UNIVERSITY OF TWENTE.

MASTER'S THESIS

CROP HARVESTERS FEED US, BUT HOW DO WE FEED THEM?

"A research on the choice of assembly in either dock or line when time costs of different material feeding principles for subassemblies are identified."

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Management Summary

Dewulf, based in Roeselare, Belgium, is a company that builds agricultural machinery. The machines which are built are mainly potato and carrot harvesters, and are sold worldwide in an order driven fashion. Almost all assembly activities are carried out in-house. The products are assembled on a fixed position or in an assembly line. These two assembly layouts are chosen based on the expected demand per year and on the physical dimensions of the product and its components. The initial layouts have changed through the years after evaluating the yearly demand and on a certain gut feeling.

The research problem is described as the difficulty to choose that assembly layout for each type of product/subassembly without any guideline that objectifies the impact of the selected and corresponding material feeding principle for every product component. In order to find a solution to this problem, the main research objective can be described as:

> ***Design a (universal) decision rule that aims at objectively suggesting an assembly layout per subassembly and corresponding feeding principle per part while minimizing costs.***

The scope of this research is focused on finding a quantitative advantage of feeding principle as opposed to its alternative. This feeding principle goes hand in hand with an appropriate assembly layout. Data used for the quantitative examination is used from BOM list and ERP database. However, there are also qualitative judgements apparent for these material feeding principles. These qualitative judgements are only a side note for the recommended answer.

Currently Dewulf makes use of two types of assembly layouts and mostly one type of material feeding principle. The feeding principle used is Kanban replenishment where typically large storage racks are placed along assembly. This type of part presentation in assembly is often called line stocking. The present assembly layouts can be divided in dock assembly and line assembly. And, in their turn, these two assembly layouts can be divided in two possible layout scenarios each. Dock assembly can be known for material feeding by use of Kit replenishment or Kit replenishment in combination with Kanban close replenishment. Line assembly can be known for material feeding by use of Kanban far replenishment or Kanban far replenishment in combination with Kanban close replenishment.

To calculate the quantitative performance of the layout scenarios it is important that the production facility is currently changed and therefore some assumptions are needed.

Literature has mostly addressed the qualitative judgements of both feeding principles, though the quantitative judgements are scarce. Line stocking (with Kanban replenishment) is mentioned as the most used material feeding principle, while Kit replenishment is mostly praised. There are two quantitative articles which are useful and are used as a basis for this research. The common findings of these articles are that Kitting is often used when space is limited and that certain parts are riding free once a Kit is used. Kanban replenishment with line stocking is often preferred in the automotive industry, or a sector alike, because assembly is done in line and a small amount of parts per assembly station are needed.

With the quantitative articles in mind, we construct cost formulations to accommodate the comparison of alternatives. These formulations address the cost of part replenishment with respect to transportation, preparation and picking costs. The comparison of material feeding principles is used for finding preference conditions wherefore a feeding principle is superior over the other. Superior means in this case, less time consuming.

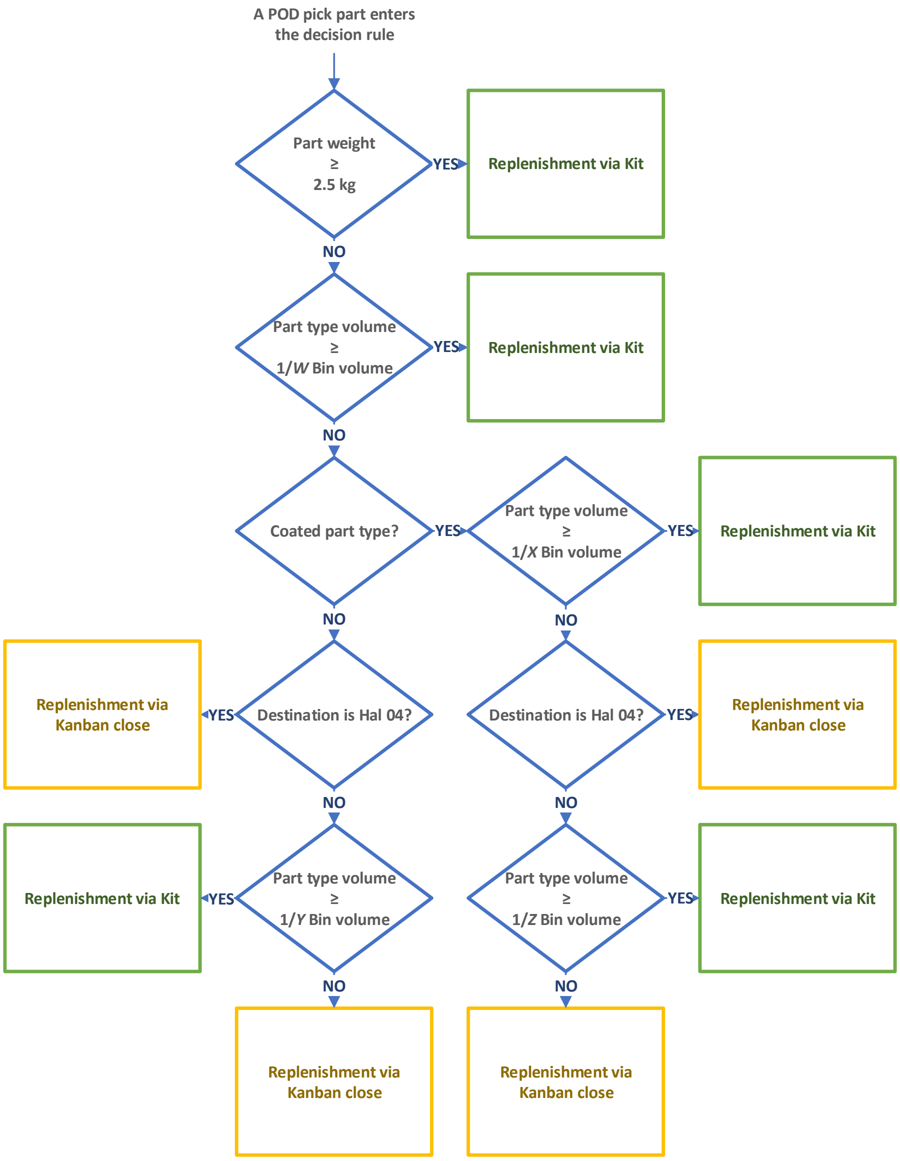
Firstly on subassembly level we search for the gross difference and conditions where Kanban far is purely compared to Kit. In order to do so, two subassemblies are examined. The main finding is that Kit is by far superior to Kanban far. Thus this finding is followed by searching for conditions where Kanban far will be superior, but this case will not be found. The only solution which was found can be categorized as a non-existent solution. Therefore:

> *"**All subassemblies and their corresponding part types can best be placed in Kit, when Kanban far is the alternative solution.**"*

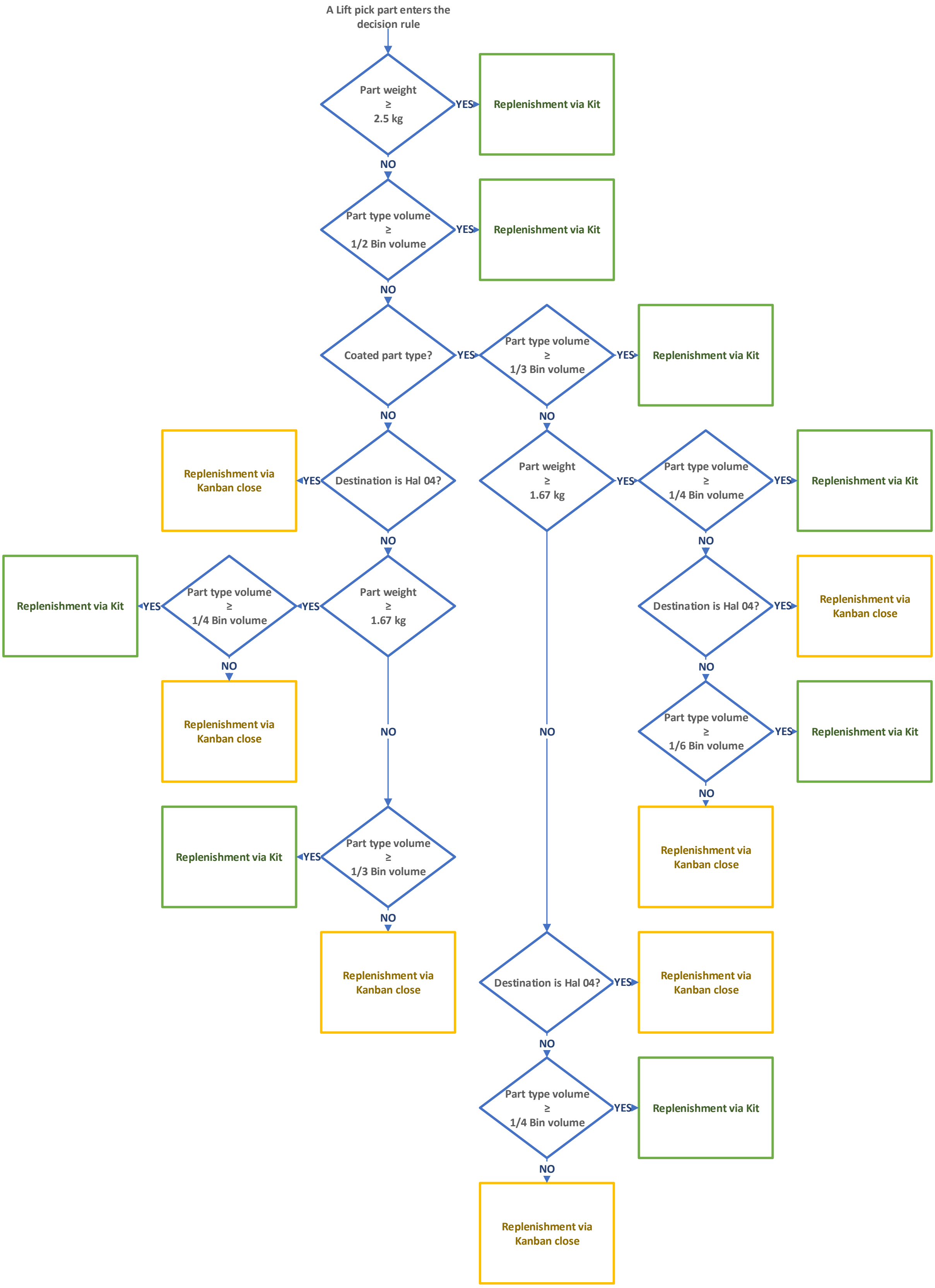
Secondly we search for the preference conditions on part level. This means that parts can better be pulled from Kanban close due to part characteristics. These parts are best not fed by kit replenishment but (usually) in great numbers along assembly.

The result of these preference condition are visualised in the two following pinball box structures.

The decision rules for POD pick parts are given in the first pinball box structure below. The values for *W*, *X*, *Y* and *Z* vary for Lager bin parts and Pallet parts. For Lager bin parts the values are: *W* = 3, *X* = 6, *Y* = 10 and *Z* = 13. For Pallet parts the values are: *W* = 18, *X* = 33, *Y* = 35 and Z = 46.

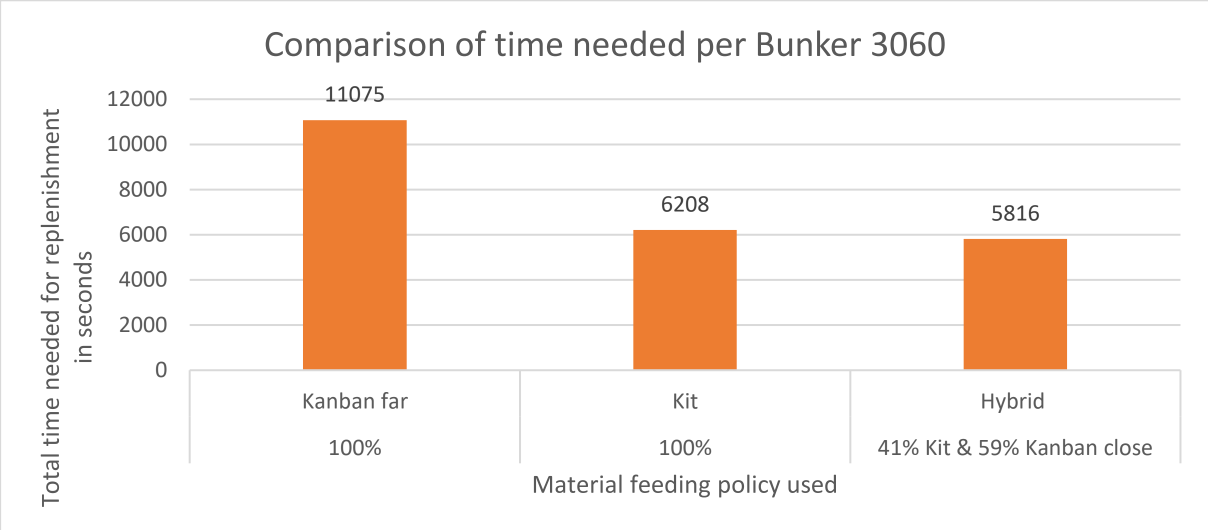


The decision rules for Lift pick parts are given in the second pinball box structure below:

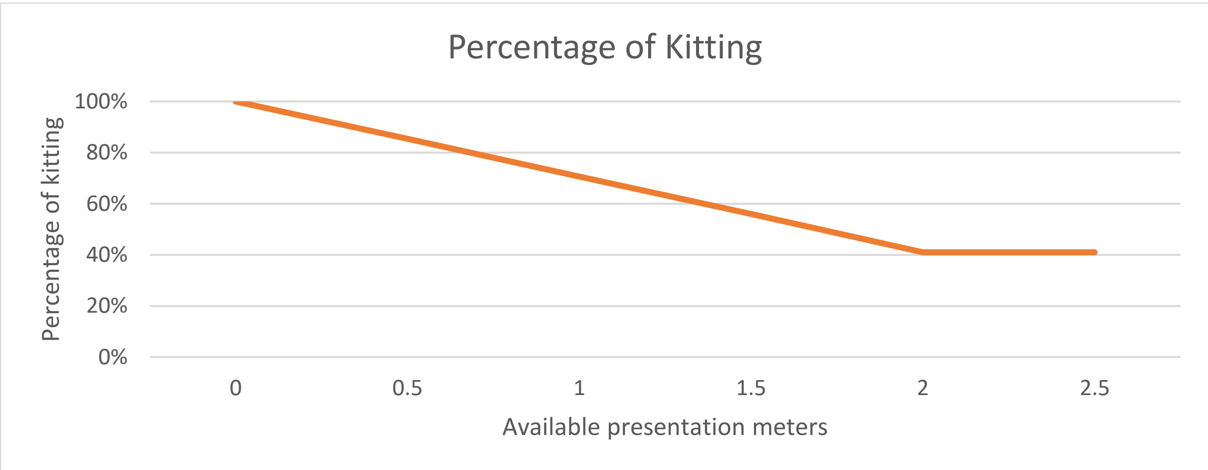


If these decision rules are put to the test, the outcome is that the time costs can be further decreased by removing parts from the kit and storing alongside assembly. This is possible when space is available.

As an example the above pinball box structures are used to allocate parts of the subassembly Bunker 3060 to a material feeding principle. The bar chart below, figure 35, shows that a pure Kit policy is 44% better as a pure policy with Kanban far. A Hybrid policy is even 47.5% better. This Hybrid policy consists for 59% of Kanban close and is 6.3% better as a pure Kit policy. Thus the amount of parts which are needed in Kanban close is very high, while the advantage as opposed to a pure Kit policy is meagre.



The following graphs shows the relationship of time cost as opposed to presentation meter available in assembly:



It is apparent that mostly Lift bin parts are suitable for Kanban close.

This following enumeration describes the action plan in terms of steps to use the decision rule and the recommendation of part placement. It should be taken into account that parts are divided into three part groups, while in practice this may change. To start with selecting the parts which need to be placed in Kanban close, the following action plan is proposed:

1. Choose a work cell were part consumption of all parts is known and the amount of kits needed on average.
2. Calculate the occurrence of a part type on an average kit.
3. Calculate the Kanban close advantage per part.

4. Translate costs to improvement per presentation meter.
5. Sort the parts with their advantages per meter from high to low.
6. Resort parts which tied on an advantage by sorting at the utilisation per presentation meter. If the advantage for different part types ties per kit, we suggest that the most parts needed per Kit is favourable for a Kanban close position.
7. Assign all parts which fit the available presentation meters of the work cell.

