FACULTEIT ECONOMIE
EN BEDRIJFSKUNDE

Materials supply of mixed-model assembly lines – bulk versus kitting versus repackaging

Aantal woorden/ Word count: 16719

Gilles Van Cauwenberge
Stamnummer/ Student number : 01203875

Promotor/ Supervisor: Prof. dr. Veronique Limère

Masterproef voorgedragen tot het bekomen van de graad van:
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Preface

This master dissertation is the final step to complete the Master of Science in Business Engineering. After succeeding the bachelor program, I have chosen the master specialization in Operations Management. My interest in operations management is also the reason why I opted for this master dissertation in Materials Supply of Mixed-model Assembly lines.

Before proceeding to the master dissertation I would like express a gratitude to the people who cooperated in the realization of this master dissertation.

First of all, I would like to thank Prof. dr. Veronique Limère to give me the opportunity to use her Doctoral Dissertation, To Kit or Not to Kit: Optimizing Part Feeding in the Automotive Assembly Industry, as a starting part for this master dissertation. Furthermore, I would like to thank Prof. dr. Limère to provide me with the necessary information, knowledge and time to get an insight in the materials supply of mixed-model assembly lines, and to be able to complete this master dissertation.

Additionally, I would like to thank my parents, family and friends for the moral support to complete this education.

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List of variables and parameters

Sets

I_b Set of all parts supplied in small boxes

I_p Set of all palletized parts

I Set of all parts; $I = I_p \cap I_b$

I_s Set of all parts used at station *s*

S Set of all work stations *s*

V_i Set of variant parts of $i \in I$; the family of part i

Parameters

a_i Maximum number of units of a part i in one pick due to physical characteristics (weight, volume) of part i

A^b Capacity of the milk run tours for boxes (number of boxes per tour)

A^r Capacity of the milk run tours for repackaging boxes (number of boxes per tour)

A^k Capacity of the milk run tours for kits (number of kits per tour)

B^r Batch size for assembling repackaging boxes

B^k Batch size for assembling kits

Δ_{is}^{bulk} Average distance for the operator at workstation s to pick from a bulk container of part i (m)

Δ_{is}^{repack} Average distance for the operator at workstation s to pick from a repackaging box of part i (m)

Δ_{is}^{r} Average distance for the operator in the supermarket to pick from a bulk container of part i to repack for station s (m)

Δ_{is}^{k} Average distance for the operator in the supermarket to pick from a bulk container of part i to kit for station s (m)

Δ^{k} Average distance for the line-operator to pick from a kit (m)

d Yearly demand for end product (= vehicle)

D^{b} Distance of the milk run tour for boxes (m)

D^{r} Distance of the milk run tour for repackaging boxes (m)

D^{k} Distance of the milk run tour for kits (m)

D_{s}^{p} Distance of transport between the pallet warehouse and work station s (m)

$depth$ The depth of the line – i.e. the perpendicular distance between the operator working at the product and the border of line (m)

f_{is} Percentage of end products for which part i is assembled at station s (frequency)

f^{r} The time to fill a repackaging box with parts (h)

FT^{k} Fixed production time for each kit (h)

H^{b} Vertical stacking height of boxes (units) on the BoL

H^{r} Vertical stacking height of repackaging boxes (units) on the BoL

L^{b} Length of a box along the line (m)

L^{r} Length of a repackaging box along the line (m)

L^{k} Length of a kit container/rack along the line (we assume no stacking of kits containers) (m)

L^{p} Length of a pallet along the line (we assume no stacking of pallets) (m)

L_{s} Available length along workstations s (m)

m_{is} Number of units of part i assembled per vehicle (if the specific variant part i is used) at station s

n_i Number of units of part i contained in the original packaging; packing quantity of part i

r_i Number of units of part i contained in the repackaging boxes; repacking quantity of part i

OC Cost of labor (per hour) of an operator (€/h)

OV Average walking speed of an operator (m/h)

$pack_i$ Supplier packaging of part i {Box, Pallet}

q_{is} Yearly usage of part i at station s; $q_{is} = m_{is} f_{is} d$

ρ^b Expected capacity utilization of the milk run tours for boxes

ρ^r Expected capacity utilization of the milk run tours for repackaging boxes

ρ^k Expected capacity utilization of the milk run tours for kits

R^b Constant cost for the replenishment of one box in the supermarket (€)

R^p Constant cost for the replenishment of one pallet in the supermarket (€)

τ^{bulk} Average time to search for the required part from bulk stock at the line (h)

τ^{repack} Average time to search for the required part from repackaging boxes at the line (h)

τ^{sup} Average time to search for the required part from bulk stock in the supermarket (h)

θ_{is} Number of units of part i that will on average be picked in one pick when part i is kitted for station s

v_i Number of units of part i that a kit can maximally hold; this categorical parameter represents the volume (small, medium, large, extra large) of part i {100, 20, 5, 1}

V^b Velocity of the material handling equipment for milk run tours for boxes (m/h)

V^r Velocity of the material handling equipment for milk run tours for repackaging boxes (m/h)

V^k Velocity of the material handling equipment for milk run tours for kits (m/h)

V^p Velocity of the material handling equipment for pallets (m/h)

w_i Weight of part i (kg)

w^k Weight constraint on one kit unit; maximum weight per kit (kg)

Variables

K_s Integer auxiliary variable

Number of kits needed at station s to assemble one vehicle

N_s^b Integer auxiliary variable

Number of facings needed to store boxes along station s (with a vertical stacking of boxes)

N_s^r Integer auxiliary variable

Number of facings needed to store repackaging boxes along station s

(with vertical stacking of repackaging boxes)

x_{is}^l Binary decision variable

$x_{is}^l = 1$, if part i is bulk fed

0, else

x_{is}^r Binary decision variable

$x_{is}^l = 1$, if part i is repacked

0, else

x_{is}^k Binary decision variable

$x_{is}^l = 1$, if part i is kitted

0, else

Cost and Time Factors

C_{kit} The yearly labor cost for kit assembly (€)

C_{repack} The yearly labor cost for repackaging (€)

C_{pick} The yearly labor cost for operator picking at the assembly line (€)

C_{repl} The yearly labor cost for the replenishment of the supermarket (€)

C_{total} The yearly labor cost (€)

C_{tpt} The yearly internal transport cost (€)

C_{tpt}^{pallet} The yearly cost for pallet transportation (€)

C_{tpt}^{box} The yearly cost for box transportation (€)

C_{tpt}^{repack} Yearly cost for repackaging box transportation (€)

C_{tpt}^{kit} The yearly cost for kit transport (€)

FC_{kit} The yearly fixed cost to assemble all kits (€)

tp_{is}^{bulk} Average time to pick a unit of part i from a bulk container at station s (h)

tp_{is}^{repack} Average time to pick a unit of part i from a repackaging box at station s (h)

tp^{k} Average time for the line-operator to pick a unit from a kit (h)

tr_{is} Average time for the operator in the supermarket to pick a unit from a bulk container of part i to repack for station s (h)

tk_{is} Average time for the operator in the supermarket to pick a unit from a bulk container of part i to kit for station s (h)

VC_{kit} The yearly variable cost to assemble all kits (€)

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1 Introduction

The increasing international competition and the technological improvements creates pressure on manufacturing companies to design and produce high customized products to meet the diverse requirements of the customers. However this has not always been the case.

Before the Industrial Revolution, most of the products were made by craftsmen. The manufacturer was responsible for delivering a complete assembled product. It was Adam Smith who developed a new way of working by applying the division of labor. The separation of tasks to assemble a product increased the productivity because a lot of labor time was saved due to specialization.

The division of labor later induced the introduction of the assembly line. In the twentieth century, Henry Ford developed an assembly line with a conveyer belt to produce the Model T. This assembly line had a major influence on the manufacturing world. Moving the work from worker to worker seemed to be a lot more efficient and increased the throughput. The assembly line technique decreased the production costs what resulted in increasing demand. The successes of Ford were copied by other car manufacturers and increased competition.

The assembly line of Ford was used to produce exclusively standardized products. The Ford T was available in only one color. Nowadays, the increasing competition forces companies to deliver customized products to differentiate themselves from their competitors. Customized products are necessary to meet the diverse requirements of customers. However these products must be delivered timely, at low prices and at high quality. This trend is called mass customization: delivering a high variety of products in a cost efficient way such that demand in all kind of market segments can be fulfilled.

Production companies must continue to find ways to meet the customer expectations with ever higher levels of efficiency. The high variety of products makes manufacturing complex and due to the pressure of high global competition there is little room for error.

This trend towards mass customization has major consequences for the production organizations. An assortment of different parts is needed to produce high variety products. Al those parts need to be supplied to the assembly line, what results in an increasing materials handling and a more complicated materials supply process (Limère, 2012). Moreover, the different parts require different tools to assemble the parts. The increasing number of parts and tools requires more work space at the stations.

The system responsible for feeding the parts to the assembly line, the materials supply system, must deliver the right parts, in the right quantity and at the right time to the right workstation (Limère, 2012). The material arrives to the company in different emballage types, mostly on pallets, containers boxes or racks. The materials can be transported by forklifts, train wagons or conveyors to the assembly line. The transportation of the materials is a complex process that must be executed in a cost-effective manner.

The different kind of materials supply systems have an influence on the material handling, transportation and the assembly operations. Delivering parts in large containers or smaller boxes will have an influence on the way material is delivered to the line and the amount of material that is stocked at the line. Moreover, the available space at the border of the line is limited. The assembly operations are influenced because a lot of material stocked at the line will require more searching time for the right parts and more walking distance for the assembly operator.

The materials supply systems that are mostly used are: line stocking and kitting. Choosing one or the other depends on the trade-off between material handling, space requirements and work-in-process. Line stocking, also known as continuous supply or bulk feeding, is the most straightforward part feeding method where parts are stored at the border of the line in units larger than one (Limère, 2012). All parts required to produce the different models will be available all the time at the border of the line, what is the main advantage. Another beneficial effect in line stocking is that there is no need to preprocess the parts before they are transported to the line. The drawback is that a lot of space is needed to store these containers at the border of the line and time is needed for the operator to find the right part. To replenish the containers, use is made of the two-bin or reorder point system. In the two-bin system, a new container is order when the first container is empty. The new bin then is supposed to arrive before the second bin is consumed. In the reorder point system, a new container is ordered when the number of parts at the line goes below a predefined quantity, according to the lead time. This level is called the reorder point.

In the kitting method, the assembly line is supplied with kits of components. A kit is a container which holds a specific assortment of parts that are used in assembly operations for a specific product. Rather than delivering parts to the assembly line in large quantities, only the parts that are necessary to complete the next product at the line are delivered (Bozer and McGinnis, 1992). Kits are a kind of a loose preassembled products that are delivered to the line in the sequence of the assembly schedule on the line. Kitting is often used when there is a high variety of parts to produce the different products. By kitting the parts before they are supplied to the line, a lot of space can be saved on the shop floor.

Another advantage is that the operator at the line does not need to search the right parts, what results in less searching time and less mistakes. However a lot of time is needed to kit the parts before they enter the assembly line.

Sequencing is a third method of line feeding. Parts are delivered to the line in the right quantity and the right sequence according to the assembly schedule. In this approach material is not stocked in large quantities at the border of the line (Limère, 2012).

A last method of line feeding is repackaging, also called downsizing. This method is used to face the main drawback of continuous replenishment. By repacking the large bulk containers with parts in smaller boxes, a lot of space can be saved at the border of the line. The walking distance for the operator is also reduced in this manner because the length of the stock at the line determines to a large extended the walking distance for the operator.

The main drawback of repackaging, kitting and sequencing is that more material handling is needed before parts can be moved to the border of the line. These material handling activities can take place at different points in time in the materials supply chain. Often, these activities are performed in the company after the parts are delivered in large containers. The place where the parts are reordered or repackaged is called the supermarket. When the place to perform these activities is limited, it can be outsourced to a third party logistics provider (Limère 2012). Another option to save material handling costs is to negotiate with the supplier that they can perform the activities related to repackaging, kitting and sequencing.

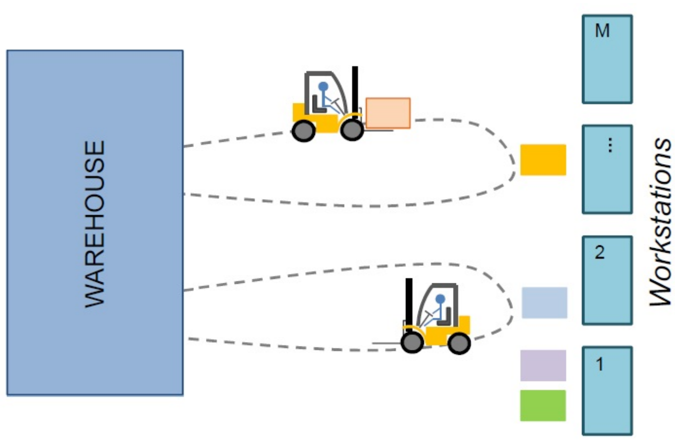

Figure 1.1: Line stocking (C.Caputo, M.Pelagagge and Salini, 2015)

Figure 1.2: Kitting (C.Caputo et al., 2015)

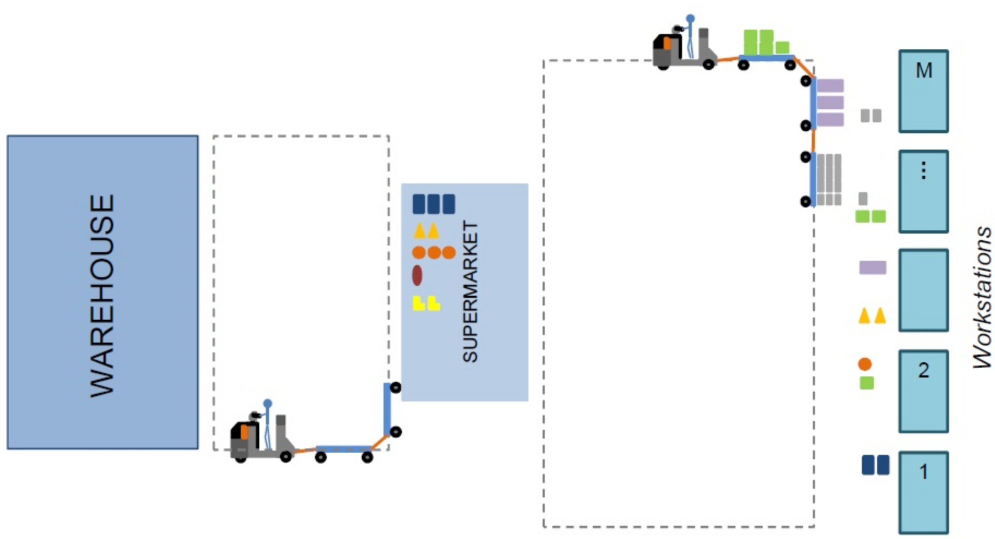

Figure 1.3: Repacakaging (C.Caputo, et al., 2015)

2 Literature Review

Originally an assembly line was used for mass production to serve as many customers as possible at a relatively low cost. Production was limited to one model at a time. Nowadays, manufacturers are obliged to produce a high variety of products to serve the specific customers' needs. Moreover these products must be produced at a low cost to be competitive. This is the way mixed model assembly lines were designed, to common exploit equipments. According to Deechongkit and Rawinkhan (2009) a lot of studies were conducted to optimize flow of operations in assembly lines but materials supply of assembly lines was often ignored. They set up a Production and Materials Flow Control (PMFC) mechanism to both control the production and materials flow of an assembly line. They formulated a multi-objective problem to measure and benchmark the different systems: travel distance of supply, time spend on material handling and investment costs. The first assembly line they investigated was the traditional assembly line were the material is positioned parallel, I-shape, to the line in containers. However in mixed-model assembly lines, the lines must be extended when a lot of optional parts have to be stored at the line. The investment costs for extending the line are high. Another way to deal with the numerous parts is to use a Set Part Supply (SPS) synchronizing system, what we call kitting. The parts are grouped in sequence of the processes at the assembly line. This saves place at the assembly line, what results in less investment costs to extend the line. However material handling increases. Another way is to use a H-shaped line. This makes it possible to shape the line to maximize the storage area near the line. The data for their study was collected in a Toyota Plant. First they compared the traditional line with the SPS synchronizing method. The SPS system saved a lot of investment costs but the time spend on material handling and the supply distance were not much reduced. The H-shaped line however compared to the SPS system saved significantly the material handling time, the supply distance and the investment costs. They concluded that material handling must be incorporated in the assembly line design and not to focus only on optimizing the flow of operations.

Bozer and McGinnes (1992) conducted a study where they evaluated the quantitative and qualitative advantages and disadvantages of kitting versus line stocking. To conduct their study, they visited a number of plants and observed several applications of kitting. In the qualitative review, they represented a list with the advantages and limitations of kitting. They mentioned that different kinds of methods are possible for kit assembly. In their opinion, the mayor limitations of kitting are mostly eliminated when the kits are not assembled far in advance but on a just in time basis. However this is not always possible.

In order to quantify the differences between kitting and line stocking, a descriptive model was developed. Bozer and McGinnes (1992) stated that setting up and operating a kitting system is a complicated task since kitting interacts with many subsystems who support the assembly operations system. Capturing all the possible interactions in the model is difficult and complicates the model, that is why they made a lot of assumptions. Firstly, they only consider kit-to-manufacturing. Kit-to-customer, where kits are formed to sell to customers is not considered in their model. Additionally, a difference was made between stationary - and travelling kits. A stationary kit is put at the border of the line and stays there until it is depleted. A travelling kit on the other hand is transported along with the product and supports several workstations. Furthermore, they assume that there is only one component container type and one kit container type. In their study they investigated the differences in material handling between kitting - and line stocking containers. No other material handling steps are considered, except container handling. The material handling that is needed to form kits is not considered. The difference in space required to store material at the border of the line is also investigated. On top of that they determined the difference in work-in-process (WIP) level. Their conclusion was that there is less space required at the border of the line when kitting is used and also the WIP level is reduced. However, kitting tends to increase the material handling. Bozer and McGinnis mentioned that their model is based on some simplistic assumptions but that it can serve as a starting point or benchmark for future model developing in this area. They also mentioned some new research directions to enhance the model. The most fundamental direction that was mentioned is the fact that they have not considered the influences of kitting versus line stocking in the operations performed at the line. First of all, operators will probably be more productive in a kitting environment. This will have an influence on the workstation cycle times. We can conclude that it is thus better to include the assembly line operations in the model.

