables \( g \) and \( h \) are depended on \( e \) and \( b \) respectively. The calculation is

\[ g = \left\lfloor \frac{L - el}{w} \right\rfloor \quad \text{and} \quad h = \left\lfloor \frac{W - bw}{l} \right\rfloor, \]

i.e. the remaining section \( NO \) of \( NK \) and \( NM \) of \( NA \) are filled with boxes.

Thus, all possible combinations of the variables \( a \) to \( h \) are found that correspond to orthogonal layouts forming a pattern of the type in Figure 11. The four-block heuristic introduced by Smith and De Cani (1980) only consider such packing where no overlapping between the blocks occurs. All block heuristics include the possibility of empty blocks. These solutions are so-called degenerated solutions. With the four-block heuristic a gap may appear in the middle of the base. Therefore Bischoff and Dowsland (1982) improved the four-block heuristic by introducing a fifth and later also sixth and seventh block.

### 2.3.4 Five- and Seven-Block Heuristic

The five- and seven-block heuristics try to improve the four-block heuristic. The five-block heuristic by Bischoff and Dowsland (1982), tries to improve a four-block solution by filling the gap which sometimes occurs in the middle of the
rectangle with another block. The seven-block heuristic, which was introduced by Dowsland and Dowsland (1983) and improved by Exeler (1988), deals with improper solutions of the four blocks. Frequently, the placement of the four blocks according to a quadruple of efficient partitions will not result in a proper solution because of overlappings either between block one and three or between block two and four. It tries to eliminate the overlapping in such way that the inevitable waste is minimised. Figure 12 shows an example\(^5\) where 32 boxes fit on the base with the four-block heuristic while 33 fit with the five-block heuristic.

The five-block heuristic was developed by the aim of improving the four-block heuristic by filling the gap in the middle of the base with a fifth block. This can be done by little additional work and expense. Bischoff and Dowsland (1982) build their algorithm on the enumeration of the best arrangement of boxes along one side for the long side and the broadside. With these combinations the most efficient patterns are found by simply enumerating them and selecting the best solution. Afterwards, the inward projection is done like in Steudel’s four-block heuristic with the same constrains concerning overlapping. With the four developed blocks it is possible to calculate the hole in the middle. This hole is then optimised by a one-block heuristic, i.e. the orientation of the block in the middle is not predefined like for the other blocks (see Figure 13).

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\(^5\) Taken from Bischoff and Dowsland (1982), p275.
In stage one the calculation of ‘efficient partitions’ of the length $A$ and the width $B$ of the base are calculated. The ‘efficient partitions’ are defined as combinations $(n,m)$ of box length $a$ and width $b$. For stage one the formulation of the heuristic is the following:

$$na + mb \leq S \quad \text{and} \quad S - na - mb \leq b,$$

i.e. it should be packed as many as fit. Afterwards, in a second step the patterns from the ‘efficient partitions’ of the four base sides are generated. In general, for rectangular bases with $x$ efficient partitions of the length and $y$ efficient partitions of the width there are $x^2 y^2 / 2$ arrangements which have to be considered (Exeler 1988). It yields $(n_l, m_l)$, $(n_r, m_r)$, $(n_t, m_t)$ and $(n_b, m_b)$ respectively for the left, right, top and bottom side respectively. To take the orientations into account the dimensions of the areas are defined as:

$$A_1 = n_l a, \quad A_2 = m_l b, \quad A_4 = m_t b, \quad A_5 = n_r a,$$

$$B_1 = m_l b, \quad B_2 = n_l a, \quad B_4 = n_r a, \quad B_5 = m_t b.$$

The area in the centre of the base needs to be as large as possible; therefore the four blocks are positioned in the four corners of the base. Thus the remaining area three in the middle of the base can be calculated. Unlike the procedure of Smith and de Cani, this one does not necessarily lead to a feasible arrangement. Configurations of an unfeasible character can be identified by:

$$A - A_1 - A_5 < 0 \quad \text{and} \quad B - B_1 - B_5 < 0 \quad \text{or} \quad A - A_2 - A_4 < 0 \quad \text{and} \quad B - B_2 - B_4 < 0.$$
The termination criterion is fulfilled if the remaining space on the pallet is less than the area needed for one single box.

The seven-block heuristic was invented by Dowsland and Dowsland (1983), because in some cases the four- and five block heuristic do not find the optimal solution due to overlappings between block one and three or between block two and four. In these cases the seven-block heuristic tries to eliminate the overlappings in such a way that the evitable waste is minimised.

![Figure 14](image1.png)  
Figure 14 Solutions of the different block heuristics

The example Dowsland and Dowsland (1983) used is explained in the following with Figure 14. The solution for this example is eight units, calculated both by the four- and five-block heuristic respectively. The procedure of the seven-block heuristic is based on the five-block heuristic by Bischoff and Dowsland (1982) and calculates nine units. The seven-block heuristic checks the unallowable solutions due to overlapping of the five-block heuristic. If such cases are found the overlapping blocks are divided into two parts. Dowsland and Dowsland allowed two possible divisions to minimise the unused space wherefore seven blocks develop (see Figure 15).

![Figure 15](image2.png)  
Figure 15 Example from Dowsland and Dowsland (1983)
1. The blocks 1a and 5a are not allowed to be larger than block 2 and 4, respectively, in the vertical direction. Simultaneously, block 1b and 5b should be larger than blocks 4 and 2, respectively, in the horizontal direction.

2. The second possibility is like case one but the other way around. Block 1a and 5a should be smaller than 2 and 4 while block 1b and 5b should be larger than 4 and 2.

This concept was enlarged by Exeler (1988) with two cases. The additional two cases are:

3. Block 5a and 5b are over the boundary lines of block 4 and 2 while block 1a and 1b are under the boundary line of 2 and 4.

4. Is like case three but the other way around. Block 5a and 5b are under the boundary lines of block 4 and 2 while block 1a and 1b are over the boundary line of 2 and 4.

The four cases all aim to minimise the unused space. A good visualisation of the four solutions can be found in Nelißen (1993). The computation time to consider all possible arrangements of the four divisions would take too much time due to the great number of possibilities.

2.3.5 Nine-Block Heuristic

Exeler (1988) developed the nine-block heuristic. The incentive was the fact that generally in most cases with increasing number of blocks the quality of the solution increased. This circumstance is for sure if the for $m>n$ the m-block heuristic considers all arrangements of all n-block heuristics. One example for this case is the seven-block heuristic which is considering all arrangements of the five-block as well as the four-block heuristic. Of course, with more blocks the heuristic becomes more complex and requires more calculation time. Therefore a consensus between the quality of the solution and the computing time has to be found. Exeler justifies his nine-block heuristic with an example where the four-, five- and seven-block heuristic arrange fewer boxes on the base than the nine-block heuristic. In the following this example is presented.
In Figure 16 the solution of the nine-block heuristic is displayed, which is able to pack 25 boxes on the base. The four-, five- and seven-block heuristics are just able to pack 24 boxes on the base.

The proceeding of the nine-block heuristic builds up from the enlarged seven-block heuristic. At first, one block is build up along the long and one along the small side of the base, which is the so-called exterior block. For the remaining rectangular space the enlarged seven-block heuristic is used. The arrangement and orientation of the exterior and remaining space depend on the start arrangements with the exterior blocks. Thus, many feasible and different combinations are possible, which are all considered within this heuristic. However the heuristic avoids solutions, in which both exterior blocks disappear. It is just feasible to have at least one of the two exterior blocks. Thus, it is avoided that the heuristic transfers into the seven-block heuristic.

Already Figure 16 displays a packing plan which is not easy to follow in a short amount of time. In most cases, in practice the packers do not have much time for packing a load unit. Therefore the packing plan should offer a fast and easily understandable structure. Due to this, in some cases the aim is to find a consensus not only with the amount of boxes in on load unit and the computation time for calculating a solution but also between the packaging times of the packers as time costs money.

### 2.3.6 Exact Procedures

Since the seventies, some exact algorithms have been developed. Nelißen (1993) suggests using these kinds of algorithms if the best heuristic solution and the minimal upper bound are not identical, i.e. the solution (no heuristic) is optimal or the upper bound is not accurate. The algorithms are based on a branch and bound structure, i.e. all possible solutions are enumerated.
Branch and bound signifies that a tree search is performed. Each node of the tree is associated with a partial packing of boxes on the pallet. A violation of a constraint in any node results in the cutting of the branch as it cannot lead to an optimal solution. There is a variety of possibilities to define the constraints and further reading to this topic can be found in Nelißen (1993).

The exact procedure for the heterogenic packing problem, which is presented in the following, is developed by De Cani (1979). The situation which has to be solved is the following:

Let \( x \) be the total number of rectangles with \( m \) different shapes. Furthermore, let \( x_i \) be the number of identical rectangles of shape \( i, i = 1,\ldots,m \), and let \( q \leq x \) be the number of squares. The rectangles have the side lengths \( l_i \cdot b_i \) \((i = 1,\ldots,m)\) and shall be arranged on a larger rectangular base \( L \cdot B \) in a manner that the unused space is minimised. Thereby, overlappings and protrusions of rectangles over the base are not allowed. Additionally, the requirement for orthogonality has to be fulfilled.

![Figure 17 Example for exact procedure of De Cani (1979)\(^6\)](image)

In the solution all small rectangles are arranged on the base, if such a solution exists. If the algorithm considers the space between the rectangles to be variable there are infinite solutions. In order to create a finite number of arrangements the rule is introduced that every small rectangle has to be arranged in such a way that shifting vertical down and horizontal to the left is not possible. In other words, it has to touch at least one part that has already

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\(^6\) Taken from Exeler (1988), pp 76-78
been placed. There are still many possible arrangements, which make the procedure quite complex in time. To enumerate all possible arrangements all sequences of the small rectangles have to be found and all orientations have to be considered. For every sequence of small rectangles and for every orientation of each rectangle there exists an arrangement tree.

Every part has two possible orientations apart from the \(q\) quadratic rectangles, which have only one. Therefore, \(2^{x-q}\) possible trees exist considering only the orientations for the \(x\) rectangles. Combined with the number of different sequences in which the parts can be sorted the total number of possible trees is

\[
\frac{n!}{\prod_{i=1}^{m} x_i!} \cdot 2^{x-q}.
\]

Note that the number of sequences depends on how many identical parts there are. In Figure 17 an example is displayed for the proceeding of the exact algorithm. The base and the seven rectangles are displayed in Figure 17 A). There, the sequence and orientation of the rectangles is already fixed. For this example \(2^7 \cdot 7! = 645120\) trees exist. At first the rectangle 1 is placed in the lower left corner of the base. Thus, the first rectangle has always just one possible arrangement if it fits on the base. The second one already has two possibilities, one on the top (B) of the first rectangle and one to the right (C). In this example the third rectangle has three possible arrangements, one with the second one on the top of the first and two with the second one to the left of the first (see D-F). In G) the only possible solution with all parts arranged on the base is displayed.

![Figure 18 Tree for example](image)
In Figure 18 the associated tree to the example is presented. There, it can be seen that just one solution exist, in which all seven rectangles are arranged on the base. The tree always has at most as many stages as there are rectangles. The nodes marked with the characters represent the appropriate characters in Figure 17. The hatched nodes are end nodes, i.e. at this stage it is not possible to arrange the next rectangle in sequence on the base without overlapping or protrusion. From these end nodes the one is chosen with the minimal unused space. Apparently this procedure is very complex and therefore time consuming, but it can be used in case where heuristic do not offer a good quality.

2.3.7 Computation Time

For the selection of an adequate solution for a packing problem of this thesis two main factors influence the decision. On the one hand the computational time and on the other hand the quality of the solution plays an important role. Exeler (1988) evaluated the four-, five-, seven-, and nine-block heuristic by a theoretical and computer-aided analysis. For the theoretical case he calculates the worst cases of time needed for solving a given problem. The results of his calculation are displayed in Table 2, whereby \( k_4 < k_5 < k_7 \). The four-, five-, and seven-block heuristics all have a complexity of \( O(n^2) \) and differ just slightly in \( k_i \ (i = 4,5,7) \). Only the nine-block heuristic is much more complex with \( O(n^4) \).

<table>
<thead>
<tr>
<th>Type of heuristic</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four-block</td>
<td>( O(k_4n^2) )</td>
</tr>
<tr>
<td>Five-block</td>
<td>( O(k_5n^2) )</td>
</tr>
<tr>
<td>Seven-block</td>
<td>( O(k_7n^2) )</td>
</tr>
<tr>
<td>Nine-block</td>
<td>( O(n^4) )</td>
</tr>
</tbody>
</table>

The computer-aided analysis is conducted with a two samples of 5000 data sets. The first 5000 data sets result in the output shown in Table 3. To test the quality of the results the solutions are compared with the upper bounds. The number of results in which the heuristic solution equals the upper bound is the lower bound (worst case) for the cases that an optimum is found because generally an upper bound is too optimistic. That does not imply that there are not more cases in which the optimum is found. In these cases the upper bound does not equal to the optimum. For the four-block heuristic 4607 of 5000 data sets result in the optimum which is equivalent to 92.14 per cent, and in just four cases the deviation is greater than one. The result of the analysis is that the
quality of the heuristics is quite equal for the four-, five-, seven-, and nine-block heuristic, which is over 90 per cent.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Computer-aided results of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heuristic</td>
<td># Achieved Optimum</td>
</tr>
<tr>
<td>Four-block</td>
<td>4607</td>
</tr>
<tr>
<td>Five-block</td>
<td>4692</td>
</tr>
<tr>
<td>Seven-block</td>
<td>4814</td>
</tr>
<tr>
<td>Nine-block</td>
<td>4586</td>
</tr>
</tbody>
</table>

Exeler also evaluated the average and maximal time needed of each algorithm\(^7\). The results are displayed in Table 4. The four-block heuristic offers the best result for average and maximum time needed, but the results differ just slightly from the five- and seven-block heuristic. The nine-block heuristic provides the worst results. It already provides the worst results for quality.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Analysis of the time needed for each heuristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heuristic</td>
<td>Average Time needed (sec)</td>
</tr>
<tr>
<td>Four-block</td>
<td>0.1575</td>
</tr>
<tr>
<td>Five-block</td>
<td>0.2249</td>
</tr>
<tr>
<td>Seven-block</td>
<td>0.3664</td>
</tr>
<tr>
<td>Nine-block</td>
<td>12.5556</td>
</tr>
</tbody>
</table>

In a second data set with 5000 samples, in which the base of the palette is doubled, the results are slightly different but the structure is the same. The second data set points out that the time needed increases heavily with the size of the problem.

Considering the results of the analysis, Exeler suggests to use the four-block heuristic if a low computational time is important and to use the seven-block heuristic for high quality requirements.