It is recommended that parts are placed according to the VASA model, which takes into account the ergonomics of picking from racks. Which practically means that all parts with the highest time advantages are best placed in a way that assembly personnel does not need to bend or reach high.

List of abbreviations

- **Assembly (process) Layout**
  The design of a floorplan of a production facility.
- **(Material) Feeding Principle**
  The method of replenishing storage which is needed in production/assembly.
- **Subassembly**
  A product of assembled parts which is a part of other product.
- **Assembly line**
  Assembling products in a fashion where multiple stations execute different tasks in order to build up the total product.
- **Assembly dock**
  Assembling products in fixed position where the products stand still and resources, machines and personnel move around it to build up the total product.
- **Line stocking**
  Presentation of parts, bins and/or racks near an assembly line.
- **Kanban replenishment**
  Way of feeding components to production based on safety stocks. Signal cards are used to mark empty storage locations, so replenishment of the stock at that location can be set in motion.
- **Kitting/Kit replenishment**
  Way of feeding components to production based on a selected amount of components which are needed for one end product.
- **BOM list**
  Bill of materials list.
- **ERP**
  Enterprise resource planning.

Table of contents

1. Introduction

In the framework of completing my Master studies Industrial Engineering and Management (IEM), with a specialisation in Production and Logistic Management at the University of Twente, I performed a research at Dewulf into assembly layouts and their corresponding material feeding principles.

In this chapter the organisation is introduced in section 1.1. Then section 1.2 briefly describes the research motivation. In section 1.3 a description of the problem is given. Section 1.4 states the research objective forming the basis of the research questions described in 1.5. Then, in section 1.6, there is a brief elaboration on the scope of this research. At last, in section 1.7, the framework used for this research is described and the outline of the rest of the report.

1.1 Organisation

Dewulf, based in Roeselare, Belgium, is a company that builds agricultural machinery. The machines which are built are mainly potato and carrot harvesters, and are sold worldwide in an order driven fashion. The company was founded in 1946 by Robert Dewulf and the first products made were ploughs. In 2008 a production facility in Brasov, Romania was opened and in 2014 there has been an acquisition of Miedema in Winsum (Friesland), The Netherlands. With the acquisition of Miedema, Dewulf can call itself a full-liner as regards to products needed cultivating potatoes and vegetables for every seasonal activity. Both companies use the same kind of production style, all assembly activities are carried out in house. In the current setting, with plants in Belgium, The Netherlands and Romania, Dewulf has approximately 275 employees.

1.2 Research motivation

Within Dewulf various types of agricultural machines are being built, or better said, assembled. The products are assembled on a fixed position or in an assembly line. These two assembly layouts are chosen based on the expected demand per year and on the physical dimensions of the product and its components. The initial layouts have changed through the years after evaluating the growth of demand on a yearly basis. Then changes are done accordingly, with respect to the floor space available.

In particular, assembly lines are changed and expanded with as basis the historical layout. Dewulf now wants to base a novel assembly principle and layout for every product based on quantitative considerations. This research is therefore based on finding a universal method to objectify the assembly layout choice. With universal is meant that the method can be used to evaluate the layout choice for the different types of machines within Dewulf, but also for the machines built at Miedema.

1.3 Problem description

As the demand for Dewulf products is growing over the years the production capacity needed is also growing for the current and upcoming product models. The current layouts are, as described in 1.2, changed and expanded based on the layout made in the first stadium of the product. This initial layout is mainly based on a feeling with the product, the expected demand and the space which is left in the buildings of the production facility. Currently, the production facility is totally filled up with assembly positions and stock which is gathered around these positions.

In case of introducing a new machine and evaluating the current setting at the end of the year, the question arises on where to create an assembly position and how to choose the way assembly is fed with components. There is a strong feeling that the choice of assembly layout and feeding principle can be done more objectively. To add to this, Dewulf also feels that the choice of these layouts is mainly between assembly lines or on single assembly docks and for the feeding principles only on Kit replenishment or Line stocking with Kanban replenishment.

The consideration is getting more important, when more space for assembly is not necessarily available in combination with the growing product demand. In addition, across the street a new warehouse is being built and therefore distance compared to the current warehouse (5 kilometres away in the nearby city) is reduced drastically. This means that direct feeding of components can be done with shorter travel times and more ease.

The main problem can be described as:

> ***It is difficult to choose an assembly layout for each type of product without any guideline that objectifies the impact of selecting a feeding principle for every corresponding product component.***

1.4 Research objective

Dewulf currently lacks the possibility to objectively choose the right assembly layout, and for each part the corresponding feeding principle. There are some methods to find the right assembly layout and there are also algorithms to calculate the right feeding principle for a product. However, these solutions are solely creating a better assembly layout or are comparing test results of using various feeding principle setups. Thus, the goal is to use these two methods to come to a joint solution. This solution entails a guideline for objectively suggesting the layout for a product and a feeding principle per subassembly when certain parameters of a product are known. Each parameter is expressed in terms of the common factor costs. Costs are a good comparable factor and it has impact when a lot of transportation is done. Transportation is not necessarily value adding while it costs at least time. Apart from the product size the limited amount of space available at the production facility is taken into account. This consumption of space is recalculated in terms of costs, too.

The main research objective can be described as:

> ***Design a (universal) decision rule that aims at objectively suggesting an assembly layout and corresponding feeding principle per subassembly while minimizing costs.***

1.5 Research questions

In this section the research objective and the corresponding research questions are described. As described in 1.3 the main problem is the possibility to objectify the decision of an assembly layout for a product where the choice of feeding principle per subassembly has great impact.

The main research question can be described as:

> ***To what extent can a decision rule suggest an assembly layout and a material feeding principle for a product?***

Answering the main research question is done in steps according to the sub questions stated below. First an analysis of the context is needed, followed by a review of literature and then this results in the design of a decision rule that is tested at the end of this research.

1.5.1 Context analysis

This part of the research is needed to picture the current situation at Dewulf. To consider an assembly layout and feeding principle, first the products from Dewulf should be known with all their specifications.

Chapter 2 is dedicated to answering the following research question:

1. What is the current situation at Dewulf with respect to products, their characteristics, their allocated assembly layout and feeding principles?

a. Which feeding principles and layouts are used at Dewulf?
b. Which products are being made?
c. What layout and feeding principle is used per type of product?
d. Which future changes at the production site are ahead?
e. What data is available per type of product and product subassembly?

1.5.2 Literature review

After the context of this research is described, a literature research to come up with a solution is needed. This part of the research will answer the questions around the present knowledge gap.

First there is an elaboration of the types of material feeding principles existing in literature, the quantitative and qualitative characteristics of these principles and the relations towards needed steps of handling material. Secondly there will be an elaboration on the types of assembly layouts, the quantitative and qualitative characteristics and finally the different approaches for solving a layout problem.

Chapter 3 is dedicated to answering the following research questions:

2. Which material feeding principles exist in literature and are appropriate to use at Dewulf?

a. Which types of principles exist?
b. What are the qualitative advantages and disadvantages of the existing principles?
c. What methods exist for quantifying the impact of usage of the different types of principles?
d. What are the written results of these quantifications and what relations can be inferred?
e. What costs can be related to using a certain type of feeding principle?
f. How can these costs be formulated?
g. In which cases should be chosen for what principle when characteristics of subassemblies are known?

3. Which types of assembly layouts exist in literature and are appropriate for the products of Dewulf?

a. Which types of assembly layouts exist?
b. What are the qualitative advantages and disadvantages of the existing layouts?
c. Which layouts (only) suit particular material feeding principles?
d. How can parts best be stored alongside assembly?

1.5.3 Design of decision rule

Now that the elaboration of the literature needed is done, the decision rule needs to be designed. With use of the available information stated in chapter 2, the impact of the currently used assembly layout(s) and material feeding principles is estimated. After that a decision rule is made and therefore the parameters needed to execute it are determined. After that the assumptions and restrictions of the rule are summed up. Followed by a description of the compatibility.

Chapter 4 is dedicated to answering the following research question:

4. To what extent is design of a decision rule possible based on the written literature and the available information?

a. To what extent can impact (on logistic and assembly processes) of the different types of principles at Dewulf be quantified?
b. Which parameters of a product and its subassemblies are required for usage of the proposed rule?
c. Which assumptions and restrictions have to be made?
d. To what extent is the proposed decision rule universally applicable?

1.5.4 Testing proposed design

Finally the decision rule should be tested on sensitivity and feasibility. Then the decision rule can be used to compare the current situation with proposed solutions for the current products of Dewulf.

Chapter 5 is dedicated to answering the following research questions:

5. How does the proposed decision rule perform?

a. How and when is a proposed feeding principle assigned in a proper fashion?
b. How sensitive is the proposed rule to its input parameters?
c. How much different is a chosen feeding principle configuration compared to the current situation?

1.6 Scope of research

The decision rule should be able to create a solution which is robust. This means that the amount of demand per year should not affect the end solution. If the needed quantity of a part changes, does the proposed feeding principle change a lot?

The research is mainly focused on finding a quantitative result where qualitative effects are mentioned. These qualitative factors have effect, but will be coped with after a quantitative answer is found.

The decision rule needs to use as less possible parameters and information on the product, because then the approach will be easier and more useful in practice.

The available space on the facility is limited to the plans made for the future. A proposed layout is restricted by this space and the assembly layout plans already set in motion.

At last, when data of assembly and picking times is not available, enough measurements, or assumptions, need to be done of representative parts/products/processes in order to make estimates in an adequate way. Internal due dates and timing of replenishments are not taken into account.

1.7 Research framework and outline

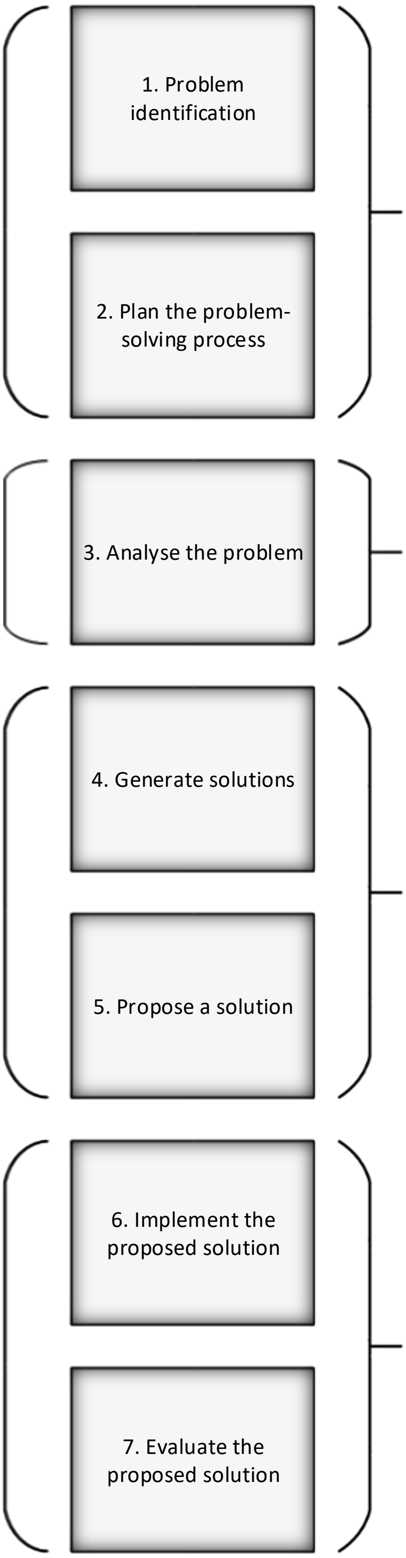
To guide the research in the right direction and solve the problem, the managerial problem solving method is introduced here. This managerial problem solving method helps to structure the research processes of action problems. Action problems are problems where an approach or current method of executing processes needs to be changed in order to gain an improvement. This research problem is an action problem, because the current layout and way of feeding materials to assembly can be changed by the proposed decision rule in order to improve.

The steps of the managerial problem solving method are as follows:

1. Problem identification
2. Plan the problem-solving process
3. Analyse the problem

4. Generate solutions
5. Propose a solution
6. Implement the proposed solution
7. Evaluate the proposed solution

A visual representation of the research framework projected on this research is visualised below. The outline of the research is described on the basis of the chapters per step of the framework.



The first chapter of the research is concluded with this section about the research framework and the report outline. The core problem is described and identified. It is explained why the problem arises and that it is valuable to be researched in terms of costs and in terms of future demand. Future demand of current and upcoming product models. The project goal and project scope are defined. Step 2, the planning of the problem-solving approach is done with use of this framework. The defined research questions can be marked as the main result of this step.

In chapter 2, the context analysis is described. A view on the different product types, the types of layout and the corresponding material feeding principles used. The context analysis describes the current situation where the problem is present. Therefore the available information on the products and their characteristics can be described. The assembly layouts and feeding principles in use will also be described. This analysis on the current situation is needed before going to the fourth step, when the solutions can be generated.

In chapter 3 the literature needed is presented, with information on assembly layout types, layout design algorithms, types of material feeding principles and algorithms to calculate the impact of different material feeding principles. This literature is needed as basis for the development of a decision rule and needs to be appropriate for use at Dewulf. Then in chapter 4 the design of the decision rule will be described, with the needed parameters and the possible outcomes. This can be done after the current situation and the literature appropriate for the problem is described. The existing approaches form a basis for the creation of the combined approach of solving a layout problem with its type of material feeding.

Chapter 5 describes usage of the proposed decision rule. Then finally, the report is concluded with a recommendation in chapter 6 and a discussion in chapter 7. The proposed solution will be analysed in this phase as an evaluation. A comparison of the performance of the current situation with a proposed solution will follow. And at last, the report will state concluding words with recommendations and discussions.

2. Context Analysis

This chapter describes the context of the research with respect to different products types, the assembly layouts, the material feeding principles and which information on the products is available. First in section 2.1 the mainly used material feeding principles are briefly described. Then in section 2.2 the different assembly layouts used at Dewulf are presented and supported with arguments. After the used layouts and material feeding principles are briefly described, the different products of Dewulf are exemplified in 2.3. These products are built up by subassemblies and widely vary in application, models and possible options. Section 2.4 presents the relevant changes which are made in the nearby future. Then in section 2.5 the available data for this research is exemplified in terms of relevant product and subassembly characteristics. Finally, section 2.6 concludes this chapter with answering the first research question.

2.1 Material feeding principle

Dewulf uses mainly one type of material feeding to the specific assembly locations. Material feeding means literally the way of presenting the needed resources to facilitate production. Without these resources the production is disrupted. In the best scenario the production only uses and requires the space needed for the production activity itself. Thus, space is not consumed by storage of resources for the particular production activity.

At Dewulf, Kanban is (mainly) used to control replenishments of stock alongside the assembly stations. This is done for most parts which means that relatively large space for stocking parts alongside the assembly stations is needed. This method of feeding materials is also known as continuous supply or line stocking. Kanban is a control system where (, often,) cards are used to signal a certain need or shortage of materials. When a storage location has a lower stock level than the set minimum, the Kanban system is used to trigger a replenishment activity to achieve a sufficient stock level at that storage location. However, some small assembly kits are being composed in the warehouse. A kit, see figure 1, is a composition of resources which facilitates the resource demand for a demarcated process. Material feeding by use of kits is currently the most obvious alternative as opposed to line stocking with use of Kanban replenishment. Instead of fixed stock locations alongside a production process, kits can be delivered in time to satisfy the resource demand. This results in less space usage of stock in a production area.

FIGURE 1 PHOTO OF A KIT AT DEWULF

The simplest way of explaining a difference in needed amount of handlings between line stocking and kits is by means of an example. This example is visualised schematically in figure 2 and figure 3. In this example a product is composed by one item A and one item B. A Kanban replenishment quantity of 5 pieces of stock is assumed. Thus when kitting is used, one item A is picked and one item B is picked. Together these form a kit which facilitates assembly at the station. The result is 4 handlings needed per assembly. Here a handling is defined as an executed transport or picking task by an operator.