Recently, C.Caputo, M. Pelagagge and Salini (2015) developed a decision model for selecting parts feeding policies in assembly lines. Different from most of the other research studies, they incorporated three different part feeding policies in their model. Most of the research studies only compare kitting and line stocking based on a simplified mathematical model. This study incorporates also just in time (JIT) supply, a different kind of continuous supply. The model of C. Caputo et al. (2015) defines the optimal assignment of feeding policy to each component type, by selecting among the three policies (kitting, line stocking and JIT) in order to minimize the total materials supply cost. Line stocking and JIT parts supply, mainly differ among the amount of transported material, the size of the containers used and the handling frequency. In the JIT supply method, only small-sized containers will be moved to the assembly stations. The containers are prepared in a supermarket and are replenished by using a Kanbanbased system. They incorporated different kind of cost factors in their model in order to be more extensive than earlier models where many relevant cost factors were neglected. The costs that are included in their model are: workers costs, investment costs, work in process (WIP) holding costs and floor space occupation costs. The worker costs include material handling costs as well as costs related the assembly line operator. Their conclusion is that the cost saving potential resulting from adopting multiple feeding policies is significant. Adapting the same policy for all components is not a cost efficient solution. They mentioned that their optimization model is only meaningful if the input data has a sufficient precision. Although the model is very detailed, some things are simplified in the research. First of all the model is aimed at single-model assembly lines. Secondly, they only incorporate single-line assembly lines. Lastly, only relevant quantitative cost drivers are included, some qualitative factors are not included yet. However, the researchers mention that the model can be extended to multi-model lines.

Hanson and Brolin (2013) collected empirical data from two case studies in the automotive assembly industry where they compared continuous supply with kitting, based on several performance measures. According to Hanson and Brolin (2013), the benefits and drawbacks associated with kitting and continues supply are often related to the settings in which the materials feeding principles are used and to how they are applied. To be able to compare the effects on the performance measures, they investigated assembly lines where kitting has replaced continuous supply. This makes it possible to compare both materials supply principles in the same setting. On top of that, the two case studies complement each other because there are differences in the kitting technique. In the two cases, the reason why the materials supply system was changed to kitting was because there was a lack of space at the border of the assembly line to present all parts needed to produce the different products. To measure the difference between kitting and continuous supply they used four performance measures. First of all they concluded that kitting reduces the man-hour consumption of assemblies because parts are presented closer to the assembly object. However that reduction in man-hour consumption was more than cancelled out by increasing man hours required for preparing and delivering the kits. Secondly, kitting is only beneficial for the quality of the final product if no mistakes are made in the kit preparation. Furthermore, if mistakes are made, then it requires more resources to correct a mistake in the kitting system. Thirdly, kitting is more flexible than continuous supply because it is easier to change the production plan and a larger number of parts can be used. Lastly, kitting reduces the space needed and the inventory at the border of the assembly line. However, the total inventory level increases with kitting because inventory is moved to the kit preparation area.

Brynzér and Johansson (1995) did a lot of case studies to evaluate different designs of kitting systems. They investigated differences in locations of the order picking activity, the work organization, the picking method, the information system and equipment. To evaluate the differences in design they used performance measures such as the picking efficiency and the picking accuracy.

Srinivasan and Gebetstadk (2011) did a case study in a Volvo Car plant in Sweden. The material flow of a mixed model assembly line was investigated at the plant. The purpose of their thesis study was to develop a decision support tool that could help Volvo Car for identifying the appropriate principles and calculating the costs of materials supply processes and assembly systems in each stage of the flow. They considered also the repackaging process in the different materials supply techniques investigated. The task of the repackaging process is to repack/downsize components of specific quantity into smaller boxes. The components in bigger emballages are unloaded from the racks in the warehouse, transported to the repacking place, downsized to defined unit loads and then transported again to main racks and stored for a temporary period. When needed, the small boxes are delivered to the assembly line. The repackaging activity is carried out manually and described in the picture below.

Figure 2.1: Repackaging activity (Srinivasan et al., 2011)

Only components that are not used frequently in the line are repacked. They investigated multiple materials supply techniques and developed flow charts for the different techniques. However they did not compare the different techniques in a quantitative analysis.

3 Research question

Previous research for assembly lines was mainly focused on the optimization of the assembly line operations itself. Little research has focused on optimizing the materials supply of assembly lines. Because the opportunity for improvement in assembly line balancing decreases, nowadays research is focusing more and more on other alternatives for improvement to stay competitive. That is why materials supply of assembly lines gets more and more attention in research studies. However most of the studies related to materials supply mainly compare kitting and line balancing in a qualitative way. On the other hand, Hanson and Brolin (2013) compared kitting and line stocking in a quantitative way but in their approach the performance of kitting was determined by completely replacing the line stocking method.

The approach of Limère (2012) to compare line stocking and kitting in a quantitative way is more reasonable because the study assumes that there is no optimal materials supply policy that outperforms the other. Limère (2012) developed a mathematical optimization model in order to assign the most cost effective line feeding policy to a certain part. In this way the materials supply system is not limited to a single policy for all the parts. However in this optimization model, only kitting was compared with line stocking. Other material supply policies, e.g. repackaging, were not considered in the optimization model.

The research study of C.Caputo, M.Pelagagge and Salini (2015) incorporated three materials supply techniques: line stocking, kitting and Just In Time (JIT). The mathematical optimization model is however limited to single-model and single line assembly lines. The materials supply of single-model assembly lines is not comparable with multi-model assembly lines because for multi-model assembly lines a lot more parts need to be supplied to the assembly line. For most of the parts many variants exist where customers can choose from. Furthermore, the analysis of the different cost factors and part characteristics is limited in the study of Caputo et al. (2015).

The objective of this study is to extend the model in the thesis of Limère (2012) with the repackaging materials supply policy. Consequently, the objective is to develop a mathematical decision model that assigns the most cost effective materials supply policy to the different parts needed at the border of the line. Three types of part feeding policies will be incorporated in the model: line stocking, kitting and repackaging. Furthermore, an extensive analysis of the model, and the parameters in the model will be performed.

The first research question is defined as:

Research question 1:

Is it possible to develop a mathematical optimization model that assigns an optimal materials supply policy, line stocking - kitting or repackaging, to the different parts based on a given plant layout and part characteristics?

Before the mathematical model is developed, the costs and benefits of each materials supply policy need to be determined. Based on those costs, the mathematical model to determine the optimal materials supply policy has to be developed. In order to solve the model, data is needed for the parameters related to the part characteristics and the plant layout. Once the model is solved, the result needs to be analyzed thoroughly.

Additionally, an analysis needs to be performed on the different parameters in the model because the parameters are case specific. This leads to the second – and third research question.

Research question 2:

Is it possible to determine part characteristics which have a significant impact on the materials supply policy that is assigned?

Different part characteristics are included in the model in order to be able to determine the optimal materials supply policy. In the analysis it is the objective to determine part characteristics which have a significant impact on the materials supply policy that is assigned.

Research question 3:

Is it possible to determine materials supply parameters which have a significant impact on the materials supply policy that is assigned and the cost factors?

The plant layout, the workstation layout, the operator productivity,… will all have an impact on the solution of the model. It is the objective to determine materials supply parameters which have an impact on the assigned materials supply policy and the cost factors in the optimal solution.

4 Modeling Approach

In the previous part the objective of this thesis was determined. In this chapter we develop a mathematical model to derive the trade-off between line stocking, repackaging and kitting for the different parts and their characteristics. First, the flow of materials and the material handling is determined. Secondly, the different cost factors are explained. Lastly, the complete mathematical model is determined. This chapter is based on Limère (2012, chapter 2).

4.1 Material flow

Parts enter the company in bulk. The parts first enter the warehouse where they are stored in their original supplier package. From there on, the flow of material is determined by the material flow method. The three different part feeding systems are explained below with their respective costs.

4.1.1 Line stocking

In line stocking, all parts are delivered to the assembly workstation in their original supplier packaging (Limère, 2012). Two different packaging types are considered: pallets and boxes. Those pallets and boxes are stored at the border of the line. Pallets are stored next to each other while boxes are stored on racks. Pallets therefore occupy more space at the border of the line. Normally, replenishment will be controlled by a reorder-point inventory system. When the number of parts in the pallet reaches the reorder point, a new one will be ordered. A forklift truck is used for internal transport, to bring a pallet from the warehouse to the border of the line. When the original packaging is a small box, internal transport is provided by a tugger train. The tugger train completes periodically a milk run tour to deliver boxes from the warehouse to the different workstations. Replenishment for boxes is controlled by a two-bin inventory system. Two boxes with the same part types are stored one behind the other at the border of the line. When the first box is empty, the second box will move forward and a new one will be ordered. In this way, only boxes with different part types are visible for the assembly operator.

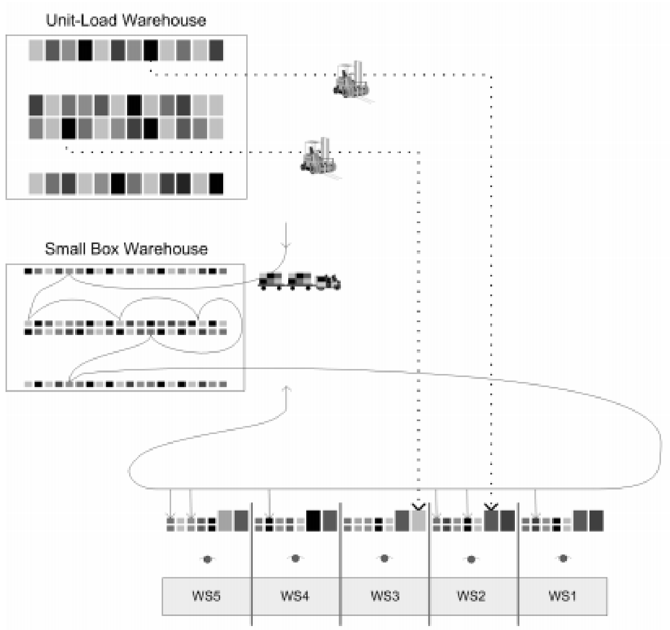

Figure 4.1: Line stocking (Limère, 2012)

4.1.2 Repackaging

Pallets occupy a lot of space when stored at the border of the line. To save space, the parts in pallets from the supplier can first be repacked in smaller boxes before they are delivered to the workstations. In the factory, the repackaging activity takes place in the supermarket. The supermarket is supplied by the warehouse with pallets and boxes in the original supplier packaging. In the central supermarket, the operator walks through the aisle and fills repackaging boxes with parts of the same type. We assume that multiple repackaging boxes of the same part type are assembled in batches in order to increase efficiency. Furthermore, we assume that only parts delivered in pallets are eligible for repackaging. Parts delivered in boxes by the supplier do not need to be repacked. Compared to the boxes in original supplier packaging, the repackaging boxes are also stored in racks at the border of the line. A two-bin inventory system will control the replenishment. When a box is empty, the box behind is moved forward and a new box is ordered. Periodically the tugger train transports boxes from the supermarket to the workstations.

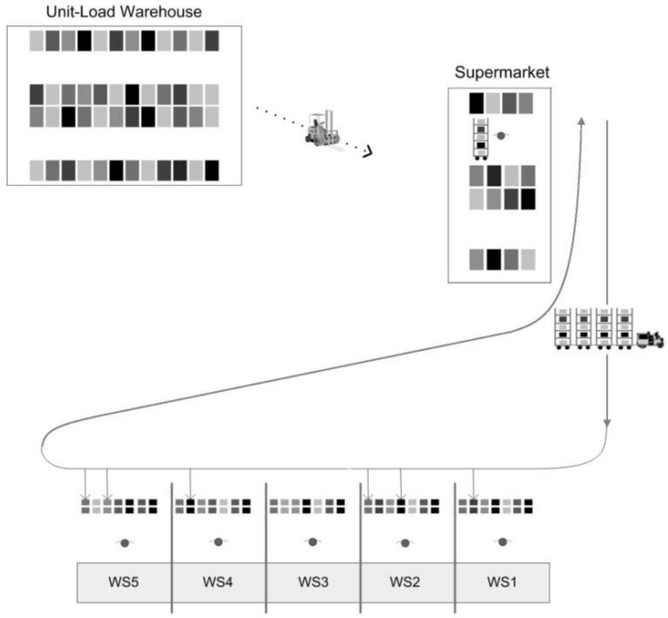

Figure 4.2: Repackaging

4.1.3 Kitting

We only consider in-house kitting in this research. As repackaging, the kitting assembly activities take place in the supermarket. The operator in the supermarket walks through the aisles and picks the needed parts. In the model, only stationary kits are considered. We assume that the central picking supermarket is logically organized in picking zones, where an aisle represents a zone which contains all variant parts that can be consolidated in a kit for a certain workstation (Limère,2012). Furthermore, kits will also be formed in batches to improve efficiency. As mentioned in the repackaging case, the supermarket is replenished by the warehouse and stores pallets and boxes. Periodically, the tugger train transports the kit containers from the supermarket to the border of the line by completing a milk run tour.

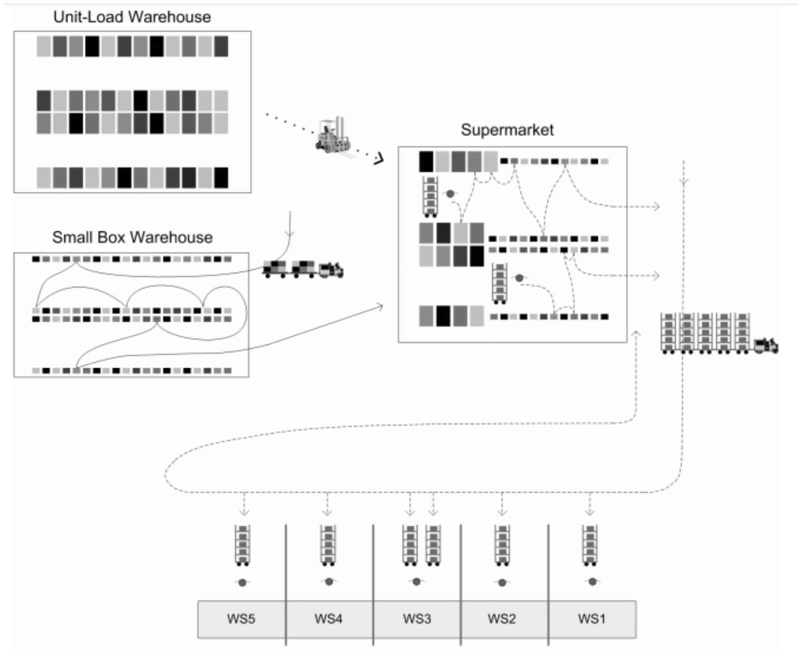

Figure 4.3: Kitting (Limère, 2012)

4.2 Cost factors

The different line feeding methods have an impact on:

- Operator efficiency: The time to search the right part at the border of the line is influenced by the line feeding method. In the kitting case no search time is assumed. The search time in the repackaging and line stocking case are almost identical. Moreover, the walking distance for the assembly operator decreases when less parts are stored at the border of the line. Therefore, the walking time in the repackaging and kitting case is lower than in the line stocking case. This influences the picking cost.
- Line space requirement: The space required at the border of the line is lower in the repackaging and kitting case. We assume that there is no work in process holding cost.
- Material handling cost: The line feeding method has also an influence on the transportation and material handling cost to deliver the parts at the border of the line. In the case of kitting and repackaging, the kits and boxes have to be assembled and parts have to be transported from the warehouse via the supermarket to the border of the line.
- Inventory cost: We assume no extra inventory cost in case of kitting and repackaging.
- Quality: Qualitative influences by the different line feeding methods is also not considered in this research.

4.3 Mathematical model

To compare the costs of the different line feeding methods, a mixed integer linear programming model is developed. The objective is to assign each part to one of the line feeding methods in order to minimize the total costs of material handling, given the part- and plant characteristics. The costs are the annual labor cost of the operators, the transportation costs, the kit assembly costs, the repackaging costs and the replenishment costs. The assignment of a part to a line feeding method is controlled by binary variables: x_{is}^{l} , x_{is}^{r} and x_{is}^{k}. When part i is delivered to workstation s in bulk, $x_{is}^{l} = 1$and otherwise 0. The list of other variables and parameters can be found in the list of variables and parameters (cf. supra). Next the formulas for the different cost components will be derived. Respectively the following cost formulas are derived: the picking costs, the transportation costs, kit assembly costs, repackaging costs and lastly the replenishment costs. Afterwards the complete model is presented. The model is an extension of the model developed by Limère (2012).

4.3.1 Picking at the line

The materials supply method influences the labor cost for picking at the line. First we consider the line stocking case. The time to pick a unit of part i from a bulk container at workstation s, tp_{is}^{bulk} is influenced by the time to search for the right part τ^{bulk} and the walking time from the assembly line to the bulk container. The operator walks twice the distance Δ_{is}^{bulk} at a velocity *OV*. This results in the following formula:

$$tp_{is}^{bulk} = 2\frac{\Delta_{is}^{bulk}}{OV} + \tau^{bulk}$$

In the repackaging case, the formula is similar. However the walking distance for the operator will be smaller because repackaging boxes require less space at the border of the line. The time to pick a unit i from a repackaging box at workstation s is:

$$tp_{is}^{repack} = 2\frac{\Delta_{is}^{repack}}{OV} + \tau^{repack}$$

In the kitting case the formula is slightly different. Because the parts are well organized in kit containers, the operator does not have to search for the right part. The operator only needs to walk the distance from the assembly line to the kit container, Δ^{k}. The time to pick a part from the kit container is:

$$tp_{is}^{k} = 2\frac{\Delta^{k}}{OV}$$

The total labor cost for operator picking at the line, C_{pick} is determined by:

$$C_{pick} = OC\sum_{s\in S}\sum_{i\in I_s} q_{is}\left[x_{is}^{l}tp_{is}^{bulk} + x_{is}^{r}tp_{is}^{repack} + x_{is}^{k}tp_{is}^{k}\right]$$

The picking time for one unit is multiplied by the yearly usage of the part q_{is}. Furthermore, we have to sum over all parts i at the workstation and over all workstations s. OC is the cost of a labor hour.

4.3.2 Transport to the line

The yearly internal transportation cost, C_{tpt} , consist of the transportation cost of pallets, boxes, repackaging boxes and kits from the warehouse (in the line stocking case) or supermarket (in the kitting and repackaging case) to the assembly workstations.