The exact algorithm needs in some case extremely long computation times. Exeler tested the exact algorithm with different samples. For the sample with a base of 1060mmx813mm and rectangles of the size 355mmx180mm the algorithm needed around 50 hours to show that not more than ten rectangles fit on the base. Computational times like this are obviously intolerable. Concerning Alvarez-Valdes et al. (2005) the exact algorithms have been able to solve problems of only moderate size which is of up to 50 rectangles. But also the aim of Alvarez-Valdes et al. (2005) to create an exact algorithm, which is able to pack up to 100 rectangles, is still not applicable for practical problems.

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\(^7\) The calculations have been made by Exeler (1988) on a Commodore PC 10 with operating system MS-DOS 2.0 and the computer language Turbo-Pascal 2.0.
2.4 Three-Dimensional Packing Problems

2.4.1 General Aspects

While the two-dimensional packing problems presented in the previous chapter already involve a certain complexity, three-dimensional problems are even more complex. For the task of packing containers with items it is generally not optimal to use a two-dimensional approach and to put as many layers as possible of an optimal two-dimensional packing plan over each other until the container is full. This is only the case for homogeneous packing problems where the orientation of the parts in z-direction cannot be changed. Here, any layer of parts has the same height independent from the packing plan, and furthermore, the feasible number of layers is given. Nevertheless, for situations where the orientation of the items can be changed or for heterogeneous packing problems, the solution needs to fully consider the third dimension. In these cases it is either possible to construct layers of items with different heights or impossible to construct layers with a constant height at all.

Besides this complexity to identify such optimal packing plans, it is also difficult to illustrate them. This makes it difficult to practically use them for the packing of containers through workers as it might be necessary to visualise them with several two-dimensional cuts. The time required to realise those schemes and the risk for mistakes are reasons why it might be better to stick to two-dimensional solutions with suboptimal but practical results. Nevertheless, in the following, two approaches for the heterogeneous three-dimensional packing problem are presented.

2.4.2 Solutions for Three-Dimensional Packing Problems

Martello et al. (2000) suggest approaches to solve the three-dimensional packing problem with heterogeneous goods. Their main focus lies on a question that is slightly different from the one asked in this thesis: How many bins are needed in order to completely pack a given set of rectangular items of different sizes? Even though this question is different from the one important for this thesis, within their branch-and-bound approach they apply an algorithm that optimally fills a single container. As this is the main question of this thesis, in the following only this part of their paper is depicted.

Before they introduce the exact algorithm, Martello et al. start with a more basic approach. Although they only use it for a proof of the worst case performance of a simple lower bound, it shows an intuitive way to reduce the three-dimensional problem in a very efficient way to several two-dimensional problems. The idea
of the algorithm is to divide all parts into groups of similar depth and to make use of a two-dimensional packing algorithm which was introduced by Martello and Vigo (1998).

They start with partitioning all parts according to their depth relative to the depth of the container. Their partitioning rule is to assign an item $j$ to subset $J_j$ if and only if the item's depth $d_j$ satisfies

$$\frac{D}{2^{i+1}} < d_j \leq \frac{D}{2^i}.$$ 

Depending on the size of the container this leads to $q = \left \lceil \log_2 D \right \rceil + 1$ different subsets of which some may be empty if there is no part with the respective depth. The result of this partitioning is that the first subset $J_0$ contains all the items which have a depth of more than $D/2$, that $J_1$ contains those with depths between a quarter and a half of $D$, and so on.

In the next step they use a two-dimensional packing algorithm for the parts in each group. This algorithm packs the parts in a way that uses as few containers as possible. For this, only the length and the height of the parts and the containers are considered. The results of this packing are several so called "bin slices" with the artificial depth of the respective subset of parts which they contain. In a third step, these bin slices are assembled to full bins by sorting the slices according to decreasing depth and assigning each slices to the earliest bin possible.

It is quite obvious that this solution does not really consider the three-dimensional quality of the problem. Within each bin slice, there is unused depth of up to almost 50 per cent in the worst case. This space cannot be used for other slices, it is merely lost. In order to improve the performance, an algorithm is required that optimises the packing plan with respect to all three dimension in the same priority.

In the following, the exact solution for a three-dimensional packing problem is shown. Martello et al. (2000) suggest an enumerative algorithm for this problem which they call "filling a single bin". The task is to identify for a given set of items $J$ a subset $J' \subseteq J$ and to assign coordinates $(x_j, y_j, z_j)$ to each item $j \in J'$ such that no item goes outside the bin, no two items overlap and the total volume of the items in $J'$ is maximised. The coordinates $(x_j, y_j, z_j)$ denote the position of the left-bottom-back corner of the respective part in a coordinate system with its origin in the lower left corner of the backside of the container, too. According to the classification in Chapter 2.1, their approach proposes a
sequential assignment heuristic because Martello et al. do not create and fill a certain pattern in the container but assign all items consecutively to its best location. To find the exact solution of the packing problem, a branch-and-bound algorithm is used. This algorithm identifies for each part all "admissible" points which lie in the corners of the items already packed and of the container itself. If item $j$ is to be assigned next, every available corner point creates a new node for the branch-and-bound tree. Like in all branch-and-bound approaches, the best solution is chosen once all possible combinations are either branched or bounded.

To identify all admissible points for item $j$, they make use of the characteristics of some properties. Firstly, it is not feasible to select coordinates such that either $x_j + h_j > W, y_j + h_j > H$ or $z_j + d_j > D$, because then the item would go outside the bin. Secondly, an optimal packing scheme always places the parts as close to the origin as possible, i.e. no item is placed in the “open space” where it could be moved backward, leftward or downward. The third property says that it is possible to find an ordering of all parts in an optimal packing such that the item's index is smaller the closer it is to the origin. Formally this means that if $i < j$,

$$x_i + w_i \leq x_j, y_i + h_i \leq y_j \text{ or } z_i + d_i \leq z_j.$$  

Martello et al. (2000) proof this by considering an associated digraph with arcs from vertex $i$ to $j$ only if property three holds. As this digraph has to be acyclic, a renumeration is possible such that $i < j$ if an arc from $i$ to $j$ exists.

A sequential packing scheme that is based on these properties follows a certain rule: Every item that is added to the already packed ones has to be placed in a corner in order to avoid unnecessary empty spaces according to property two. Due to property three, only those coordinates can be chosen such that at least one of three possible relations between the new item and each previously assigned part exists: Either, the new item lies (a) above, (b) right of or (c) in front of each "old" item. Formally this means that if $I$ is the set of already stored parts, the coordinates of an item $j \in J \setminus I$ need to satisfy

$$S(I) = \{(x, y, z) : \forall i \in I, x \geq x_i + w_i \text{ or } y \geq y_i + h_i \text{ or } z \geq z_i + d_i\}.$$  

Through this, property three creates an "envelop" around the items in the container such that a new part can only be placed outside this envelope. A two-dimensional example of this envelope is illustrated in Figure 19.
According to property two, any new item can only be placed in a corner of the envelope. In their approach, Martello et al. apply an algorithm called 2D-CORNERS that identifies all admissible corners for two-dimensional problems and use the results to determine the three-dimensional corners. For this, the container is divided into slices alongside its depth. This partitioning is done in a way that all items in the respective bin slice completely fill the slice’s depth. Thus, at every coordinate satisfying $z = z_i + d_i$ a slice ends. Through this definition, within each slice there can only be two blocks with two different depths: Each point either has the depth of the slice (if a part is located there) or a depth of zero (if there is no part) which means that a two-dimensional algorithm can be applied without loss of information.

In the following let $I$ be the set of items currently packed in the slice $s$. In order to find the set of admissible two-dimensional corners $C'(I)$ the items are resorted according to their total height in the container $y_j + h_j$ (and not according to their individual height $h_j$). If several items are on the same level, the item with its end point $(x_j + w_j)$ further to the right comes first. Outside of 2D-CORNERS, the initial indexing of all packed items according to property three remains unchanged. The following depiction of the algorithm is taken from Martello et al. (2000):
Algorithm 2D-CORNER:

Begin

Comment: If no item has been placed yet, the only corner point is the origin;
If \( I = \emptyset \) then \( C'(I) = \{(0,0)\} \) and return;

Comment: Phase 1 (identify the extreme items \( e_1, \ldots, e_m \));
\[ \bar{x} := m := 0; \]
For \( j := 1 \) to \( |I| \) do

If \( x_j + w_j > \bar{x} \)

Then \( m := m + 1; \quad e_m := j; \quad x := x_j + w_j; \)

Comment: Phase 2 (determine the corner points);
\( C'(I) := \{(0,y_{e_1} + h_{e_1})\}; \)
For \( j := 2 \) to \( m \) do

\( C'(I) := C'(I) \cup \{(x_{e_{j-1}} + w_{e_{j-1}}, y_{e_j} + h_{e_j})\}; \)
\( C'(I) := C'(I) \cup \{(x_{e_m} + w_{e_m}, 0)\}; \)

Comment: Phase 3 (remove infeasible corner points);
for each \( (x'_j, y'_j) \in C'(I) \) do

if \( x'_j + \min_{i \in I, i < j} w_i > W \) or \( y'_j + \min_{i \in I, i < j} h_i > H \)

then \( C'(I) := C'(I) \setminus \{(x'_j, y'_j)\} \)

end.

In Phase 1 the algorithm finds all so called extreme items, which are items whose end points mark a position where the slope of the envelop changes (coming from the left-hand side) from horizontal to vertical. The x-coordinates of these items are necessarily the x-coordinates of the corner points (with the exception of the leftmost corner point if it lies directly at the beginning of the container). Beginning with the lowest indexed item in \( I \), an item is “extreme” if it ends further to the right as all previous (in terms of the index) ones. Due to the previous sorting of the parts according to non-increasing total height the focus on only the x-coordinates is sufficient to ensure that no item is chosen which does not end in a corner point.

After all extreme items are found, the coordinates of the corner points can be created by combining the x-coordinate of the end point of any \( e_j \) with the y-
coordinate of the end point of \( e_{j+1} \). Additionally, there are corner points on the left-hand side of the container at the total height of the item \( e_i \) and on the bottom of the container at the total width of \( e_a \). In Phase 3 all those corner points are eliminated which are too close to the upper or the right-hand side of the container so that none of the items which have not been packed yet would fit there.

![Figure 20 Corners in the three-dimensional container](image)

It is possible that there are some false corner points among all points in the bin slices found by 2D-CORNERS. As shown in Figure 20, there are some corners in the two-dimensional case which are none in the three-dimensional view because they lie at \((x,y,z)\)-coordinates where no item ends. These “dominated” corner points are marked with empty circles and can be identified through the simple criteria that any corner point \((x'_a, y'_a, z'_a)\) is eliminated that satisfies

\[
x'_a = x'_b \quad \text{and} \quad y'_a = y'_b \quad \text{and} \quad z'_a < z'_b
\]

for any other set of coordinates in \( C'(I) \). The real corner points are marked in Figure 20 with black dots. In order to find all admissible three-dimensional corner points \( C(I) \), Martello et al. (2000) apply an algorithm called 3D-CORNERS. The following algorithm is very similar to the one in their paper although it is slightly changed in one aspect.
Algorithm 3D-CORNERS:

Begin

Comment: If no item has been placed yet, the origin is the only corner point;
If \( I = \emptyset \) then \( C(I) = \{(0,0,0)\} \) and return;

Comment: Identify and sort the set of bin slices;
\( T := \{0\} \cup \{z_i + d_i : i \in I\} \) (without duplicating equal values in \( T \));
Sort \( T \) by increasing values and let \( T = \{z'_1, \ldots, z'_r\} \);

Comment: Initialise values;
\( C(I) := C'(I) := \emptyset; \quad k := 1; \)

Comment: Identify all slices that allow the placing of at least one more part;
While \( k \leq r \) and \( z'_k + \min_{i \in r_4} \{d_i\} \leq D \) do

Begin

Comment: Define the set of parts in the current slice (difference to Martello et al. (2000));
\( I_k := \{i \in I : z_i + d_i > z'_k \land z_i \leq z'_k\} \);

Comment: Identify all two-dimensional corners;
apply 2D-CORNERS to \( I_k \) yielding \( C'(I_k) \);

Comment: Only add the true corner points to \( C(I) \);
for each \( (x'_j, y'_j) \in C'(I_k) \) do
  if \( (x'_j, y'_j) \notin C'(I_{k-1}), \quad \forall s < k \)
  then \( C(I) := C(I) \cup \{(x'_j, y'_j, z'_k)\} \);
end

Comment: Only add the true corner points to \( C(I) \);
for each \( (x'_j, y'_j) \in C'(I_k) \) do
  if \( (x'_j, y'_j) \notin C'(I_{k-1}), \quad \forall s < k \)
  then \( C(I) := C(I) \cup \{(x'_j, y'_j, z'_k)\} \);
end

end.

This algorithm works as follows. In the case that the container is still empty, there is only one admissible corner point because the first part is always placed in the origin. As soon as at least one part has already been packed the set \( I \) is non-empty and the main algorithm begins. It starts with identifying all bin slices. One bin slice is always the backside of the container where \( z = 0 \) and any additional slice ends at the end point in z-direction of at least one part the bin (see Figure 21). Because the algorithm identifies these slices with respect to increasing indices instead of increasing z-coordinates it is necessary to sort them with respect to their position in the container. Let \( r \) be the total number of slices. Afterward it is checked for all slices whether they allow enough free space to the front side of the box so that at least one of the yet unpacked items can fit in. Due to this test it is possible that only \( k^* < r \) slices are actually usable.
For each slice $k$ satisfying this condition, the set $I_k$ of all those parts is identified which begin with the slice or before it and which exceed it in z-direction. This means that those items ending exactly with the slice $k$ (and thus defining it) do not belong to $I_k$. In Figure 22 this can be seen as slice IV does not include item 4. For each $I_k$ the algorithm 2D-CORNERS is applied yielding all two-dimensional corner points as illustrated in Figure 22. After identifying all relevant coordinates for slice $k$ only the "real" corners in set $C(I_k)$ are added to the set of three-dimensional corner points $C(I)$. A non-real corner point $(x, y, z)$ is characterised by the fact that in one of the previous slices the algorithm 2D-CORNERS found a real corner with coordinates $(x', y', z')$, $z' < z$. In other words, point $(x, y, z)$ lies on a straight line in z-direction from point $(x', y', z')$. As the slices do not necessarily increase in z-direction with increasing $k$, it is possible that such a false corner is identified across several slices (i.e. $s > 1$ in the above algorithm).

In order to identify the optimal packing plan for the bin, both algorithms, 2D-CORNERS and 3D-CORNERS, are implemented into a branch-and-bound scheme. The branching is set up as a complete enumeration of all possible combinations of placing the parts into the container. If the set $I \subset J'$ is currently packed, the above algorithm determines the set of all admissible corners points $C(I)$ and assigns all remaining items $j \in J' \setminus I$ to all those positions where they
do not exceed the containers borders. This means that in the first step, i.e. \( C(\emptyset) = \{(0,0,0)\} \) a branch is created for every item placed in the origin if the bin.