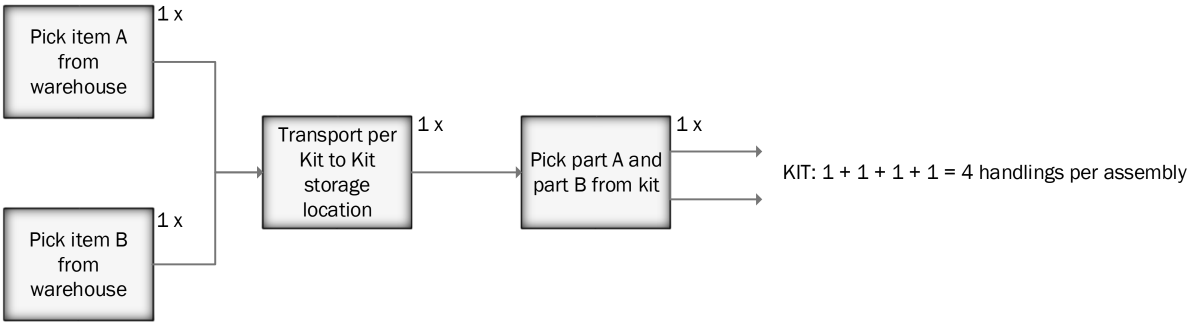


FIGURE 2 KIT REPLENISHMENT EXAMPLE

When Kanban replenishment is used, 5 items A are picked. Then these five items are transported to their Kanban location and later on picked per piece for use at the assembly station. In an analogous manner this cycle is executed for item B. This results in 2.8 handlings per assembly. This is a very superficial comparison, but it shows that the amount of handlings per Kanban piece is in this example lower than the kit piece. Though the weight of each handling is most likely not the same and Kanban locations take space at the assembly location.

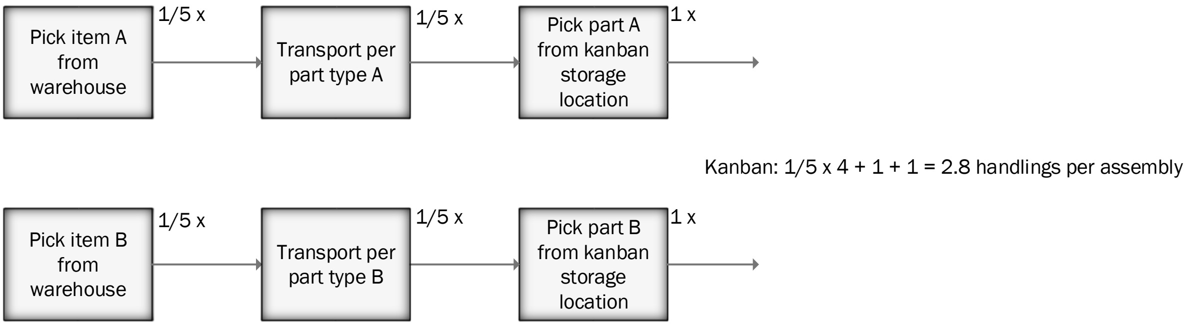


FIGURE 3 LINE STOCKING WITH KANBAN REPLENISHMENT EXAMPLE

More on the theoretical advantages and limitations of the use of line stocking and kitting are described in chapter 3, the literature review.

2.2 Assembly layouts

Within Dewulf two types of layouts are used to assemble products. Dock or line assembly. These layouts are based on the size and demand of the product and size and demand of individual stock keeping units. An assembly line is often used when a machine demands a lot of hours in assembly, the yearly demand is high and a relatively tight delivery schedule is needed. For all other machines an assembly in dock is sufficient. These assembly layouts are in their turn driven by the used feeding principle. To denote the different layout choices in a simplistic manner, four scenarios can be distinguished. These scenarios show an assembly layout with the associated material feeding principle(s). It is illustrated as one assembly station which is fed by use of Kanban far, Kanban close and/or Kitting. Later on it is explained which layout is matching either dock or line assembly. Kanban far means that the parts are not close to assembly, which leads to additional picking time as opposed to the singles, kits and Kanban close. Singles are parts which do nowhere nearly fit a pallet or kit, or require a special assembly process. Kanban far is an appropriate description at Dewulf because the machines at assembly are large, which generally means that their parts are large. These parts take a lot of space in racks alongside assembly. As a result, the average amount of travel time per pick will most probably be high if all those large items are presented next to each other. Kanban close is not appropriate for large stock keeping units, else a lot of parts will again be far from assembly. The kits and singles are placed close to the assembly station to accommodate one assembly process. These single parts are not kept on stock by use of Kanban and are produced when an order is made. Bulk replenishment of parts is also treated as a single part replenishment, as their transport is also executed for one item type, per bulk crate. Sometimes parts are longer than a pallet is, but are still placed on a pallet. A reason or rule for that placement is also further investigated in chapter 4.

These four scenarios are visualised schematically in figure 4. The availability for placement of part types alongside assembly in the scenarios is given in the illustrations. This availability is related to the presence of material feeding principles in each scenario, illustrated by blue containers. Scenarios I and II represent scenarios where kitting is used on subassembly level. Scenarios III and IV represent scenarios where Kanban far is used on subassembly level.

I. The first scenario shows the scenario where an assembly station is fed with stock keeping units by use of kit and single items only. Single items are delivered per piece/crate with the same distance towards the assembly workplace as kits.

II. The second scenario shows the scenario where an assembly station is fed with materials by use of kits and small stock keeping units replenished by Kanban. Kanban parts are

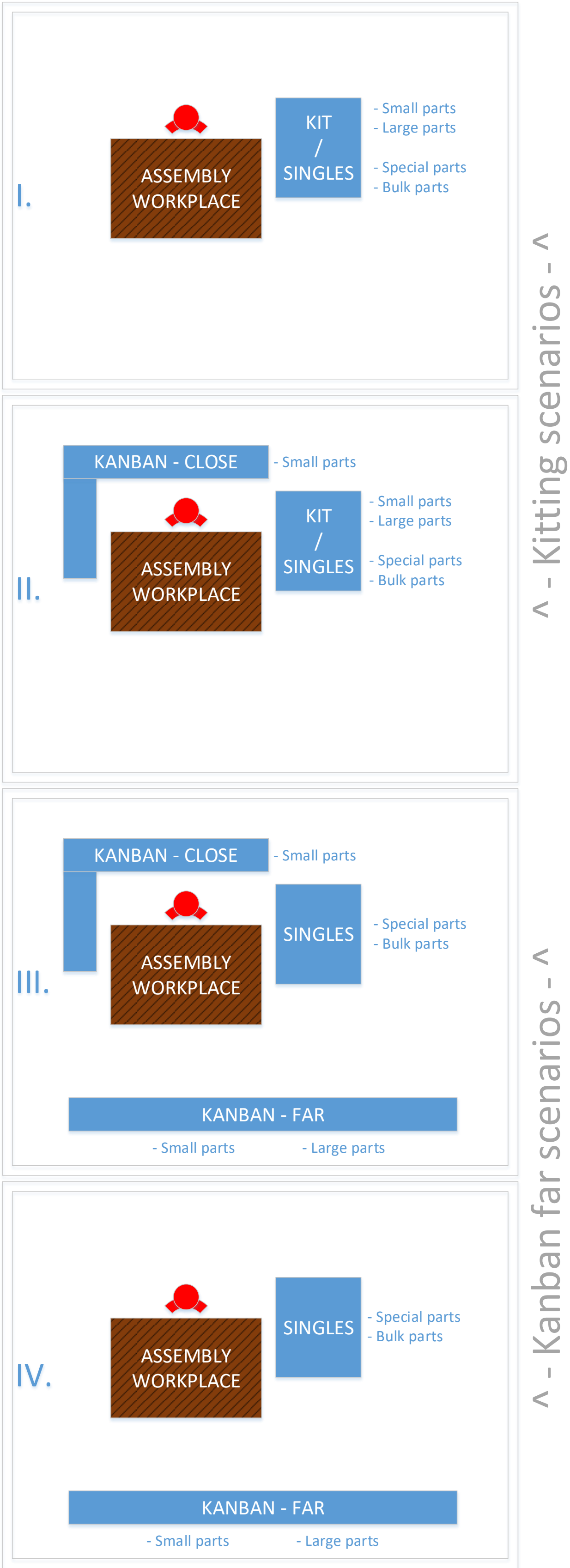


Figure 4 Layout scenarios with given availability of part type placement per material feeding principle

positioned close to the workplace. Since small parts may be placed in Kanban close and in kit, a guideline is needed based on part characteristics in order to assign their best possible location. Single items are delivered per piece/crate with the same distance towards the assembly workplace as kits.

III. The third scenario shows the scenario where an assembly station is fed with materials by use of a large Kanban space, positioned further away from the workplace and small stock keeping units replenished by Kanban. These small parts can be positioned close to the workplace. Since small parts may be placed in Kanban close and in Kanban far, a guideline is needed based on part characteristics in order to assign their best possible location. Single items are delivered per piece/crate and are positioned with the same distance towards the assembly workplace as kits would be in scenarios I or II.

IV. The fourth scenario shows the scenario where an assembly station is fed with materials by use of a large Kanban space positioned further away from the workplace. Single items are delivered per piece/crate with the same distance towards the assembly workplace as kits would be in scenarios I or II.

Introduction of these four scenarios will contribute to understanding and, later on, choosing for line or dock assembly. Scenarios I and IV represent the clear difference of kit versus Kanban replenishment. If a subassembly is best made from kit(s) then scenario I is applicable as assembly layout. When a product or subassembly is best made from Kanban far then scenario IV is applicable as assembly layout. So the rough choice will be between scenarios I (dock) or IV (line) at Dewulf. However, each assembly contains small parts and singles. Thus on choice of scenario I, the final layout of the station will most likely resemble scenario II and if scenario IV is appropriate, resemblance with scenario III will occur.

In figure 5 the difference of line versus dock assembly is given in a simple schematic illustration. For an amount of assembly tasks line assembly can be used to execute the tasks divided over different stations. Each station has assigned tasks and stock alongside the line in Kanban far. Since the tasks are split up, the amount of Kanban space in Kanban far per station can be relatively large. When dock assembly is used for the same amount of tasks, all the tasks are executed at one dock. That one dock has relatively little space for the usage of Kanban. This shows dock assembly suits scenarios I and II with Kit replenishment best and vice versa. In similar manner, line assembly suits scenario III and IV with Kanban far replenishment best and vice versa. Nevertheless, this does not mean that line and dock assembly need to be fed by one type of material feeding principle. Or even Kanban usage in a dock assembly. A hybrid composition per assembly can also be the better configuration. Cost of replenishment per product or subassembly determine the best layout.

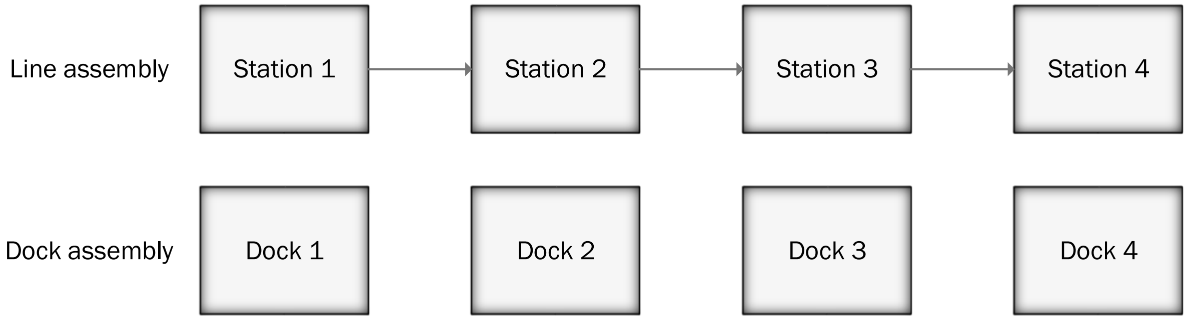


FIGURE 5 LINE VERSUS DOCK ASSEMBLY

More on the theoretical advantages and limitations of the use of line and dock assembly is described in chapter 3, the literature review.

2.3 Products

The products which are made at Dewulf in Belgium are, as described in chapter 1, crop harvesting machines. These products can be divided into two groups, the ones that are assembled in a line and the ones that are assembled in dock(s).

2.3.1 Assembly in line

There are only two types of machines assembled in line. These machines are the "Kwatro" and "3060" self-propelled potato harvesters. These machines demand a lot of hours in assembly paired with a relatively high yearly customer demand.

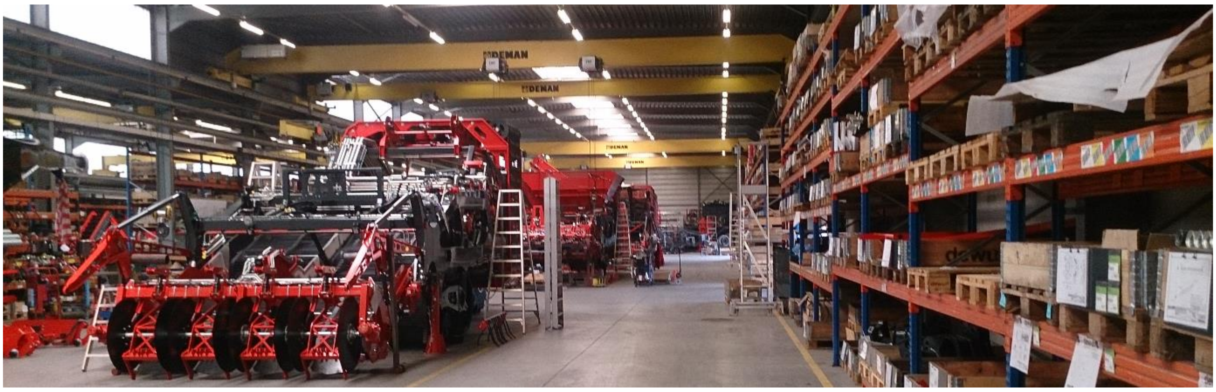


FIGURE 6 PART OF THE KWATRO ASSEMBLY LINE

The Kwatro is a harvester which harvests four rows of potatoes over a width of three meters. This machine is the biggest product made by Dewulf and it is at least 14 meters long. The space in line is large in terms of assembly space and therefore Kanban space. The Kwatro consists of a large amount of subassemblies which are divided over five stations. There is relatively much space around the assembly stations and therefore some pre-assemblies are executed alongside the line. The variation in product variants and options is attributable to relatively small parts. The Kanban far locations are placed against the wall which is practical in terms of space but not in terms of placement and picking. The large parts are not picked easily or fast.

The 3060 is a harvester which harvests two rows of potatoes over a width of one and a half meters. This machine is around 13 meters long. Subassemblies are divided over 4 or 5 stations depending on the current demand. The space in line in terms of assembly space is compared to the Kwatro a lot smaller and there is no direct space left for pre-assemblies. The variation in product variants and options is attributable to relatively large parts as opposed to the variation of the Kwatro. The Kanban locations are also placed somewhat closer towards assembly. However, there is less space to replenish these locations. Figure 7 shows a 3060 harvester.

FIGURE 7 DEWULF 3060 SELF-PROPELLED POTATO HARVESTER

2.3.2 Assembly in dock

All machines, except the Kwatro and 3060, are trailed potato harvesters, different types of carrot harvesters and other specific crop harvesters that are made in an assembly dock. This is mainly due to the demand and time to assemble per type of machine, which is relatively low in terms of Dewulf machinery. Moreover the variation is large in these machine models, which does not suit line assembly.

The assembly docks are currently using Kanban for a great share of the needed parts. The Kanban parts are used by a few types of models, which justifies their placement. Although the supported interpretation of dock assembly, in section 2.2, states that dock is most likely to be fed by use of kitting. A picture of a dock assembly station of a carrot harvester is shown in figure 8. There are some Kanban locations visible and in front of the picture a subassembly is taking up space.

As stated, these machine models have relatively low yearly demand and a high part variety. All Dewulf machinery can be seen as complex in terms of the amount of parts per machine. Eventually all machine models, including the 3060 and Kwatro, are low volume and high variety if compared to a sector like the automotive industry.

FIGURE 8 CARROT HARVESTER ASSEMBLY DOCK

2.4 Future changes

In the nearby future, timespan of approximately one year, a new warehouse will be in use close to the production site in Roeselare. Currently 5 kilometres from the production site a warehouse location is rented. In the future setting, parts can be delivered more efficiently due to the closeness and technology of the new warehouse. Besides this change of warehouse location, the flow of parts and subassemblies will be changed. Moreover, most of the pre-assembly and final assembly positions change. This choice of Pre-assembly (4) and Final assembly (5) areas comes with a certain available space. A layout plan of the future production facility in Belgium is drawn schematically in figure 9.