Transportation of pallets is executed by a forklift truck. The forklift truck travels the distance from the warehouse to the workstation, D_s^p, at a velocity V^p. To get the yearly transportation cost for part I, we have to multiply by the yearly usage rate q_{is} and divide by the packing quantity n_i. When we sum over all the palletized parts at the workstation and over all the workstations, the yearly transportation cost for pallets can be defined by:

$$C_{tpt}^{pallet} = OC\sum_{s\in S}\sum_{i\in I_s\cap I_p} x_{is}^{l}\left(2\frac{D_s^p}{V^p}\frac{q_{is}}{n_i}\right)$$

Transportation of boxes in the original supplier packaging is performed by a tugger train. The tugger train, with velocity V^b, completes periodically a milk run tour, with tour distance V^b, from the warehouse to the workstations. Furthermore, the yearly number of tours to the line depends on the number of boxes that need to be supplied to the station, q_{is}/n_i , on the capacity of the tugger train, A^b, and on the expected capacity utilization of the tugger train, ρ^b. As mentioned before, parts that arrive to the company in boxes will not be repacked. Therefore, use is made of $\left(1 - x_{is}^{k}\right)$ because only in the kitting case these parts will not be delivered to the workstation in boxes. The yearly transportation cost for boxes can be defined by:

$$C_{tpt}^{box} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_b} \left(1 - x_{is}^k\right) \left(\frac{\frac{D^b}{V^b} \frac{q_{is}}{n_i}}{A^b \rho^b} \right)$$

The transportation of repackaging boxes is similar as the transportation for normal boxes. It is also executed by a tugger train, with velocity V^r, but the milk run tour starts from the supermarket instead of the warehouse. Use is made of $i \in I_s \cap I_p$ because only palletized parts are eligible for repackaging. The transportation cost for repackaging boxes can then be defined by:

$$C_{tpt}^{repack} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is}^r \left(\frac{\frac{D^r}{V^r} \frac{q_{is}}{r_i}}{A^r \rho^r} \right)$$

Transportation of kits is also organized as a milk run tour. The tugger train, with velocity V^k, pulls several kit containers from the supermarket to the workstations. The yearly number of kits that need to be supplied to the station is $K_s d$, where K_s is the number of kits needed at station s to assemble one vehicle, and d is the yearly demand for vehicles. The yearly number of tours to the line then depends on $K_s d$, on the capacity of the tugger train, A^k, and on the expected tugger capacity utilization, ρ^k. The cost for kit transport is thus:

$$C_{tpt}^{kit} = OC \sum_{s \in S} \frac{\frac{D^k}{V^k} K_s d}{A^k \rho^k}$$

The total transportation cost is the sum of the costs for the four separate transportation types:

$$C_{tpt} = C_{tpt}^{pallet} + C_{tpt}^{box} + C_{tpt}^{repack} + C_{tpt}^{kit}$$

4.3.3 Kit assembly

In the supermarket, kits must be assembled by the operator before they can be transported to the workstations. The average time to pick a part i from the bulk container to kit for station s, tk_{is} , depends on the opportunity to assemble kits in batches. The opporunity for batch picking part i to assemble it in a kit for station s, θ_{is}, i.e. the number of units of part i that will on average be picked in one pick when the part is kitted, is then defined by (Limère, 2012):

$$\theta_{is} = max\left\{min\left(\frac{q_{is}}{d}B^k, a_i\right), \frac{m_{is}}{\lceil m_{is}/a_i \rceil}\right\}$$

With,

q_{is} Yearly usage of part i at station s

d Yearly demand for end product

B^k Batch size for assembling kits

a_i Maximum number of units of a part i in one pick due to physical characteristics (weight, volume) of part i

m_{is} Number of units of part i assembled per vehicle (if the specific variant part i is used) at station s

We will give an example to understand the formula for θ_{is}. Consider six parts that need to be kitted. The table below gives a summary of the part characteristics and the calculated values for θ_{is}. The kit batch size B^k is assumed to be five kits. We notice that the average usage of all parts, q_{is}/d, is equal but m_{is} and a_i vary.

	part 1	**part 2**	**part 3**	**part 4**	**part 5**	**part 6**
m_{is}	1	5	1	5	1	5
q_{is}/d	50%	50%	50%	50%	50%	50%
a_i	1	1	3	3	5	5
θ_{is}	1	1	2,5	2,5	2,5	5

Table 4.1: Example to understand the equation (Limère, 2012)

If we look at the resulting opportunity for batch picking we can see that as long as a_i = 1, this means that the physical part characteristics do not allow that the part is picked at more than one unit at a time, θ_{is} = max {1; 1} = 1.

When a_i = 5, a higher opportunity for batch picking exists. The real value for θ_{is} then depends on the one hand on the average usage of a part within a batch of kits, $(q_{is}/d)B^k$. This is the first term in the formula. But on the other hand also the spread of usage matters. The figure below gives examples for the real usage of a part with m_{is} = 1 and a part with m_{is} = 5. These examples are randomly drawn. We can see that the usage of a part with m_{is} = 1 is equally spread over time, but the usage of a part with m_{is} = 5 takes place in lumps of five units. This lumping induces a higher opportunity for batch picking, namely five parts will be picked at once. In the formula this is realized by the latter term, $m_{is}/\lceil m_{is}/a_i \rceil$, and θ_{is} = max {2.5; 5} = 5.

When a_i = 3, the physical characteristics of the part avoid that one can benefit from the demand in lumps and θ_{is} = 2.5 in both cases (m_{is} = 1 and m_{is} = 5).

Obviously θ_{is} can never be less than 1, because none of the subterms can be less than 1.

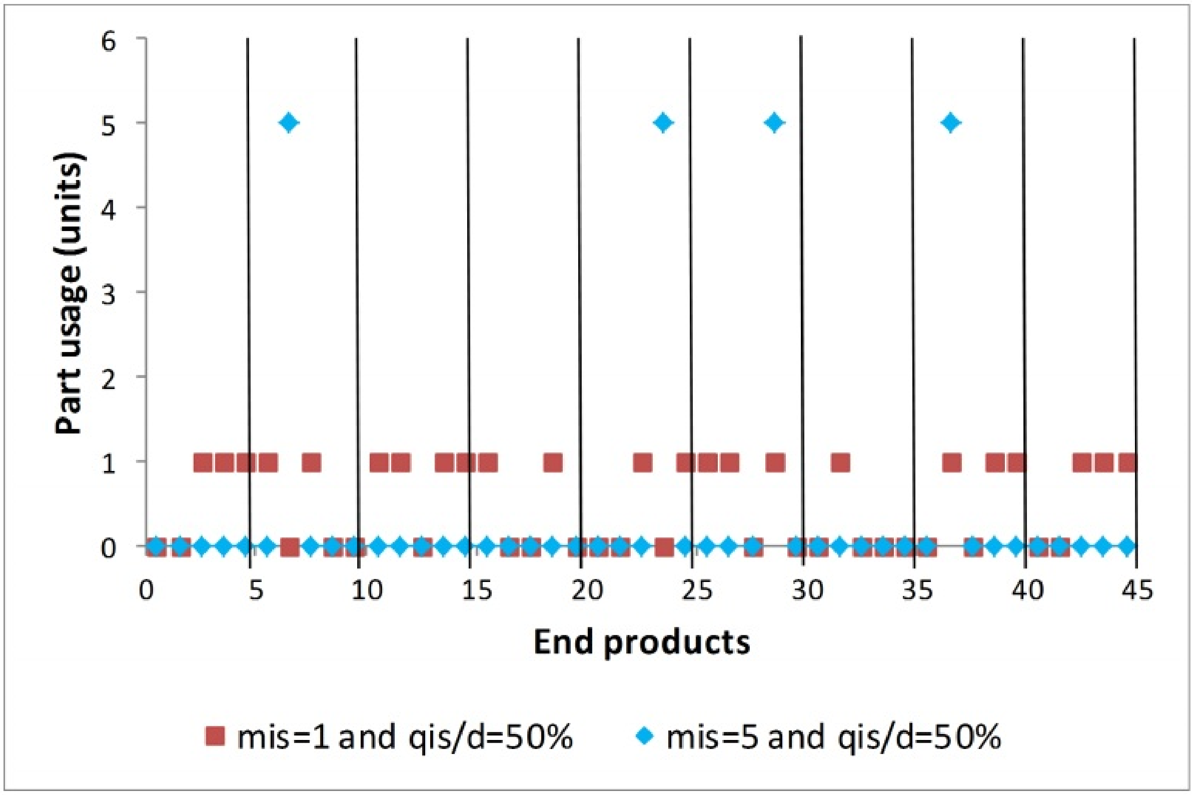

Figure 4.4: Real usage of two parts with an equal average usage rate but a different m_{is} (Limère, 2012)

The average time to pick a part i from the bulk container to kit for station s, depends on the time to search the right part, τ^{sup}, the distance from the bulk container to the kit container, Δ_{is}^{k} , and the walking velocity, OV. If we divide this by the batch size when forming kits, we get the average time to pick a part for kitting:

$$tk_{is} = \frac{\left(2\Delta_{is}^{k}/_{OV}\right) + \tau^{sup}}{\theta_{is}}$$

If we multiply this by the yearly usage of part i at station s, q_{is}, and we sum over all parts used at station s and over al workstations, we get the yearly labor cost for kit assembly:

$$C_{kit} = OC \sum_{s \in S} \sum_{i \in I_s} x_{is}^{k} q_{is} tk_{is}$$

4.3.4 Repackaging

In the supermarket, the parts in bulk containers are repacked in smaller boxes. The time it takes for the operator to find the part that has to be repacked is: τ^{sup}. The operator walks with a transpallet, loaded with repackaging boxes, to the bulk container. The time it takes to walk to the bulk container and back, depends on the distance, Δ_{is}^{r} , and the operator velocity, OV. Furthermore, we assume as in the kitting case that repackaging is done in batches, with size B^r. If we multiply the time to fill one repackaging box, f^r, by the batch size, B^r, we get the time to fill all the boxes. If the sum of the walking time, the search time and the fill time is divided by the number of parts in the repackaging boxes, $B^r r_i$, we get the average time it takes to take one unit from a bulk container of part i to repack for station s:

$$tr_{is} = \frac{\left(2\Delta_{is}^{r} / OV \right) + B^r f^r + \tau^{sup}}{B^r r_i}$$

Multiplying the time to repack one unit by the yearly usage of part i at station s, q_{is} , and summing over the parts used at stations s and over the workstations, we get the annual labor cost for repackaging:

$$C_{repack} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is}^{r} q_{is} tr_{is}$$

4.3.5 Replenishment of the supermarket

$$C_{repl} = \sum_{s \in S} \sum_{i \in I_s \cap I_p} \left[\left(1 - x_{is}^{l}\right) \frac{q_{is}}{n_i} R^p \right] + \sum_{s \in S} \sum_{i \in I_s \cap I_b} \left[\left(1 - x_{is}^{l}\right) \frac{q_{is}}{n_i} R^b \right]$$

The labor cost to replenish the supermarket is determined by a constant cost for the replenishment of one box, R^b, and a constant cost for the replenishment of one pallet, R^p. Use is made of $\left(1 - x_{is}^{l}\right)$ because only parts that are supplied in bulk to the line do not come from the supermarket.

4.3.6 Constraints

The objective is to minimize the total yearly costs for material handling. This optimization is subjected to some constraints. First, the constraints are derived and then an overview of the complete model is given.

First of all, a restriction for the decision variables is needed. A part can only be assigned to one of the line feeding methods. If for example part i is delivered to workstation s in bulk, then it can't be repacked or kitted at the same time. The constraint is defined as:

$$x_{is}^{l} + x_{is}^{r} + x_{is}^{k} = 1 \qquad \forall s \in S, \forall i \in I_s$$

Another restriction for the decision variables is the result of the supplier packaging type. The assumption is made that parts delivered in boxes from the supplier, will not be repacked. Therefore the following constraint has to be added:

$$x_{is}^{r} = 0 \qquad \forall s \in S, \forall i \in I_s \cap I_b$$

Additionally, constraints related to kitting are derived. The kit container can only hold a maximum volume of parts and the weight of a kit container is also restricted. If the total weight of the parts for station s exceeds the limit w^k, then more than one kit container has to be supplied to the workstation. Furthermore, if the total volume of the parts for station s is higher than the volume of the kit container, more than one kit container has to be supplied to workstation s. The weight and volume constraint for kits are respectively given by:

$$K_s \geq \sum_{i \in I_s} \left[x_{is}^{k} \left(\frac{m_{is} w_i}{|V_i|} \right) / w^k \right] \qquad \forall s \in S$$

$$K_s \geq \sum_{i \in I_s} \left[x_{is}^{k} \left(\frac{m_{is} / v_i}{|V_i|} \right) \right] \qquad \forall s \in S$$

To save space at the border of the line, boxes from the supplier and repackaging boxes are stacked on racks. The sum of all parts delivered in boxes divided by the stacking height, H^b and H^r, gives the number of racks needed to store the boxes at the border of the line, N_s^b and N_s^r. The constraints for original supplier boxes and repackaging boxes are respectively given as:

$$\sum_{i \in I_s \cap I_b} \left(\frac{x_{is}^l}{H^b} \right) \leq N_s^b \qquad \forall s \in S$$

$$\sum_{i \in I_s \cap I_p} \left(\frac{x_{is}^r}{H^r} \right) \leq N_s^r \qquad \forall s \in S$$

At the border of the line there is only space available for a limited amount of pallets, boxes and kits. The available length along workstation s is given by L_s. The sum of the pallets multiplied by their length, plus the length of the boxes times the facings needed to store the boxes, plus the number of kits times the length of a kit container must be smaller than the available length of the workstation.

$$N_s^b L^b + N_s^r L^r + \sum_{i \in I_s \cap I_p} x_{is}^l L^p + K_s L^k \leq L_s \quad \forall s \in S$$

Finally, the following constraints are added to ensure that if one part in a family is assigned to a certain materials supply method, all variant parts are assigned to the same method. The assumption that all variant parts have to be assigned to the same materials supply method depends from case to case and can be omitted if desired. The following formulas are therefore optional.

$$x_{is}^l = x_{js}^l \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i$$

$$x_{is}^r = x_{js}^r \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i$$

$$x_{is}^k = x_{js}^k \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i$$

4.3.7 The complete model

Above, all the cost functions and the constraints were explained. Next, an overview from the complete model is given:

$$\min C_{total} = C_{pick} + C_{tpt} + C_{kit} + C_{repack} + C_{repl}$$

$$C_{pick} = OC \sum_{s\in S} \sum_{i\in I_s} q_{is} \left[x_{is}^l \left(2 \frac{\Delta_{is}^{bulk}}{OV} + \tau^{bulk} \right) + x_{is}^r \left(2 \frac{\Delta_{is}^{repack}}{OV} + \tau^{repack} \right) + x_{is}^k \left(2 \frac{\Delta^k}{OV} \right) \right]$$

$$C_{tpt} = C_{tpt}^{pallet} + C_{tpt}^{box} + C_{tpt}^{repack} + C_{tpt}^{kit}$$

$$C_{tpt} = OC \sum_{s\in S} \sum_{i\in I_s \cap I_p} x_{is}^l \left(2 \frac{D_s^p}{V^p} \frac{q_{is}}{n_i} \right) + OC \sum_{s\in S} \sum_{i\in I_s \cap I_b} (1 - x_{is}^k) \left(\frac{\frac{D^b q_{is}}{V^b n_i}}{A^b \rho^b} \right)$$

$$+ OC \sum_{s\in S} \sum_{i\in I_s \cap I_p} x_{is}^r \left(\frac{\frac{D^r q_{is}}{V^r r_i}}{A^r \rho^r} \right) + OC \sum_{s\in S} \frac{\frac{D^k}{V^k} K_s d}{A^k \rho^k}$$

$$C_{kit} = OC \sum_{s\in S} \sum_{i\in I_s} x_{is}^k q_{is} \left[\frac{\left(2\Delta_{is}^k / OV \right) + \tau^{sup}}{\theta_{is}} \right]$$

$$C_{repack} = OC \sum_{s\in S} \sum_{i\in I_s \cap I_p} x_{is}^r q_{is} \left[\frac{\left(2\Delta_{is}^r / OV \right) + B^r f^r + \tau^{sup}}{B^r r_i} \right]$$

$$C_{repl} = \sum_{s\in S} \sum_{i\in I_s \cap I_p} \left[(1 - x_{is}^l) \frac{q_{is}}{n_i} R^p \right] + \sum_{s\in S} \sum_{i\in I_s \cap I_b} \left[(1 - x_{is}^l) \frac{q_{is}}{n_i} R^b \right]$$

Subject to,

$$x_{is}^l + x_{is}^r + x_{is}^k = 1 \qquad \forall s \in S, \forall i \in I_s$$

$$x_{is}^r = 0 \qquad \forall s \in S, \forall i \in I_s \cap I_b$$

$$K_s \geq \sum_{i \in I_s} \left[x_{is}^k \left(\frac{m_{is} w_i}{|V_i|} \right) / w^k \right] \qquad \forall s \in S$$

$$K_s \geq \sum_{i \in I_s} \left[x_{is}^k \left(\frac{m_{is} / v_i}{|V_i|} \right) \right] \qquad \forall s \in S$$

$$\sum_{i \in I_s \cap I_b} \left(\frac{x_{is}^l}{H^b} \right) \leq N_s^b \quad \forall s \in S$$

$$\sum_{i \in I_s \cap I_p} \left(\frac{x_{is}^r}{H^r} \right) \leq N_s^r \quad \forall s \in S$$

$$N_s^b L^b + N_s^r L^r + \sum_{i \in I_s \cap I_p} x_{is}^l L^p + K_s L^k \leq L_s \quad \forall s \in S$$

$$x_{is}^l = x_{js}^l \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i \qquad \textit{Optional}$$

$$x_{is}^r = x_{js}^r \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i \qquad \textit{Optional}$$

$$x_{is}^k = x_{js}^k \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i \qquad \textit{Optional}$$

4.4 Conclusion

The developed mathematical optimization model can be used to determine the most cost efficient materials supply method for the different parts while taking into account product and part characteristics. The model determines if each part needs to be delivered in bulk, repacked or kitted in order to be most cost effective. The formulas developed in the model approximate the real cost factors. In the next chapter, the formulas are analyzed and reformulated in order to approximate the cost factors in more detail.

5 Extended model

In the previous part a linear mathematical model was developed in order to minimize the total material handling cost. Here we want to take a closer look on that model and approximate the cost factors in more detail. The model is an extension of the model developed by Limère (2012).

5.1 Picking at the line

First, a closer look is taken at the picking cost in case of bulk feeding. The formula developed in the base model is:

$$tp_{is}^{bulk} = 2\frac{\Delta_{is}^{bulk}}{OV} + \tau^{bulk}$$

An average value of the real walking distance was assigned to Δ_{is}^{bulk}. The parameter Δ_{is}^{bulk} does not correspond to the real walking distance at the line because it does not take into account the real organization at the line. For example when a lot of parts are kitted, the walking distance for the operator will be shorter because less parts will be stocked at the border of the line.

To approximate the walking distance more accurately, the organization of the stock at the border of the line is taken into account. We assume that the distance from the line to the border of the line, *the depth,* is fixed. On average, the operator has to walk the depth of the line plus a quarter of the real length of the occupied space at the border of the line (Limère, 2012). The occupied space can be calculated according to the space constraint in the base model. The sum of the length of the bulk containers, the length of the racks for boxes and the length of the kits, gives the total length of the stock at the border of the line. Thus, Δ_{is}^{bulk} can be calculated as follows:

$$\Delta_{is}^{bulk} = depth + \frac{N_s^b L^b + N_s^r L^r + \sum_{i \in I_s \cap I_p} x_{is}^l L^p + K_s L^k}{4}$$

The value of Δ_{is}^{bulk} is still an average of the real distance. However, the average is more accurate than in the base model. Furthermore, the distance is now calculated as a *Manhattan distance*. This means that we pretend the operator will only walk perpendicular to the line and along the border of the line. In reality however, the operator will cut of the corners and go straight to the container.