Martello et al. (2000) suggest the following bounding. Let \( v_i \) be the volume of item \( i \in J' \). With this, the volume \( V_i \) of the current packing scheme is \( V_i = \sum v_i \). Let \( F \) be the volume of the currently best filling. As soon as no other item can be added to the bin at a certain branch, it is bounded and if \( V_i > F \) \( F \) is updated and the branch-and-bound algorithm backtracks. Additionally, a branch is bounded as soon as it becomes obvious that it cannot lead to a solution better than \( F \).

For this, the concept of the envelope around the currently packed items is used because it was shown above that new parts can only be added outside this envelope. If the volume of the items plus the remaining space outside the envelope is smaller than \( F \), the respective branch is bounded and the algorithm backtracks. Note that the envelope is generally not completely filled with items but has some free space. Its size can be calculated as the product of the two-dimensional envelope around every bin slice identified in 3D-CORNERS and the depth of this respective slice. Given the two-dimensional corner points \( C'(I_k) = \{(x'_{11},y'_{11}),..., (x'_{e_e},y'_{e_e})\} \), the area \( A(I_k) \) around the parts inside a bin slice is

\[
A(I_k) = x'_{11} H + \sum_{i=2}^{e_e} (x'_{i-1} - x'_{i-2}) y'_{i-1} + (W - x'_{e_e}) y'_{e_e}.
\]

This formula just calculates the product of length and width of all blocks between the corner points. Due to the characteristics of the corner points, the first term is zero as long as there is an item left that fits in top of the column of parts in \( I_k \) with x-coordinates in the origin. If this block of items either completely fills the height of the container or makes it impossible for any other item to be packed on top of it, the envelope touches the top of the bin. The same situation is relevant for the last term, which is zero as long as block \( I_k \) leaves enough space for another part on the bottom of the bin. In the case that a packing scheme does not allow any further item to be added, the envelope necessarily covers the whole area, thus \( A(I_k) = WH \).

Given these two-dimensional measures for the envelopes, it is possible to calculate the total volume \( V(I) \) of the envelope in the container. This volume is

\[
V(I) = \sum_{k=1}^{k_k} (z'_{k-k-1}) A(I_{k-1}) + (D - z'_{k_k}) A(I_{k_k}).
\]

53
For this formula, it is important to distinguish between the total number of slices \( r \) and the number of usable ones \( k^* \) because all the space in front of slice \( k^* \) is lost. Thus, it needs to be included in the envelope which is achieved through the last term of \( V(I) \).

With the terms introduced above, it is possible to calculate the theoretically best volume that can be packed in the container at a current branch. If

\[
\sum_{i \in I} v_i + (B - V(I))) \leq F,
\]

it is not possible to achieve a higher utilisation of the container than with the currently best solution. Thus it does not make sense to follow this branch any further and it is bounded so that the algorithm backtracks. As long as Formula (2.1) is not satisfied, all admissible corner points are identified and all unpacked items are assigned (if possible).

This algorithm works best if all items in \( J \) are sorted to non-increasing volume. According to Martello et al. (2000) this characteristic can be found for most packing algorithms, independent from the number of dimensions they cover. This exact approach is very time consuming because it calculates a great number of possible combinations to pack the container. Therefore, Martello et al. suggest another, additional embracing branch-and-bound scheme which relies at first on faster heuristics and does not require the use of ONEBIN in every step. Nevertheless, as their approach becomes even more complex through this, it is not discussed any further here.

It becomes clear that the three-dimensional packing problem is multifaceted. The problematic mainly comes from the integer condition and the high number of possible combinations to pack each container. These facts are the reason why it makes sense to reduce a problem to the two-dimensional case as often as possible. Especially when all items are of the same rectangular size, the relaxation from three to two dimensions usually does not lead to significantly lesser performance. This is due to the fact that it should generally be possible to pack layers that have a constant height.

### 2.5 Conclusion

In this chapter, the characteristics of as well as several approaches for the packing problem have been presented. Through this, some insights have been made. At first, there are many different specifications of the packing problem. Secondly, all specifications are generally quite complex to solve and depending
on the approach require long computation times. Thirdly, to choose an approach for a certain problem, both the speed and the quality of the available algorithms are relevant criteria. The application of heuristics is the most common way in practice because they offer a good trade-off between these two criteria.

The knowledge from this chapter is applied in Chapter 4.3.1, where a tool for the packing of the load units at BMW is developed. Before that, the following Chapter 2 deals with the current situation at BMW.
3 Current Situation

In this chapter the reader shall get an overview about the current situation of the material flow, the load units, and the assembly parts at BMW. The current situation is the foundation and source for the information required for the analysis, which will follow in the next chapter.

3.1 Material Flow

This section deals with the flow of the load units from the suppliers to the assembly line and back. All relevant processes are broken down to subprocesses as this is necessary for the allocation of the costs.

The material flow is important for this thesis as it describes the path of the load units through the system. In order to create a structured display of the material flow, the process mapping presented in Chapter 1.6 is applied. This is important to understand the assignment of expense ratios to the appropriate processes in Chapter 4.4.

For the issue of this thesis, the relevant products are the containers. From this it follows, that only an excerpt of the whole material flow of BMW is examined. There are more warehouses and handling processes than presented in the following. Nevertheless, they are not related for the standard load units and they can thus be skipped. Due to the reuse of the load units, their path can be described as a circle without starting point or end. Nevertheless, as the load units are used to support the supply of the assembly parts, it makes sense to define the supplier as the starting point of the process and the assembly line as its end. In between these two stations, several processes take place which are displayed in Figure 23.

![Figure 23 Container flow for the BMW plants](image)

Three core processes can be identified, which are transportation, storing and the intraplant transportation of the containers. This map is to some extent

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8 One could argue that the starting point for the load units is their acquisition and their end point the disposal. Nevertheless, as such a perspective poses too much attention on the less relevant aspects of the containers; it would not make sense to use it here.
generic as it could be applied to almost any manufacturing company. Anyway, this should not be surprising as the level of aggregation is very high.

In the following, this map needs to become more detailed. For this I segmented the core processes into sub processes. This step sometimes requires the differentiated consideration of the three production sites in Dingolfing, Munich and Regensburg. As there are significant similarities in the flow in all three plants – but especially in Dingolfing and Munich – they are examined together as often as possible. Whenever there are important differences, they are pointed out in the process mapping.

Figure 24 displays a detailed map of the material flow in Dingolfing and Munich. A similar presentation for the plant in Regensburg is shown in Figure 25.

The starting point of the material flow for all plants can be distinguished in internal and external suppliers. Internal suppliers are other BMW plants and external suppliers are independent companies. Both kinds of suppliers deliver assembly parts and modules for the final production of the cars. As there are differences in the execution and calculation of these two kinds of deliveries, the transportation is also divided into the two sub-processes external and interplant transportation. Furthermore, the returning of the empties is part of this process. After the reception of the parts, the storing takes place in different kinds of warehouses where all plants use automatic and block storages. In Regensburg there is additionally a high-bay rack. The high-bay rack is a shelf, which like the automatic storage only is capable of a special size of load units.
For the internal transportation process there are two possibilities: The first one is the transportation of containers by trailer and the second one by AMA. The finishing point of the flow of load units is the assembly area. This area is divided into two instances for Dingolfing and Munich and one for Regensburg. The reason for this is that Dingolfing and Munich both assemble on more than one floor while Regensburg assembles on just one. From the finishing point the empty containers flow back to the supplier.

Besides this standard material flow, there are also special delivery strategies which are synchronised with the production. These strategies are Just-In-Sequence (JIS) and Just-In-Time (JIT) deliveries. With JIS, a specified set of assembly parts is delivered at a defined time-spot and in processing sequence. With JIT, a certain type of parts is delivered exactly at that time when their stock is about to run out. Deliveries synchronised with the production are supplied directly to the assembly area and are not stored in the warehouses. Both for JIS and JIT mostly specialised load units are in use. Due to the fact that the standard load units considered in this thesis are mainly not involved in these synchronised processes the further analysis concentrates on standard processes with storekeeping.

In the following subchapters the three core processes are discussed further.

### 3.1.1 Transportation

The transportation processes for the three plants are very similar. The purpose of this chapter is to give an understanding for the assignment of the expense ratios in Chapter 4.4. Thus, the processes are described on the example of the plant in Dingolfing.

The plant in Dingolfing has around 700 internal and external suppliers for over 25,000 different parts, wherefore the plant has around 900 places for unloading. Every day, around 12,500 load units with purchased parts are delivered. The
transportation to the BMW plants has several characteristics. At first the type of transportation can be categorised into truck, train, ship and, airplane transportation. The backbone of the BMW transportation network are the trucks. Together with the train it covers the overland transportation. While the train is very cheap for high volume transportations, it is rather inflexible and needs significantly more transportation time than a truck. This causes that over 95 per cent of overland transportation is done by truck. The supply by ship is mainly conducted for the plants in Spartanburg, USA, and South Africa. The possibility of transportation by airplane is by far the most expensive option. Its biggest advantage is the rapidness which allows worldwide delivery in between 24 to 48 hours. Thus, airfreight is only used in exceptional cases. Due to the fact that the considered containers are mostly supplied by truck and the location of the suppliers using these containers I concentrate on truck transportation in the following.

The distances from the suppliers to the plant in Dingolfing are displayed in Figure 26. Furthermore, the number of different articles that are delivered from the respective distances is given. It becomes obvious that there is a great diversity of parts from close to far distances.

Another categorisation which can be made in the transportation process is the interplant transportation and the transportation from external suppliers to the BMW plants. Interplant transportation is taking place between the production sites in Germany. Besides the automobile producing plants in Regensburg, Munich, Dingolfing and Leipzig, there are production sites for semi-finished goods in Landshut and Wackersdorf. The network with distances between these plants is displayed in Figure 27.
The interplant transportation is executed by external shipping companies. For this special contracts exist that assign complete routes from one plant to another to one shipper.

In a similar manner contracts are negotiated with shippers for the transportation of the assembly parts from external suppliers. The concept for external suppliers is to assign one shipper for a certain area. This shipper uses one hub where he consolidates the shipments from all suppliers in his area. From this hub and sometimes other, selective points the shipper supplies the BMW plants on a main run. This concept is displayed in Figure 28.
The advantage of this concept is that it is self-regulating and self-operating because the shippers assume all planning. Additionally it is easier to integrate new suppliers as this is a standardised procedure. However, there are disadvantages like a multitude of contracts and interfaces. During the time of this thesis, this concept was in review and BMW was in negotiations to centralise the external transportations to one large shipper.

### 3.1.2 Storing

After the trucks have arrived at the plants and the data of their delivery has been recorded they are unloaded at the warehouses. The storing in the three plants is not as uniformly as the transportation because each plant has its own internal infrastructure. This is one of the reasons why the material flow of Regensburg required its own presentation in Figure 25. The three different kinds of warehouses are automatic and block storages as well as high-bay racks.

In the automatic storages of BMW the storing and removal from storing is automated. Furthermore, the whole system is aligned to handle the most common load units as efficient as possible. Due to this, the storage compartments are tailored to contain only this type of load unit. In order to trigger the dispatch of a certain assembly part, a simple prompt in the computer system is required. The block storage, on the other hand, is a conventional warehouse in form of a large hall. Here, forklifts are used in order to store and remove the load units. While all working processes have to be done manually, there are no restrictions concerning the sizes of the load units.

Caused by the large diversity of variants of the assembly parts and the need for decreasing inventory the frequency of deliveries increased in the last years. In order to handle this, the storage structures have changed significantly. Therefore the conventional block storage has given way to the automatic high rack warehouse. The fraction of the total storing area covered by the block warehouses dropped from originally 50 per cent to 15 per cent in Dingolfing. Reasons for this are savings in personal costs, very efficient land use, high turnover efficiency, and short access time. However, disadvantages of the automation are high investments as well as high susceptibility to failure.

There are two kinds of capacity that are important for these storages. The first (and obvious) one is the maximal number of load units it can hold. The second one is the number of transactions that the system can handle, i.e. the number of storages and removals per time. While the first capacity can be described by
the (fixed) number of compartments, the transaction-capacity depends on the actual positions of the load units in the high rack. This is due to the fact that the positions determine the required transaction times in form of the travelling time.

In the following, the warehousing situation in Dingolfing is discussed in more detail. As the warehouses in Dingolfing, Munich and Regensburg all offer very similar characteristics, advantages and restrictions an additional discussion of the other plants would not offer significant new insights. In Dingolfing there are automatic high rack storages in two places. The maximum technical capacity of both storage and removal from storage in the automatic warehouse in hall 86 approximates 3,850 load units per day. At the moment there are in average around 3,848 storages and 3,845 removals of storage of load units per day. Therefore the capacity limit is reached, although in average only 13,749 of totally 20,664 storing positions are in use. In hall 81 the second automatic high rack with a maximal capacity of storage and removal of storage of 1,900 load units per day of each have a utilisation of 2,068 and 2,007 load units per day, i.e. the capacity is exhausted as well.\(^9\) The maximal storing positions of 5,600 are nearly at the capacity limit with an average of 4,674 occupancies. It becomes obvious that both automatic high racks are more than working to full capacity of storage and removal. Because of this a certain amount of AMA-capable load units are transferred from the automatic high rack in hall 86 into the conventional block storage in hall 84. Therefore, a connection to the AMA was constructed, so that even though these containers are stored in the block storage the transportation is done by AMA and not by trailer.

The conventional block storage in hall 84 covers 16,795 square meters. Every day, around 2,700 storages and removals of load units are made. The capacity for storing and removing is variable because it can be adopted by employing additional storage personal. No information about the maximal capacity of this storage exists due to the fact that there is no fixed structure in which the load units are stored. In fact, containers of the same type and load are just stacked. Through this several factors like the storage of different container sizes, different stackability of containers, driveways and principles like First-In-First-Out do not allow the specification of a fixed capacity. The second conventional block storage in hall 87 makes around 650 storages and removals of containers per day. Also for this storage a maximal capacity is not known. In interviews with the storage personal it became clear that there is still capacity in the conventional block storage for units.

\(^9\) As stated above, the possibility to exceed the maximal capacity is due to the fact that this capacity is only an average value.
3.1.3 Handling

Handling occurs in all steps of the internal material flow of BMW. In the following this internal material flow of the three production sites in Dingolfing, Regensburg and Munich is explained in more detail. This is essential because this flow is completely accompanied by the standardised load units and it is necessary to understand it in order to analyse the cost effects of a new container. The actual handling and production processes are different between the three plants. Nevertheless, their basic structure is similar from the level of abstraction which is relevant for this thesis in order to assign expense ratios to the different processes. Because of these similar characteristics, the same kind of analysis can be conducted in all plants. Figure 29 illustrates the different steps in the handling of the load units.