In the new setting Pre-assembly (4) and Final assembly (5) are split up in two areas. However, the choice of line or dock assembly can be made for both processes. Thus the consideration of dock versus line is made for the Pre-assembly (4) area and Final assembly (5) area in this research. Pre-assembly docks can feed Final assembly docks, Pre-assembly docks can feed Final assembly lines, Pre-assembly lines can feed Final assembly docks and Pre-assembly lines can feed Final assembly lines. Available and unavailable information of these changes are also described in section 2.5.

FIGURE 9 FUTURE PRODUCTION FACILITY PLAN WITH POSSIBLE PART FLOWS

In figure 10 the intended framework of the preferred material handling steps is visualised. Each step visualised by an orange box represents a handling operation which obviously costs time. Different steps of kit or Kanban usage are noticeable. Although, there can also be some differences in picking, transporting and placing times between the same steps. These steps are then influenced by the variables, and part and subassembly characteristics.

First the right picking costs are based on the part characteristics. Then the preparation and placement of (kit) pallet costs are determined. Transport distance, and thus travel time, is depended on the final destination and the part finish. When Kanban (far) is used, additional picking cost in assembly are apparent.

Using Kanban should lead to less travelling in Warehouse (1). As every part type does not need replenishment when a new machine is ordered. When kit replenishment is cheaper, the best feeding principle is obviously kit and therefore the assembly layout will most likely resemble an assembly dock. The other way around will most likely resemble an assembly line.

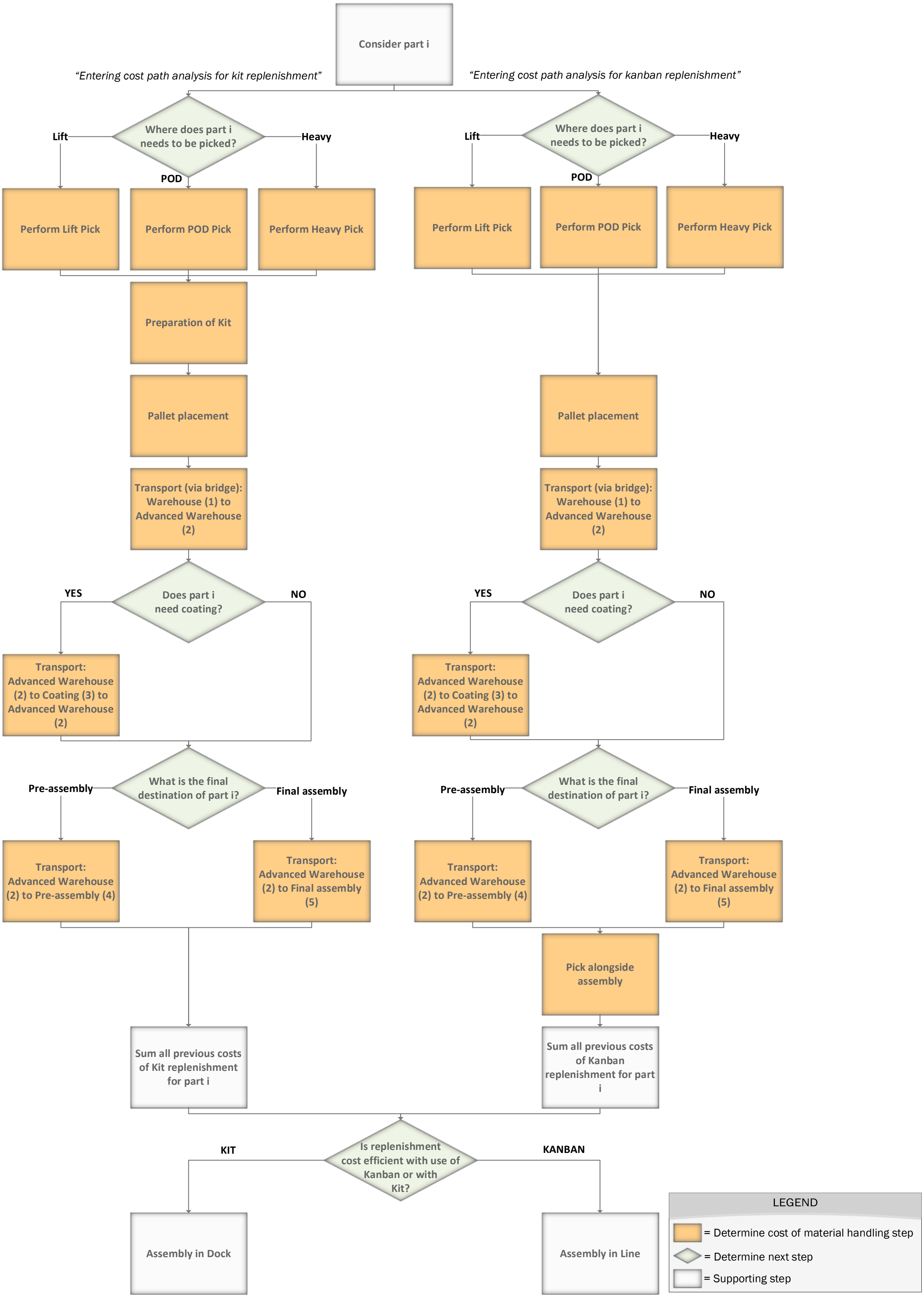


FIGURE 10 COST DECISION OF KIT VERSUS KANBAN BASED ON THE RESPECTIVE FLOW

2.4.1 Warehouse (1)

In the new Warehouse (1) three different part types can be identified. Heavy parts, POD (Picking On Demand) parts and lift parts. These parts have their own zones. Heavy pick, POD pick and lift pick area. Originally, in the “old” warehouse there was also a division of parts, but this change has already been put into motion. Thus the old setting is irrelevant for this research. In figure 11 a simple schematic visualisation is given of the fact that picks from the three picking areas are consolidated central in the warehouse. After consolidation the parts can be transported to the Advanced warehouse (2).

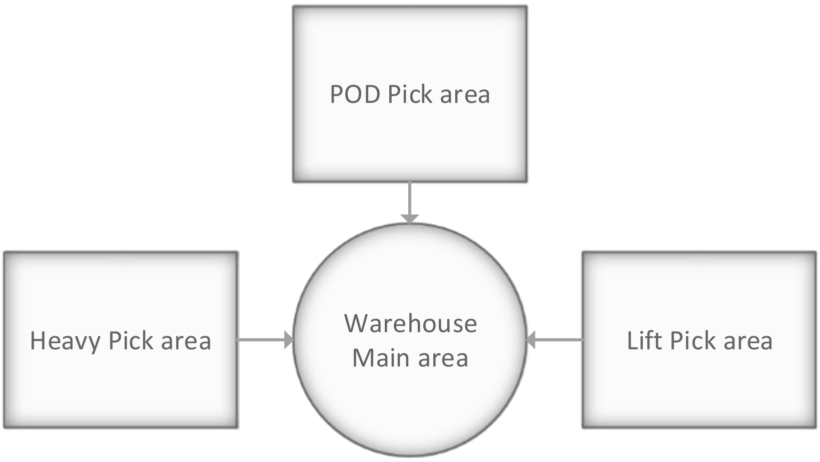


FIGURE 11 PICK AREAS

The lift pick parts are placed in one of the eight vertical lifts which can facilitate storage of a lot of (small) parts in a few square meters of floor space. Thereby, a lot of parts can be presented to the picker by use of this ingenious lift system. The parts are picked from bins and put into other bins on a picker cart. This cart, when full, is transported by the picker to the main area of the Warehouse (1). The parts need to fit in a bin in order to be appropriate for these lifts. Figure 12 shows the future layout of eight lift modules along one aisle.

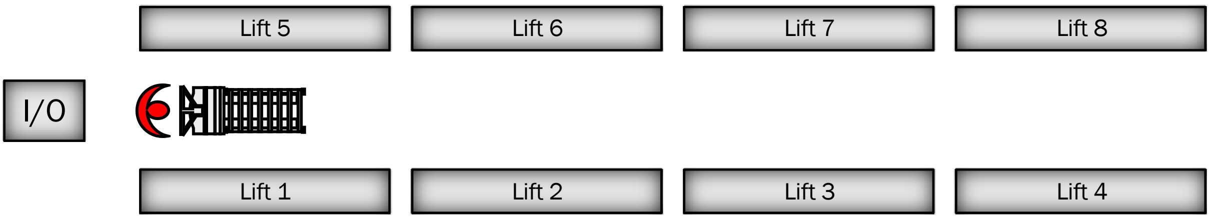
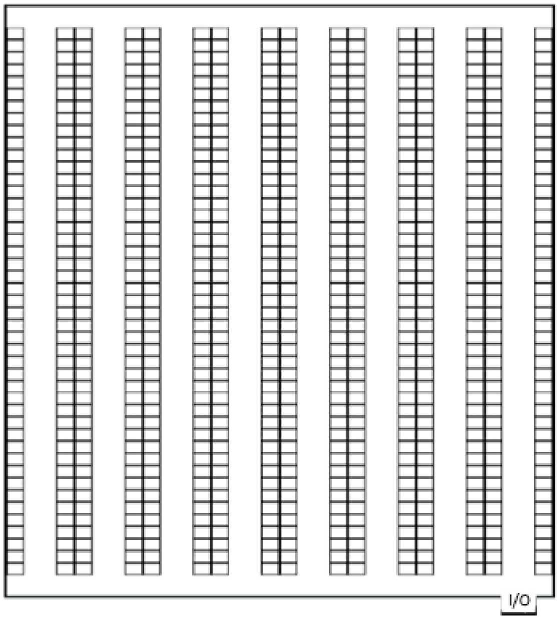


FIGURE 12 LIFT PICK AREA LAYOUT PLAN



The POD pick parts are placed on pallets and are put away into racks. These racks are placed along 8 aisles. The picker will make a milk run through the aisles gathering parts in the POD pick zone. This picking activity also ends in the main area of the Warehouse (1). The parts which are appropriate for this POD zone fit on a pallet (or large bins on a pallet), are not too heavy for manual handling or are small parts that have a high demand. That last group of small parts is not placed in lift because of that high demand. Picking a large quantity from POD is then assumed to be more efficient. Figure 13 represents a visualisation of the POD pick area.

FIGURE 13 POD PICK AREA LAYOUT PLAN

The heavy pick parts are placed on pallets or different carrying objects. These parts are heavy, large or heavy and large and are therefore not picked easily. All parts are placed on floor level, which means no stacking. The parts can be picked, and placed on a pallet lift truck, by use of an overhead crane. After picking, the parts also end up in the main area of the Warehouse (1). Figure 14 visualises the future layout of two rows of heavy part storage. Due to the alignment in two rows, like the lift pick area, picking is done along one aisle. The yellow object symbolises an overhead crane.

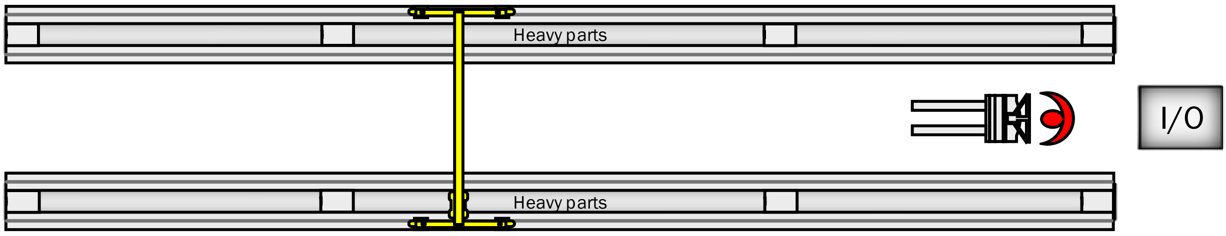


FIGURE 14 HEAVY PICK AREA LAYOUT PLAN

Besides these three picking zones, some space will be allocated to items with a high demand. This can be applicable to all types of parts, but this is not yet determined and designed. So this will not be included in the research.

When picking is done, another employee will place the parts on a pallet and will take the gathered parts towards the Advanced warehouse (2) by use of a forklift. To get to the advanced warehouse the forklift can travel through a bridge over the road. On the Advanced warehouse (2) side there is a lift to accommodate the height difference from the bridge and the shop floor.

2.4.2 Advanced warehouse (2)

An Advanced warehouse (2) is established as decoupling point of the Warehouse (1). From here parts will be transported to Coating (3), Pre-assembly (4) or Final assembly (5). All parts will be placed on floor level.

Currently the assembly line of 3060 harvesters and some pre-assemblies are situated in this area.

2.4.3 Hal 08. Coating (3)

This area will remain as it currently is. Coating of parts will still be done here. The only difference is the flow of parts. If a lot of kits are recommended, the sequence of parts in coating will be different. However, the main difference will be storage of the finished parts. Transportation of finished parts back to Advanced warehouse (2) should directly be initiated. As opposed to decoupling coated parts from the coating area itself. This often leads to parts eating up the already limited space while waiting for transport.

2.4.4 Hal 04. Pre-assembly (4)

In this area all pre-assemblies will be assembled. Finished assemblies will eventually move to the final assembly in Hal 02.

Currently a few assembly docks and some pre-assemblies are situated in this area. The Kanban locations hold parts for the docks, but also for the 3060 assembly line. Moreover, different pre-assemblies are now built in over five different areas.

2.4.5 Hal 02. Final assembly (5)

All final assembly activities are situated in this area. This assembly area is fed by pre-assemblies and other parts. These other parts facilitate assembly of pre-assemblies on the machines or can only be fitted on the machines when certain pre-assemblies are attached to it.

Currently the Kwatro assembly line, some assembly docks, machining and welding is situated in this area. In the future, machining and welding will be done at another location.

2.5 Data availability

The perception of line and dock, part and product characteristics, and the new layout plan determine what information is needed for this research. Some of this information is available and some is not (yet) available.

2.5.1 Available

All available information is described in the following enumeration.

1. For each machine there is a BOM (Bill of Materials) list available. This list incorporates each part of a machine and in what level of the machine this part is needed. To make this BOM useful, data from the used ERP (Enterprise Resource Planning system) can be linked to each part. Data which can be linked is:
   - Quantity per machine.
   - Size per part.
   - Weight per part.
   - Required final finish per part.
   - The type of demand group (example: Kanban).

1	Number	Name	Quantity
2	958102850	EGELBAND ONDER RA	1
3	0021020	BOLT M10X20 DIN933 8.8 G	2
4	85812207	CLEVIS PIN M D30JS9X135	2
5	70315096	CLEVIS PLATE M D30	1
6	0000017751	SHAFT D30H9X147	1
7	958101800	EGELBAND ONDER	1
8	958101783	AANDRIJVING EGELBAND	1
9	958101782	AANDRIJFAS EGELBAND	1
10	7023055	AANBOUTFLENS D180 D40 B	2

FIGURE 15 BOM EXAMPLE

A part of a BOM is partially shown in figure 15. The different levels in a BOM for every part can be seen by the offset in column one.

2. Appliances, like pallets and bins, are used to stock and transport parts. The measures, and therefore their stock and transport capacity, are known. A list of appliances is visualised in appendix A.

3. The future changes, as mentioned in section 2.4, describe a layout plan. This layout plan and production halls are known, therefore the available space for the assembly areas is known. The assembly areas will be reorganised, but the dimensions of the halls will not change.

4. Estimates of assembly times of total machines are known. These give an indication of the high variation in the actual end products. The amount of assembly hours per type of machine and machine model vary greatly.

5. The seasonality of demand over the year is known. Every year there is a peak of demand during four months. To cope with this demand every employee fulfils extra working hours during the high season. A visualisation of demand pattern is shown in appendix B.

2.5.2 Unavailable

As described earlier there is information which is not (yet) available. This shortage of data is resolved by calculations, estimations, assumptions and measurements. In the below enumerations the relevant missing data are mentioned.

1. All parts need to be picked in Warehouse (1), where the picking times depend on their storage location. All parts are consolidated in the main area of the Warehouse (1) and are placed in either the heavy, POD or lift area. The placement of the parts depend on their size, weight and demand. After the picking process the parts need to travel towards Advanced warehouse (2). The following data are missing and have to be resolved:
    - Picking times of lift, POD and heavy parts.
    - Average distance of Warehouse (1) to Advanced warehouse (2), including lift time of bridge level to the floor level of Advanced warehouse (2).

2. In Advanced Warehouse (2) parts are temporarily placed till transport is continued. The parts are placed on the floor, minimising or exterminating picking time. When transport will be continued, parts will move to Pre-assembly (4), Final assembly (5) or first back and forth to Coating (3). The following data are missing and have to be resolved:

- Average distances of Advanced warehouse (2) to Hal 08. Coating (3), to Hal 04. Pre-assembly (4) and to Hal 02. Final assembly (5).