The same methodology can be used to reformulate the picking time of repackaging boxes at the line. The time to take a part from a repackaging box is given by:

$$tp_{is}^{repack} = 2\frac{\Delta_{is}^{repack}}{OV} + \tau^{repack}$$

In the base model again an average distance was assigned to Δ_{is}^{repack}. We can use the same formula as in the bulk case for the walking distance to a repackaging box. The formula for Δ_{is}^{repack} becomes:

$$\Delta_{is}^{repack} = depth + \frac{N_s^b L^b + N_s^r L^r + \sum_{i \in I_s \cap I_p} x_{is}^l L^p + K_s L^k}{4}$$

It is important to keep in mind still an approximated measure is used, however the approximation is more detailed and closer to the real distance. The main advantage of this formulation of the picking distance is that it takes into account that kiting and repackaging does not only shorten the picking distance for parts in the kit or repacking box, but it also shortens the picking distance from the remaining bulk containers as the line stock diminishes. The drawback of this formulation is that the model becomes non linear. However a solution to this issue will be explained later.

The formula for the total labor cost of picking at the line does not change and is still given by:

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[x_{is}^l tp_{is}^{bulk} + x_{is}^r tp_{is}^{repack} + x_{is}^k tp_{is}^k \right]$$

5.2 Kit assembly

A second formula we want to refine is the cost formula for the kit assembly process. It is assumed that empty kit containers are provided at one side of the supermarket and full kit containers are picked up at that other side of the supermarket. This ensure a smooth flow of kits through the supermarket. The operator walks through the aisle, picks the right parts from the racks and fills the kit container. Because the operator always walks through the entire aisle, there is a fixed production time for each kit. The fixed production time, FT^k, is the time to walk through the aisle without picking anything. The total number of kits that need to be supplied to the line per year is $\sum_{s \in S} K_s d$. The fixed cost for all kits is thus (Limère, 2012):

$$FC_{kit} = OC \cdot FT^k \sum_{s \epsilon S} K_s d$$

The variable kitting cost is incurred for every part that needs to be kitted. The distance the operator needs to walk to pick each part is half the width of an aisle in the supermarket, $\Delta_{is}^k = aisle\_width/2$. The formula to pick a unit of part i from a bulk container to kit for station s remains:

$$tk_{is} = \frac{\left(2\Delta_{is}^k / _{OV} \right) + \tau^{sup}}{\theta_{is}}$$

The variable cost for all kits, VC_{kit} , is the sum of the kitted parts at station s and the sum over all stations:

$$VC_{kit} = OC \sum_{s \in S} \sum_{i \in I_s} x_{is}^k q_{is} tk_{is}$$

The total labor cost for kit assembly is then:

$$C_{kit} = FC_{kit} + VC_{kit}$$

5.3 Solution methodology

The adapted formula for picking at the line makes the model non linear. A methodology is used to linearize the non linear formulas in the model.

The non-linear terms are in the cost of picking from a bulk container and from a repackaging box:

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[x_{is}^l \left(2 \frac{\Delta_{is}^{bulk}}{OV} + \tau^{bulk} \right) + x_{is}^r \left(2 \frac{\Delta_{is}^{repack}}{OV} + \tau^{repack} \right) + x_{is}^k \left(2 \frac{\Delta^k}{OV} \right) \right]$$

With,

$$\Delta_{is}^{bulk} = depth + \frac{N_s^b L^b + N_s^r L^r + \sum_{i \in I_s \cap I_p} x_{is}^l L^p + K_s L^k}{4}$$

$$\Delta_{is}^{repack} = depth + \frac{N_s^b L^b + N_s^r L^r + \sum_{i \in I_s \cap I_p} x_{is}^l L^p + K_s L^k}{4}$$

The binary variables, x_{is}^{l} and x_{is}^{r} , are multiplied with a function of multiple variables, i.e. Δ_{is}^{bulk} and Δ_{is}^{repack} are a function of N_s^b, N_s^r, x_{is}^{l} and K_s.

Torres (1991) explains how products of a binary variable and a function of continuous variables can be replaced by a new continuous variable if some specific constraints are added. This transformation is based on the technique introduced by Glover for bilinear products. The transformation is presented next for a mixed integer product $yF(x)(y \in \{0,1\}, x \in \mathbb{R}^n$.

The mixed product $yF(x)$ may be replaced by a new continuous variable $p \in \mathbb{R}$ and by adding the constraints:

$$p \geq F(x) - U(1-y)$$

$$p \geq Ly$$

$$p \leq F(x) - L(1-y)$$

$$p \leq Uy$$

where $L < F(x)$ and $U > F(x)$ for all feasible $x \in \mathbb{R}^n$.

Because the mixed integer products in our model appear in the objective function and we deal with a minimization problem, the two "smaller than or equal to" constraints may even be discarded as they will be satisfied automatically (Torres, 1991). For our model, the reformulation is the following:

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[2\frac{p_{is}^{l}}{OV} + x_{is}^{l}\tau^{bulk} + 2\frac{p_{is}^{r}}{OV} + x_{is}^{r}\tau^{repack} + x_{is}^{k} 2\frac{\Delta^{k}}{OV} \right]$$

If $L = 0$ and $U = depth + \frac{L_s}{4} + \epsilon$, we get the following additional constraints:

For Δ_{is}^{bulk} where $y = x_{is}^{l}$ and $F(x) = \Delta_{is}^{bulk}$:

$$p_{is}^{l} \geq \Delta_{is}^{bulk} - \left(depth + \frac{L_s}{4} + \epsilon\right)(1 - x_{is}^{l}) \qquad \forall s \in S, \forall i \in I_s$$

$$p_{is}^{l} \geq 0 \qquad \forall s \in S, \forall i \in I_s$$

$$0 < \Delta_{is}^{bulk} \qquad \forall s \in S, \forall i \in I_s$$

$$depth + \frac{L_s}{4} + \epsilon > \Delta_{is}^{bulk} \qquad \forall s \in S, \forall i \in I_s$$

For Δ_{is}^{repack} where $y = x_{is}^{r}$ and $F(x) = \Delta_{is}^{repack}$:

$$p_{is}^{r} \geq \Delta_{is}^{repack} - \left(depth + \frac{L_s}{4} + \epsilon\right)(1 - x_{is}^{r}) \qquad \forall s \in S, \forall i \in I_s$$

$$p_{is}^{r} \geq 0 \qquad \forall s \in S, \forall i \in I_s$$

$$0 < \Delta_{is}^{repack} \qquad \forall s \in S, \forall i \in I_s$$

$$depth + \frac{L_s}{4} + \epsilon > \Delta_{is}^{repack} \qquad \forall s \in S, \forall i \in I_s$$

5.4 The complete model

When all the equations and constraints mentioned above are combined, then we get the following model:

$$\min C_{total} = C_{pick} + C_{tpt} + C_{kit} + C_{repack} + C_{repl}$$

$$C_{pick} = OC \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[2\frac{p_{is}^{l}}{OV} + x_{is}^{l}\tau^{bulk} + 2\frac{p_{is}^{r}}{OV} + x_{is}^{r}\tau^{repack} + x_{is}^{k} 2\frac{\Delta^{k}}{OV}\right]$$

$$C_{tpt} = C_{tpt}^{pallet} + C_{tpt}^{box} + C_{tpt}^{repack} + C_{tpt}^{kit}$$

$$C_{tpt} = OC \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is}^{l} \left(2\frac{D_s^{p}}{V^{p}}\frac{q_{is}}{n_i}\right) + OC \sum_{s \in S} \sum_{i \in I_s \cap I_b} (1 - x_{is}^{k}) \left(\frac{\frac{D^{b} q_{is}}{V^{b}\, n_i}}{A^{b}\rho^{b}}\right)$$

$$+ OC \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is}^{r} \left(\frac{\frac{D^{r} q_{is}}{V^{r}\, r_i}}{A^{r}\rho^{r}}\right) + OC \sum_{s \in S} \frac{\frac{D^{k}}{V^{k}} K_s d}{A^{k}\rho^{k}}$$

$$C_{kit} = OC \sum_{s \in S} \sum_{i \in I_s} x_{is}^{k} q_{is} \left[\frac{\left(2\Delta_{is}^{k}/OV\right) + \tau^{sup}}{\theta_{is}}\right]$$

$$C_{repack} = OC \sum_{s\in S} \sum_{i\in I_s \cap I_p} x_{is}^r q_{is} \left[\frac{\left({2\Delta_{is}^r}/{OV} \right) + B^r f^r + \tau^{sup}}{B^r r_i} \right]$$

$$C_{repl} = \sum_{s\in S} \sum_{i\in I_s \cap I_p} \left[\left(1 - x_{is}^l\right) \frac{q_{is}}{n_i} R^p \right] + \sum_{s\in S} \sum_{i\in I_s \cap I_b} \left[\left(1 - x_{is}^l\right) \frac{q_{is}}{n_i} R^b \right]$$

Subject to,

$$x_{is}^l + x_{is}^r + x_{is}^k = 1 \qquad \forall s \in S, \forall i \in I_s$$

$$x_{is}^r = 0 \qquad \forall s \in S, \forall i \in I_s \cap I_b$$

$$K_s \geq \sum_{i\in I_s} \left[x_{is}^k \left(\frac{m_{is} w_i}{|V_i|} \right) / w^k \right] \qquad \forall s \in S$$

$$K_s \geq \sum_{i\in I_s} \left[x_{is}^k \left(\frac{m_{is}/v_i}{|V_i|} \right) \right] \qquad \forall s \in S$$

$$\sum_{i\in I_s \cap I_b} \left(\frac{x_{is}^l}{H^b} \right) \leq N_s^b \qquad \forall s \in S$$

$$\sum_{i\in I_s \cap I_p} \left(\frac{x_{is}^r}{H^r} \right) \leq N_s^r \qquad \forall s \in S$$

$$N_s^b L^b + N_s^r L^r + \sum_{i\in I_s \cap I_p} x_{is}^l L^p + K_s L^k \leq L_s \qquad \forall s \in S$$

$$\Delta_{is}^{bulk} \geq depth + \frac{N_s^b L^b + N_s^r L^r + \sum_{i\in I_s \cap I_p} x_{is}^l L^p + K_s L^k}{4} \qquad \forall s \in S, \forall i \in I_s$$

$$\Delta_{is}^{repack} \geq depth + \frac{N_s^b L^b + N_s^r L^r + \sum_{i\in I_s \cap I_p} x_{is}^l L^p + K_s L^k}{4} \qquad \forall s \in S, \forall i \in I_s$$

$$\Delta_{is}^{bulk} - \left(depth + \frac{L_s}{4} + \epsilon \right) (1 - x_{is}^l) \leq p_{is}^l \qquad \forall s \in S, \forall i \in I_s$$

$$\Delta_{is}^{repack} - \left(depth + \frac{L_s}{4} + \epsilon \right) (1 - x_{is}^r) \leq p_{is}^r \qquad \forall s \in S, \forall i \in I_s$$

$$p_{is}^l \geq 0 \qquad \forall s \in S, \forall i \in I_s$$

$$p_{is}^r \geq 0 \qquad \forall s \in S, \forall i \in I_s$$

$x_{is}^{l} = x_{js}^{l} \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i \qquad$ *Optional*

$x_{is}^{r} = x_{js}^{r} \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i \qquad$ *Optional*

$x_{is}^{k} = x_{js}^{k} \qquad \forall s \in S, \forall i \in I_s, \forall j \in V_i \qquad$ *Optional*

5.5 Conclusion

In this chapter, the mathematical model was extended in order to become more detailed approximations of the cost factors. First of all, a closer look was taken at the picking costs at the line. The walking distances of the operators were adjusted by taking into account the real organization at the border of the line. Secondly, also the cost formula for the kitting assembly was refined.

In the next chapter, a data set from a case study is described. This data set allows to run the models and analyze the models (cf. infra).

6 Data description

To determine the trade-offs between line stocking, repackaging and kitting, a data set is needed. As this master dissertation is an extension of Limère (2012), the same approach will be used. The dataset generated from an industrial case study will be used primarily. Furthermore, other datasets will also be generated by the algorithm developed in Limère (2012).

First, a short description of the case company will be given. Secondly, the data needed for the model will be described. Lastly, the data generated from the case study will be explained in more detail.

6.1 Case company

The company where the case study took place is a truck manufacturing company. The assembly line investigated is a mixed-model assembly line. Different truck-models are assembled on the same assembly line. Furthermore each truck can be completely customized according to the customer's needs. That is why a lot of parts are needed at the assembly line.

In our model, the focus is on the parts that are delivered from the supplier to the manufacturing plant in bulk (Limère, 2012). Parts that are supplied to the line in-sequence form suppliers are not investigated. Furthermore, small parts that are supplied in small cardboard boxes are also left out of consideration. Those parts are common parts like nuts and bolts, and do not take a lot of space at the border of the line. Furthermore, often many units of these parts are needed, what makes it not efficient to kit or repack them.

When the parts mentioned above are left out of consideration, there remains a dataset of 1726 parts. For computational reasons, what will be mentioned in the next chapter, only 1000 of those parts will be considered in the analysis. The parts are delivered from the suppliers to the factory in two different packaging types: boxes and pallets. In this study it is the purpose to investigate if it is more cost-efficient to repack some parts or to make kits out of some parts instead of supplying them all in bulk to the assembly line.

6.2 Structure of the data

Now, the input needed for the model will be described. Different parameters are needed in order to solve the model. First we will describe some general parameters and parameters related to the layout of the factory. Secondly, the part specific parameters will be described. The complete list of variables and parameters can be consulted in the beginning of this study.

- Plant layout
    - Distance from the warehouse to each of the work stations (D_s^p): needed to calculate the costs for fork lift transportation of pallets.
    - Distance of the milk run tours by tugger trains for the supply of boxes (D^b), repackaging boxes (D^r) and kits to the line (D^k).
    - The cost to replenish respectively one box (R^b) and one pallet (R^p) from the warehouse to the supermarket.
- Workstation layout
    - The average walking distance for an operator to pick from a kit (Δ^k).
    - The average walking distance for an operator to pick from bulk containers (Δ_{is}^{bulk}). This distance is larger than the distance to a kit.
    - The average walking distance for an operator to pick from a repackaging box (Δ_{is}^{repack}). This distance is also larger than the distance to a kit.
    - The length of available storage area along a workstation (L_s). The border of the line is organized in one facing along the direction of the moving assembly line (x-direction). Boxes are stacked on racks vertically (z-direction).
- Supermarket layout
    - The average walking distance for an operator to pick from bulk containers to kit for station s (Δ_{is}^k).
    - The average walking distance for an operator to pick from bulk containers to repack for station s (Δ_{is}^r).
- Operator productivity
    - The walking velocity of an operator (*OV*).
    - The average time to search for the required part from bulk stock at the line (τ^{bulk}).
    - The average time to search for the required part from repackaging boxes at the line (τ^{repack}).

- The average time to search for the required part from bulk stock in the supermarket (τ^{sup}).
- The hourly labor cost of an operator (*OC*).
- The kit batch size (B^k): the number of kits that are assembled in a batch.
- The repackaging batch size (B^r): the number of repackaging boxes that are assembled in a batch.
- The average time it takes for an operator to fill a repackaging box (f^r).

- Material equipment capacity
  - Vehicle velocities for forklift trucks (V^p) an tugger trains (V^b, V^r and V^k).
  - The maximum number of units a tugger train can transport in one milk run (boxes (A^b), repackaging boxes (A^r) and kits (A^k)).
  - The expected capacity utilization of the tugger trains, given the variety in demands (ρ^b, ρ^r and ρ^k).
- Packaging dimensions
  - The length of a box (L^b), a repackaging box (L^r), a pallet (L^p) and a kit container (L^k) along the line.
  - The height at which boxes (H^b) and repackaging boxes (H^r) are stacked at the border of the line (number of boxes).
  - The maximum weight of a single kit (w^k).

Now, we mention the part specific parameters from the dataset. Every part will have the following characteristics:

- Part number: a unique key for each part (index i).
- Station: the workstation to which the part needs to be supplied (index s).
- V_i: the part family to which part i belongs. A part family is a group of variant parts from where the customer can choose from. Never more than one of the variant parts of the same family is assembled on an end product.
- $|V_i|$: The cardinality of the part family to which part i belongs.
- f_{is}: percentage of end products for which part i is assembled at station s (frequency).
- m_{is}: number of units of part i that will be assembled on an end product at station s (if that end product needs part i).

- q_{is}: yearly usage of part i at station s. This can be determined from f_{is}, m_{is} and the production d of the end product over the time horizon: $q_{is} = d \times f_{is} \times m_{is}$
- w_i: weight of part i
- $pack_i$: supplier packaging of part i {Box, Pallet}
- n_i: unit-load of part i in its supplier packaging (number of parts)
- r_i: number of parts of part i in a repackaging box
- v_i: volume measure for part i
- a_i: maximum number of units of a part in one pick due to physical characteristics (weight, volume) of part i.

6.3 Data analysis

Here, we will describe the data obtained from the case company in more detail. The data will be presented in the same order of the previous section.

- Plant layout

The assembly line in the case company consist of three parallel line segments. The high bay warehouse is located to the right of these line segments. The small box warehouse is located in the lower right part of the plant. Transportation for the high bay- and the small box warehouse is executed by respectively forklift trucks and a milk run system. The distance from the warehouse to each of the work stations (D_s^p) ranges from 54 to 302 m. The distance of the milk run tour for kits (D^k), for boxes (D^b) and repackaging boxes (D^r) is 1640 m. The replenishing cost for pallets and boxes is respectively €1,2 and €0,2.

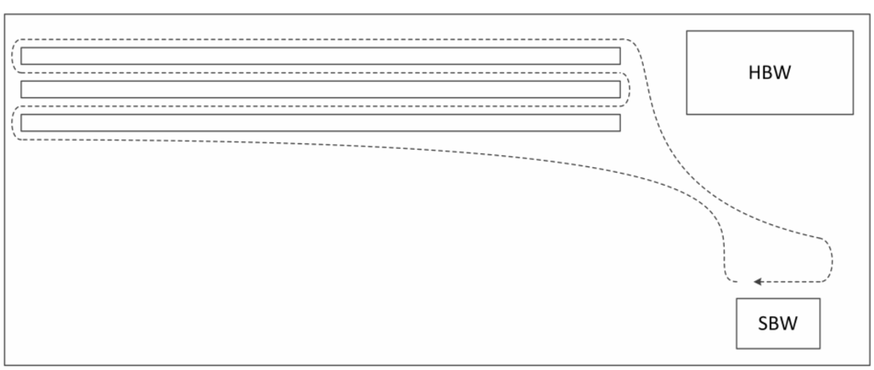

Figure 6.1: Layout of the manufacturing plant (Limère 2012)

- Workstation layout

The exact length of the workstations is 13 m. However, if the space of supplier-sequenced parts and parts packed in small cardboard boxes are left out of consideration, there remains 8 m (L_s) of available storage area. The average distance for a line operator to pick from a kit container (Δ^k) is 1,5m. The distance to pick from a bulk container (Δ_{is}^{bulk}) and repackaging box (Δ_{is}^{repack}) is varied from 2 to 3 meters depending on the usage rate of the part.

- Supermarket layout

The average distance for the operator in the supermarket to repack (Δ_{is}^{r}) or to kit (Δ_{is}^{k}) part i for station s, ranges from 2 to 3 meter depending on the usage rate of the part.

- Operator productivity

The operator walks at a speed (*OV*) of 3600 m/h. The labor cost of an operator (*OC*) is 30 euro per hour. The average time to search the right part in the supermarket (τ^{sup}) is set at 0,0003 h. The average time to search for the right part from bulk stock (τ^{bulk}) and repackaging boxes (τ^{repack}) at the line is 0,0003 h. The average time it takes for an operator to fill a repackaging box (f^r) is 0,01 h.