The handling begins at the reception of the parts where forklifts take the load units from the trucks into the warehouses and to the connection point of the automatic high rack, respectively. The assignment of the load units to the warehouses depends on their size. Like stated above, the automatic high rack can only hold load units with the square measurement of 1240mmx835mm. All other load units as well as those which the automatic warehouse cannot hold due to capacity reasons are taken to the block storage. Should there be the need to rearrange the load units in the warehouses, this work would also be part of the handling. Such situations are exceptions which are not very important.

![Figure 29 Handling processes in Dingolfing and Munich](image)

The main part of the handling is the transportation of the load units from the warehouses to the assembly area. For this intraplant transportation there are
two possibilities, the automatic integration system (AMA) and the trailer transport. The AMA is a fully automatic chain conveyor, which assures the supply of purchased parts from the warehouse to the assembly area. Figure 30 shows some picture of this conveyor system. Originally, it was only connected to the automatic warehouse but due to capacity problems of the warehouse, a connection point to the block storage was added. Like the automatic warehouse, only load units with the square measurement of 1240mmx835mm are capable for the automatic transportation. If these containers are stored in the automatic warehouse, the whole delivery is automated. Only one step of manual handling from a forklift is required to carry the load unit from the arrival point in the assembly hall to the actual assembly line. If 1240mmx835mm-containers are stored in the block storage, there is an additional need for a forklift to carry them to the connection point of the AMA.

![Automatic integration system](image)

All larger load units are loaded by forklift onto trailers and are carried from the block storage to the assembly area. In this case, the handling effort depends on the destination of the load unit in the assembly hall because the production takes places on the ground floor and on the first floor. This differentiation is important because the trailers cannot reach the first floor. If the container’s destination is the ground floor, a forklift is required only once to unload the trailer and take the load unit to the assembly line. If the container needs to be delivered to the first floor, an extra handling from a forklift is necessary to unload the trailer into an elevator. Once the elevator has reached the upper level, the containers are taken by forklift to the assembly line.

In the above pages the material flow of the containers from the suppliers to the assembly line is described. Through this the different ways of transportation and the different steps in handling are identified. With this information the allocation of costs to these processes is possible.
3.2 Load Units

In this chapter the containers in the centre of the later analysis are presented and their purpose at BMW is explained.

BMW uses several different standardised load units of which only some are relevant for this thesis. I received a list of these relevant load units from BMW. Already Wilson (1965) stated that a certain diversity of load units in use is economically advantageous. He identifies a trade-off between handling and purchasing on the one hand and inventory utilisation on the other hand. The handling and purchasing costs are minimised if one box size is used for all parts, while the inventory costs are minimised if boxes exactly fit each product size because in this case almost no space is left unused.

In the following the affected load units are described shortly. Table 5 displays the main characteristics of these containers. By definition, the longer side of a container’s base is always set as its length and this denotation will also be used for the new load unit. Within the analysis there have been nine different load units in consideration. Eight of them are standardised load units and one is a specialised one, which is the last container in Table 5. According to BMW Group (2000)\textsuperscript{10} BMW’s definition of standardised and specialised load units is as follows:

The application of standard load units is possible within all plants and categories. They do not belong to any specific part family and do not feature any fixtures. BMW standard load units are appointed only for transportation of parts between the supplier and the BMW group. It is not allowed to use them for purposes other than intended, e.g. intern manufacturing circulation of any supplier, intermediate storage of unfinished goods or supply of preliminary supplier. For the specialised load units the same rules apply except their usability for every part family and every plant.

\textsuperscript{10} packaging compendium, which shall inform the supplier about the requirements of BMW concerning packaging
Table 5  Load unit description

<table>
<thead>
<tr>
<th>Ident No.</th>
<th>Outside dimension in mm</th>
<th>Description</th>
<th>Tare in kg</th>
<th>Load capacity in kg</th>
<th>Stacking factor</th>
<th>Life Span in years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>Width</td>
<td>Height</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0016</td>
<td>1240</td>
<td>840</td>
<td>675</td>
<td>Large Heavy Cargo</td>
<td>90</td>
<td>2000</td>
</tr>
<tr>
<td>2012</td>
<td>1600</td>
<td>1200</td>
<td>990</td>
<td>Foldable Pallet Cage</td>
<td>160</td>
<td>500</td>
</tr>
<tr>
<td>3725</td>
<td>1230</td>
<td>830</td>
<td>970</td>
<td>Large Full Wallet Load Unit</td>
<td>125</td>
<td>1000</td>
</tr>
<tr>
<td>4444</td>
<td>1240</td>
<td>835</td>
<td>970</td>
<td>BMW Pallet Cage violet</td>
<td>90</td>
<td>1000</td>
</tr>
<tr>
<td>6266</td>
<td>1600</td>
<td>1200</td>
<td>1450</td>
<td>Foldable Large Pallet Cage</td>
<td>182</td>
<td>300</td>
</tr>
<tr>
<td>6270</td>
<td>1600</td>
<td>1200</td>
<td>730</td>
<td>Foldable Small Pallet Cage</td>
<td>128</td>
<td>500</td>
</tr>
<tr>
<td>6286</td>
<td>1240</td>
<td>835</td>
<td>500</td>
<td>Small Full Wallet Load Unit</td>
<td>78</td>
<td>1000</td>
</tr>
<tr>
<td>6969</td>
<td>1240</td>
<td>835</td>
<td>990</td>
<td>Large Load Unit Foldable</td>
<td>90</td>
<td>700</td>
</tr>
<tr>
<td>0204</td>
<td>1600</td>
<td>1200</td>
<td>1450</td>
<td>Special Pallet Cage Foldable</td>
<td>182</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 5 shows that the square measure of the considered load units’ size is either around 1200mmx800mm or around 1600mmx1200mm, i.e. the surface area of the large load unit is double of the smaller one. Therefore it is obvious that there is a big gap in between. The assignment of this thesis is to bridge this gap with an economical solution. Only the grey marked load units in Table 5 are capable for the automatic integration system (AMA). The other ones are too large and are therefore stored in the conventional warehouse.

The most frequently used load unit is the 4444, which is displayed in Figure 31. Due to its popularity at BMW the AMA is aligned to this load unit. This standardised load unit is in use since the seventies. In 1996 there was a changeover from the DIN load unit to the specific BMW load unit build like the DIN load unit but with extra stringer. Thus the quality became better and repairs and defects became less. The square measure of the box pallet is the size of euro-pallets, which square measure of \((L \times W)\) 1240mmx835mm. This load unit is constructed accordant to DIN 15155 (1986), which describes the load unit as “box pallet with mesh side panels and two front side flaps”. It is one of the most widely used load units in the automobile industry and therefore a pallet pool
subsists, so that the variation of load units can be balanced between the different automobile manufacturers by renting or leasing containers. On this account the main subject of the investigation of this thesis is the load unit with the measurement of a 4444-container.

In this section, those load units have been presented to which the new containers have to be compared.

3.3 Assembly Parts

*This chapter deals with the way BMW assigns the assembly parts to the load units and the development of their geometry in the last years.*

BMW distinguishes the assembly parts according to their size. For this, there are the three categories of large, medium and small parts. Table 6 displays the classification of the parts in these categories due to their measurements.

<table>
<thead>
<tr>
<th>Category of Parts</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
</tr>
<tr>
<td>Small</td>
<td>&lt; 0,54m</td>
</tr>
<tr>
<td>Medium</td>
<td>0,54m to 1,2m</td>
</tr>
<tr>
<td>Large</td>
<td>&gt;1,2m</td>
</tr>
</tbody>
</table>

Following these criteria it is appointed, in which container the parts are packed, stored and delivered. At this point the decision is made which load unit fits best for the new part. Furthermore, the type of packaging is geared to the financial value of the part and its quality demand. This means that in some cases special packing gear and material is used.

According to the trend of modular design of new parts and larger automobiles the BMW Group assumed a growing geometry of individual parts. This assumption has been approved by the diploma thesis from Eßbach (2005)\textsuperscript{11}. In his thesis he investigates by dint of mathematical calculation methods in the development of the geometry of parts. Therefore he used data from division VT-301, which records data about measurement and weight of all new parts. In the diploma thesis, Eßbach uses the above categories of parts as the measurements of the respective categories do not develop consistently.

\textsuperscript{11}The analogous title in English can be translated as follows: „The development of the geometry of parts and its impact on area and load unit planning in the division “Parts and Accessories” in the BMW Group”.

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Therefore a joint analysis of the whole spectrum of parts would not have much significance.

Via regression analysis and coefficient of determination respectively it turned out that not every category of parts is growing. It is emphasised that the large and medium parts show growth in the time span of the analysis. For the large parts the average growth of the volume is around 2.3 per cent per year and for the medium parts it is around 0.65 per cent per year. In contrast the small parts show a steady size.

Reasons for the growth of parts are miscellaneous and can be put down to the interaction of several factors. One factor is the vehicular outside dimension. This growth is not only asserted at premium segments like the 7 series. It also can be observed for middle class cars like the 3 series as Eßbach shows. One reasons for the growing outside dimension is the status symbol character of BMW premium segment automobiles like the 6 series or the 7 series. This characteristic can be achieved among others through the size of the auto body. Additionally technical progress is a factor for growth. These technical novelties and extras need space to be stored in the car. Furthermore the trend towards modular design enlarges the parts, which are delivered as already assembled parts. At last the growing product range and the growing number of parts per car are responsible for the growth. The trend for growth of parts is also an important aspect in Eßbach (2005). He suggests via time series analysis that the average part’s volume will also grow in the future.

In my diploma thesis the main attention is turned to the medium parts as these are packed in the large load units which are centre of the analysis. For these parts the result of the investigation of Eßbach supports the assumption of the growth of parts. Nevertheless, the relative small growth alone does not allow any conclusion whether a new load unit would be reasonable. Therefore investigations have to be made if the utilisation can be improved in the new load unit.

### 3.4 Conclusion

This chapter had the purpose to understand the material flow, load units and assembly parts relevant for this thesis. The detailed material flow with the two main processes of handling and transportation allows the assignment of costs to the load units in Chapter 4.4. The discussion of the load units provides information about the relevant load units and their usage. The presentation of
former research of the assembly parts suggests a growth of their size which can support the introduction of a new load unit.
4 Analysis

In this chapter, the cost savings through the introduction of a new load unit are determined. For this, the relevant data is gathered, appropriate container sizes are identified and their possible utilisation approximated. Finally, the transportation and handling costs are assigned.

The analysis phase contains the absorption of the current situation. According to Arnold (2003) the definition for the absorption of the current situation is the acquisition and evaluation of the active state of the material flow. The aim of this step is to develop a concept, to plan the activities and to select resources like conveyor technique and storage techniques in order to realise an economical material and data flow.

In this case the aim is to get a better understanding of the process and therefore to calculate the cost differences. Thus the processes had to be analysed at first to select the relevant parameters for the comparison of costs. Therefore the transportation and handling process have been acquired. In Chapter 3.1 the current situation for handling and transportation in Dingolfing, Regensburg and Munich is described. Afterwards the parameters for the calculation were defined. In the next part the concentration lies on this parameters and where I extracted them from.

4.1 Data

The collection of data is the first important step in order to calculate the cost savings. This chapter shows which data is relevant and how it was gathered.

For the analysis the following information for every assembly part is required:

- SNR – Article Code
- Size of Part
- Load Unit Number
- Size of Load Unit
- Storage Location
- Location of Assembly
- Supplier Location
- Supplier Distance

The article codes are necessary to determine the utilisation and to assign the costs explicitly to one article. For the calculation of the utilisation, both the size of the parts and of the load units (and thus their number) are required. To assign the transportation costs, the location of the supplier and the distance between supplier and plant for each part is necessary. The data concerning the storage and assembly location is used to allocate the handling costs.
The two databases “SLMG”\textsuperscript{12} and “Extra!”\textsuperscript{13} serve as base data for the analysis of the utilisation degree of the old and new load units. The database SLMG has been created for the analysis of logistic costs and helps to plan part families. It delivers the needed information like article code, belonging load unit, measurements of load unit, supplier distance, storage location, and location of assembly. The database is design in the way that there is a row for each assembly part. In the columns all other information related to this part are stored. As the size and the weight of the article are missing in this database the database “Extra!”, which contains this information, is added and merged into it. The division VT-301 at BMW is responsible for the data entry of every new part. This division collects the new parts’ characteristics like measurement and weight and enters them into the database “Extra!”. The merger of both databases delivers the base data for the analysis.

At the time of the analysis the database SLMG exists for the plants Dingolfing, Regensburg and Munich. It contains all active article codes. Article codes are called active if at least one of the following criteria is met:

- Open delivery schedule,
- Booking of outward stock movement in the last 90 days,
- Within the demand horizon, or
- Contract is available in the system for administration and information.

In the SLMG list for Regensburg the information supplier distance is missing. I used a tool implemented in Excel which calculates the distances from the supplier to the plant in Regensburg with the postcode. These distances are just the air-line distances and therefore shorter than in reality for most cases. Additionally it is only able to calculate distances within Germany. Even though these two aspects reduce the quality of the data, this simplification only reduces the potential savings through a new container instead of overestimating it. This is due to the fact that if a part offers savings in the new container, these savings are lower the shorter the distances. Thus, it is only possible that some parts which would offer savings are not detected while there will not be parts which offer “fake” savings in the calculation. To achieve better results in the future I suggest adding the real distances into the database.

The reliability of the data can be derogated by faulty insertions or contempt of the entry instruction. During the merger of the two databases a significant

\textsuperscript{12} Sachnummern Logistisches Mengengerüst

\textsuperscript{13} Proprietarily developed computer application for warehousing of BMW.
amount of data got lost due to the fact that the database “Extra!” does not contain the measurements for several parts. This loss rests with around 50 per cent of all parts for Munich and Regensburg and around 30 per cent for Dingolfing. Nevertheless the merged database can still be seen as a good representative base as over 4250 data sets exist.

In the above section it was reasoned what kind of data is required and how this data was gathered. Even though the merging of two databases caused the loss of some information, a base was found on which the analysis in Chapter 4.3 can be built.

4.2 Optimal Container Size

_in this section, two sizes for the new load unit are determined. This is necessary for the utilisation calculation in Chapter 4.3._

To determine the optimal size for a load unit, several aspects have to be considered and a certain diversity in the sizes of load units makes sense (Wilson 1965). Wilson states that there is a trade-off between minimising “box cardboard costs and warehouse space costs” and “box inventory, handling, and purchase costs” (p. 135). The former objective suggests that all load units should exactly fit to the parts they store because this eliminated unused space. This objective can be translated to the transportation costs in this thesis as is demonstrated in Chapter 4.4.1. The general maintenance costs for the containers as well as the handling costs are minimised if only one container size is used for all products. At BMW this effect can be observed concerning the AMA. The problem is to select the optimum number and sizes of boxes which minimise the total system costs. For this thesis, this problem reduces to identifying the best size for the new load unit that should be introduced additionally to the existing ones.