3. There is also data unknown regarding general purposes. Transporting issues and the choice of parts for consideration of a feeding principle. The parts to be considered need be filtered from BOM. The following data are missing and have to be resolved:
   - Average speed of the transporting vehicle (forklift truck).
   - Amount of empty travels per loaded travel.
   - Parts to consider based on certain characteristics.
4. Specifically for kit replenishment the time to prepare a kit and the amount of parts per kit needs to be known. The following data are missing and have to be resolved:
   - Preparation time needed per kit.
   - The kit sizes to consider.
5. Specifically for Kanban replenishment picking, placement and the quantity on a location of a part needs to be known. Kanban replenishment quantities from the current situation cannot be used when changes, as described in section 2.4, are being made. The following data are missing and have to be resolved:
   - Kanban picking time at assembly.
   - Kanban placement time.
   - Kanban quantities.

2.6 Conclusion

This chapter is concluded with an answer on the first research question. The first research question reads as follows:

What is the current situation at the Dewulf with respect to products, their characteristics, their allocated assembly layout and feeding principles?

At Dewulf line stocking in combination with Kanban replenishment is mostly used to feed materials to assembly. A respectively small amount of replenishments is done by use of kitting, namely for some relatively small assemblies. Four scenarios are introduced to explain layout differences according to Dewulf. Two scenarios, 1 and 4, respectively lead to assembly in dock or assembly in line. While the other two scenarios, 2 and 3, respectively lead to a hybrid feeding mode within a dock or line assembly station. The products made are crop harvesters which consume a lot of space in assembly. Variety of parts within and between these machines is high while the demand per different machine model is relatively low. To accommodate assembly of this wide variety a lot of machine models are made in dock and only two machine types are made in an assembly line. These two machines have a relatively high demand, in terms of Dewulf machinery. The current situation will be changed towards a clear division on pre-assembly and final assembly. Moreover a new warehouse will deliver parts via an established advanced warehouse area. Mainly characteristics of machines and their parts can be considered as available data. The amount of unavailable data is enumerated and is overcome by use of calculations, estimations, assumptions and measurements.

3. Literature review

This chapter describes the existing literature relevant to answering the second and third research question. The goal is to find a foundation for the built of a decision rule.

In the first section, 3.1, the existing and appropriate material feeding principles are discussed. First an introduction with qualitative advantages and limitations is described. Followed by a selection of quantitative models for the consideration of these principles. Then section 3.2 with elaborates on different assembly layouts. The qualitative advantages and limitations of the different assembly layouts are followed by the existing quantitative models. As a result, section 3.3 concludes this chapter with answering the second and third research question.

3.1 Material feeding principles

As already introduced in chapter 2 Kanban replenishment can be used as a control mechanism of stocking parts in an assembly area. Kit replenishment is a counterpart of continuous supply and has many advantages. But when is kit replenishment better than continuous supply, and vice versa?

According to literature line stocking, also described as continuous supply, is used most in assembly industries (Bozer & McGinnis, 1992; Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012). However, when exploring the literature, the amount of papers stating its advantages towards kitting is limited as opposed to the widely mentioned positive research on the advantages of kitting. This trend of kitting is gaining interest, while Hua and Johnson (2010) state that the computational proof often stays behind. Although Bozer & McGinnis (1992) and Limère et al. (2012) describe models to find a cost difference by use of a case. An optimal allocation of a relatively small problem can even be found on part level (Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012).

As a side note of this literature review, sequential supply/sequencing is also described as a counterpart of the already mentioned feeding principles. This is more or less a variant on line stocking, but replenishment is done in small timed quantities which resembles kit replenishment. Sequential supply focusses on the right timing and sequence of a selection of parts to assembly. All parts in assembly are presented in the sequence of their consumption (Sali, Sahin, & Patchong, 2015). Moreover it is seen as appropriate for a need of small amounts of the same components at a station (Johansson & Johansson, 2006). This selection of parts does not necessarily form a complete kit for a whole assembly operation and timing of parts to assembly is mentioned as not within the scope of this research. Therefore the research of feeding principles is only on line stocking with use of Kanban replenishments and on kit replenishments.

3.1.1 Line stocking with Kanban replenishment

As stated above, line stocking is still most often used in assembly line production. All parts, and their variants, are stored in containers/boxes near the assembly area. For every part variant there is an individual container (Sali & Sahin, 2016). The replenishment of this stock alongside assembly is usually triggered by use of a Kanban signal card. When a Kanban stock location contains less than a determined minimum level, the Kanban card is removed to signal the replenishment activity. Since the introduction of Kanban systems, Kanban has made a good team with line stocking (Sali, Sahin, & Patchong, 2015).

According to Akturk and Erhun (1999) Kanban systems are effective for limiting the amount of inventories at the production floor. It is a manual method to harmoniously control production in a rather simple manner (Akturk & Erhun, 1999). When using line stocking no extra material handling activities are needed. However the presentation of part variants near assembly consumes relatively much space, could lead to a rise in inventory costs and assemblers need to pick and search for the needed parts (Karlsson & Svanström, 2016). It is said to be difficult to apply line stocking at mixed-model assembly lines (Usta, Oksuz, & Durmusoglu, 2017). Kanban replenishment systems would only perform well in firms which have a production sequence which is highly repetitive, stable and where product variety is low (Sellers & Nof, 1986; Hua & Johnson, 2010). Especially small batch and Make-to-Order production environments are often not appropriate (Zijm, 2000; Sendil Kumar & Panneerselvam, 2007).

Demand of product variety is increasing and therefore causes for a lot of space along assembly when line stocking is used. However, Neumann and Medbo (2010) state that line presentation can be reduced by use of a narrow bin layout, see figure 16 below. This would lead to better performance at the line with regard to required space, walking distance and a decreased cycle time (Neumann & Medbo, 2010). Part 16.A of figure 16 represents a front side view of the presentation of big boxes with large quantities of parts along assembly. Part 16.B represents a presentation of small bins which contain the same part types as 16.A does, but the quantities are smaller. The big box layout has resemblance to a Kanban far presentation, while a narrow bin layout has resemblance to a Kanban close presentation.

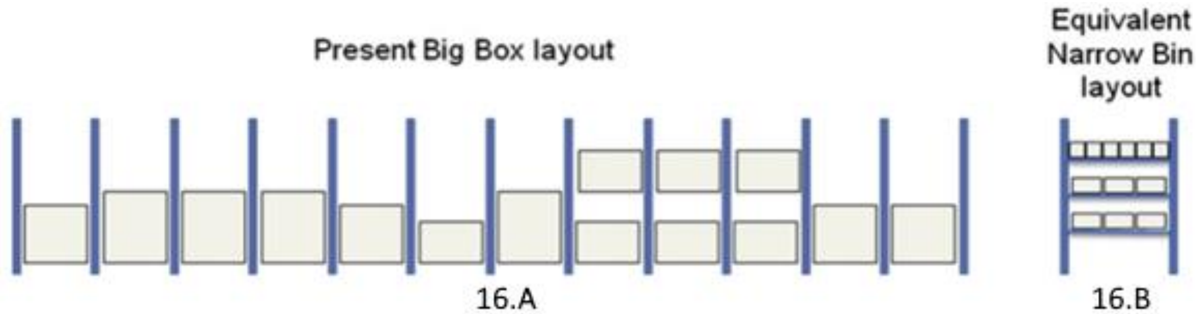


FIGURE 16 BIG BOX LAYOUT (16.A) VERSUS NARROW BIN LAYOUT (16.B) (NEUMANN & MEDBO, 2010)

Besides these reasons for and against line stocking and or Kanban replenishment, qualitative advantages and limitations are mentioned in literature. These qualitative judgements are described in the below enumerations.

Advantages of line stocking with Kanban replenishment

1. A clear overview of facts considering production, like production capacity, without computerised help (Sugimori, Kusunoki, Cho, & Uchikawa, 1977; Akturk & Erhun, 1999; Faccio, Gamberi, & Persona, 2013).
2. Safety stock can be minimised. Especially when assembly in a linear fashion is normally plagued with inconsistent patterns of demand further towards the end of the line (Sugimori, Kusunoki, Cho, & Uchikawa, 1977; Faccio, Gamberi, & Persona, 2013).
3. Additional material handling is not needed (Usta, Oksuz, & Durmusoglu, 2017). At least, when no repacking or downsizing is done.
4. Reduction in costs associated with information and real-time control can be achieved, especially for relatively cheap and low turning items (Sugimori, Kusunoki, Cho, & Uchikawa, 1977; Faccio, Gamberi, & Persona, 2013).
5. Practical way of pulling parts (Ding, 1992). Inventory is replenished without complex control methods.
6. Parts are continuously available at the assembly station (Bozer & McGinnis, 1992).

Limitations of line stocking with Kanban replenishment

1. Assembly operators need to walk large distances when gathering parts (Bozer & McGinnis, 1992; Limère, 2011), especially in high variety production environments.
2. Searching for parts in the assembly facility consumes time, which can be seen as nonvalue adding (Limère, 2011).
3. Cycle times tend to be longer, because the parts are waiting longer before their actual consumption (Limère, 2011).
4. Large containers with large parts have a negative impact on handling (in terms of ergonomics) (Limère, 2011).
5. Inventory level along assembly can be too large and can consume lots of space (Limère, 2011). This is especially the case in companies with products of high variation and low volume.
6. Assembly requires a great amount of inventory space to store all (variants of) parts (Bozer & McGinnis, 1992; Limère, 2011).
7. The internal transport processes can be inefficient. Individual container replenishments need to be pooled with other replenishments to gain an economies of scale solution (Limère, 2011).
8. When using stock at line, with use of Kanban, assemblers tend to optimise locally (Carlsson & Hensvold, 2008). More small assembly operations are executed than needed, so the extra assembled parts are placed back in stock. Leading to double handling of parts and extra stock at line, as some parts are consumed before an order is confirmed.
9. A lot of capital is tied up to stock held on the floor (Bozer & McGinnis, 1992). Typically stock is available in large quantities in assembly, but also in warehouse.

3.1.2 Kit replenishment

Over the past decades customers request more and more variation in product assortment. This leads to an increasing amount of different parts needed on the shop floor. This trend causes for a step towards the use of kitting (De Cuypere, De Turck, & Fiems, 2013).

A kitting operation entails the collection of necessary parts for one individual end product. Collection is done in a suitable container and executed before the actual replenishment at assembly. This assortment of parts in a container is called a kit (Bozer & McGinnis, 1992; De Cuypere, De Turck, & Fiems, 2013). Kitting can be seen as a possible strategy for feeding materials to assembly. Instead of delivering part specific containers to assembly, with a determined amount of the same parts, kitting delivers a specific kit container with all necessary parts for assembly of one end product (Bozer & McGinnis, 1992; Som, Wilhelm, & Disney, 1994; Brynzér & Johansson, 1995; Medbo, 2003; Ramachandran & Delen, 2005; Ramakrishnan & Krishnamurthy, 2008).

Sometimes two types of kitting are mentioned in literature. Travelling and stationary kits. A travelling kit moves, with the product, from station to station. After feeding multiple stations the kit will be fully consumed. A stationary kit is placed at one station and will remain in the same position till it is fully consumed (Bozer & McGinnis, 1992).

Kit replenishment is often chosen when product variety is large, the space on the assembly floor is limited and production volumes are low (Sellers & Nof, 1986; Hua & Johnson, 2010). The common considerations for choosing kit replenishment are according to Ding (1992) part sizes, lot sizes and kit sizes. In the metal industry parts are often heavy and unwieldly and the lot sizes can be small. This often leads to kit replenishment for parts that fit the kit, but an alternative approach for extraordinary parts (Ding, 1992). When considering manual assembly, gathering parts can take up a great share of the available assembly time. Although this is greatly correlated with the presentation and location of parts to pick (Hanson, Medbo, & Medbo, 2012). Johansson & Johansson (2006) mention that kit replenishment is less advantageous when used in assembly lines and when only a few components per assembly station are needed.

However besides these reasons for and against kitting, qualitative advantages and limitations of kit replenishment are widely mentioned in literature. These qualitative judgements are described in the below enumerations.

Advantages of kit replenishment

1. Space is saved in the assembly area and work-in-process inventory at workstations is reduced. Most parts and subassemblies stay in warehouse till demand is confirmed by an order (Bozer & McGinnis, 1992; Medbo, 2003; Hua & Johnson, 2010).
2. The assembly area stays more organised and free of unnecessary parts (Schwind, 1992; Bozer & McGinnis, 1992; Medbo, 2003; Usta, Oksuz, & Durmusoglu, 2017).
3. Product changeovers are easily realised because the majority of parts and subassemblies are not in stored at the assembly stations (Bozer & McGinnis, 1992).
4. High flexibility and control is reached. Only a kit has to be guided to assembly as opposed to the guidance of multiple part types to multiple assembly locations (Bozer & McGinnis, 1992; Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012). The flow of parts can therefore be seen as more visible and transparent (Sellers & Nof, 1986; Ding, 1992). Especially on parts which are costly and/or perishable (Bozer & McGinnis, 1992; Schwind, 1992).
5. Material delivery to assembly stations is facilitated by means of abolishing the supply of individual part locations (Bozer & McGinnis, 1992).
6. Product quality and assembly station productivity potentially increase. Needed parts are easily accessible and available for the assembler (Bozer & McGinnis, 1992).
7. Small quantity operations with high variety are facilitated with ease (Bozer & McGinnis, 1992).
8. Due to the choice of fixation of individual parts in a kit, robotic handling can be accommodated (Bozer & McGinnis, 1992).
9. Material handling (time) will overall be reduced (Sellers & Nof, 1986; Ding, 1992; Johansson & Johansson, 1990; Medbo, 2003; Ramakrishnan & Krishnamurthy, 2008).
10. Time to search for parts in assembly will be eliminated (Ding, 1992; Medbo, 2003; Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012).
11. Better control over work-in-process (Usta, Oksuz, & Durmusoglu, 2017). The number of existing kits determines the work-in-process level (Ding, 1992). Shorter lead times can be achieved (Medbo, 2003).
12. Kitting obliges the use of the latest version of BOM (Schwind, 1992).
13. Assembly from kit is easier to learn for (new) personnel (Medbo, 2003).
14. Pushing kits to assembly functions as a work instruction for the assembler. A kit can simplify assembly of a complex product (Medbo, 2003).
15. Missing parts in a kit are easily noticed in the preparation process or when delivered at assembly (Schwind, 1992).
16. Walking and picking time of assemblers will be reduced drastically (Johansson & Johansson, 1990), due to a more condensed part storage along the assembly line (Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012).
17. Working conditions of assembly operators are improved (Hua & Johnson, 2010; Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012).

Limitations of kit replenishment

1. Assembly of the kits itself can be seen as an extra handling activity (Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012). This preparation of a kit consumes time and effort while it cannot directly be seen as a value adding activity (Bozer & McGinnis, 1992; Limère, 2011; De Cuypere, De Turck, & Fiems, 2013). Although the kitting activity can be seen as value-adding with respect to potential improvement for the assembler (Öjmertz, 1998).
2. Due to the kit preparation process the probability of damaging parts while handling may increase. Some parts may be fragile. Not all parts are therefore suitable for kit (Bozer & McGinnis, 1992; Johansson & Johansson, 2006; Limère, 2011).
3. Storage space in warehouse may increase (Limère, 2011), especially when kits are made before an order is confirmed (Bozer & McGinnis, 1992).
4. Assignment of (on-hand) parts to a kit requires additional planning (Limère, 2011), especially when the kit contains multiple common parts (Bozer & McGinnis, 1992; De Cuypere, De Turck, & Fiems, 2013).
5. Temporarily shortage of kit parts may result in kitting an incomplete kit. This leads to a reduction of efficiency of the operation. More handlings and therefore time is needed (Bozer & McGinnis, 1992; Ronen, 1992; Limère, 2011; Caputo, Pelagagge, & Salini, Modeling Errors in Kitting Processes for Assembly Lines Feeding, 2015).
6. Kitting of defect parts which are repeatedly used in kit lead to part shortage and inefficiency at assembly. Already made “defective” kits also need to be reassembled (Bozer & McGinnis, 1992; Caputo, Pelagagge, & Salini, 2015).
7. Parts prone to failure during assembly require a special treatment in kit. One may consider providing spare pieces of that part to the kit or at assembly to accommodate for the possible failure (Bozer & McGinnis, 1992).
8. Shortages of parts can lead to removing that parts from already prepared kits. This will also lead to double handling and will make the shortage even bigger (Bozer & McGinnis, 1992; Limère, 2011).
9. Not all parts fit on a kit, mostly due to size (Bozer & McGinnis, 1992; Ding, 1992).
10. Working conditions are worse since work has a tendency to become more monotonous (Carlsson & Hensvold, 2008).
11. If the production schedule changes, while the kit is already present in assembly, the whole kit needs to be removed or it will unnecessarily consume space (Limère, 2011).
12. The sequence of production needs to be clear to deliver the right kit to the right assembly station (Limère, 2011).