- Material equipment capacity

The model usages average velocities that include loading and unloading time. The velocity for forklift trucks (V^p) is 2880 m/h and for tugger trains doing the milk run tours, the velocity is 2410 m/h (V^b, V^r and V^k). A tugger train will be able to transport 60 boxes per tour (A^b), 60 repackaging boxes per tour (A^r) and 70 kits per tour (A^k). On average the capacity utilization of the tugger trains will be 50% for boxes (ρ^b), 50% for repackaging boxes (ρ^r) and 80% for kits (ρ^k).

- Packaging dimensions

Along the line, boxes (L^b), repackaging boxes (L^r) and kits (L^k)occupy 0,8 m whereas pallets (L^p)occupy 1 m. Boxes are vertically stacked on racks on 4 levels high (H^b and H^r). The maximum weight of a kit (w^k) is 50 kg.

An overview of the parameters is given in Table 6.1.

Parameter	Value
OC (€/h)	30
OV (m/h)	3600
Δ^{bulk}_{is} (m)	
$q_{is}>2500$	2
$2500\geq q_{is}>800$	2,5
$q_{is}\leq 800$	3
Δ^{repack}_{is} (m)	
$q_{is}>2500$	2
$2500\geq q_{is}>800$	2,5
$q_{is}\leq 800$	3
Δ^{k}_{is} (m)	
$q_{is}>2500$	2
$2500\geq q_{is}>800$	2,5
$q_{is}\leq 800$	3
Δ^{r}_{is} (m)	
$q_{is}>2500$	2
$2500\geq q_{is}>800$	2,5
$q_{is}\leq 800$	3
Δ^{k} (m)	1,5
A^{b} (number of boxes)	60
A^{k} (number of kits)	70
A^{r} (number of boxes)	60
B^{k}(number of kits)	5
B^{r} (number of boxes)	5
d (trucks/year)	3500

Parameter	Value
D^{b} (m)	1640
D^{k} (m)	1640
D^{r} (m)	1640
f^{r} (h)	0,01
H^{b} (number of boxes)	4
H^{r} (number of boxes)	4
L^{b} (m)	0,8
L^{k} (m)	0,8
L^{p} (m)	1
L^{r} (m)	0,8
L^{s} (m)	8
R^{b} (€)	0,2
R^{p} (€)	1,2
T^{bulk} (h)	0,0003
T^{repack} (h)	0,0003
T^{sup} (h)	0,0003
V^{b} (m/h)	2410
V^{k} (m/h)	2410
V^{p} (m/h)	2880
V^{r} (m/h)	2410
w^{k} (kg)	50
ρ^{b}	0,5
ρ^{k}	0,8
ρ^{r}	0,5

Table 6.1: Case study paramers

7 Solving the models

7.1 Description software

The base and extended model developed in the previous chapters are implemented in IBM ILOG CPLEX Optimization Studio 12.7. To run the software, use is made of an Intel Core i7 processer with 2,10GHz and 8GB RAM memory.

The dataset used to run the model is explained in the previous chapter. The complete dataset contains 1773 parts. For the base model, the processing time when solving the model for the 1773 parts is limited. The processing time for the extended model is however very long while solving for 1773 parts. This makes it hard to perform an extended analysis of the models. That is why the dataset is reduced to 1000 parts on 67 workstations. In this way the processing times are below 15 seconds what makes it reasonable for the analysis in the following chapter.

The data file in Excel with the part characteristics and the general problem features are read into CPLEX. After running the model the values of the decision variables are exported to another Excel file. This gives a clean overview of the results and will be useful to analyze the data.

7.2 Results base model

In the base model use is made of an average walking distance for the operator at the line to pick the parts, what makes the model less detailed than the extended model. This model is a mixed integer programming model with 3000 binary variables and 201 integer variables. The CPU time to solve the model is 4,11 seconds. After solving the model to optimality, the total cost for material handling amounts to €205 707. A detail of the costs and the assignment of the parts to a line feeding method, is given in Figure 7.1 and Figure 7.2:

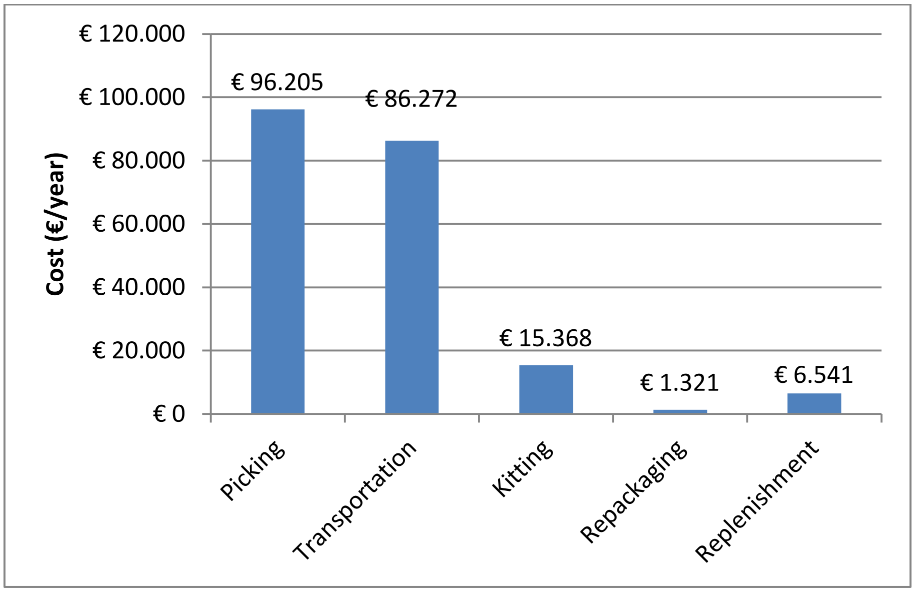

Figure 7.1: Base model: cost detail

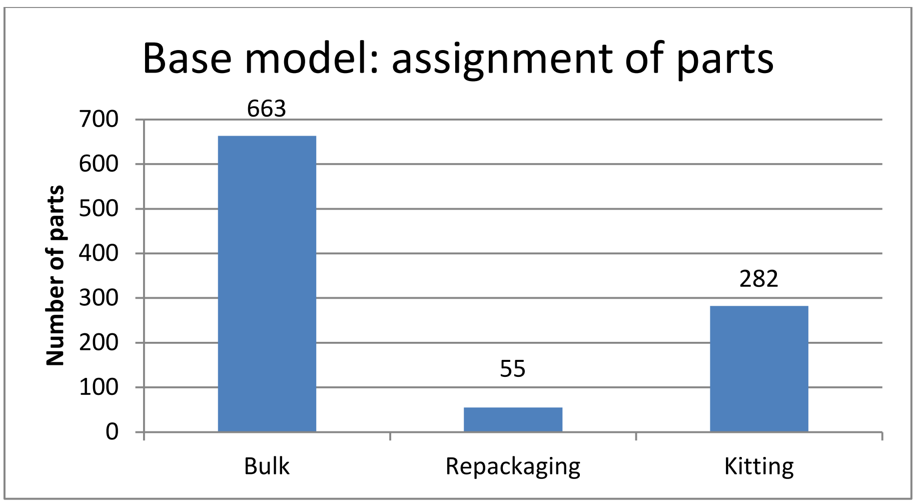

Figure 7.2: Base model: assignment of parts

As can be seen in the figures, the majority of the parts are delivered to the line in bulk (663 parts). The remaining parts are mostly kitted and only 55 parts are repacked in the optimal case. From the cost detail, we derive that the picking – and transportation costs determine the largest part of the total costs. The cost of kitting and repackaging is low in comparison with the picking – and transportation cost because most of the parts are delivered to the line in bulk.

In Figure 7.3, a cost detail of different scenarios is given. Firstly, the model is solved to optimality without the space constraint. In this scenario, only 12 parts will be kitted. The remaining parts will be supplied to the line in bulk. The total cost without space constraint is €191 983 which is lower than the total cost of the optimal solution with space constraint. However, this scenario is not feasible because only limited space is available at the border of the line. If we compare the assignment of parts between the scenarios with – and without space constraint, we can conclude the following: when there is less space available at the border of the line, some parts need to be repacked in smaller boxes or need to be kitted in order to have all parts available at the border of the line. This will increase the total cost of material handling as the transportation, repackaging and kitting cost will significantly increase.

The second scenario is the all bulk scenario without space constraint. This scenario is quite similar as the previous scenario. All parts are supplied to the line in bulk which results in no repackaging -, kitting - and replenishment costs. This scenario is again unfeasible and the total cost of material handling is €192 046.

The third scenario is the all repack scenario. As explained before, the assumption is that only palletized parts can be repacked. In this scenario, we impose that all palletized parts are repacked. The parts supplied in boxes can be delivered to the line in bulk or in kits. The transportation and repackaging cost increases dramatically in this case. The advantage of this scenario, is that the space needed at the border of the line decreases significantly, what makes the solution feasible. The total cost for this case amounts to €321 767.

The fourth scenario is the all kit scenario with a total cost for material handling of €359 208. The picking cost, is significantly lower in this scenario because searching the right part for the operator at the border of the line is eliminated. However, the cost for transportation increases because transportation by a tugger train is less efficient compared to transportation of bulk stock. Additionally, there is a significant cost incorporated to form the kits in the supermarket.

Lastly, we have the scenario where repackaging is not allowed as a materials supply policy. The total cost for this scenario is €211 479 which is € 5 772 or 2,81% higher than the optimal scenario where line stocking, kitting and repackaging is used. As mentioned before, only 27% of the parts are eligible for repackaging because they are supplied to the plant in pallets. This makes the percentage repackaging in the optimum scenario with space constraint low (5,5%). Even in this case the total costs are reduced with almost 3% so it is more efficient to implement repackaging in the materials supply system.

From the different scenarios we can conclude that repackaging and kitting increase the cost of material handling. However, in order to have a feasible solution some parts need to be repacked or kitted, otherwise the space constraint is not satisfied. Additionally, the scenarios revealed that implementing only one line feeding method in the materials supply system leads to significantly higher costs. In order to be cost efficient, the materials supply system needs to integrate the three line feeding methods.

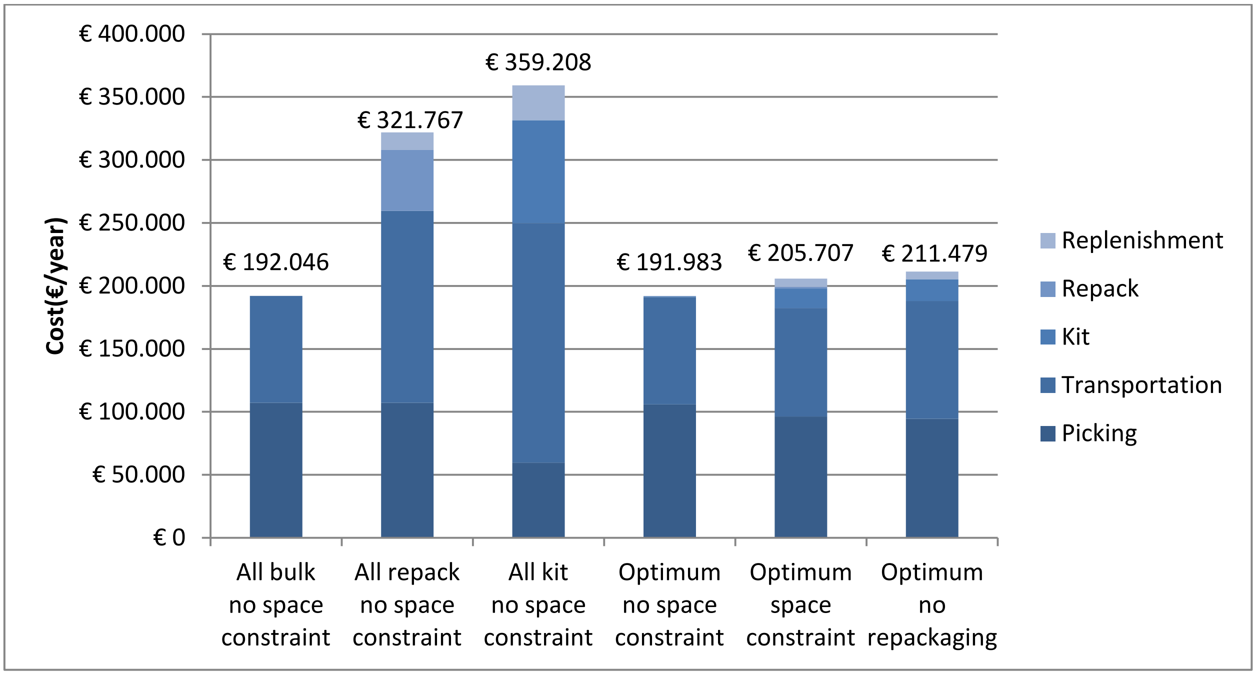

Figure 7.3: Base model: cost detail different scenarios

7.3 Results extended model

In the extended model, the walking distance for the operator at the border of the line is approximated in more detail. The approximation takes into account the real organization at the border of the line, what makes the picking cost more accurate. When a lot of parts are repacked or kitted, the stock at the border of the line reduces what reduces also the walking distance for the operator and vice versa.

The detailed approximation of the picking cost increases the complexity of the model because a lot of variables and constraints need to be added. The model is a mixed integer programming model with 3000 binary variables and 201 integer variables. Furthermore, 4000 auxiliary float variables are added. The CPU time to solve the model is 14,27 seconds. When the model is solved to optimality, the total cost of material handling amounts to €222 489. A cost detail and the assignment of parts from the optimal solution are given in Figure 7.4 and Figure 7.5:

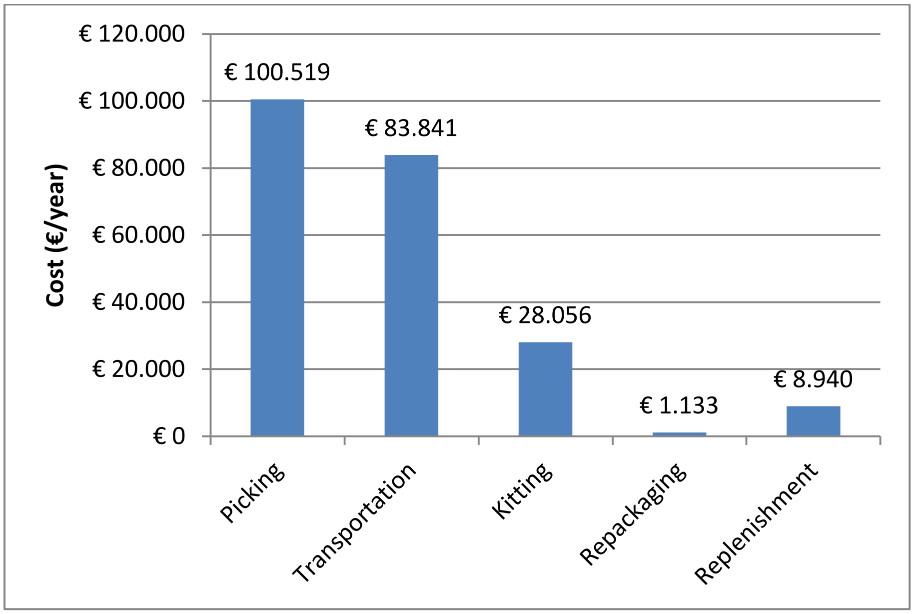

Figure 7.4: Extended model: cost detail

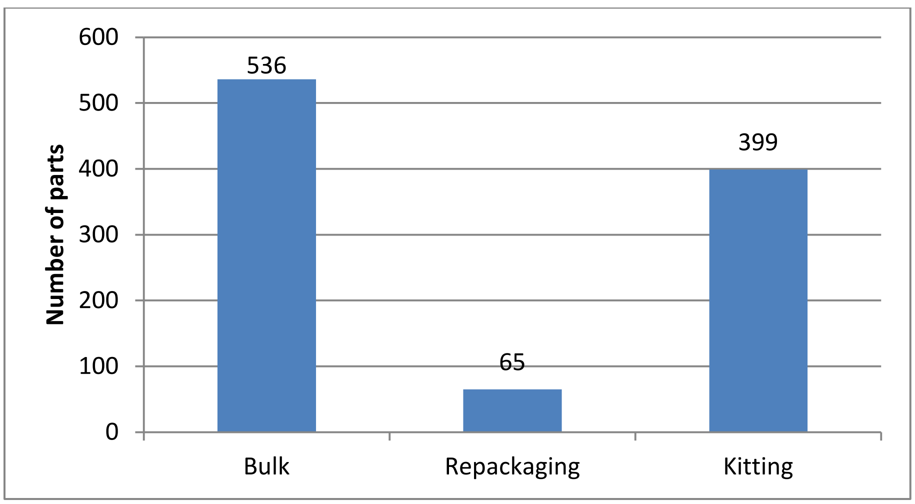

Figure 7.5: Extended model: assignment of parts

Most of the parts are delivered to the line in bulk in the optimal case. The remaining parts are mostly kitted and only 65 parts are repacked. The picking – and transportation cost determine the largest part of the total cost.

Figure 7.6 visualizes a cost detail of different scenarios. First of all, the space constraint is relaxed. The optima with – and without space constraint are almost identical, except three parts that used to be kitted are now delivered to the line in bulk. This means that the available space at the border of the line is sufficient to store all the parts when the model is solved to optimality with space constraint. Making the available space at the border of the line higher has only a small positive impact on the total cost.

The second scenario is the all bulk scenario, with a total cost of €301 678. When all parts are delivered to the line in bulk, a lot of space is needed to store them at the border of the line. As the extended model takes into account the real organization at the border of the line, the walking distance for the operator will increase. That is why the picking cost in the all bulk scenario is significantly higher compared to the other scenarios.

The all repack scenario has significantly lower picking costs than the all bulk scenario because the space needed at the border of the line is lower when using repackaging boxes. A drawback is that the transportation cost increases because transporting repackaging boxes is less efficient. Furthermore, a cost is incorporated for repacking the parts and for replenishment of the supermarket. The total cost is €336 772.

The total cost for material handling when all parts are kitted is €364 654. The transportation cost increases further when all parts need to be supplied to the line in kits. On the other hand, kits occupy the least space at the border of the line, what results in the lowest picking cost.

Lastly, the scenario is considered where repackaging is not allowed as a materials supply policy. The total cost increases with €3 765 or 1,69%. This is a rather small increase in the total cost but the percentage repackaging in the optimal scenario with space constraint is low (6,5%) mainly because only 27% of the parts are delivered to the plant in pallets. When more parts are delivered from the supplier to the plant in pallets, the cost reduction of adding the repackaging policy will normally be larger.

Delivering all the parts in bulk to the line is inefficient due to the large picking costs. However, delivering all the parts in repackaging boxes or kits is also inefficient because the transportation cost is very high in those cases and a cost for forming the repackaging boxes and kits has to be incorporated. The materials supply system functions most efficient when the three line feeding methods are incorporated.