As stated in Chapter 1.5, the container needs to fit both to a range of assembly parts and to the measurements of the means of transportation. Although these two problems are interrelated they will be decomposed and solved consecutively. In this chapter, two possible sizes are selected and in Chapter 4.3 the suitability of these sizes with respect to the parts is tested. The two sizes are chosen with the objective to fit well into the means of transportation while considering constraints regarding the available space at the assembly lines and the removal deepness.
For the utilisation of the means of transportation, the truck measurements are relevant because they almost completely cover the transportation to the plants (cf. Chapter 3.1.1). For this, their length, height and width are restricting factors for the load unit. A variety of different trucks ranging from small vehicles to large ones is used to deliver the load units. Especially length and height differ from truck to truck and there is no data available under which circumstances which vehicle is used. Therefore it is not possible to fully consider these two dimensions for the new load unit. For the height, this does not pose a true problem for this thesis, as the following model to identify the optimal number of parts per container works on a two-dimensional approach.\textsuperscript{14} The length varies strongly between different trucks. Thus, the length of the new box needs to be set independently from the truck utilisation. The only alternative would be to use BMW’s average standard length of 13.6m for all trucks and this would be too rough an estimate. Thus, neither the height nor the length of the trucks is considered to identify the optimal measurement of the new container with regard to the vehicle loading.

This leaves the trucks’ width as the only important factor to increase the truck utilisation. This means that only one dimension of the new load unit needs to be set with regard to the trucks’ size. As the orientation of the box during transportation does not matter, this can be either the box’s length or width.\textsuperscript{15} BMW plans with a general width of 2.5m for trucks. This is a common planning size because it does not change significantly from truck to truck. As cargo securing equipment has to be considered the transportation division TG-24 at BMW recommends to calculate with an available width of 2.46m. To achieve an optimal utilisation of the trucks’ width an outside measurement of either 1.23m or 0.82m is recommendable. This would allow storing either two or three of the containers next to each other without leaving unused space in the truck. From these two options, the smaller one is very similar to the size BMW uses for its 4444-containers and is therefore not considered any further. Based on this analysis, one side of the new load unit should have an outside measurement of 1.23m. The other dimension should be chosen with respect to the remaining constraints.

In all plants the production space is restricted, i.e. the space for load units at the assembly line is rare. The assembly lines are designed as illustrated in Figure 32: While the cars are assembled, they are placed on a conveyor which also carries the workers. Next to the conveyor there are continuous platforms with a

\textsuperscript{14} Furthermore, the height of the new container is generally not considered in this thesis.

\textsuperscript{15} Keeping in mind that the length of a box is defined as its longer side.
depth of 1.4m. Here, the load units are placed. The load units need space both for their base measurement and to open their flap. The current width of the platform is tailored for the 4444-container with a depth of 0.8m. Thus, if a larger load unit should be stored at the assembly line adaptations have to be made. Otherwise they would get too close to the line and their flaps could not be opened without endangering the quality of the automobiles. There are two possible adaptations to solve this problem. One solution could be a flap for the new load unit, which does not open to the front (like the 4444 has). An example for this is a flap, which would be pushed downwards parallel to the container front. With such a flap, containers with a depth of around 1m could be stored without risks for damage at the cars. The second solution is to enlarge the continuous platform in front of the assembly line, so that it is possible to store the containers farther from the line. A possibility for this are the replacement modules highlighted in yellow in Figure 32. Nevertheless, this solution has two disadvantages. Firstly, it would cause extra costs for installing these modules and secondly there is not always sufficient free space around the assembly lines to place them.

Another aspect is the so-called “removal deepness”, i.e. the arm length which is required for the assembler to remove parts. The removal of parts out of a container has to be easy and quick. If a container is too deep smaller assemblers might not be able to pick up parts from its hindmost corner or its bottom. In an interview with workers from the assembly area it became clear that for containers with a depth of 1.2m or more the removing becomes difficult. Especially, if the containers are stacked it is too complicated and takes too
much time to remove the parts. Thus, both the available space at the assembly line and the removal deepness suggest that one side of the new load unit should shorter than 1.2m.

Based on these results, two different sizes are chosen. To optimally utilise the trucks, both sizes should have the length of 1.23m. In the catalogues of KTP\textsuperscript{16} the most common load units with a width around 1.23m have a length of either 1.02m or 0.8m. The latter size is exactly the one BMW uses for its 4444-load units. Therefore, the size of 1.23mx1.02m is chosen which has an inside measurement of 1.2mx1m (KTP 2005). This box was also suggested by BMW in the beginning of this thesis. Another possible measurement is 1.23mx1.23m. As stated above there are certain disadvantages to this measurement. Despite these possible complications, I selected both measurements for the analysis in the next chapter to get a better insight in the consequences of larger load units and whether there is a trend in the reaction of the costs on the container’s size.

In this chapter two alternative container sizes for the following analysis were identified. For this, the truck measurements, the space at the assembly line and the removal deepness were considered.

4.3 Capacity of Containers

This chapter investigates the possible utilisations of the two selected load units and compares them to the current way the items are packed. In order to do so, for each assembly part the number of parts that can be packed into the new containers is compared to the utilisation of the existing container. Depending on the respective part, comparisons with all old containers introduced in chapter 3.2 are made. To solve this rather complex, three-dimensional packing problem a two-step approach is used. At first, a heuristic for a two-dimensional packing problem is applied to determine the number of parts per layer in the container. Secondly, these results are extrapolated to incorporate the third dimension.

4.3.1 Four-Block-Heuristic

In this subchapter, a heuristic is applied to determine the possible number of parts per layer in each box. This requires the sizes of all parts in the created database (cf. Chapter 4.1). As presented in Chapter 2, this problem is quite complex and generally requires an algorithm for its solution. As the database with the parts is based on Microsoft Excel the ambition is to integrate the algorithm into the Excel-datasheet. Through this the utilisation can be calculated

\textsuperscript{16} Kunststoff Palettentechnik GmbH, one of BMW’s suppliers for load units.
automatically and there is no need to import the results back to Excel. For the automatic calculation of parts per layer I programmed a macro in Visual Basic which automatically reads the required data, uses the Excel solver for the calculation and writes the results in the respective cells in the spreadsheet. The Excel-Solver is a special Excel-tool, which allows the solution of optimisation problems with constraints. For this, it is necessary to define an objective cell, the changeable cells and the restrictions. All cells have to be directly or indirectly related to the objective cell or the constraints. By using different optimisation techniques, the Solver adjusts the values in the changeable cells until the objective cell has reached its goal under consideration of the constraints. Further information about the Solver can be found in the help function of Microsoft Excel.

In the following, the algorithm is explained and its code in Visual Basic is displayed in Appendix A. The first step of the algorithm is to create a setup. This means that it initialises with a certain size for the load unit and it reads the measurements of the next item to be considered. Through this, I do not have to use a notation to distinguish between different parts and load units in the packing-heuristic itself. After the initialisation, the calculations for a certain setup are made using a four-block heuristic similar to the one introduced by Smith and de Cani (1980) which is presented in chapter 2.3.3. I selected the four-block heuristic as it is most suitable due to its low computational time while still providing sufficiently good quality compared to the other block heuristics (see chapter 2.3.7).

In Figure 33 this four-block heuristic is illustrated. Let \( l \) and \( w \) be the length and width of the item as well as \( L \) and \( W \) the length and width of the load unit, respectively. The container is divided into four logical blocks with given orientations of the items. This means that the parts are placed horizontally in blocks one and three and vertically in blocks two and four.
For each block $i, i = 1, \ldots, 4$ there are two decision variables, one for the number of items packed next to each other in L-direction, $l_i$, and one for the number of items packed in W-direction, $w_i$. Obviously, all decision variables are integers and need to be greater or equal to zero. Through this, the number of items in one block can be easily calculated as the product $l_i w_i$. Furthermore, the length and width of block $i$ result in $L_i = l_i \cdot w_i$ and $W_i = w_i \cdot w_i$, respectively. From this, the objective function to maximise the total number of items $N$ can be given through the sum of parts in each of the four blocks, i.e.

$$\text{Max } N = l_1 \cdot w_1 + l_2 \cdot w_2 + l_3 \cdot w_3 + l_4 \cdot w_4$$

The placing of the items needs to consider two kinds of constraints. One constraint is that the blocks do not exceed the length and width of the container, respectively. The other constraint is that neither the blocks 1 and 3 nor the blocks 2 and 4 overlap. The first constraint is implemented through the following equations.

$$L_1 + L_2 \leq L \quad \text{and} \quad L_3 + L_4 \leq L$$

$$W_1 + W_4 \leq W \quad \text{and} \quad W_2 + W_3 \leq W$$

The length of block one and two as well as of block three and four shall not be larger than the total length of the base area. The same is necessary for the
width of the base area and therefore the width of the block one and four as well as of block two and three shall not be larger than the width of the base area.

To avoid overlappings of the blocks in diagonal positions, i.e. blocks one and three as well as blocks two and four, additional restrictions have to be introduced. These constraints require that the sum of the length of blocks one and three must not be larger than \( L \) if at the same time the width of these two blocks is greater than \( W \) and vice versa. The same is necessary for the blocks two and four. Unfortunately, it is problematic to implement such IF (or AND) constraints in the Excel Solver. I tried to avoid this problem by introducing a binary variable that replaced these formulations but it also caused the Solver to come to wrong results. Therefore I simplified the overlapping-constraints in the following way:

\[
L_4 + L_2 + W_4 + W_2 \leq L + W \\
L_1 + L_3 + W_1 + W_3 \leq L + W
\]

The sum of the length and width of both blocks one and three as well as of both blocks two and four shall not be greater than the sum of the total length and width of the base area. According to the objective function, the Solver changes the values of the eight adjustable cells until it has found a solution for which it cannot find a further improvement. After the Solver has calculated the best solution for the current setup, the value of the objective cell is written into the database. Thus, having completed this procedure for all combinations of parts and load units the results of this algorithm are three new values in the database for each assembly part, namely the number of parts that can be packed in one layer in the existing and in the two new containers.

Obviously, these generated packing plans are generally not optimal. This is due to several reasons. The most evident reason is that a four-block approach is only a heuristic. This aspect is intensified through the simplified formulation of the overlapping-constraint. The formulation has the flaw that it does not consider some combinations which are feasible. For example the setting given in Figure 33 for the blocks one and three. The sum of their lengths surpasses the container’s length by more than the empty space between their widths. On the other hand, the heuristic does not allow solutions that do not really fit into the container. Thus, the results of this four-block heuristic are generally too pessimistic. Further reservations concerning the quality of the results come from the fact that the parts are assumed rectangular although they are not. This
approach does not consider the possibility of nesting, though.\textsuperscript{17} As discussed in Chapter 2.3, the approach of considering the smallest containing rectangle as rectangular outside measurement is in many cases the only practical possibility. Finally, each part can be packed with three different orientations, i.e. it can be placed with its bottom, front or side downward (Bischoff and Dowsland 1982). The algorithm places all items with their height and length downward as this is common practice at BMW and so this should not reduce the quality of the approach.

In total, these inaccuracies do not pose too great a problem for the further analysis because the results from this algorithm are only used to compare the utilisation of the old and new containers. In other words, the algorithm is just used to find the relative change in the number of parts per layer from one load unit to the other. It should not be applied for the actual packing plans and for this, BMW should use their own, three-dimensional tool "PackAssistant". Unfortunately, I could not use this tool for my thesis, because it is still being developed. Furthermore, the beta-version has very long computation times and requires the complete CAD-data of all parts, which cannot be automatically read into the database. Thus, I had to make use of this more simple approach.

\subsection*{4.3.2 Extrapolation}

In order to assign the transportation and handling costs to the parts in the different load units, the number of parts per container is required. Thus, the results of the heuristic for the packing of one layer in the old and the two new containers are only a makeshift and act as a basis for the extrapolation of the numbers to consider the third dimension. A simple way for such an extrapolation would be to calculate the number of different layers that fit into the containers and multiply it with the number of parts per layer. Nevertheless, this approach would be very vulnerable to the inaccuracy of the four-block heuristic and would completely ignore all nesting.

In order to reduce such imprecision, the information from the heuristic is combined with BMW's information about the actual packing of the existing units. The database in the Excel-spreadsheet contains the utilisation degree of the old units in the way they are currently packed. These values consider potential nesting possibilities and resemble exactly how well BMW is able to pack the load units. For the extrapolation these utilisation degrees are multiplied with the

\textsuperscript{17} "Nesting" describes situations in which parts can be stored in a way that requires less space than the sum of the sides of their containing rectangles. This is often possible for homogeneous packing problems of bended parts.
relation between the results from the heuristic for the old and new load units. In other words, the percentage growth in the number of parts in one layer from the old to the new container is multiplied with the actual utilisation degree of the old load unit.

There are two implicit assumptions in this approach. The first one is that the nesting in the new containers is possible in the same way as in the old one. This assumption should be quite reasonable for most parts because the nesting mainly depends on the shape of the parts and not on the size of the container. Secondly, by using the current utilisation this approach assumes that the old and the new load units have the same height. As the height is not to be covered in this thesis, it is necessary to make an assumption about it. While any kind of assumption causes inaccuracy, this way allows a better comparison of the containers. Furthermore, it is unlikely that a height will be chosen that is different from all existing load units because their heights have also been subject to prior optimisations.

Even though no costs have been assigned yet, these results allow checking whether a new load unit offers savings in transportation if the transportation costs are assigned per volume (which is common). This is due to the fact that the new load unit leads to lower transportation costs than the old one if it requires less volume per part. To identify cases like this a simple formula can be applied. Let the indices \( o \) and \( n \) stand for the old and new load unit, respectively and let the remaining variables be defined as in Chapter 4.3.1. Then it can be said that a new load unit leads to reduced transportation costs, if and only if the performance indicator \( PI > 1 \), where

\[
PI = \frac{N_n}{N_o} \cdot \frac{L_o W_o}{L_n W_n}
\]

If the indicator is greater than one, the increase in the number of parts in the container is larger than the increase in size. This means that more items per volume can be packed. For parts with an indicator less than one the new container on the other hand will lead to higher transportation costs. Figure 34 illustrates a simple example to display such utilisation improvement. In the example the old load unit is able to store six parts. Although the new load unit is just 25 per cent larger it can store eight parts which is an increase of 33 per cent. Thus, in this case \( PI = \frac{1.33}{1.25} = 1.064 > 1 \).
This indicator is added to the database so that it is easier to identify parts with potential for saving transportation costs. Nevertheless, this indicator does not yet show whether the new container is economically preferable in terms of total costs because it does not allow a statement about the handling costs. Therefore the cost comparison in Chapter 4.4 is the significant basis for decision.