3.1.3 Quantitative models

In literature multiple articles are dedicated to calculating the cost incurred with the used material feeding principles. Algorithms are proposed for the cost for picking, in-plant transport, picking in assembly and preparation (Sali, Sahin, & Patchong, 2015). With these algorithms models or cost formulations are made to calculate and find the most appropriate feeding principle.

Sali et al. (2015) describe an overview of reviewed papers which are dedicated to the comparison of line feeding principles. This comparison is partly used and adjusted for this research, and shown in table 1. Used papers for the comparison are available quantitative research papers which compare line stocking with kit replenishment and use time consumption and space requirement as comparison criteria’s.

Paper	Modelling method (sequence)	Comparison criteria
Bozer & McGinnis (1992)	- Cost formulation - Trade-off	- Time consumption - Space requirement

		- Work-in-process
Caputo, Pelaggage & Salini (2008)	- Cost formulation - Linear programming model	- Time consumption - Space requirement - Work-in-process
Limère et al. (2012)	▪ Cost formulation ▪ Linear programming model	▪ Time consumption ▪ Space requirement
Sali & Sahin (2016)	▪ Cost formulation ▪ Linear programming model	▪ Time consumption ▪ Space requirement

TABLE 1 QUANTITATIVE RESEARCH PAPER COMPARISON

Bozer and McGinnis (1992) have made, the first quantitative research on, a comparison of kitting modes versus line stocking. This is done by use of a descriptive model. A descriptive model depicts which quantities or values can be compared, while the actual weight of each of these values is not determined. The compromises for time consumption due to material handling, the required space in assembly and work-in-process between kit replenishment and line stocking are presented. The resulting compromises of stationary kits versus line stocking of the used numerical example are visualised in figure 17. Kitting is ought to be in favour regarding container flow, required space and the average work-in-process. Line stocking ought to be in favour regarding the amount of storage and retrieval operations. Missing in this research is the impact of the picking activity. Sali et al. (2015) state that this may result in significant differences. Besides that, the used case is supplemented by some noteworthy assumptions of part characteristics and size of kit and line stock containers. Part size and weight can make a difference in how appropriate a feeding principle is. The proposed trade-offs are made on a comparison of pure policies.

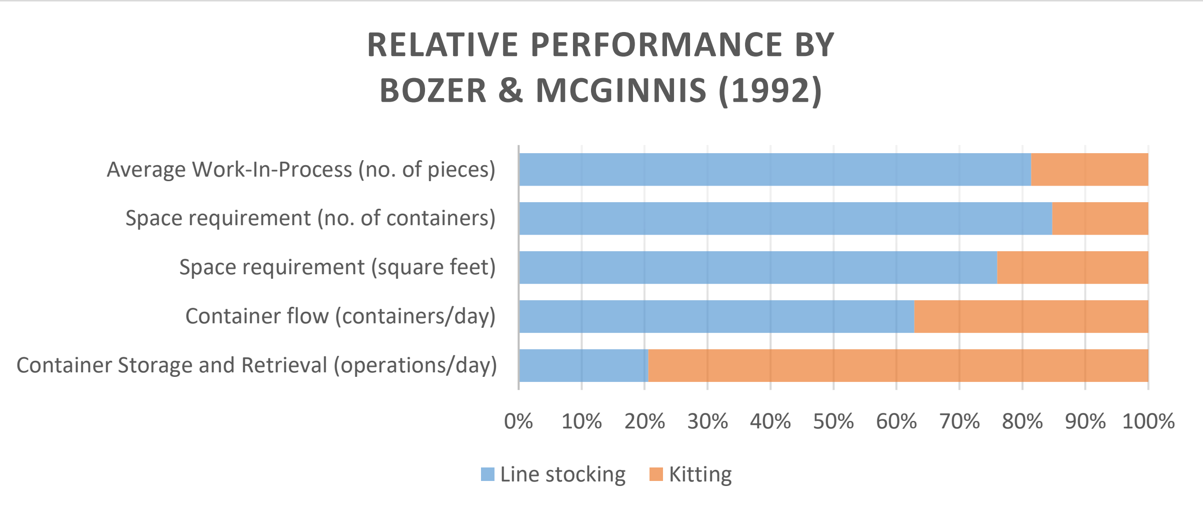


FIGURE 17 LINE STOCKING VERSUS KITTING: TRADE-OFF RESULTS

Caputo et al. (2008) describe a comparison of line stocking versus kit replenishment with travelling kits. First cost formulations for work-in-process, space occupation and material handling are proposed. Assumed that all stock is stored at the border of assembly for a single model (without variant parts) in case of line stocking. Space occupied by kits at the shop floor is neglected. As main result a hybrid policy will lead to the best results. The hybrid solution for the used case is two times better than an all kitting solution, which is the second best solution, in terms of costs. The hybrid solution is a division of material modes on part level.

Limère et al. (2012) have made, like Bozer and McGinnis (1992), a comparison of line stocking versus stationary kit replenishment. Their aim is to find the optimal solution when all variables are translated to labour cost. The formulations of costs are dedicated to picking at the border of the assembly line, kit assembly, transport and replenishment of the preparation area. When infinite space is available in assembly, a pure line stocking solution is the best approach regarding time cost reduction. However when a space constraint is added, the optimal solution leads to a hybrid solution with kitting and line stocking. It can be concluded that there are some cases where kit is less time costly than line stocking. The effect of kitting on the total time cost is seen in figure 18. In this graph the total time cost is only slightly increasing as the percentage of kitting increases. However this is until a certain point when 75% is already in kit. This slight increase is most probably attributable to "free riding" of parts when additional kits are added. When a new kit is allocated to parts, there is a high probability that there space is left for some parts to be traveling on the kit "for free". This leads to a minimal increase in total time cost. The hybrid solution in this case is in terms of time cost savings 38.1% better than an all kitting solution. The optimal solution is also in line with the predictions of free riders. 42% of parts are kitted, while as opposed to an all kitting solution only 20% of the total amount of kits is needed.

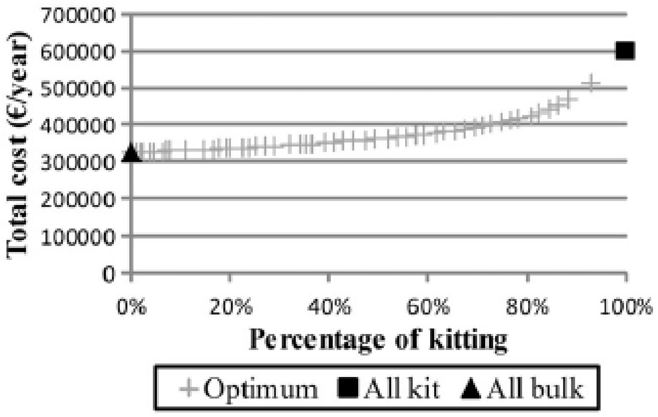


FIGURE 18 TOTAL TIME COST AS OPPOSED TO THE PERCENTAGE OF KITTING (LIMÈRE, VAN LANDEGHEM, GOETSCHALCKX, AGHEZZAF, & MCGINNIS, 2012)

Next to the numerical results, Limère et al. (2012) try to identify part characteristics which make it appropriate for a specific material feeding principle. Like Bozer and McGinnis (1992) a trade-off can be described. Kitting is (almost) only chosen when a space constraint is added, but which part characteristics are then favourable for kit?

- Large parts that consume a relative large space at the border of the assembly line and cause for a minimal time increase when placed in kit. Especially variant parts which can be used once for an assembly.
- Parts that are kitted in an efficient way regarding the amount of handling time needed. Some kits can be picked in batches which can compensate for the extra handling as opposed to stocking bulk at line. A lot of parts in the kit can for instance be free riding, which almost resembles bulk transport.
- Relatively small parts have an advantage as opposed to larger parts. When large parts are put in kit, smaller parts can often get a free ride as they are placed on the remaining space of the kit.
- Large parts which are normally stocked on pallets can free up much space at assembly. The probability that this part will be placed in kit is higher than for parts which are smaller and stocked in boxes. This is the case when available space in assembly is a constraint.

The conducted research of Sali and Sahin (2016), which is based on Sali et al. (2015), shows resembling results with those of Limère et al. (2012). Line stocking is compared with kit replenishment and the goal is to find a material feeding principle with timed deliveries at minimum time cost. The formulation of the different time costs is also divided into picking at the border of the assembly line, kit assembly, transport and replenishment of the preparation area. The storage costs represent a very small proportion of the total costs, which is stated as a negligible difference between the different methods.

Besides that al transportation time costs are assumed to be the same as a tugger train always travels the same distance. Like Limère et al. (2012) already stated is material feeding least time costly when stock is placed along the line in bulk packages. However there are some cases where kit replenishment is better than line stocking. Small parts can often ride free, while there are few cases when line stocking still remains least time costly. Mentioned are small parts that do not have (much) variants, have a high demand and can be held in large quantities in a single container. These parts are often nuts, bolts, washers, screws and so on. Characteristics which make kitting favourable are stated as:

- Kitting is preferred when a part comes in certain variants. These parts need more than one position in a line stocking approach, while consuming one spot in kit. Especially large and bulky parts increase the part presentation length of line stock locations causing for large walking distances for assembly operators.
- On the other hand, large parts are not appropriate for bulk picking in kit preparation. Whole crates cannot be picked in one handling and one large part (container) consumes a lot of space in kit.

3.1.3.1 Time cost formulations

The algorithms and time cost formulation which are proposed in literature are discussed in this section. This is done in the same division as stated by Limère et al. (2012). The formulation of this research is described further because it is the first research to assign a material feeding principle for each single part. Besides that the parameters and used variables are all mentioned, which is not the case in Caputo et al. (2008). Sali et al. (2015) describe a similar approach as Limère et al. (2012), although complexity is raised with the timing of parts added. Also timing of part deliveries is not included in this research.

The division of time costs on picking at the border of the assembly line, kit assembly, transport and replenishment of the preparation area are described below. The time cost formulation is taken from Limère et al. (2012), which forms a basis of the formulation of time costs at Dewulf. No travelling kits are considered as a paced line is not applicable at Dewulf. Also the kits are heavy and not easily moved around assembly.

Variables are expressed as:

- OC = operator cost per hour.
- q_{is} = yearly usage of part i at station s.
- $\frac{q_{is}}{n_i}$ = yearly usage of a box or pallet of part type i at station s.
- x_{is} = binary decision variable for part i at station s which is set to one if replenished by line stocking or set to zero for kit replenishment.
- tp_{is}^{bulk} = time to pick a bulk replenishment of part i from line stock based on travel distance of operator.
- tp^k = time to pick a part from kit k based on travel distance of operator.
- M = amount of parallel aisles in the y-direction.
- k = amount of storage locations per aisle.
- N = amount of different items to pick in an order.
- y = length of the storage rack along the aisle in the y-direction.
- x = length of the storage rack along the cross-aisle in the x-direction.
- $\frac{D_s^p}{V^p}$ = travel distance of pallets, taken by forklift truck with speed V^p, from warehouse to the line stock location at station s.

- $\frac{D^b}{V^b} = \frac{D^k}{V^k}$ = travel distance of boxes and kits in the milk-run tour used by tugger train which delivers to the line. Each tour has the same total distance.
- A^b = the capacity of boxes on the tugger train.
- ρ^b = expected utilisation of box capacity on average milk-run tour of tugger train.
- K_s = amount of kits needed at station s to assembly one end product.
- d = yearly demand of end product.
- A^k = the capacity of kits on the tugger train.
- ρ^k = expected utilisation of kit capacity on average milk-run tour of tugger train.
- tk_{is} = average pick time of part i for station s from a part container in the supermarket.

Picking at assembly

In order to get the needed parts to assembly, first the parts need to be picked from their storage location at the line. Parts are either stored in bulk or in kit. Picking in line is assumed to be done per piece in both feeding modes. Picking time of bulk parts is based on the walking distance added by an average search time, while for kits no search time is added.

The total labour cost for picking done by assembly operators is given by C_{pick} and expressed in formula 3.1. The time cost for picking is the sum of picking time for all parts i at all stations s.

$$C_{pick} = OC \cdot \sum_{s \in S} \sum_{i \in I_s} q_{is} \left[x_{is} tp_{is}^{bulk} + (1 - x_{is}) tp^k \right], \tag{3.1}$$

The walking distance per part for pickers is an average distance along the border of the assembly line (Limère, Van Landeghem, Goetschalckx, Aghezzaf, & McGinnis, 2012).

However in practice, like at Dewulf, parts can also directly be picked from Warehouse (1). In most warehouses parts are stored along aisles with storage locations on both sides of the aisle. To set out a picking route of orders, part locations should be known. To make an estimate one can assume that parts for an order are uniformly distributed over the possible storage locations. The traversal strategy, s-shape strategy, can be used for calculation of the expected travel distance. With this strategy a complete aisle is traversed when at least one part needs to be picked there. Hall (1993) describes a formula for this calculation. However this calculation was based on the assumption of infinite possible storage locations on the given aisle length. Schuur (2016) changed the formulation to a discrete expression, with finite storage locations. The expression of the expected distance for the vertical and horizontal movement is given in respectively formula 3.2 and 3.3 below. This calculation is based on an I/O point which is placed in front of the middle aisle.

$$tot.est.\ distance\ in\ y - direction = My \left(1 - \frac{\binom{(M-1)k}{N}}{\binom{Mk}{N}} \right) \tag{3.2}$$

$$tot.est.\ distance\ in\ x - direction = \left(1 - \left(\frac{1}{2}\right)^{N-1} \right) \left(2x \left(\frac{N-1}{N+1} \right) \right) + \left(\frac{1}{2}\right)^{N-1} x \left(\frac{N}{N+1} \right) \tag{3.3}$$

Transport to assembly

The storage location is Warehouse (1) in case of Dewulf, however some researchers like Limère et al. (2012) assume that parts are brought to a supermarket by use of the same feeding mode. This supermarket is a consolidation area which is placed in a central place as opposed to all assembly areas. Here parts are picked for kit assembly and kits are assembled. Transport time only differs for different material feeding principles when the parts leave the supermarket. The bulk packages picked for line stocking will be directly brought to line, but also have to travel that same distance to supermarket first.

The time cost of transport, C_{tpt}, can be expressed as the sum of time costs for pallet, box and kit transport.

$$C_{tpt}^{pallet} = OC \cdot \sum_{s\in S} \sum_{i\in Is\cap Ip} x_{is} \left(2 \cdot \frac{D_s^p}{V^p} \cdot \frac{q_{is}}{n_i}\right) \tag{3.4}$$

$$C_{tpt}^{box} = OC \cdot \frac{\sum_{s\in S} \sum_{i\in Is\cap Ib} x_{is}\left(\frac{D^b}{V^b} \cdot \frac{q_{is}}{n_i}\right)}{A^b \rho^b} \tag{3.5}$$

$$C_{tpt}^{kit} = OC \cdot \sum_{s\in S} \sum_{i\in I_s} \frac{\frac{D^k}{V^k} K_s d}{A^k \rho^k} \tag{3.6}$$

Transport of parts is done in two ways. The pallets with parts are transported directly from warehouse to the assembly line with use of a forklift truck, while boxes and kits are delivered by use of milk –run tours. Boxes are moved from the warehouse to the supermarket or are directly delivered by use of milk-run to the stations. The milk-runs are done by use of a tugger train. For the delivery of the stations, no boxes or pallets are repacked, but are picked and transported to assembly in their original package. The size of boxes is larger than the kits in the case of Limère et al. (2012), which means that from an amount of transport handlings bulk is most likely advantageous. Kits are formed by use of repacking, which also means an extra activity. Besides Limère et al. (2012), Sali et al. (2015) does also not account for repacking. Although at the Dewulf, repacking is needed due to the nature of the size and weight of parts.