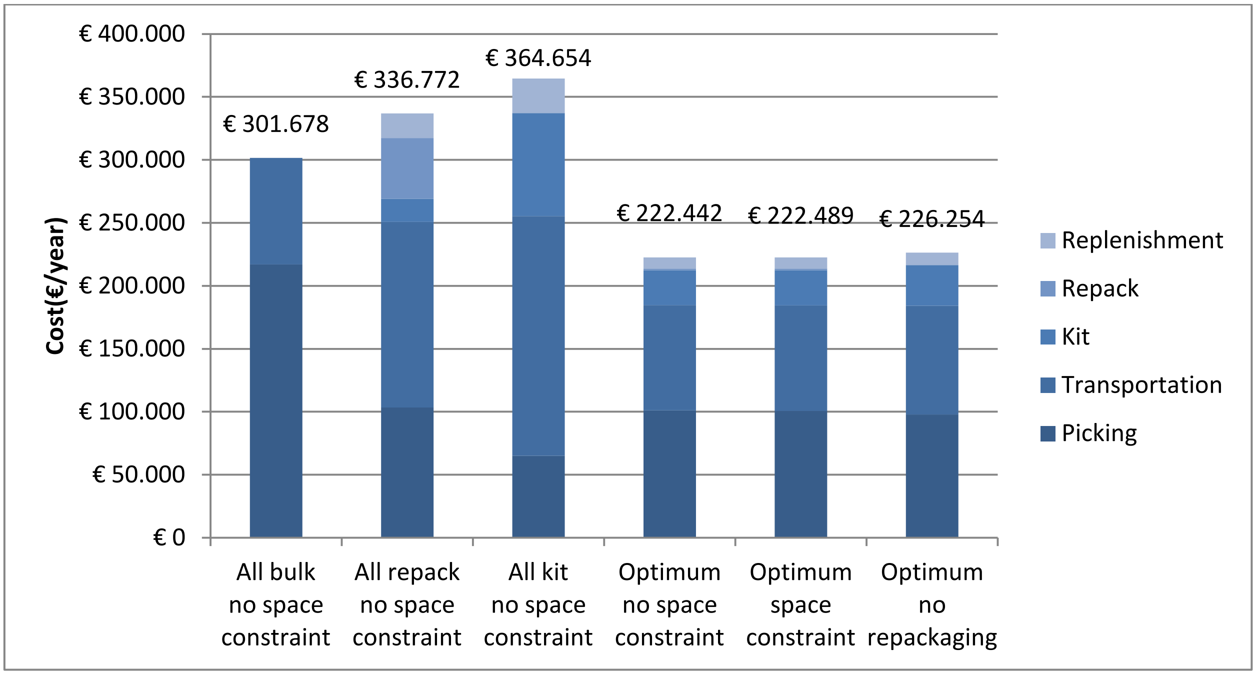

Figure 7.6: Extended model: cost detail different scenarios

7.4 Comparison base model and extended model

As mentioned before, the walking distance for the operator at the border of the line is approximated in more detail in the extended model. Therefore, variables and constraints need to be added, what leads to a higher computational effort for the CPU. This can be seen by comparing the runtime of the CPU for the base model (4,11 seconds) and the extended model (14,27 seconds). When the dataset increases, it can be the case that the runtime for the extended model is very high to solve the model.

One of the largest cost determinants for material handling is the picking cost. Comparing the base – and the extended model reveals that there is a significant difference between the picking costs in the all bulk scenarios (Figure 7.7). The base model uses average walking distances for the operator at the border of the line, which are independent of the organization of the stock at the border of the line. The walking distance stays the same when the space occupied by the stock at the border of the line changes. Therefore the picking cost is underestimated in the all bulk scenario of the base model. In the extended model however, the walking distance for the operator increase when there is a lot of stock stored at the border of the line. This results in a higher picking cost.

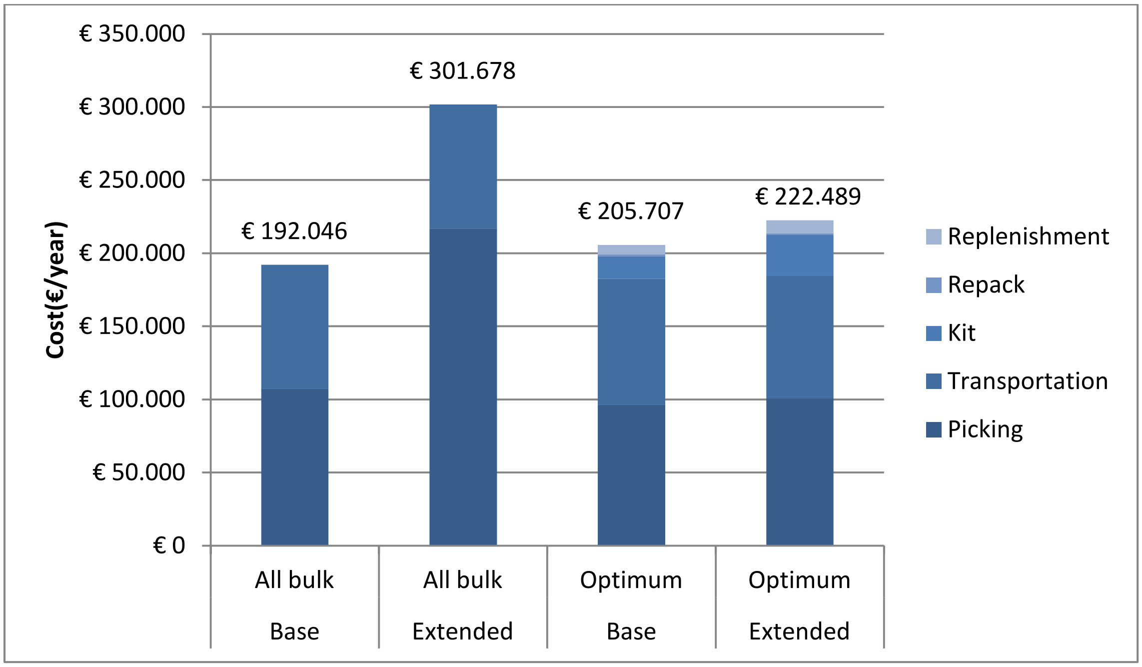

Figure 7.7: Comparison base – and extended model: cost detail

As the number of parts delivered to the line in bulk increase, it will result in a higher picking cost when the real organization of the stock is incorporated. However the transportation cost will decrease. The picking – and transportation cost are the two largest cost determinants of material handling. The tradeoff between these costs determines for a large extend the optimal solution. Figure 7.7 shows that more parts are repacked and kitted in the extended model than in the base model. In every case, the majority of the parts are delivered to the line in bulk. The base model underestimates the picking cost and that is why more parts are delivered to the line in bulk compared to the extended model.

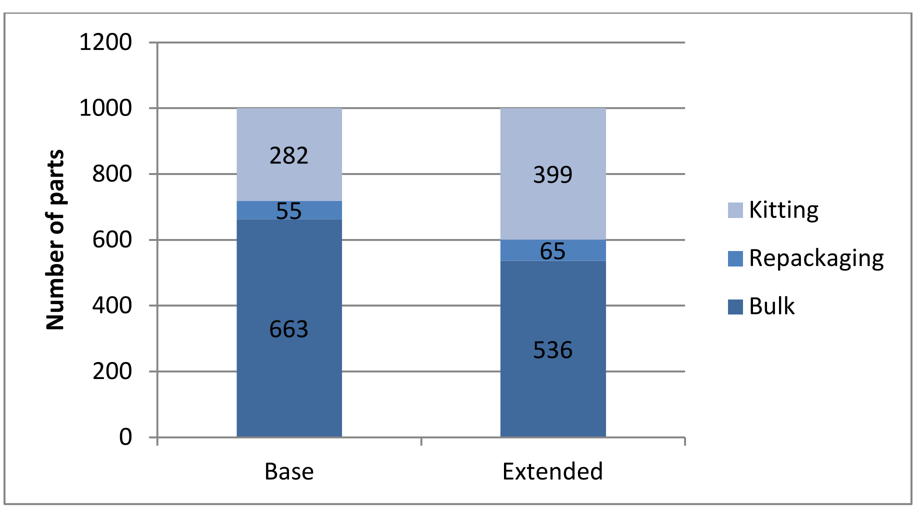

Figure 7.8: Comparison base – and extended model: assignment of parts

8 Analysis

In this part, a thorough analysis of the model will be performed. The data from the case study described in chapter 6 (the initial dataset) and five other datasets will be used for the analysis. First of all, the impact of different part characteristics on the materials supply policy will be determined. Secondly, a sensitivity analysis will be performed on the materials supply parameters of the dataset. The impact of a change in a parameter on the materials supply costs and the materials supply policies will be investigated. Our focus is particularly on the repackaging policy because a sensitivity analysis of line stocking versus kitting is already performed in Limère (2012). Furthermore, exclusively the extended model will be used to perform the analysis.

8.1 Impact of part characteristics

The initial dataset from the case study described in chapter 6 contains 1000 parts. Every part is determined by a part number and has its specific characteristics: weight, volume, number of parts in a pallet, usage rate,…. Parts are delivered from the supplier to the plant in pallets or in boxes. As mentioned previously, the assumption is that only parts supplied in pallets are able to be repacked. The overview in Figure 8.1 makes clear that the majority of the parts are supplied in boxes (720 parts). That is why repackaging is only used for 6,5% of the parts in the optimal case. When only the palletized parts are considered, the repackaging policy is used for 23% of the parts.

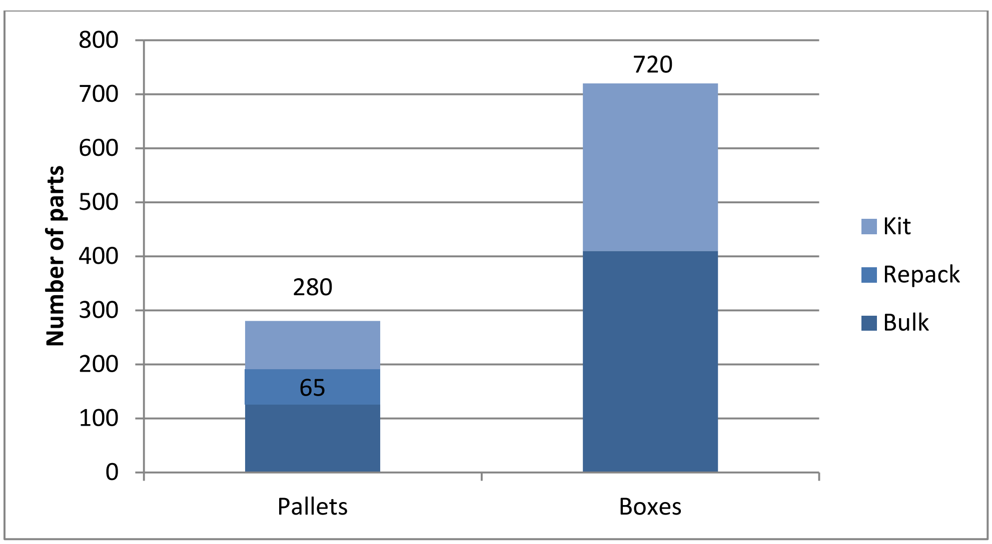

Figure 8.1: Assignment of parts for different packaging types

The five other datasets that are used for the analysis contain different parts compared to the dataset of the case study, but the materials supply system and consequently the plant layout are the same. The only difference between the datasets is the number of parts and the part characteristics. An overview of the properties of the datasets and the results after solving the datasets is given in Table 4.1.

	# parts	# workstations	% pallets	% repackaging	Total cost
Dataset 1	1818	106	30,47%	6,88%	464877
Dataset 2	1718	111	29,51%	5,47%	391298
Dataset 3	1099	67	35,85%	3,00%	259756
Dataset 4	1758	113	31,40%	5,63%	391025
Dataset 5	907	60	31,64%	7,06%	204965

Table 8.1: Properties datasets

As the focus is on analyzing the repackaging policy, only palletized parts are considered to determine the impact of the part characteristics. We will formulate some hypothesizes about the influence of the part characteristics on the assigned materials supply policy. These hypothesizes will be checked based on the dataset and optimal solution of the case study, and the five other datasets. The part characteristics will be split in different levels and for each level, the assigned materials supply policies will be investigated. Based on the results, the hypothesis will then be checked. The levels are chosen in order that every category contains almost the same number of parts.

First of all we take a closer look at the impact of the size of a part.

8.1.1 Impact part size

Hypothesis 1:

Parts that have a lower chance to be repacked are parts that take up a lot of space in a repackaging box.

When parts take up a lot of space in a repackaging box it means that only a few parts can be put in a repackaging box until the box is full. In this case, a lot of repackaging boxes need to be transported to the line to meet the demand. The transportation cost will be very high and will eliminate the positive effect of reducing the walking distance for the operator at the line when repackaging is used. When parts take little space in a repackaging box, a lot of parts can be put in a repackaging box until the box is full. Few replenishments of the boxes are then needed and the positive effect of reducing the walking distance for the operator will be larger than the negative effect of an increased transportation cost.

In the datasets, there are two measures that correspond to the size of a part. First of all we have the number of units of part i that a kit can maximally hold (v_i). This measure has an inversely proportional relationship with the volume of the part. Low values for v_i correspond to large parts and vice versa. In Figure 8.2, the parts of the initial dataset are grouped in small, medium and large parts for respectively high -, moderate – and low values of v_i. For every group the number of parts assigned to the different materials supply policies are shown. We can see that for small parts 56% are repacked, and for large parts only 9%. This result positively confirms our hypothesis. For small parts it is more efficient to repack the parts in smaller repackaging boxes and vice versa for large parts.

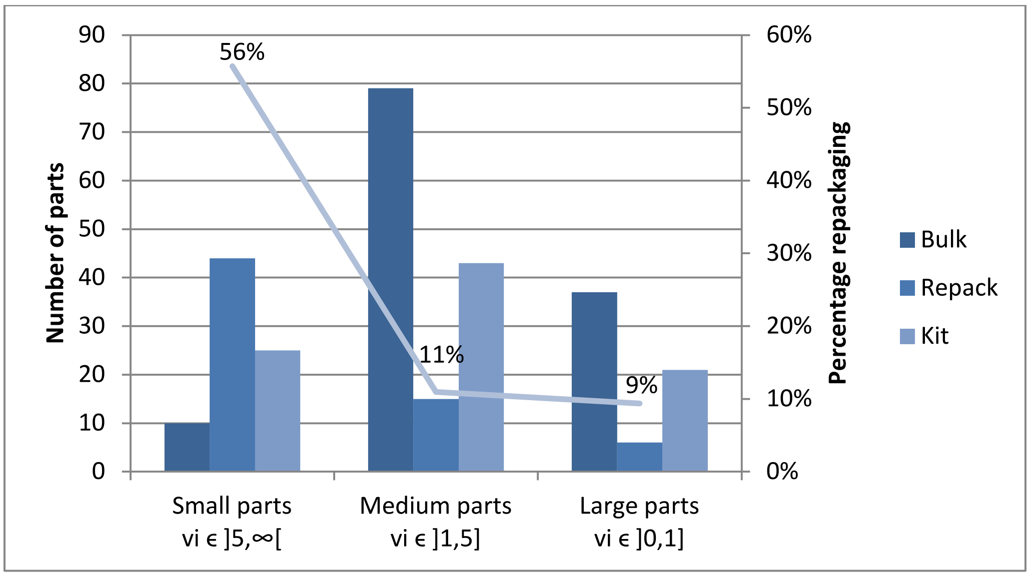

Figure 8.2: Impact of v_i on the materials supply policy

For the other datasets the results are comparable. In Figure 8.3, the percentage repackaging for every dataset and category are given. The larger the parts, the lower the percentage repackaging. This also confirms the hypothesis.

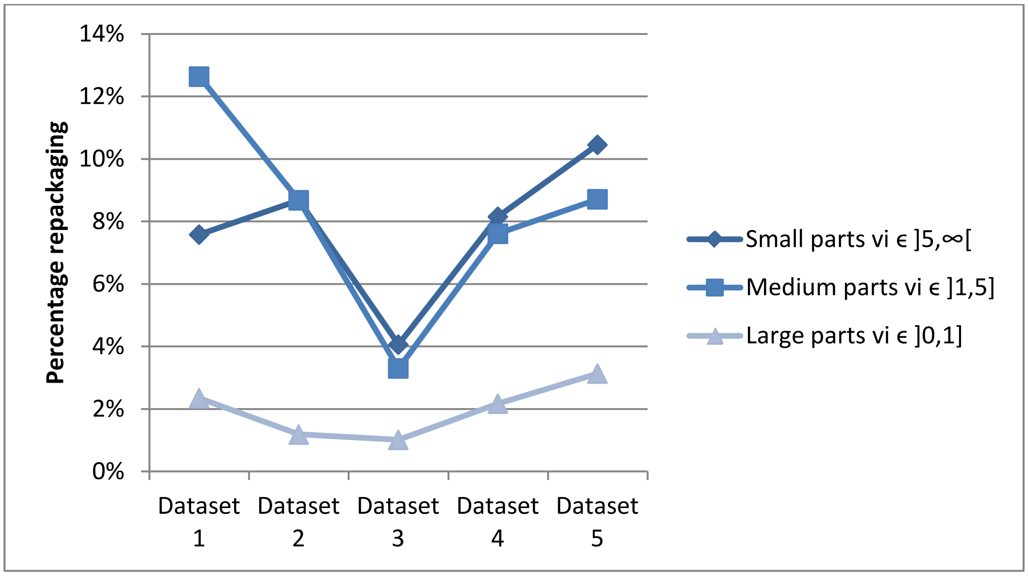

Figure 8.3: Impact of v_i on the percentage repackaging

Another part characteristic that corresponds to the size of a part is the number of units of part i that a pallet contains (n_i). When a pallet from the supplier contains a lot of parts (n_i is high), even after repackaging, the repackaging box will contain a lot of parts and vice versa. In Figure 8.4, the parts are grouped in few -, moderate – and many parts. We can see that when n_i is small, only a few parts are repacked (10%). When n_i is large the majority of the parts are repacked (61%). This result confirms the hypothesis. When $n_i$is large, after repackaging, the repackaging box will still contain a lot of parts. That is why few replenishments are needed and the transportation cost remains relatively low in the repackaging case. However the walking distance for the operator decreases when a pallet is replaced by a repackaging box at the border of the line.