For the comparison of the load unit 4444 with the new size of 1200mmx1000mm the indicator is greater than one for 682 out of 1,473 considered article codes in Dingolfing. For the size of 1200mmx1200mm this is the case for 737 assembly parts. However, it cannot be generalised that the larger load unit is better. There are several examples for article codes which fit better into the 1200mmx1000mm load unit than in the 1200mmx1200mm size. This analysis shows that about half of the articles have the potential for lower transportation costs. Thus, already at this state of the analysis it can be reasoned a new load unit larger than the 4444-container is reasonable concerning utilisation improvements. This supports the initial thesis that the geometry of some parts has outgrown the current standard load units.

All in all, the result of this subchapter is the total utilisation degree of the new load units, which is needed in the following analysis to calculate the costs per part.

### 4.4 Allocation of Costs

*This chapter concentrates on the comparison of the transportation and handling costs regarding the old and the two new load units.*

To compare the transportation and handling costs of the different load units it is necessary to define an allocation base that satisfies two requirements: Firstly it needs to be possible to allocate all types of costs to this base and secondly it should show the absolute savings potential on a meaningful scale. For this, the
total transportation and handling costs per year for each article number are calculated. These costs are determined in the following way: At first, the transportation and handling costs for all three considered load units and for each assembly part are calculated. For this, the relevant expense ratios of transportation and handling are allocated to the article code. Based on this the potential savings per part are derived and multiplied with the yearly demand. This approach allows identifying those items with the highest total potential for cost savings. Nevertheless, it is obvious that already the costs per part allow a statement whether the new load unit would lead to higher or lower costs. This is important for those parts for which no information about yearly demand is available.

To identify the relevant expense ratios, the steps in the material flow presented in Chapter 3.1 have to be considered. For every possible way through the flow chart in Figure 24 and Figure 25 different costs occur. Additional combinations arise due to the fact that the transportation costs depend on the distance of the plant to the supplier. As explained in the total cost model in Chapter 1.5.2, other costs for the load units are purchasing, maintenance and disposal costs. These kinds of costs are not included in the analyses. Instead, they are discussed in the context of the material of the load unit in chapter 4.6, where the advantages and disadvantages of steel and plastic containers are examined.

Due to confidentiality issues the actual expense ratios must not be published in this thesis. In the following subchapters, BMW’s approach to determine the transportation and handling costs is presented and the ratios are applied to the results of Chapter 4.3.

**4.4.1 Transportation**

As main cost drivers for the transportation costs BMW identified the distance, the volume and the frequency of supply. The introduction of a load unit with a new size obviously has neither an effect on the distance, which is given through the choice of the suppliers, nor on the frequency of supply, which is given through the ordering strategy. The load unit does have a significant influence on the volume that is required to transport a delivery, though. The dimensions of the container determine both how many parts it can hold and how well it can be stored in the trucks. Thus, to answer the purpose of this thesis, the effect of the load unit’s size is considered as the relevant leverage on the transportation costs.
In the following the expense ratios for transportation provided by BMW are explained. As all transportation is executed by external shippers it should be possible to allocate these costs directly to the deliveries. Due to the large number of different shippers and contracts, this approach would be too complicated. Therefore, BMW consolidates the costs into rates that only depend on the shipped volume. Different approaches are used to determine these values for external and interplant transportation. There are some similarities, though: All expense ratios consider both the delivery of the load units and their returning as empties. Furthermore, the truck toll in Germany is not considered.

The expense ratios for external transportations are established by the division “Planning and Cost Accounting for Transportation”. There are several inbound agreements with different shippers and these agreements consist of different expense ratios depending on the distance and origin of the deliveries. To simplify this diversity, division uses a clustering method. Clustering means that different ratios are aggregated if they have similar characteristics. In this case this characteristic is the price for the delivery of a certain volume. These prices differ from shipper to shipper and BMW found out that they mainly depend on both the distance and the origin of the transportation. Thus, the clustering identifies appropriate areas and ranges for the distance and assigns average values for the expense ratios to them.

The main criterion for this aggregation is the cluster accuracy because otherwise the results are too inaccurate. BMW decided that the prices of all shippers in a certain cluster must lie in a range of around plus or minus twenty per cent of the average value. If this criterion is not fulfilled a new cluster area or cluster distance is introduced. The calculation methodology of the cluster is the following:

1. Choose a cluster with a certain area and range of distances
2. Calculate the average value of the transportation costs from all shipping routes in this cluster
3. Check if the deviation of the price of any shipper in this cluster is greater than plus or minus 20 per cent
   - if yes, change the cluster in terms of either the area or the distance. If in some cases the clusters are too small, increase the tolerance to +/- 30 per cent
   - if not, use this cluster
Applying this procedure, seven different cluster areas and 28 different distances were found. The areas include Bavaria together with Baden-Württemberg, the rest of Germany, Ireland and UK, the Czech Republic as well as Mainland, Southern and Eastern Europe. Mainland Europe consists of Belgium, the Netherlands, Switzerland and Austria. Southern Europe is formed by France, Portugal, Spain and Italy. Eastern Europe includes Poland, Hungary and Slovenia. Separately to Eastern Europe the Czech Republic forms a cluster on its own due to its price deviations. Additionally an extra cluster was needed for the United Kingdom and Ireland.

For the interplant transportation there are significantly less different contracts because the route between two plants is completely assign to one shipper. Thus, a clustering is not required. BMW calculates these expense ratios for each route based on the contracts and an average utilisation of the trucks of 70 per cent.

The expense ratios correspond to the volume of the delivery and include the returning of the empties. The volume refers to the amount of space in the truck that is occupied and the expense ratios are based on the assumption that the proportion of full and empty load units is 1:1. Thus, they do not consider the foldability of some old load units or potentially of the new load unit. If it is possible to fold the container, it needs less space in the truck which directly reduces the transportation costs. To incorporate such foldability it is necessary to divide the costs into the actual delivery and the way back. For this, the following adaptation is used: Let $c_i$ be the original expense ratio for transportation and let $c_i^*$ be the ratio considering the folding (both in Euro per cubic metre). Furthermore, let $\alpha$ be the fraction in per cent of the original size to which the container can be folded. Then the reduced transportation costs $c_i^*$ amount to

$$c_i^* = c_i \left(1 + \frac{\alpha}{100} \right).$$

Practically this means that the costs for the delivery and the way back are assumed to be equal. Therefore, the delivery is weighted with the full volume while for the way back only the reduced transportation volume of the empties is considered. Through this it is obvious that in order to realise the full potential for cost savings through the new load unit, it is important that it can be folded. For the “folding-factor” $\alpha$ I assumed the value of $\frac{1}{3}$ which corresponds to the average factors of the existing foldable containers.
With these expense ratios the cost for transportation can be added to the Excel-database. In order to determine whether the new load unit offers cost savings for a part, the following proceeding is used: At first, the transportation costs per container are calculated. For this, the volumes of the load units are relevant which can be easily calculated. This volume is then multiplied with the relevant expense ratio of the respective assembly part. For this, the information about the suppliers in the database is relevant. As the containers hold different numbers of items a direct comparison of these values is not possible. Thus, they are broken down to costs per part, i.e. the costs per load unit are divided by the number of parts in the load unit which has been calculated in Chapter 4.3. This procedure results in three cost values for each part, i.e. one for the old load unit and two for the new ones. For a concrete application of this cost allocation see the example in Chapter 4.5.

The reaction of the handling costs on the introduction of a new load unit depends on two factors. These factors are the number of parts per container and the volume of the container. From this it follows that such article numbers offer great savings, which are currently packed in a non-foldable load unit. This is not surprising because the folding allows a significant reduction of the transportation costs so that great savings can be generated by replace non-foldable load units by foldable ones. As already described with the performance indicator in Chapter 4.3.2, a larger container does not necessarily lead to lower transportation costs because it does not have to cause a better exploitation of the space. Thus, in order to minimise the transportation costs for a certain part the container size needs to be tailored as specifically as possible to the part’s shape. Through this the unused space in the container – and thus in the truck – is minimised which in reverse means that the expense ratios can be distributed on more parts.

### 4.4.2 Handling

The second cost driver in the material flow is the handling. Generally, BMW identified the two factors “amount of load unit movements” and “amount of picks for sequencing” as main cost drivers for handling (BMW 2005b). Load unit movements happen in all steps illustrated in Figure 29 and are the lever of handling which is important for this thesis. The amount of picks, on the other hand, refers to special handling processes in the small-parts warehouses which do not involve standard load units. Thus, it cannot be considered in the following.
For every handling step costs arise. These costs depend on several factors, which are based on the different handling processes through which the load units run from goods receipt to the assembly area. These factors are

the place of storage, i.e. the conventional or the automatic warehouse (or the high-bay rack in Regensburg),

the type of transportation, i.e. forklift, trailer, elevator and AMA, and

the place of assembly, i.e. the ground floor or the first floor of the assembly area.

The place of storage and the type of transportation depends on the size of the load unit while the place of assembly depends on its content. BMW generalises these costs through several expense ratios for handling. Table 7 shows the different expense ratios for Dingolfing resulting from different combinations and based on the place of storage. Each cross (“x”) stands for a specific expense ratio. In order to obtain the total expense ratio for a certain load unit all values in the respective row have to be summed up.

<table>
<thead>
<tr>
<th>Warehouse</th>
<th>Goods Receipt</th>
<th>Warehouse Type</th>
<th>Transportation Type</th>
<th>Assembly Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Automatic Block</td>
<td>Automatic Trailer</td>
<td>Ground Floor</td>
</tr>
<tr>
<td>H86</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>H81 RL</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>H84</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>H84</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>H87/81</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>H87/81</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

As described in Chapter 3.1, for the automatic transportation the location in the assembly area does not matter so that the costs are the same in both cases. For the transportation by trailer it does matter which floor the load unit goes to because for the first floor an extra handling step is required. The combinations described in the table are simplified and abstracted for a better understanding. While at BMW generally more possibilities and therefore handling costs exist, this is just the extract of possibilities which is important for the analysis of this thesis. Therefore for this analysis six different possibilities of handling exist. Each of these possibilities consists of four components, which affect the final expense ratio. Thus, it is possible to allocate one specific expense ratio to every assembly part.
In Munich the cost allocation is stronger consolidated as there is only one expense ratio for the conventional block storage and one for the automatic high-rack. No differentiation is made if the transportation to the assembly area is done by trailer or AMA. Nevertheless, the division into ground floor and first floor exists, too. Through this, four different expense ratios for handling result for Munich. In Regensburg the handling costs are assigned still simpler than in Munich due to the missing levels in the assembly area. There only three expense ratios exist for the three different types of warehouses.

The calculation of these expense ratios is conducted on the basis of the actual costs within a certain time span. In the following, it is presented for the example of Dingolfing. In Dingolfing the ratios are determined by the division “Logistics Planning and Product Projects”. For this all turnover processes are observed, i.e. all material movements between goods receipt, warehouse, and float to the assembly line. The removal of parts out of the load units at the assembly line is not considered as handling but as part of the assembly process. For the expense ratios, only the variable costs are considered which are affected by three categories: personnel costs, material costs and costs from external service providers. To determine the variable costs of labour the total costs for labour are divided into 80 per cent fixed and 20 per cent variable. In a similar way the total material costs are divided into fixed and variable. For this, the same percentage fractions are used as for the labour costs. For the costs from external service provider the differentiation between variable and fixed cost depends on the contract and is therefore always different. From these variable costs the expense ratios per handling are derived. The sum of all variable costs is divided by the total number of containers within the considered time span. With their use it is possible to easily determine handling costs for a part from the goods receipt to the assembly area.

By using these expense ratios, the handling costs can be added to the database. This requires for each part information concerning warehouse type, transportation type, and assembly area. For each part the handling costs are at first calculated per load unit. Similar to transportation, the costs per container are not comparable as they hold different numbers of parts. Therefore, the costs are broken down to costs per part. Again, this is illustrated in the example in Chapter 4.5.

As all handling effort is directly related to the containers, it is obvious that the handling costs per part are lower the more parts are packed. A new load unit with a higher utilisation will cause the amount of load unit movements to drop,
e.g. if instead of six old load units only five new containers are needed for the handling of the same number of parts. It follows that the handling costs suggest the introduction of a container that is as large as possible. Nevertheless, not all assembly parts benefit from a new container (of reasonable size) because of the extra costs that occur as the new load unit is not AMA-capable. This holds especially a disadvantage for those parts which are currently stored in the 4444-load unit and which are assembled on the first floor. Here, both the higher costs for the trailer as well as the costs for the elevator-handling accrue. Thus it becomes clear that for handling there is more than one factor which impacts the costs per part.

4.4.3 Results

With the transportation and handling cost per part it is possible to calculate the total cost by simply summing both values. The total cost per part for every single article number and the three load units make it possible to directly compare the cost savings in Dingolfing. As the costs per part are rather small and the amount of cost savings per time also depend on the daily demand, I calculated the savings per year. For this, I assumed 21 working days per month, i.e. 252 working days per year. The yearly savings can be calculated by multiplying the total cost per part with the daily demand and the working days per year.

From 1,905 assembly parts in Dingolfing 1,388 (73 per cent) offer positive savings through the introduction of a new load unit of the size 1200mmx1000mm. In Munich this is the case for 487 of 517 (94 per cent) parts and in Regensburg from 1,597 article numbers there are savings greater than zero for 702 parts, i.e. 44 per cent. These results show that there is a high potential for savings in all three plants especially in Munich and Dingolfing. For the actual introduction of the new container, a pilot programme should be conducted. For this it would be wise to choose those assembly parts which offer the highest savings potential because this holds the lowest risk of migrating wrong items and allows realising the highest savings as soon as possible. I filtered all article numbers which provide yearly saving larger than 5,000 Euro for Dingolfing. These article numbers, which are around 80, are potential candidates for testing and implementing. The list is displayed in Appendix B. With these parts a total saving of nearly 0.9 Mio. Euro per year can be achieved.

For Regensburg and Munich I could only calculate the total cost savings per part as the SLMG-database does not contain the daily demand of these plants.
It was also not possible to easily merge a database with the daily demand of the article codes into mine. Currently, it is only possible to manually query the daily demand and enter it into my spreadsheet. Therefore, I suggest that this missing information should be added to the database in order to fully benefit from the results of this thesis. Otherwise, the packing planner in Regensburg and Munich will have to rely on their knowledge of the daily demand in order to identify the items with high cost savings in the new container. For this, the cost savings per part are an important orientation.