Assembly of kits

As kits are a collection of different parts, this collection needs to be gathered. The gathering of these parts cost time and is given by C_{kit}. Research of Limère et al. (2012) describes that multiple parts can be picked at once, based on a certain probability. Further this kitting process is assumed to be done in batches. The picking cost for one pick, which can be multiple parts at once, is defined by the search time in the supermarket added by the walking time to the part container. The labour cost allocated to the assembly of kits is expressed in formula 3.7. The time cost for assembling kits is the sum of assembly time for all parts i for all stations s.

$$C_{kit} = OC \cdot \sum_{s\in S} \sum_{i\in I_s} [(1 - x_{is}) q_{is} t k_{is}] \tag{3.7}$$

At the Dewulf, the assembly of a kit will be done in the main area of the warehouse. This means that the picks for kit are coming directly from the original storage location. In the case of Limère et al. (2012) the supermarket, where the kit preparation is executed, is delivered by bulk boxes and pallets from warehouse.

Replenishment of kit supermarket

The supermarket which is used to assemble the kits is replenished by use of bulk deliveries. The replenishment of one box and one pallet is represented by constant time costs. The constant values are an assumption of the average cost. Like the line stock deliveries to the line, this replenishment time cost are based on the labour cost needed to transport the unit-load or box. As with the replenishment of line stock, no repacking or downsizing is done.

3.1.3.2 Models

According to literature of Hua and Johnson (2010) there is not yet a clear method to solve the consideration of which feeding principle to choose for what parts. However as said above, Bozer & McGinnis (1992) presented a trade-off and later Limère et al. (2012) gave examples on how to solve the consideration on certain conditions. These conditions are not the same for each instance, but can give a guideline for the approach in this research like the described timecost formulations above.

As stated earlier the formulations, definitions and choice of time costs to account for differ in the cases used in literature. Hence, after the time cost formulations are made the goal and result of the researches are also different. Bozer and McGinnis (1992) made a trade-off based on pure policies. This trade-off indicates the impact on time cost due to the choice of a pure policy for all parts. Caputo et al. (2008), Limère et al. (2012) and Sali et al. (2015) formulate a linear programming model which aims at finding a hybrid solution regarding the time costs. A linear programming model is a tool for solving optimization problems (Winston, 2004). The goal and objective function is to find an optimal value, maximum or minimum, given a set of decision variables and restrictions. These decision variables need to satisfy constraints. A constraint must be a linear equation or a linear inequality. Caputo et al. (2008), Limère et al. (2012) and Sali et al. (2015) minimize total time costs by use of assigning each single component to a feeding principle.

The assumptions, restrictions and formulations of Caputo et al. (2008), Limère et al. (2012) and Sali et al. (2015) are different. This is due to the choice of importance of aspects depicted by the researchers and also due to the cases used. However, the formulation of time costs of Limère et al. (2012) can be adapted to this research. As said in the previous section, the variables and parameters are clear and can be reformulated. The proposed linear programming models in the last three articles mentioned are not an exact fit for this research. Besides linear programming models, the trade-off from Bozer and McGinnis (1992) cannot form an exact guideline for the formulation of a decision rule for Dewulf. But, it can be of use in formulating the trade-offs in this research. As said above, the proposed trade-offs of Bozer and McGinnis (1992) are based on pure policies. While in this research the decision rule is actually based on trade-offs which is based on a hybrid policy, and therefore on part-level. To come to a hybrid policy, pure policies are considered first. The favourable part characteristics for use of kitting stated by Limère et al. (2012) and Sali et al. (2015) can be used to evaluate the proposed decision rule.

3.2 Assembly layouts

In order to facilitate an assembly process, workstations need to be arranged in a layout which is effective for the amount of time effort put in by the operators/machines. This assembly layout is determined by the characteristics of the product and therefore its material feeding principle.

Firstly description of four main types of assembly layouts, namely product layout, fixed location layout, cellular layout and process layout. The relation of production volume and product variety towards appropriateness of assembly layout types is visualised in figure 19. The product layout can be described as a layout which is appropriate for high production volumes and low variety. The processes at workstations are arranged such that repetitive production of similar products can be executed in an efficient consecutive order. The fixed location layout the product is the centre and all resources, machines and operators move around and towards it. This type of layout is often appropriate for low production volumes and low varieties. Although often large sized products are assembled in such layout, which can have some high variety. A process layout has machines or operators arranged such that similar operations can be executed. High variety and low production volume is typical. The last layout type is a group/cellular layout, which facilitates similar production steps in grouped areas. Various products are treated for the same type of operation in a certain cell (Drira, Pierreval, & Hajri-Gabouj, 2007).

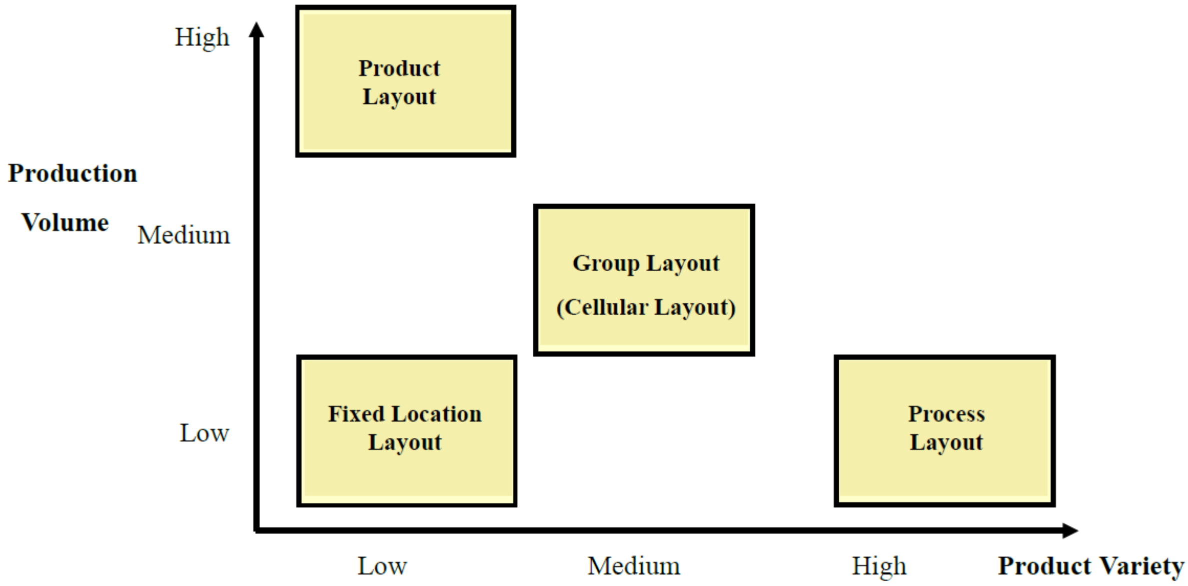


FIGURE 19 ASSEMBLY LAYOUT TYPE AS OPPOSED TO PRODUCTION VOLUME AND PRODUCT VARIETY

The decision on dock versus line is as described mainly determined by the used material feeding principles. A dock assembly is an arrangement of operations where the product is fixed and resources are pulled towards it. This dock can be seen as one assembly work station. The reasons for usage of a dock assembly are often a low demand, a high variety in the option mix and a large amount of people working on the same task is not advantageous. The assembly in line is a layout where an end product is produced along various work stations (Bozer & McGinnis, 1992), which are usually appropriate for a low variety. Srinivasan and Gebretsadik (2011) state that an assembly line is a series of consecutive work stations, where products are fixed on a position. The needed operations for an end product are divided over multiple stations. The reasons for usage of line assembly are often a high demand, a low variety in the product mix and the product production tasks can be split up by a relatively low amount of different parts needed per workstation.

Within in a workstation a work cell can be described. A work cell is the arrangement of resources, machines and operators within one workstation. The arrangement determines the efficiency of the workstation. The placement of a product and the parts on stock along assembly are of importance at Dewulf. Picking speed is depended on the placement of parts in racks according to Finnsgård (2013). This is due to the impact of ergomics for the work cell operators. A model can be presented which denotes favourable part positions in racks for operators (Finnsgård, 2013).

3.2.1 Dock assembly

As stated above, dock assembly is a type of fixed location layout. With this arrangement of parts, machines and personnel a throughput of a mix of product models can be facilitated. These products are placed in a fixed position during assembly.

Qualitative advantages and limitations of dock assembly (or fixed product layout) are mentioned in literature. These qualitative judgements are described in the below enumerations.

Advantages of assembly in dock

1. Flexible, store only parts which are needed for all possible end products made in the assembly space.
2. Task for personnel are broad. Diversification of tasks is more challenging for personnel.

3. End product is less prone to damage due to transport or movement in line. When finished, the complete product can leave the facility.
4. Options and variations are easily blend into the process.

Limitations of assembly in dock

1. Less space available in assembly, usually, with respect to all parts needed for all tasks. When storage of parts is needed for wide variety of end products it is not possible.
2. Usually less assembly space to work with more personnel at a time.
3. Difficult to plan on personnel and resources.
4. Difficult to let new personnel start with such a broad package of tasks.

3.2.2 Line assembly

As stated above, line assembly is a type of product layout. With this arrangement of parts, machines and personnel a throughput of a low variety of product models can be facilitated. These products are placed in a fixed position during assembly, but move from position to position. Each position is dedicated to a few task of finalising the end product.

There are different types of assembly lines, namely paced and un-paced lines (Bukchin & Russell, 2005). Dewulf has un-paced lines, because throughput is relatively low and can switch from work station to workstation. This is mainly due to the nature of the products and the demand of those products. The harvesters are usually not sold by hundreds, thus setting up a very long line with a lot of workstations is not efficient.

Qualitative advantages and limitations of line assembly (or product layout) are mentioned in literature. These qualitative judgements are described in the below enumerations.

Advantages of assembly in line

1. Large presentation space along line, which results in a buffer of a lot of part types and picking for the assembler should result in relatively short walking times.
2. An assembly line has a more or less pushing charter. All personal in the line are responsible for the total throughput. A pushing character means that an assembler needs to work at a certain pace in order to remain ahead of the previous assembler.
3. Simple tasks for personnel due to the split up over work stations. Therefore, personal shortage is less likely to happen.

Limitations of assembly in line

1. The assembly line is arranged for a limited amount of end products. All storage locations are dedicated for that amount of end products. Another type of end product cannot be made in the same assembly line and personnel is used to the line.
2. A large amount of space is needed to accommodate for the line. The line is usually split up into a lot of workstation with a very limited amount of tasks per station.
3. People need to be used to each other, in order to make the line work. When issues occur, every others should be able to cope with the problem.
4. The work tends can be boring for personnel. The limited task package is more easily learned.

3.2.3 Work cell design

A work station is a definition for the space where personnel are positioned in order to finish a certain task. A work cell is the space in which workstations are positioned. Within each work station, and therefore work cell, space, persons, materials and machines need to be aligned in order to make the process efficient. When alignment is done properly, throughput can be boosted and ergonomics improve. Due to the right alignment, walking times can be shorter.

The alignment of machines is not an issue at Dewulf, as assembly does not make use of very heavy industrial equipment. Some small power tools are often sufficient, with exception of an overhead crane. Such a crane is needed for some of the Heavy pick parts.

The alignment of resources (in racks) is important in this research. When the placement of part racks can be chosen, the placement in the racks itself will be the next problem. This placement in racks is heavily influenced by the picking ergonomics. The *VASA model* can be used to coordinate the right placement of parts in racks (Finnsgård, 2013), see figure 20 below. The favourable part positions are, in order of importance, given by the green zone, yellow zone and red zone.

FIGURE 20 SCHEMATIC REPRESENTATION OF VASA MODEL (FINNSGÅRD, 2013)

3.3 Conclusion

Literature has mostly addressed the qualitative judgements of both feeding principles, though the quantitative judgements are scarce. Line stocking (with Kanban replenishment) is mentioned as the most used material feeding principle, while Kit replenishment is mostly praised. There are two quantitative articles which are useful and are used as a basis for this research. The common findings of these articles are that Kitting is often used when space is limited and that certain parts are riding free once a Kit is used. Kanban replenishment with line stocking is often preferred in the automotive industry, or a sector alike, because assembly is done in line and a small amount of parts per assembly station are needed. The time costs for Transportation, Preparation and Picking are often accounted for.

Two types of layouts can be distinguished at Dewulf, namely Dock and Line assembly. Dock assembly is known for a versatile assembly workstation, where Kit replenishment is most appropriate. In a Dock is limited space, while a wide variety of products can be build. Line assembly is known for facilitating production of a low variety of products. Within these workstation types, resources, personnel and equipment need to have a position. These positions are of influence for the efficiency in terms of movements executed by the picker.

4. Design of decision rule

After the completed literature review, this chapter describes the design of the decision rule in the steps stated below.

In section 4.1 the goal of the decision rule is explained, where the used general assumptions are enumerated. With use of these assumptions the relevant time cost aspects are described. In section 4.2 favourable conditions for the four depicted scenarios are derived, so section 4.3 describes the outcome of applying the decision rule. When finally, section 4.4 concludes this chapter.

4.1 Goal

The goal and objective of the decision rule is, eventually, to give '*a guideline on when to choose the least costly material feeding principle per part*'. Each decision is based on preference conditions.

Firstly, in section 4.2.1, the preference conditions towards a feeding principle on subassembly level are derived. In this case a preference condition is a characteristic of a subassembly which leads to a favourable material feeding principle. For example, a subassembly with more than 30 reckoned lift pick parts may be in favour of kit replenishment. Or, a subassembly with a higher amount of kits needed with respect to the amount of Kanban pallets needed may be in favour of Kanban replenishment. In order to find such preference conditions scenarios 1 and 4, from chapter 2, are compared.

Secondly, in section 4.2.2, the preference conditions towards a feeding principle on part level are derived. In this case a preference condition is a characteristic of a part which leads to a favourable material feeding principle. For example, a part with a length of 50 centimetres or more may be in favour of Kit replenishment. Or, a part with demand of 20 or more pieces may be in favour of Kanban replenishment. In order to find such preference conditions scenarios 1 and 2 and scenarios 3 and 4, from chapter 2, are compared.

In order to compare the different scenarios, the time cost of each material handling operation must be known. These costs are influenced by assumptions, but also by variable and fixed parameter values. The variable and fixed parameter values are based on either calculations, estimations or facts.

4.1.1 General assumptions

This section describes the general assumptions which are made. In the next section, 4.1.2, these general assumptions are used to formulate the relevant time cost aspects.

The parameter values corresponding with the time cost formulations are given in the next section, where their specific assumptions are exemplified. The below list of assumptions are used to formulate the restrictions, variable parameters and fixed parameters.

General assumptions are explained and enumerated below:

1. *Kits can have two sizes at Dewulf*. Either a small kit of 1700 mm in width or a larger one which is 2700mm in width. Both kits are 800mm in length. A photo of a small kit which will be used at Dewulf is visualised in figure 21 below.

FIGURE 21 PHOTO OF A SMALL KIT PALLET

2. *The kits are divided in coated and uncoated kits.* This is assumed because the parts which need coating obviously need to go to the coating area. The other parts can make another route through the facility and need to be kept together. Parts that need coating can follow the route: Warehouse (1) --> Advanced warehouse (2) --> Hal 08. Coating (3) --> Advanced warehouse (2) --> Hal 04. Pre-assembly (4) or Hal 02. Final assembly. Parts that do not need coating can follow another route: Warehouse (1) --> Advanced warehouse (2) --> Hal 04. Pre-assembly (4) or Hal 02. Final assembly.
3. *Kit preparation space and time is not an issue.* Space in Warehouse (1) is considered sufficient in terms of preparation area and storage of kits which are needed on short notice. The timing of arrival of these parts is not considered in this research.
4. *Kit pallets stored alongside assembly are non-stackable.* If kits would be stacked alongside assembly, the possibility to pick (heavy) parts is made challenging. Besides that kits may vary in height on the top surface, which also does not accommodate stacking.
5. *Special/single items are parts that need a specific treatment.* These parts are either coming from deviant location or are hefty and are transported per piece. Limère et al. (2012) also state this specification. The special/single items are delivered to assembly on their own and therefore have no impact on the choice of material feeding principle on subassembly level. The placement of such parts has only impact on the available space in assembly.
6. *Bulk items are parts that have a high demand.* Because the demand is high Kanban replenishment is assumed to be less advantageous than a bulk crate delivery to assembly. This is also described by Limère et al. (2012). The bulk items are delivered to assembly on their own and therefore have no impact on the choice of material feeding principle on subassembly level. The placement of such parts has only impact on the available space in assembly.
7. *All parts, except special items and bulk crates, are picked in Warehouse (1).* Parts are consolidated on either a Kit or a pallet.
8. *All parts, except special items and bulk crates, are transported on pallets.* Bins and POD pallet parts are placed on pallets. Transport of the pallets is facilitated by forklift trucks.
9. *No picking time of pallets are considered in Advanced warehouse (2).* In Advanced warehouse (2) pallets with parts are placed on the floor, therefore parts are easily picked.
10. *A replenishment tour from Warehouse (1) to assembly is not always efficient in terms of utilization of the available transport capacity.* As replenishments are called by Kanban signal cards, the timing may cause for suboptimal sequence of replenishment deliveries.