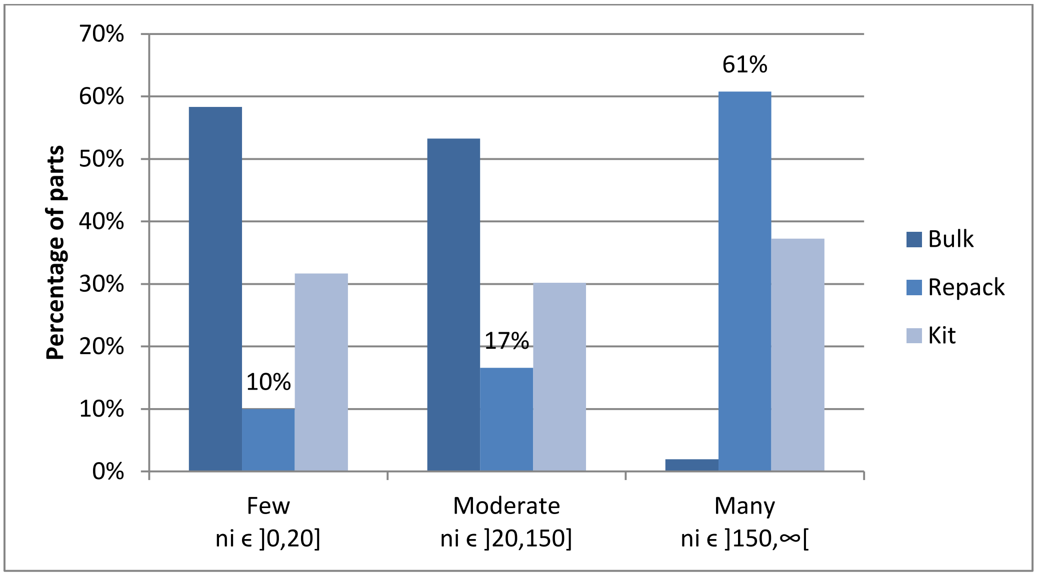

Figure 8.4: Impact of n_i on the materials supply policy

The analysis of the other datasets is again comparable. The higher the number of parts in the supplier packaging, the higher the percentage repackaging for every dataset (Figure 8.5). The hypothesis is consequently confirmed for each dataset.

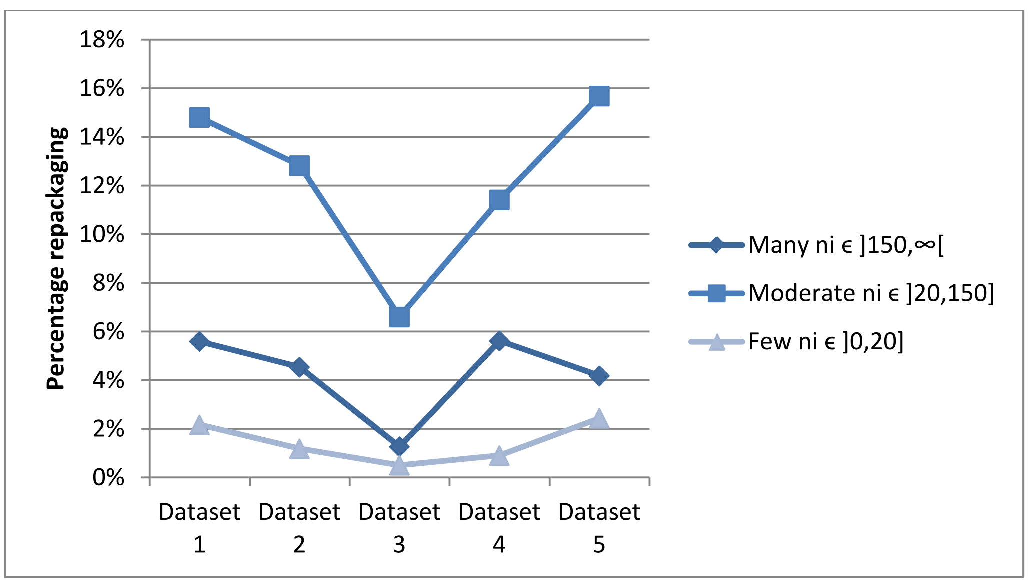

Figure 8.5: Impact of n_i on the percentage repackaging

Lastly, also the weight w_i of a part is positively correlated with the number of parts that can fit in a repackaging box. In most of the cases, large parts will be heavier than small parts. From Figure 8.6, it can be seen that light parts are repacked more often than heavy parts. However the relation is less distinctive than in the previously mentioned characteristics because the density of a part has also an influence on the weight of a part. In the initial dataset 37% of the light parts are repacked and 11% of the heavy parts.

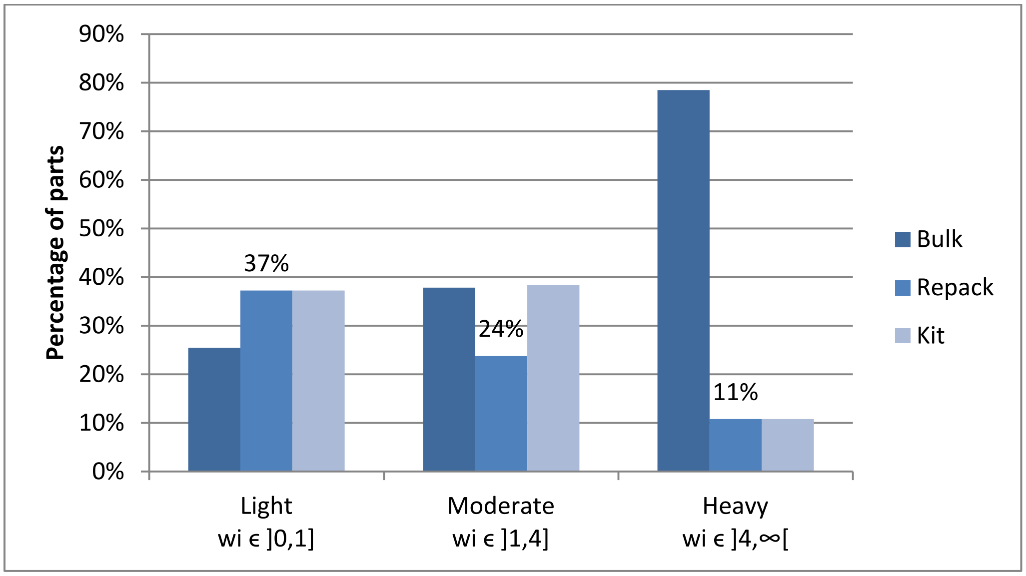

Figure 8.6: Impact of w_i on the materials supply policy

The relation in the five other datasets is less distinctive. For some datasets heavy parts are repacked more often, and for other datasets light parts are repacked more often (Figure 8.7). Therefore, we conclude that there is no significant relationship between the weight of a part and the assigned materials supply policy.

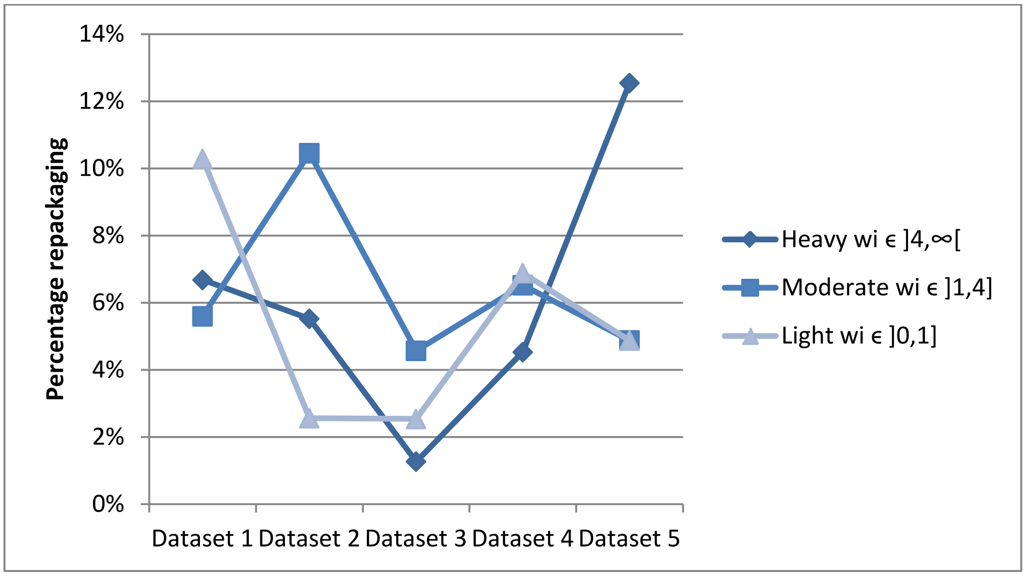

Figure 8.7: Impact of w_i on the percentage repackaging

8.1.2 Impact demand rate

Additionally, we think that the demand for a part influences the materials supply policy. Parts with a high demand rate will normally be delivered to the line in bulk to save transportation costs, whereas parts with a low demand rate will normally be delivered to the line in repackaging boxes or kits to save space.

Hypothesis 2:

Parts that have a higher chance to be repacked, are parts with a low demand rate.

When parts with a high demand rate are repacked, a lot of replenishments are needed because only a limited number of parts fit in a repackaging box. The transportation cost to deliver the repackaging boxes to the line will be high and will eliminate the reduction in picking costs due to space savings at the border of the line. When the demand rate for a part is low, it will take a while until the repackaging box is depleted at the line. The transportation cost for those parts will increase but the decrease in picking costs will be higher what makes it more efficient to repack the parts.

The usage rate of part i at workstation s (q_{is}) is the part characteristic that determines the demand rate for part i. In Figure 8.8, the parts are grouped in low -, moderate – and high usage parts. Again our hypothesis is conformed because we can see that low usage parts are repacked in 48% of the cases and high usage parts are never repacked. Parts with a high usage rate are in 79% of the cases delivered to the line in bulk, in order to keep transportation costs low.

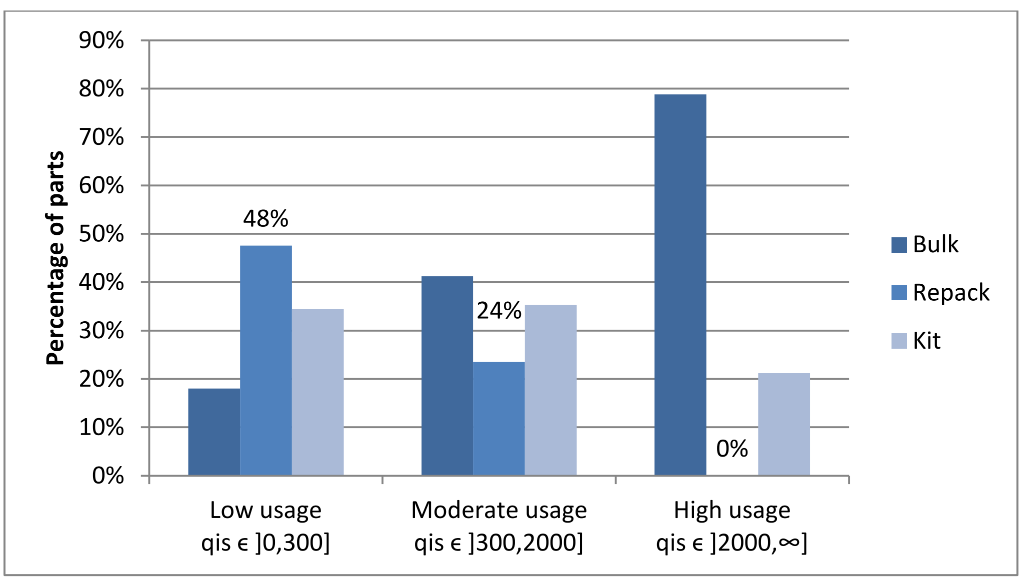

Figure 8.8: Impact of q_{is} on the materials supply policy

The same relation applies for the other datasets. The higher the usage rate, the lower the percentage repackaging (Figure 8.9). Except for dataset four, the relation does not hold. However, In general we can confirm the hypothesis.

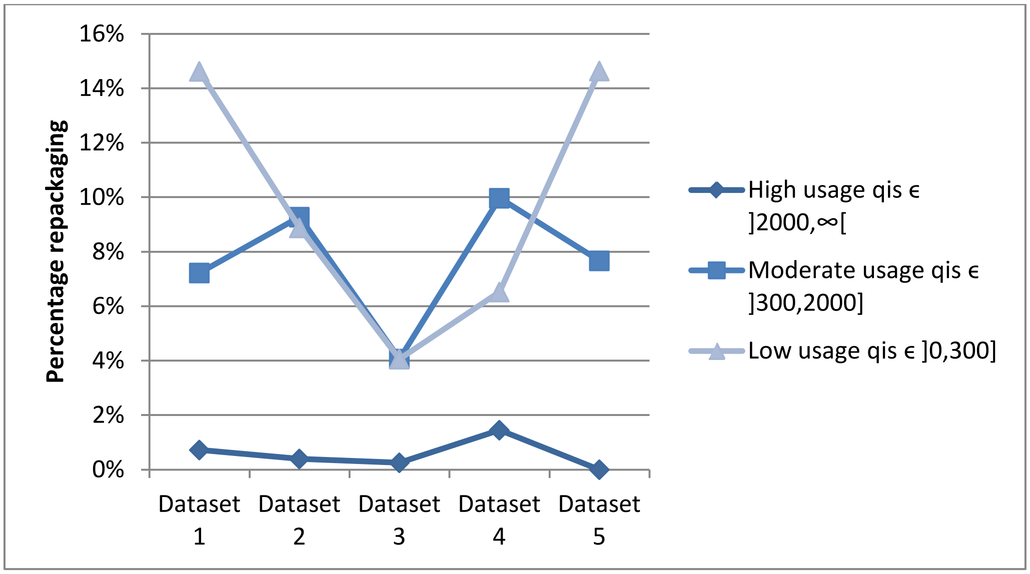

Figure 8.9: Impact of q_{is} on the percentage repackaging

8.1.3 Impact number of variant parts

The last part characteristic that is investigated is the size of the part family. When a lot of variant parts exist of part i, the demand of part i per end product will be relatively low because the chance the customer chooses that part is relatively low. When the demand for the part is low, based on the previous hypothesis, it is better to repack the part and save space at the border of the line. In this way the walking distance for the operator will be reduced what results in more efficient picking.

Hypothesis 3:

Parts that have a higher chance to be repacked, are parts that belong to a large part family.

In Figure 8.10, the parts are grouped in small-, medium – and large part families. For small part families, only 2% of the parts are supplied to the line in repackaging boxes. The usage rate of those parts is relatively high what makes repackaging not the most efficient materials supply policy. When the size of the part family increases, the percentage repackaging increases as well. For large part families, 40% of the parts are repacked. In this case the demand for the part in the end product will be relatively low because the customer can choose from many variant parts. This makes it beneficial to repack the parts and save space at the border of the line.

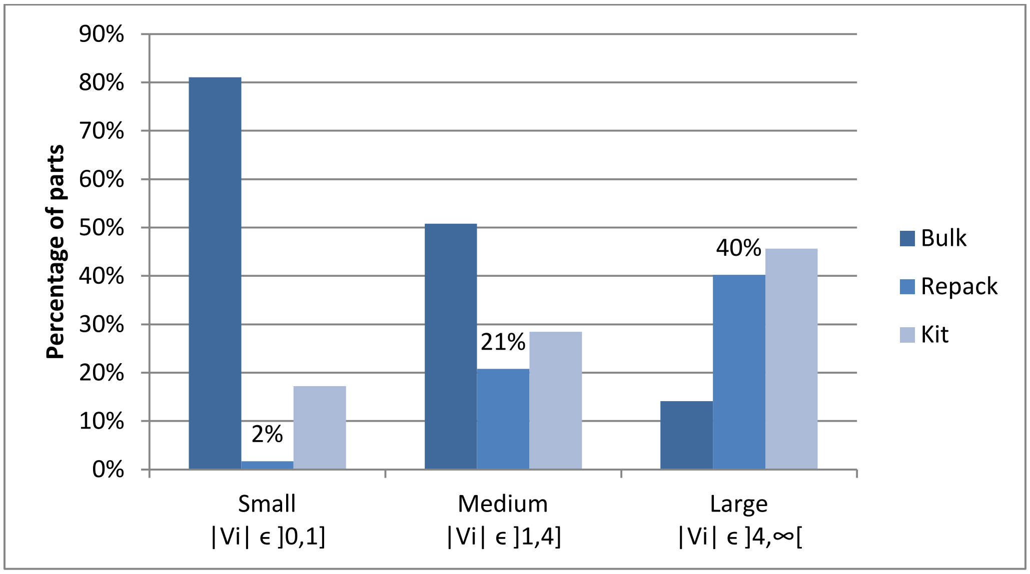

Figure 8.10: Impact of |Vi| on the materials supply policy

The analysis of the other datasets gives the same results. Large part families have a higher percentage repackaging than small part families (Figure 8.11). However the relationship between medium and large part families is reversed for dataset 1, 3, 4 and 5. In general however, we can confirm our hypothesis that larger part families have a higher percentage repackaging than small part families.

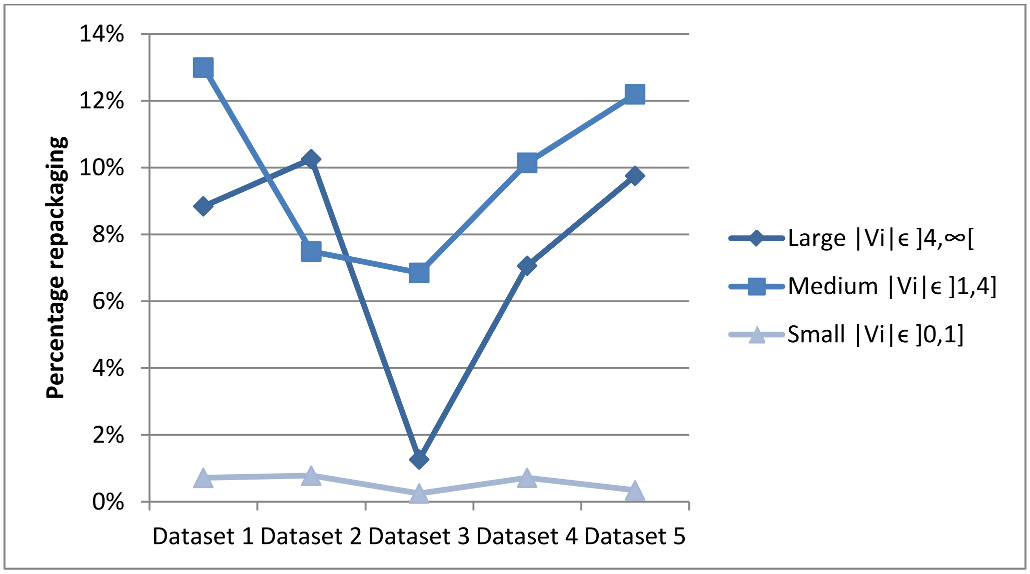

Figure 8.11: Impact of |Vi| on the percentage repackaging

8.1.4 Conclusion

From the analysis we can conclude that part characteristics have a significant influence on the materials supply policy. By analyzing the data from the case study and five other datasets, all the formulated hypothesis were confirmed. The size of a part, the demand rate and the size of the part family all have a significant influence on the material supply policy. However, not only the part characteristics determine the materials supply policy. Parameters related to the plant layout and operator productivity will also have a significant influence on the line feeding policy. The next part analyzes the impact of the materials supply characteristics.

8.2 Impact of materials supply characteristics

In the previous part, the impact of part characteristics on the materials supply policy was determined. The analysis of the part characteristics was based on the materials supply parameters of the case study. These parameters are case specific and will consequently differ from plant to plant. In this part, a sensitivity analysis will be performed to determine the impact of changing materials supply parameters on the optimal solution. Hypothesizes will be formulated about the impact of the parameters on the materials supply policy and on costs, and will be checked based on the dataset of the case study. The extended model will be exclusively used for this analysis.