Altogether it can be observed that those article numbers offer savings which are currently stored in non-foldable containers and which have a performance indicator greater than one. This result is quite logical as it means that the utilisation of the new load unit increased more than its size compared to the old one. Load units which are stored in the automatic high rack and are transported by the AMA to the assembly line in the first floor generally offer the lowest savings. Here, the better utilisation often cannot compensate the extra costs for double handling and trailer transportation. As with most analyses, these results are only approximate values. Thus, the real savings potential will certainly differ from the values in the Excel-spreadsheet and it is unsure whether it deviates in positive or negative direction. There is a reason, though, to support the thesis that the true savings are in tendency higher than estimated. This is due to the fact that the expense ratios for the handling of load units with the AMA are assumed to be zero. In reality, this is most likely not the case because also a completely automatic handling requires regular costs, like e.g. power and maintenance. Thus, the costs for the 4444-load units can be assumed higher than in the analysis which further increases the savings potential for some parts.

In the following an example is presented in order to illustrate the exact approach of the analysis.

4.5 Example

In this chapter an example of the analysis is presented in order to illustrate the approach described in the last sections.

The considered part has the article number 7151493. This article code belongs to the underlay shelf in the front of the car and is displayed in Figure 35.
The part is delivered from JSP International GmbH in 74182 Obersulm, which is 310 kilometre away from Dingolfing. It is delivered five days per week in the 4444-load unit and is stored in the conventional block storage in hall 84 and assembled on the first floor of the assembly area. At the moment there are 35 parts in the container. According to my calculation with the four-block heuristic it should be possible to fit 20 parts within each layer into the container. The calculations of the utilisation degree for the 1200mmx1000mm load unit results in 32 and in 37 for the 1200mmx1200mm load unit. That is a percentage growth of 65 and 85 per cent respectively. As the actual utilisation degree for the 4444-load unit is 35 the utilisation degree therefore for the both new container are 56 and 65 respectively. The real utilisation degree after manually packing the parts into a container of the size 1200mmx1000mm is 60. This is 4 parts more than the calculation of my analysis. This fact is due to the measurement for the thickness or heights of the part. In the database it is said to be 4 cm, but in real it is around 3.5 cm at the thickest location of the part. For this part it is also possible to use nesting. Two parts can be packed in that way that it becomes a cubic of the thickness of 6 cm. The other dimensions like height and length stay the same. The increase of the utilisation degree is over 70 per cent although the load unit is just 25 per cent larger. That can be traced back to the fact that the dimension of the part is extremely unfavourable for the 4444-container. In Figure 37 it becomes obvious that much space is unused as the container is just 800mm deep and the part 890mm long. Therefore the part has to be laid along its long side of 1200mm, so that the rest space of 310mm cannot be used. It is not possible that the rest-space of 310mmx800mmx800mm is utilised by the part in any orientation. Thus, only 27 parts fit with its smallest and longest side at the bottom in the first layer and on top of the 27 parts, there are 8 parts laid flat (see Figure 36).
In the 1200mmx1000mm container the part fits with its longest side along the 1000mm side of the container, so that just a space of 110mmx1200mmx800mm is left. This space can be used by further 3 parts. Therefore in the first layer there are 41 parts instead of 35. On top it is possible to lay 2 staples of 8 parts next to each other, so that there it is possible to lay 16 instead of 8.

The calculation of cost in particular for this part is explained in the following. The part with the article code 7151493 is daily delivered from the 310 kilometre distant Obersulm. If the transportation cluster is used and the cost are broken down per part, the transportation cost per part are 0.28 Euro for the old container for the two new container the costs are 0.22 and 0.23 Euro per part respectively if all containers are not foldable. The lower costs for the new load units result from the better utilisation per volume in the new container. The performance indicator from Chapter 4.3.2 for the new load unit is 1.28 for the smaller container and 1.23 for the larger one, which results from the container’s enlargement of 25 and 50 percent but an utilisation degree growth of 60 and 85 per cent respectively. This irregular growth results from the dimension of the part. The rectangular measurement of the part is 0.89mx0.59mx0.04m. This measurement is disadvantageous for the measurement of the 4444-container (1200mmx800mm). The part just fits with its long side along the long side of the container, where 0,31m are left. As the width of the container is just 800mm the parts cannot be packed vertical to the long side. If additionally the foldability of the new container is considered the transportation costs add up to 0.15 and 0.11 Euro per part respectively. With a daily demand of 783 parts savings of (0.28-0.15)*783*21*12 = 25,651 Euro per year for the measurement of 1200mmx1000mm can be made for transportation and 33,543 Euro per year for the measurement of 1200mmx1200mm respectively.

The exact calculation is only available in the Excel-database due to the confidential requirements of BMW.
The handling process for this part is the following. The part is stored in hall 84, which is the conventional block storage. This is one of the cases in which an automatic high rack capable container is stored in the conventional container due to the capacity utilisation of the automatic one. The container is supplied by the AMA to the assembly area. Afterwards it does not matter if the container is demanded on the first or ground floor and no trailer transportation is needed.

The handling costs in hall 84 are 4.37 Euro per container and 6.86 Euro per container for handling for the 4444-container. The costs per part result therefore in 0.22 Euro per part. For the new containers the costs per container are more expensive due to the transportation per trailer. Therefore the costs are 2.38 Euro per container more expensive and the costs per part result in 0.24 and 0.21 Euro respectively. For handling there are negative savings of \((0.22-0.24)*783*21*12 = -3,946\) Euro per year and \((0.22-0.21)*783*21*12 = 1,973\) Euro per year respectively.

The sum of transportation and handling costs per part are 0.5 Euro per part for the 4444-container and 0.39 and 0.32 Euro per part respectively for the new
ones. This results in savings of $(0.5-0.39)*783*21*12 = 21,704$ Euro per year and $35,517$ Euro per year respectively.

This example shows two things. At first, it illustrates the proceeding of the analysis described in Chapters 4.3 and 4.4 and secondly it stresses that there are assembly parts that offer significant saving potential.

### 4.6 Discussion of Material

*This chapter discusses the possible materials of which a new load unit can be made. For this, the price development of the raw materials is examined and the technical characteristics of these materials are discussed.*

For the new load unit, it has to be decided whether steel or plastic or even a mixture of both is the best solution concerning price, durability and handling. In the last five years the prices for steel and plastic have changed quite often. Especially the price for plastics has been rising because of the climbing oil prices.

#### 4.6.1 Steel Price Development

From January 2003 the steel prices have been rising since the fiscal year chance 2004/2005 as can be seen in Figure 38 (steelonthenet.com 2005). The average steel prices climbed from US $ 337 per ton to US $ 662.80 per ton, i.e. the prices nearly doubled. In Mai 2004 the Statistical Federal Office (2004) informed in a press release that the prices are at the highest stage since 1989, for single kinds of steel like ferroconcrete the prices are on a historic maximum. According to ThyssenKrupp Steel (2005) the cause of these extreme prices was the domination of the world steel market by the boom in China, which led to a shortage of steel and raw materials, with a corresponding impact on prices. The boom in China led to strongly expanding demand for steel from China, which caused supply bottlenecks and very high prices for raw materials and steel products. China increased its share of world steel production to 25 per cent. Not only China had a production growth of 21 percent also other countries increased their output by a total of around 4 per cent. Therefore the world trade market reached a new record. A temporarily easing of tension in early summer was caused by a more restrictive lending policy in China, which led to slower growth in demand and therefore decreasing prices. In the fourth quarter the prices were raised step by step. In order to pass on drastic increases on the cost side caused by the appreciation of the euro prices hikes were necessary.
According to MEPS (2005) the global steel prices are set to fall further. Several causes are responsible for the doldrums on the stainless steel markets. Reasons are summer holidays in the northern hemisphere, high stocks and the weakening of raw material prices.

It becomes apparent that the steel prices depend on many factors. According to Bacon and Blyton (2005) the steel price is vastly affected by the business cycle. If the demand increases the price climbs rapidly but sinks slowly after the demand declines and recovers considerably slower if the demand grows again. Generally speaking steel prices are difficult to quantify or diversify as a large diversity of types and grading of commodities, large dimension of price reduction as well as effects of currency fluctuations exist.

According to Consline Research and Consulting (2005) the relaxation on both the demand and the supply side will lead to lower steel prices. Consline considers two scenarios. The first one considers indicators for falling prices, which are currently full stocks and growth of demand is slowing down, especially from China. Additionally the Chinese effort to dampen the economic overheating is working and the world economy is growing slower. Furthermore steel mills are not always able to forward higher prices to their customers. Therefore and simultaneously another indicator a lot of analysts believe that steel prices will fall during the year. The second scenario about at least constant prices mentions that China’s economy is going to grow steadily with around 8 to
9 per cent during the next years. Moreover, investments into fixed assets will grow at around 16 per cent. By cutting production to the level of demand steel companies are trying to hold prices stable. Additionally steel producers will at least try to forward higher input prices, especially for iron ore, but even for energy and transportation, to their customers. Consline’s outlook is that the steel prices will stay on high levels, but not inevitably on the highest point. That is because of the massive price hikes from 2004 and a slower growth of the economies in China and the world. On the other hand the demand is still increasing and not covered by new production capacities.

In Consline’s opinions the steel prices will fall in 2005 but the price level will stay in the mid term. Reasons are lower demand and lacking willingness of customers to accept higher prices. Therefore further increases are not realistic. On the one hand in the future costs for raw materials are assumed to stay high and are improbable to sink as well the demand from China is going to stay high and grow steadily. The economic growth until 2007 is estimated to be at least 8 per cent per annum. It comes along that transportation and energy costs are increasing as well. On the other hand although the industry demand is still growing double-digit it is slowing down. The world economic as well as the Chinese economy is lower and slower than expected. Additionally the higher production and rising capacities are indicators for lower prices.

4.6.2 Plastics Price Development

Plastic is becoming more and more relevant as packaging material. The prices for plastics have been varying quite a lot in the last years as can be seen in Figure 39 (PlasticsEurope 2005).
If the market of raw materials for plastic production is watched in West Europe between the year 1995 and 2005 as displayed in Figure 40 (PlasticsEurope 2005) it becomes obvious that the raw materials are subject to heavy price fluctuations and rises. In Figure 39 and Figure 40 it can be seen that the ups and downs in the market for basic plastics and raw materials are in the same terms. Additionally cognizable becomes the heavy climb since 2003. That can be traced back to the fact of the lack of raw materials, which let the prices rise. Moreover, the prices have been to low so far and have not been negotiable.

In 1995 the worldwide demand for polymers is extreme high especially in South Asia. The high capacity utilisation arouses high loss of production. Additionally there is an undersupply of the cracker and problems occur with the equipment in 1999. The heavy demand especially in China for polymers comes along. In 2004 benzene becomes historically rare and in autumn equipment problems for ethylene with crackers tighten the tense situation.
There is a close relationship between plastic and oil prices as presented in Figure 41 (PlasticsEurope 2005). Although the oil price underlies a much heavier price fluctuation it becomes apparent that the prices are correlated. That is because the raw material needed for the plastic production accrue during the oil production. The plastic prices are just much straighter and smoother than the oil prices. In 2001 there has been a heavy price retracement for oil as well the plastic prices started to fall slightly. As the prices for oil were climbing sharply in 2003 the plastic prices followed slowly.

4.6.3 Comparison of Alternative Materials

Both analyses in the chapters before show that the prices are quite unstable. The plastic prices as well as the oil prices have been rising and falling in the last month. The trend for both prices is growth, although the situation on the steel market is relaxing since the first quarter of the year 2005. Concluding it is not possible to give a suggestion only with the material prices. Other aspects have to be considered, too. This will be done in the next chapter.

The choice of the material for the load unit is an important decision as it has influence on the purchasing price, maintenance costs and lifetime. In this chapter the advantages and disadvantages of steel and plastic load units are considered.

At the moment all standardised load units are made of steel due to the cheap price. The standardised load unit 4444 in steel has several disadvantages and advantages which are displayed in Table 8.

One of the most relevant characteristics is the foldability because of lower transportation cost for the empties, which is not offered by this load unit. Additionally the high weight is negative because if the load unit is foldable the empty load units cannot be stabled on the AMA due to its high weight.
Table 8  Advantages and disadvantages of steel container

<table>
<thead>
<tr>
<th>Advantages:</th>
<th>Disadvantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low price</td>
<td>• Bad quality of surface (rust, dints, distant bars, etc.), wherefore additional precautions for parts are required</td>
</tr>
<tr>
<td>• High availability</td>
<td>• Dependence on steel market and on the supplier in Eastern Europe</td>
</tr>
<tr>
<td>• High loading capacity (1500kg, stackability: five times)</td>
<td>• Risk of injury from the closing mechanism (e.g. uptight flap or distant bars)</td>
</tr>
<tr>
<td>• Long lifetime (around 16 years)</td>
<td>• High tar weight (90 kg)</td>
</tr>
<tr>
<td>• Multi-purpose applicable</td>
<td>• Individual parts are not easy to change, e.g. impressed sides</td>
</tr>
<tr>
<td>• Great circulation in the automobile industry, demand fluctuations can be balanced easily</td>
<td>• Antiquated technique (closing mechanism, rust, not foldable)</td>
</tr>
<tr>
<td>• Load unit can be rented on the market</td>
<td></td>
</tr>
</tbody>
</table>

Plastic packages are used more and more since the last ten years as standardised load units. New manufacturing methods make it possible to produce more flexible and cheap. The amount of returnable containers made of plastic has been increasing to 65 per cent at BMW within the last years. Already now all load units for small parts are plastic container. Containers made of plastic have the following advantages and disadvantages (see Table 9).

Table 9  Advantages and disadvantages of plastic container

<table>
<thead>
<tr>
<th>Advantages:</th>
<th>Disadvantages:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Optimal protection of parts</td>
<td>• Low loading capacity</td>
</tr>
<tr>
<td>• Low Tara weight</td>
<td>• Lower lifetime</td>
</tr>
<tr>
<td>• Easy handling</td>
<td>• Fire load problematic</td>
</tr>
<tr>
<td>• Foldable</td>
<td>• Damaging more frequently</td>
</tr>
<tr>
<td>• Low injury danger</td>
<td></td>
</tr>
</tbody>
</table>

A third solution could be a mixture of both materials. Due to the characteristics of the two different materials it is advisable to use plastic for the container and to strengthen the container with steel, e.g. base frame of the load unit or the edges of the container.

The results of this chapter can be summarised as follows. The prices both for steel and for oil have been very volatile and are difficult to predict. Therefore, the choice of material should mainly be based on the technical characteristics instead of on the price. The characteristics suggest introducing a load unit that is made of a combination of steel and plastics.
4.7 Conclusion

In Chapter 4 the introduction of a new load unit was examined based on concrete data. Two container sizes were identified and analysed with a packing heuristic. Based on these results, a cost allocation allowed the comparison of the new sizes with the existing containers. The results show significant savings potential. Concerning the material choice, both the price and the technical characteristics have been discussed and the combination of steel and plastics was found to be advantageousness.
5 Resume

In this chapter, a resume about the results of the analysis is given concerning the identified purpose and sub-problems in Chapter 1. Furthermore, the potential risks of the analysis and its results are presented. The risk analysis in mind, a conclusion is made which restates the findings of the analysis. At the end suggestions for further research are given and recommendations are made for further implementations.