8.2.1 Impact of workstation layout

First, the impact of the workstation layout will be analyzed. The parameter L_s determines the available length along workstation s to store bulk stock, repackaging boxes and kits. The following hypothesis is formulated based on this parameter:

Hypothesis 1:

Decreasing the available length along a workstation to store parts will increase the percentage repackaging. The effect on costs will be an increase in transportation costs and decreasing picking costs.

Decreasing the available length along the workstation results in less space to store the parts that are needed at the workstation. Repackaging boxes and kits occupy less space at the border of the line than bulk stock. Consequently, repackaging boxes or kits need to replace bulk stock when the available space is decreased. The number of parts delivered to the line in repackaging boxes will increase what results in a higher transportation cost. However the average walking distance for the operator to pick parts at the border of the line will decrease which has a positive influence on the picking cost.

In Figure 8.12, the effect of the length of a workstation on the materials supply policy is shown. It is clear that the percentage of parts that are repacked increase when the available space is reduced. Also the percentage of parts that are kitted increase with a reduction in the available space at the border of the line. This is in line with the first part of the hypothesis.

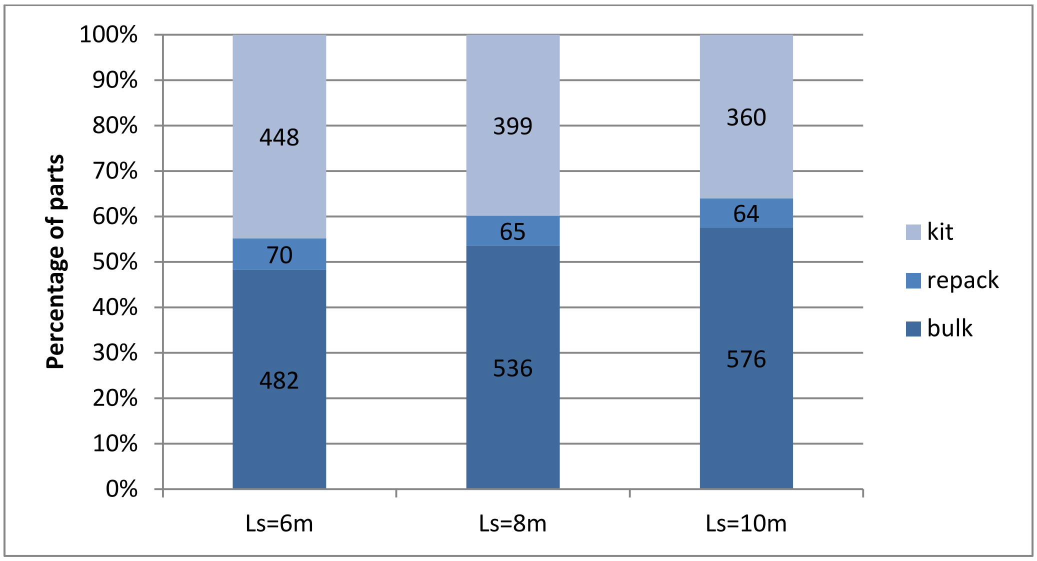

Figure 8.12: Impact of Ls on the materials supply policy

In Table 8.2, an overview of the costs are given for every length of the storage. Reducing the length of the storage at the workstations from 8m to 6m results in a total cost increase of €3.490, which is only 1,56%. The total picking cost decreases due to a large decrease in the cost of picking bulk stock. On the other hand, the total transportation cost increases because more parts are delivered to the line in kits and repackaging boxes, and the transportation cost of kits and repackaging boxes on a per unit basis is more expensive than the transportation of kits. These results confirm the hypothesis.

	L_s=6m	L_s=8m	L_s=10m
Total cost	€ 225.979	€ 222.489	€ 221.677
Total picking	€ 96.376	€ 100.519	€ 102.175
Total transportation	€ 87.294	€ 83.841	€ 82.150
Picking bulk	€ 70.514	€ 76.168	€ 78.289
Picking repackaging	€ 1.540	€ 1.365	€ 1.403
Picking kit	€ 24.323	€ 22.986	€ 22.484
Transportation pallets	€ 29.151	€ 30.913	€ 31.296
Transportation boxes	€ 23.304	€ 24.935	€ 24.685
Transportation repackaging	€ 4.216	€ 2.475	€ 1.926
Transportation kits	€ 30.622	€ 25.519	€ 24.243
Kitting	€ 30.233	€ 28.056	€ 27.692
Repackaging	€ 1.930	€ 1.133	€ 882
Replenishment	€ 10.147	€ 8.940	€ 8.777
% Repackaging	7,00%	6,50%	6,40%

Table 8.2: Overview impact of Ls

8.2.2 Impact of supermarket layout (Dr and Dk)

Secondly, the impact of the supermarket layout is determined. The supermarket, where kitting and repackaging takes place, is located close to the assembly line in the case study. However in some plants this is not possible due to a limitation in space availability. When the supermarket is located further away from the assembly line, the distance of the milk run tour for repackaging boxes and kits will increase. The following hypothesis is formulated for these parameters:

Hypothesis 2:

Locating the supermarket further away from the assembly line decreases the percentage repackaging. The total costs will increase because of an increase in picking- and transportation costs.

Locating the supermarket further away from the line increases the distance of the milk run tours. This will make repackaging and kitting less attractive. The result is that the percentage of parts repacked will decrease. Furthermore the total transportation cost will increase because it takes longer to transport the kits and repackaging boxes from the supermarket to the workstation. The picking cost will increase because more parts will be delivered to the line in bulk, what increases the walking distance for the operator.

In Figure 8.13, the impact of an increase in the transportation distance for milk run tours from 1640m to 2460m on the materials supply policy is given. When the transportation distance increases the percentage repackaging decreases which is conform to the hypothesis.

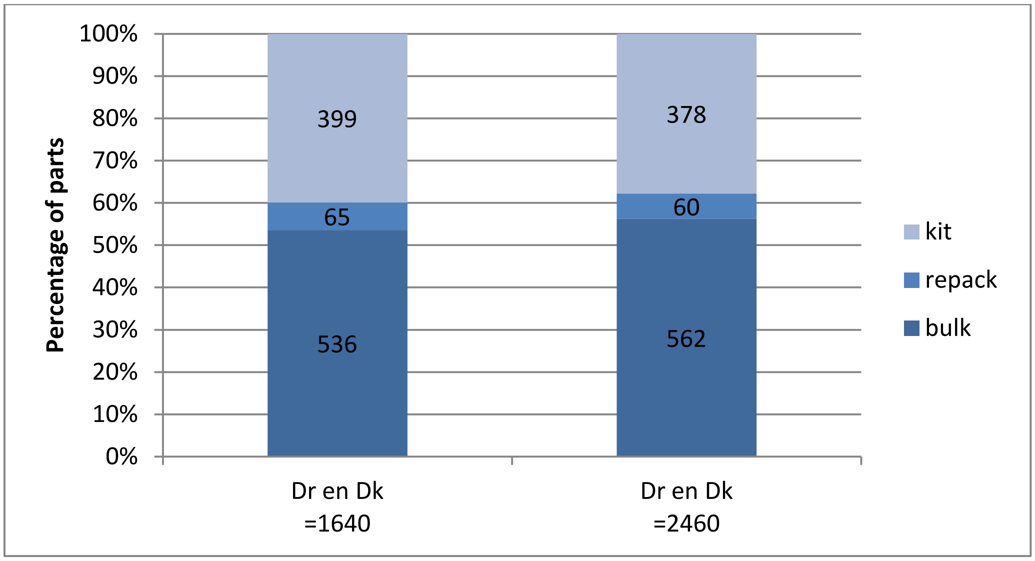

Figure 8.13: Impact of Dr and Dk on the materials supply policy

Furthermore, from the overview in Table 8.3, it is clear that the total cost increases with €12.951 or 5,82%. This is mainly the result of an increase in the transportation cost of repackaging boxes and kits because it takes longer to complete the milk run tours. Also the picking cost increases slightly because more parts are delivered to the line in kits or repackaging boxes what increases the walking distance for the assembly line operator. The results from the dataset confirm the hypotheses that the location of the supermarket further away from the assembly line, increases the percentage repackaging, and the transportation – and picking costs.

	Dr en Dk = 1640m	Dr en Dk = 2460m
Total cost	€ 222.489	€ 235.440
Total picking	€ 100.519	€ 103.947
Total transportation	€ 83.841	€ 96.621
Picking bulk	€ 76.168	€ 81.436
Picking repackaging	€ 1.365	€ 1.170
Picking kit	€ 22.986	€ 21.341
Transportation pallets	€ 30.913	€ 32.225
Transportation boxes	€ 24.935	€ 26.770
Transportation repackaging	€ 2.475	€ 3.176
Transportation kits	€ 25.519	€ 34.450
Kitting	€ 28.056	€ 25.820
Repackaging	€ 1.133	€ 970
Replenishment	€ 8.940	€ 8.081
% Repackaging	6,50%	6,00%

Table 8.3: Overview impact of Dr en Dk

8.2.3 Impact of operator productivity (f^r)

Lastly, the impact of the operator productivity is analyzed. A determinant of the operator productivity is the time it takes for the operator to fill a repackaging box (f^r) which takes place in the supermarket.

Hypothesis 3:

The longer it takes to fill a repackaging box, the less parts will be repacked. Furthermore the total cost will increase.

When the operator in the supermarket executes the repackaging activity less productive, the operator cost to fill a repackaging box will increase. This makes repackaging less efficient what will result in a lower percentage repackaging. It is reasonable that the total cost will increase when the repackaging activity is more expensive. However, it is difficult to determine which cost factor will determine the cost increase. The repackaging activity will be more expensive per unit but as the percentages repackaging will decrease, the total repackaging cost can also decrease.

In the graph and table below, the impact of increasing f^r from 0,01h to 0,02h is shown. The percentage repackaging decreases from 6,5% to 4,7% which corresponds to the hypothesis. The increase in the total cost is limited to €760 annually. These results from the dataset confirm the hypothesis.

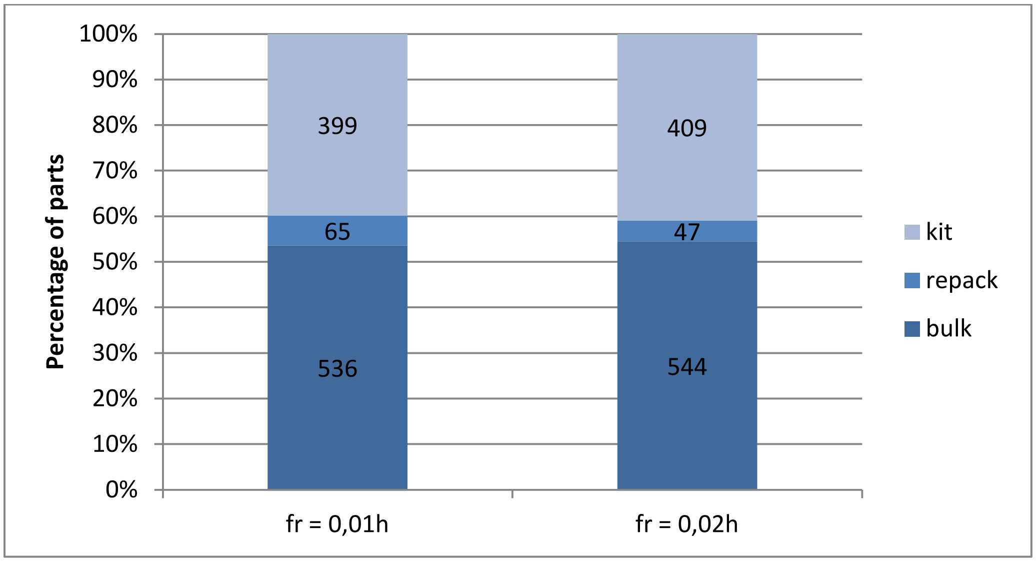

Figure 8.14: Impact of f^r on the materials supply policy

	f^r = 0,01h	f^r = 0,02h
Total cost	€ 222.489	€ 223.249
Total picking	€ 100.519	€ 101.151
Total transportation	€ 83.841	€ 83.670
Picking bulk	€ 76.168	€ 77.250
Picking repackaging	€ 1.365	€ 849
Picking kit	€ 22.986	€ 23.052
Transportation pallets	€ 30.913	€ 30.767
Transportation boxes	€ 24.935	€ 24.869
Transportation repackaging	€ 2.475	€ 1.239
Transportation kits	€ 25.519	€ 26.795
Kitting	€ 28.056	€ 28.260
Repackaging	€ 1.133	€ 1.114
Replenishment	€ 8.940	€ 9.054
% Repackaging	6,50%	4,70%

Table 8.4: Overview impact of f^r

8.2.4 Conclusion

The materials supply parameters are case specific and will differ from plant to plant. The analysis of the materials supply parameters revealed that those parameters can have a significant impact on the materials supply policy and the total cost. Redesigning the plant layout or the workstation layout and improving the productivity of the operator will therefore have a significant impact on the optimal assignment policy.

9 Conclusion and direction for further research

The objective of this thesis is to extend the dissertation of Limère (2012) and optimize the materials supply system of mixed-model assembly lines. Three materials supply methods; line stocking, kitting and repackaging, are considered for the optimization of the materials supply system. A mathematical optimization model was developed that assigns the most cost efficient materials supply policy to each part needed at the border of the assembly line. The analysis of the model focuses on the repackaging policy as the line stocking – and kitting policy were already analyzed extensively by Limère (2012).

The next part describes how the research questions were addressed in this thesis study.

9.1 Review research questions

Research question 1:

Is it possible to develop a mathematical optimization model that assigns an optimal materials supply policy, line stocking - kitting or repackaging, to the different parts based on a given plant layout and part characteristics?

Before the mathematical model was developed, the material flows related to each materials supply policy were determined together with the impact on the different cost factors. Based on this analysis a mixed integer linear programming model was developed. The objective of the model was to minimize the total cost of material handling. The decision variables determine which materials supply policy has to be assigned to each part. In the base model, an average figure for the walking distance of the operator at the border of the line was used to determine the picking cost. The extended model however takes into account the real organization of the stock at the border of the line which leads to a more accurate approximation of the picking cost. The models were solved in CPLEX 12.7 by using the data of the case study. After solving the models, the most efficient materials supply policy for each part is known together with the value of the relevant cost factors. The running time for the base model was only 5 seconds. However, for the extended model the running times were on average 15 seconds for a dataset of 1000 parts.

The results of the extended model have shown that incorporating the repackaging policy in the materials supply system reduces the total cost of material handling. The cost reduction was however limited but this was mainly because the dataset containes a low level of palletized parts. For datasets with a higher level of palletized parts the cost reduction would normally be larger.

Furthermore, the scenario analysis of the extended model revealed that the properties of the repackaging policy can be positioned in between the line stocking – and kitting policy. The repackaging policy has lower picking costs than the line stocking policy but higher picking costs than the kitting policy. This is because bulk stock requires more space to store the parts than repackaging boxes and kits require less space than repackaging boxes. On the other hand, the transportation cost for repackaging boxes is larger than the transportation cost of bulk stock. The transportation cost of kits per unit is even larger than the transportation cost of repackaging boxes.

The repackaging policy combines the advantages and disadvantages of both the line stocking and the kitting policy. However this does not mean that it is efficient to implement exclusively the repackaging policy in the materials supply system because the cost of considering only the repackaging policy is a lot higher than the optimal solution of combining the three materials supply policies. The conclusion is that in order to keep the costs as low as possible, the three materials supply policies need to be integrated in the materials supply system.

Research question 2:

Is it possible to determine part characteristics which have a significant impact on the materials supply policy that is assigned?

The analysis revealed that part characteristics have a significant impact on the materials supply policy assigned to each part. The optimal solutions of six datasets were analyzed in order to test the formulated hypothesis. The following hypothesizes were confirmed based on the analysis:

- Parts that have a lower chance to be repacked are parts that take up a lot of space in a repackaging box.
- Parts that have a higher chance to be repacked, are parts with a low demand rate.
- Parts that have a higher chance to be repacked, are parts that belong to a large part family.

The characteristics of the parts and consequently the characteristics of the product determine for a large extent the materials supply policy that is most cost effective to deliver the parts to the assembly line.

Research question 3:

Is it possible to determine materials supply parameters which have a significant impact on the materials supply policy that is assigned and the cost factors?

Not only the part characteristics determine the materials supply policy. The analysis of the materials supply parameters revealed that the plant layout, workstation layout, operator productivity,… all have an impact on the optimal solution. The following hypothesizes were confirmed based on the analysis:

- Decreasing the available length along a workstation to store parts will increase the percentage repackaging. The effect on costs will be an increase in transportation costs and decreasing picking costs.
- Locating the supermarket further away from the assembly line decreases the percentage repackaging. The total costs will increase because of an increase in picking- and transportation costs.
- The longer it takes to fill a repackaging box, the less parts will be repacked. Furthermore the total cost will increase.

The materials supply parameters and consequently the plant layout, workstation layout,… have a significant impact on the assigned materials supply policy for each part but also on the cost factors. This model can be used to analyze the impact on the materials supply system when the plant layout is redesigned. Therefore, the model is an interesting decision making tool to analyze the advantages and disadvantages of different plant layouts.

9.2 General conclusion

Optimizing the materials supply system for multi-model assembly lines becomes increasingly important as more and more parts are needed at the assembly line due to the extensive customization. Extensive customization leads to an increase in the number of variant parts and creates pressure on the materials supply system. The objective of this paper was to analyze the tradeoffs of three different materials supply policies: line stocking, kitting and repackaging and to get an insight in the benefits of integrating the three policies in the materials supply system. Furthermore, a decision making tool was developed for operations managers in order to be able to determine the most cost efficient materials supply policy for each part. Additionally, the model is able to analyze the effect of changing the plant layout or other materials supply parameters.

9.3 Direction for further research

Integrating the inventory and ordering policy

The mathematical model developed in this thesis study optimizes the materials supply of parts to the assembly line. The parts required to perform the assembly operation need to be continuously available at the border of the line. When a kit with certain parts, a repackaging box or bulk stock needs to be replenished, and there are no parts available in the supermarket or in the warehouse this can lead to an interruption of the assembly line operation. Consequently, the inventory and ordering policy have a significant influence on the operation of the materials supply system and the assembly operation. In future research, it would be interesting to integrate the materials supply system with the inventory and ordering policy. In this way for every part, a part availability level can be determined based on the required service level of the end product. With the determined service level for every part, the appropriate safety inventory and the appropriate ordering policy can be determined in order to guarantee the availability of the parts in the warehouse and the supermarket. Therefore, coordinating the materials supply system with the inventory and ordering policy can significantly increase the performance of the materials supply system and the assembly operation.

Integrating the optimization of supermarket layout

The layout of the supermarket and the positioning of the bulk stock in the supermarket has a significant influence on the efficiency of the repackaging activity. Therefore, in future research, it can be interesting to determine the appropriate layout of the supermarket and the optimal position of the bulk stock for every part in the supermarket based on certain characteristics of the parts and the demand rates for the parts that need to be repacked.

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