The purpose of the thesis was identified as the evaluation to which amount cost can be saved by introducing a new standardized load unit and which size would be recommendable. In the following chapter these questions are answered.

5.1 Summary of Results

In this chapter the results of the analysis are summarised. It addresses the purpose and the associated sub-problems.

The analysis in the previous chapter shows a potential for savings of around one million Euro per year, if a new load unit is implemented for a range of about 80 products. The most suitable size for the container concerning the limitations of the assembly area and the truck measurement is 1200mmx1000mm.

To get these results the identified sub-problems in chapter 1 have been examined and solved. At the beginning of the analysis a total cost model has been created in order to identify the relevant cost parameters of this study. Transportation, handling and maintenance cost have been identified as main influencing factors. In order to understand the processes involving load units the current situation was analysed by process mapping. Through this, the different steps of transportation and handling were identified. The process mapping also included the determination of the expense ratios for transportation and handling. Subsequently, possible sizes for the new load unit were created. For this, limitations from the assembly area and the truck size were identified and the sizes of 1200x1000mm as well as 1200x1200mm were chosen. In fact, the size 1200mmx1200mm is not really suitable because of its great removal deepness. Therefore, it was only used to analyse trends in the development of the handling and transportation costs with respect to the container size. For these sizes the utilization degrees were determined with a four-block heuristic. The four-block heuristic was selected due to its good trade-off between quality and computational time. The expense ratios were assigned to the different load units and, thus, a cost comparison was possible. As the cost comparison per part is
not very meaningful for the total savings potential, e.g., if the daily demand is low, the comparison was made per year.

The cost comparison results in several assembly parts that offer savings and others which would cause higher costs in the new container. Considering only the 80 parts with the highest potential, costs savings of around 1 million Euros should be possible. The range of suitable article numbers offers savings between around 1,000 and 30,000 Euro per year. Dividing the total savings into transportation and handling costs shows that in total they come from lower transportation costs while the effort for handling increases in most cases. The savings in transportation sum up to around one million Euro while the savings for handling are negative of around 35,000 Euro for the 80 parts with the highest potential. This is the case although the average utilization increases through the new load unit. This is due to the incapability of the new size to the AMA which triggers additional costs. The analysis shows that the transportation costs can more than compensate these negative effects of the handling costs. The transportation costs do not only offer savings due to the better utilization degree. Instead, the savings can also be traced back to the foldability of the new load unit because this significantly reduces the costs to return the empties. For the maintenance costs a qualitative analysis of the two materials steel and plastics has been conducted. The analysis suggests a combination of steel and plastic for the construction of a new load unit.

Concluding, the analysis identified large savings with the implementation of a load unit with the measurement 1200mmx1000mm.

5.2 Risk Analysis

In this chapter possible risks due to assumptions or changes are analyse and the stability of the results within the limitations is examined.

In most analyses risks can occur due to limitations which have a significant impact on the reliability of the results. In this analysis the following risks were identified:

1. Geometry of parts and nesting assumption
2. Storing capacity
3. Data quality
4. Reliability of expense ratios
5. Sensitivity of costs per part
6. Supplier Consequences
A risk can be the assumption that the geometry of parts is growing. However, this is not a real risk because the analysis is based on the current data and no future prospects are made. The new container is reasonable for active article codes which are in use right now. Therefore no risk exists. Another risk could be that the four-block heuristic does not consider nestings. Therefore the data for the packed parts might be wrong. Additionally, the assumption of the consistent growth of non-nested and nested parts might be wrong and therefore the percentage expansion. Nevertheless, it was necessary to choose a heuristic with sufficient speed. Furthermore, the inclusion of the current nesting in the results for the new load units should at least lead to better results than an approach that completely leaves out this aspect. Finally, an important advantage of a new container will be its foldability. The positive effect of this is not influenced by possible inaccuracies in the heuristic.

In Chapter 3.1.2 the warehouse capacities have been discussed. The result of the discussion was that the automatic high rack is at the capacity limit and the conventional block storage still has capacities. Through the implementation of a new load unit the automatic high rack is released and the utilisation of the block storage is increased because the new container cannot be stored in the automatic high rack. Due to this change the capacity of the block storage can be exceeded. This issue needs more consideration. Within such consideration the capacity utilisation of the trailer and the elevator is advisable because for these elements the capacity limit can be reached, too. However, to minimise this risk it is advisable to introduce the new load unit stepwise. This way, the effect on the block storage capacity can be observed. The savings for an assembly will not be lower through this as there no critical mass is required.

The analysis is based on data, which reliability is uncertain. It is possible that errors in stats like storage location or part dimension exist. I made some controls with some samples, which all were right. Additionally many article numbers have not been considered until now as the measurements or some other data is missing. This risk is based more on not detecting all potential of savings than on overestimating the savings by wrong assumptions. This risk should not be too high as much saving potential has already been detected.

The argumentation of the analysis is based on the expense ratios developed by the accounting of BMW. These expense ratios do not always correspond to the action committed basis and therefore cannot guarantee that exactly these expense ratios will apply for the new container. But too optimistic predictions are not presumably because the handleings cost for the AMA are estimated with
zero costs, although there are fixed costs like maintenance and energy consumption. These costs are ignored and should make the results even more positive than they already are. However, the risk can occur that the expense ratios do not reflect reality. That is a risk, which is not easy to avoid, as it is not measurable.

The costs per part differ in some cases just about one or two cents. If the daily demand for such a part is high cost savings can be earned per year. But due to the fact that the expanse ratios are just average values it is possible that they are not conform to reality. Thus, low but positive cost differences may fast change into negative cost differences, i.e. low part price differences are very sensitive concerning small changes or inaccuracy of the expense ratios. Therefore I suggest selecting parts for the new container with a higher cost differences per part.

The suppliers of BMW might be negatively affected by a standard load unit with a new measurement. If they have aligned their infrastructure to the size of the current load unit, they will have to invest in changes. In some cases, these costs could be directly or indirectly allocated to the costs for BMW. Nevertheless, as most suppliers handle several different sizes of load units, most of them should be flexible concerning the size. Other automobile manufacturers already use the suggested size of 1200mmx1000mm, so that the case that a supplier would be negatively affected by the different size is very small.

All in all I appraise the risks as relatively small, so that the analysis is accurate.

### 5.3 Conclusion

Considering all aspects of this thesis, it can be said that there is potential for high cost savings by introducing a foldable load unit with a size of 1200mmx1000mm. From the point of view of this thesis, a new container should be introduced which is made of a combination of steel and plastics and is foldable. The savings potential results from the fact that the transportation costs are able to more than compensate the negative effects of higher handling costs. The overall risks for the introduction of such a load unit are relatively small and therefore the new size should be implemented.
5.4 Further Research

In this chapter recommendations are made for further research and investigations in areas, which were not reached due to the delimitations or could not be completed in the study.

To ensure reliable results the databases of Dingolfing, Regensburg and Munich have to be complete, up-to-date and accurate. Therefore, the missing information about the daily demand of the parts should be added to the databases in Munich and Regensburg in order to fully benefit from the results of this thesis. In Regensburg the distances from the supplier to the plant have to be entered to ensure accurate results. In Dingolfing the data of the SLMG database have to be updated as the data is from October 2004. Also investigations should be made in other manufacturing sites in other countries. This analysis should be done not only in automobile producing sites but also in sites for manufacturing of finished products, which deliver the automobile plants.

Further research should be made on foldable load units. This study did not only identify cost savings due to better utilization but especially due to foldability of the new load unit. Thus, it might be advantageous to also replace existing containers with foldable ones of the same size.

The storage capacity of the block storage is not examined so that it is possible to make statements about its capacity limit nor its current capacity utilisation. For the answering of the question how many load units can be transferred from the automatic high rack to the block storage a capacity analysis is needed.

Finally, there exists no information about the fact, if suppliers have aligned their infrastructure like conveyor technique to a specific load unit size of BMW. The information is needed to make statements about the influence on these kinds of supplier.

5.5 Further Recommendation

This section gives recommendations concerning a new load unit with respect to the short-, medium- and long-term planning. The recommendations refer both to a new load unit and to the general processes of BMW.

My suggestion from the results of the analysis is to introduce the measurement 1200mmx1000mm as alternative container. This size satisfies all limitations and discharges the automatic warehouse. As material I suggest to use a
combination of steel and plastics. With the recommended material and size a pilot should be started.

For implementation in the start phase a high potential part like the article codes suggested in chapter 4.5 should be selected. With that part a test with the new load unit should be done, in a similar proceeding as BMW is currently doing with an alternative container of the size 1200mmx800mm. Afterwards if the test offers positive effects more and more parts should be transferred into the new load unit until restrictions, e.g. warehouse capacity, are reached or problems occur. The article numbers which provide saving larger than 5,000 Euro for Dingolfing are potential candidates for that kind of proceeding. The list is displayed in Appendix B. This is my suggestion for the short-term planning.

For the medium-term I would suggest to invent a planning tool for the packaging planner, which makes it easier to find the cheapest container for a part. The packaging planner could calculate with the PackAssistant\(^\text{19}\) the utilisation degree of the contemplable container sizes. Afterwards the tool calculates the costs per part with the calculated utilisation degree and the information about the material flow through the BMW supply chain. Thus it is possible to find the cheapest container for the part. If this cost comparison is not made I worry that the packaging planners - with the higher cost for non-AMA-capable container in mind - are not going to use the new measurement. It has to be clear what are the advantageous of the new measurement.

For the long-term planning I suggest to include this analysis into the future planning for the intern storage and conveyor system planning. At the moment the system is quite inflexible and already at its capacity limits. If a new automatic high rack and conveyor technique is planned it should be considered to make the system more flexible for other container sizes. The removal storage and storage capacity (in terms of containers per time) should be adapted to the storing capacity of the automatic high-rack (in terms of number of containers). Thus, the current situation can be avoided that the storing capacity is far below its capacity limit due to the fact that the removal and storing capacity is already at its limits.

\(^{19}\) The PackAssistant is a three dimensional packing tool to store non cuboid boxes with nesting in a given container. It is developed by Fraunhofer-Institut SCAI / MVI SOLVE-IT GmbH (www.packassistant.de)
**List of Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMA</td>
<td>Automatische Montageanbindung = Automatic Integration System</td>
</tr>
<tr>
<td>BFW</td>
<td>Bayrische Flugzeugwerke</td>
</tr>
<tr>
<td>BMW</td>
<td>Bayrische Motorenwerke</td>
</tr>
<tr>
<td>JIS</td>
<td>Just in Sequence</td>
</tr>
<tr>
<td>JIT</td>
<td>Just in Time</td>
</tr>
<tr>
<td>SLMG</td>
<td>Sachnummern Logistisches Mengengerüst (Database)</td>
</tr>
</tbody>
</table>
List of Literature


BMW Group (2000): *Verpackungshandbuch*; BMW AG, München


BMW Group (2000): *Verpackungshandbuch*; BMW, München

BMW Group (2005a): *Behälterkatalog*; BMW, München

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Soliman, F. (1998): *Optimum level of process mapping and least cost business process re-engineering*; University of Technology, Sydney, Australia


Steudel, H. (1979); Generating pallet Loading Patterns: A Special Case of the Two-Dimensional Cutting Stock Problem; *Management Science* 25(10), 997-1004


Appendices

A. Appendix: Solver Macro Code

Sub Solverloop()

Dim MyRange, MyResult As Range
Dim r, myrownum As Integer
Dim MyInputL, MyInputB As Long

Sheets("Solver").Select
Set MyResult = Range("B36") 'Assignment of the solution cell from the Sheet Solver to the variable MyResult
Sheets("Daten").Select
Set MyRange = Range("B399:D1554") 'Selection in the Sheet Daten of the used rows in the three columns Length, Width and Solution. The concrete area has to be defined by the user.
myrownum = MyRange.Rows.Count 'Assignment of the number of rows in MyRangeweist to the variable
Range("D1").Select 'Jumps with the cursor into the cell

'Implementation of the four-block heuristic with constraints
Sheets("solver").Select
SolverReset
SolverOptions MaxTime:=1000
SolverOK SetCell:=Range("B36"), MaxMinVal:=1,
ByChange:=Range("B32:E33")
SolverAdd cellref:=Range("B32:E33"), relation:=4
SolverAdd cellref:=Range("B32:E33"), relation:=3, formulatext:=0
SolverAdd cellref:=Range("C16"), relation:=1, formulatext:=Range("B6")
SolverAdd cellref:=Range("C17"), relation:=1, formulatext:=Range("B6")
SolverAdd cellref:=Range("C18"), relation:=1, formulatext:=Range("B7")
SolverAdd cellref:=Range("C19"), relation:=1, formulatext:=Range("B7")
SolverAdd cellref:=Range("C21"), relation:=1, formulatext:=Range("B8")
SolverAdd cellref:=Range("C22"), relation:=1, formulatext:=Range("B8")

For r = 1 To myrownum

'1. Transfer Lenght and Width into the Sheet
Sheets("Daten").Select 'Assignment of the currently used part values to the variables MyInputL and MyInputB
MyRange.Cells(r, 1).Select
MyInputL = ActiveCell.Value
MyRange.Cells(r, 2).Select
MyInputB = ActiveCell.Value

Sheets("Solver").Select 'Enters the current length and width of the part into the solver
Range("E6").Select
ActiveCell.Value = MyInputL
Range("E7").Select
ActiveCell.Value = MyInputB

'2. Solver running
Sheets("solver").Select
Range("B32").Select
ActiveCell.Value = 1
Range("B33").Select
ActiveCell.Value = 1
Range("C32").Select
ActiveCell.Value = 1
Range("C33").Select
ActiveCell.Value = 1
Range("D32").Select
ActiveCell.Value = 1
Range("D33").Select
ActiveCell.Value = 1
Range("E32").Select
ActiveCell.Value = 1
Range("E33").Select
ActiveCell.Value = 1
SolverSolve UserFinish:=True
'SolverSolve UserFinish:=True
'SolverSolve UserFinish:=True

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Next r
End Sub
### B. Appendix: List of parts for Dingolfing

Parts with savings larger than 5,000 Euro per year

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**Sum of savings per year**

932411
Declaration of Academic Honesty

I herewith declare, in lieu of oath, that I have prepared this thesis on my own, using only the materials mentioned. Ideas taken, directly or indirectly, from other sources, are identified as such.

Location, Date

Signature of Student