11. *The actual bins, pallets and kits travelling back to Warehouse (1) are still considered as loaded travels.* These containers can be taken in a transport cycle where new parts are gathered for a milk-run.
12. *When placing parts in kit, the shape of parts can play a role in the possibility of the placement.* If the square meters are insufficient, the parts may still fit as each part has a boundary box. Therefore a boundary box reduction is added to the kit placement. An example is given in figure 22 below. The part has a size calculated by the square meter size given in the dotted line. Although the part itself is nowhere near the size of the square.

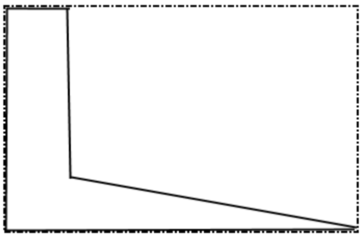


FIGURE 22 BOUNDARY BOX REPRESENTATION OF A PART

13. *When picking from Kanban far, assembly operators pick and then place the part alongside assembly with the same distance towards the workplace as kits and Kanban close.* All parts are picked first, so the sub assembly can be made without interference of a new picking operations.
14. *When picking from Kanban far, assembly operators execute picking for one end product.* Thus the amount of picks are the same as the needed picks for a kit.
15. *When picking in Warehouse (1) is done, repacking, or downsizing, is used.* In the case of Limère et al. (2012) replenishment of Kanban locations is done by delivery of boxes or pallets. This means no repacking. Though repacking is used at Dewulf since the parts are often hefty.

4.1.2 Cost aspects

Now that the goal and assumptions are exemplified, the relevant cost formulations of the material handling operations are presented in 4.1.2.1. These formulations are compared to the ones presented in the literature study of chapter 3. Followed by the fixed parameter values in 4.1.2.2, which are derived from estimations, calculations and facts. Besides fixed parameters also variable parameters are determined. This is done by use of additional formulations described in 4.1.2.3 and their corresponding parameters described in 4.1.2.4.

4.1.2.1 Time cost formulations

The relevant cost aspects are *Picking and Preparation* and *Transportation*. Limère et al. (2012) and Sali et al. (2015) describe similar aspects, but the actual formulations differ due to the studied cases and different assumptions made. The differences in comparison with literature are highlighted in the time cost aspects below.

The time cost formulations below describe the time cost per subassembly i. With these formulations a comparison of pure policies can be made. This comparison is made to find the fitting layout and with use of kitting the amount of needed kits needs to be calculated. When the preference conditions of a pure policy are known, the preference conditions on part level are found by changing subassembly i to part type i. These preference conditions on part level tell when to deviate from a pure policy on subassembly level.

In order to describe the time cost formulations, the below list clarifies the meaning of the upcoming symbols used. When i is used in a symbol combination, it is meant as subassembly type i for section 4.2.1 or part type i for section 4.2.2.

Symbols:

- $C_{pick.kbn1}$ = Time cost of picking and preparing Kanban parts for one subassembly i in Warehouse (1).
- $C_{pick.kit}$ = Time cost of picking and preparing Kit parts for one subassembly i in Warehouse (1).
- $C_{pick.kbn2}$ = Time cost of picking Kanban far parts for one subassembly i in Pre-assembly (4) or Final assembly (5).
- $C_{tpt.kbn04}$ = Transportation time of pallets for one subassembly i from Warehouse (1) to Pre-assembly (4).
- $C_{tpt.kbn02}$ = Transportation time of pallets for one subassembly i from Warehouse (1) to Final assembly (5).
- $C_{tpt.kit04}$ = Transportation time i from Warehouse (1) to Pre-assembly (4).
- $C_{tpt.kit02}$ = Transportation kits for one subassembly i from Warehouse (1) to Final assembly (5).
- PP_1 = Average part placement time per (kit) pallet.
- PP_2 = Average kit preparation time per kit pallet.
- $Pick_1$ = Average picking time in Lift pick area per pick.
- $Pick_2$ = Average picking time in POD pick are per pick.
- $Pick_3$ = Average picking time in Heavy pick area per pick.
- $Pick_4$ = Average picking time in Kanban far per pick.
- α_{04} = Time reckoned for transport of an uncoated (Kit) pallet from Warehouse (1) brought to Hal 04. Pre-assembly (4).
- α_{02} = Time reckoned for transport of an uncoated (Kit) pallet from Warehouse (1) brought to Hal 02. Final assembly (5).
- β_{04} = Time reckoned for transport of a coated (Kit) pallet from Warehouse (1) brought to Hal 04. Pre-assembly (4).
- β_{02} = Time reckoned for transport of a coated (Kit) pallet from Warehouse (1) brought to Hal 02. Final assembly (5).
- DB = Distance Warehouse (1) to Advanced warehouse (2).
- D08 = Distance Advanced warehouse (2) to Coating (3).
- D04 = Distance Advanced warehouse (2) to Pre-assembly (4).
- D02 = Distance Advanced warehouse (2) to Final assembly (5).
- ELT = Ratio of empty to loaded travels.
- TL = Average lift time per pallet.
- V = Average speed of a forklift truck.
- CO = Operator cost per second.
- $T1_{.i}$ = Travel time in Warehouse (1) when Kanban order quantities apply.
- $T2_{.i}$ = Travel time in Warehouse (1) when Kit order quantities apply.
- UCP_i = Amount of pallets needed for uncoated parts.
- CP_i = Amount of pallets needed for coated parts.
- UCK_i = Amount of kits needed for uncoated parts.
- CK_i = Amount of kits needed for coated parts.
- $L_{1.i}$ = Amount of reckoned Lift picks when Kanban order quantities apply.
- $L_{2.i}$ = Amount of reckoned Lift picks when Kit order quantities apply.
- $P_{1.i}$ = Amount of reckoned POD picks when Kanban order quantities apply.
- $P_{2.i}$ = Amount of reckoned POD picks when Kit order quantities apply.

- $H_{1.i}$ = Amount of reckoned Heavy picks when Kanban order quantities apply.
- $H_{2.i}$ = Amount of reckoned Heavy picks when Kit order quantities apply.

Additional and supporting formulations of variable parameters used below are described in 4.1.2.3.

Table rows and formulas below are marked for their purpose by colour. Yellow is used for Kanban only, green for Kit only and grey for universal cases.

Picking and preparation

Limère et al. (2012) and Sali et al. (2015) describe costs concerned with picking at the border of assembly. Picking at Dewulf is executed in the Warehouse (1), in Pre-assembly (4) and Final assembly (5). The time cost of picking in assembly is only add up when Kanban far is used. Since the picking time cost is not accounted for when parts are placed with the same distance towards assembly.

The time cost of picking in Warehouse (1) is influenced by the amount of parts and its part characteristics. Parts are picked from their location in the Lift pick area, POD pick area or the Heavy pick area. Such that average picking times are respectively given by $Pick_1$, $Pick_2$ and $Pick_3$. The amount of picks needed is assumed to be affected by the possibility of picking multiple parts at once, like also used in Limère et al. (2012) for kit replenishment. This possibility seems appropriate in practice because multiple, relative small, parts will often be picked at once. Repacking is executed for every part type at Dewulf, except for bulk replenishments. In its place Limère et al. (2012) and Sali et al. (2015) describe the preparation before assembly, where a milk-run is accounted for. In this milk-run part types are picked per box or pallet for Kanban replenishment. The total operator travel time per product in Warehouse (1) at Dewulf is given by $T_{1.i}$ for Kanban and $T_{2.i}$ for Kitting.

Instead of assembly and preparation of kits, which is proposed in literature, the placement on pallets, PP_1, in general is also accounted for. Although Kit assembly, PP_2, consumes extra time as the Kit pallet needs to be prepared for the right parts.

Instead of replenishment of the supermarket, as mentioned in literature, the storage at the border of assembly at Dewulf can be seen as a supermarket. This replenishment activity is accounted for in the picking calculation. Kit and Kanban replenishment of this "supermarket" is started by means of picking in Warehouse (1).

Time cost of picking and preparing Kanban parts for one subassembly i in Warehouse (1), $C_{pick.kbn1}$, is then given in formula 4.1 by the travel time in Warehouse (1), $T_{1.i}$, added by the sum of pallet placement time, PP_1, times the amount of pallets needed for uncoated parts, UCP_i, and coated parts, CP_i, added by the amount of reckoned Lift picks, $L_{1.i}$, POD picks, $P_{1.i}$, and Heavy picks, $H_{1.i}$, times the respective average picking times $Pick_1$, $Pick_2$ and $Pick_3$.

$$C_{pick.kbn1} = T_{1.i} + \sum_i \left(PP_1 \cdot (UCP_i + CP_i) + L_{1,i} \cdot Pick_1 + P_{1.i} \cdot Pick_2 + H_{1.i} \cdot Pick_3 \right) \quad (4.1)$$

The formulations, and corresponding parameters, of $T_{1.i}$, UCP_i, CP_i, $L_{1.i}$, $P_{1.i}$ and $H_{1.i}$ are described in 4.1.2.3 and 4.1.2.4.

Time cost of picking and preparing Kit parts for one subassembly i in Warehouse (1), $C_{pick.kit}$, is then given in formula 4.2 by the travel time in Warehouse (1), $T_{2.i}$, added by the sum of pallet and kit placement time, respectively $PP_1$and PP_2, times the amount of kit pallets needed for uncoated parts, UCK_i, and coated parts, CK_i, added by the amount of reckoned Lift picks, $L_{2.i}$, POD picks, $P_{2.i}$, and Heavy picks, $H_{2.i}$, times the respective average picking times $Pick_1$, $Pick_2$ and $Pick_3$.

$$C_{pick.kit} = T_{2.i} + \sum_i \left((PP_1 + PP_2) \cdot (UCK_i + CK_i) + L_{2.i} \cdot Pick_1 + P_{2.i} \cdot Pick_2 + H_{2.i} \cdot Pick_3 \right) \quad (4.2)$$

The formulations, and corresponding parameters, of $T_{2.i}$, UCK_i, CK_i, $L_{2.i}$, $P_{2.i}$ and $H_{2.i}$ are described in 4.1.2.3 and 4.1.2.4.

Time cost of picking Kanban far parts for one subassembly i in Pre-assembly (4) or Final assembly (5), $C_{pick.kbn2}$, is given in formula 4.3 by the sum of the amount of reckoned Lift picks, $L_{2.i}$, POD picks, $P_{2.i}$, and Heavy picks, $H_{2.i}$, times the average picking time in Kanban far, $Pick_4$.

$$C_{pick.kbn2} = \sum_i \big((L_{2.i} + P_{2.i} + H_{2.i}) \cdot Pick_4 \big) \qquad (4.3)$$

The formulations, and corresponding parameters, of $L_{2.i}$, $P_{2.i}$ and $H_{2.i}$ are described in 4.1.2.3 and 4.1.2.4.

A calculation example for usage of the above three formulas, (4.1), (4.2) and (4.3), is described in figure 23 below.

A subassembly X consists of 100 part types and needs to be assembled in Hal 04. Pre-assembly. These 10 part types can be divided into 50 part types from Lift pick area, 30 from POD pick area and 20 from Heavy pick area.

There is no advantage of picking multiple parts at once for Kit in this example, so the amount of reckoned picks remains respectively 50, 30 and 20 picks. Thus $L_{2.i}$ = 50, $P_{2.i}$ = 30 and $H_{2.i}$ = 20. However, for Kanban there is a picking advantage, the amount of reckoned picks becomes respectively 30, 20 and 20 picks. Thus $L_{1.i}$ = 30, $P_{1.i}$ = 20 and $H_{1.i}$ = 20.

As there is an advantage of Kanban due to the amount of reckoned picks, the average amount of storage locations to be visited is also lower. The travel time in Warehouse (1) for subassembly X when Kanban is used is 60 seconds. Thus $T_{1.i}$ = 60. The travel time in Warehouse (1) for subassembly X when Kit is used is 90 seconds. Thus $T_{2.i}$ = 90.

The amount of pallets for Kanban replenishment needed per subassembly X is 1.5 for coated parts and 1 for uncoated parts. Thus UCP_i = 1 and CP_i = 1.5. The amount of Kits needed for coated and uncoated parts are both equal to 1. Thus UCK_i = 1 and CK_i = 1.

The fixed parameters, see table 2, are the parameters given by PP_1, PP_2, $Pick_1$, $Pick_2$, $Pick_3$, $Pick_4$.

Cost of picking and preparing Kanban parts for one subassembly X in Warehouse (1):

$$C_{pick.kbn1} = T_{1.i} + \sum_i \big(PP_1 \cdot (UCP_i + CP_i) + L_{1,i} \cdot Pick_1 + P_{1.i} \cdot Pick_2 + H_{1.i} \cdot Pick_3 \big)$$

$$C_{pick.kbn1} = 60 + 60 \cdot (1 + 1.5) + 30 \cdot 36 + 20 \cdot 72 + 20 \cdot 225 = 7230 \; seconds$$

Cost of picking and preparing Kit parts for one subassembly X in Warehouse (1):

$$C_{pick.kit} = T_{2.i} + \sum_i \big((PP_1 + PP_2) \cdot (UCK_i + CK_i) + L_{2.i} \cdot Pick_1 + P_{2.i} \cdot Pick_2 + H_{2.i} \cdot Pick_3 \big)$$

$$C_{pick.kit} = 90 + (60 + 90) \cdot (1 + 1) + 50 \cdot 36 + 30 \cdot 72 + 20 \cdot 225 = 8850 \; seconds$$

Cost of picking Kanban far parts for one subassembly X in Hal 04. Pre-assembly (4):

$$C_{pick.kbn2} = \sum_i \big((L_{2.i} + P_{2.i} + H_{2.i}) \cdot Pick_4 \big)$$

$$C_{pick.kbn2} = (50 + 30 + 20) \cdot 72 = 7200 \; seconds$$

FIGURE 23 CALCULATION EXAMPLE FOR FORMULAS (4.1), (4.2) AND (4.3)

The total cost of picking is either $C_{pick.kit}$ or the sum of $C_{pick.kbn1}$ and $C_{pick.kbn2}$ times the operator cost per second, *OC*.

Transportation

Transport is facilitated by forklift trucks which can handle (Kit) pallets. Limère et al. (2012) refer to this as a point-to-point transport. On each pallet there is certain available capacity of parts or bins. In literature of Limère et al. (2012) and Sali et al. (2015) most transportation is handled by tugger trains. This is less appropriate at Dewulf because of the size of parts, thus only point-to-point transport is used.

After parts are picked in Warehouse (1), the parts need transportation to either Pre-assembly (4) or Final assembly (5). This transportation time is influenced by the amount and size of parts that do need or do not need coating, the travel distance towards destination, the ratio of the amount of empty and loaded travels, *ELT*, and the average speed of the forklift truck, *V*. The travel distances are given by *DB* for Warehouse (1) to Advanced warehouse (2) via the bridge, *D08* for Advanced warehouse (2) to Coating (3), *D04* for Advanced warehouse (2) to Pre-assembly (4) and *D02* for Advanced warehouse (2) to Final assembly (5). To accommodate the height difference of Warehouse (1) and Advanced warehouse (2) a lift is used with an average lift time per pallet, *TL*.

The time reckoned for transport of an uncoated (Kit) pallet from Warehouse (1) brought to Hal 04. Pre-assembly (4), α_{04}, is given in formula 4.4 by the amount of travels, including empty travels, *ELT*, times the lift time per pallet, *TL*, added by travel distance *DB + D04* divided by average forklift speed *V*.

$$\alpha_{04} = (1 + ELT) \cdot \left(\frac{DB+D04}{V} + TL\right) \tag{4.4}$$

The time reckoned for transport of an uncoated (Kit) pallet from Warehouse (1) brought to Hal 02. Final assembly (5), α_{02}, is given in formula 4.5 by the amount of travels, including empty travels, *ELT*, times the lift time per pallet, *TL*, added by travel distance *DB + D02* divided by average forklift speed *V*.

$$\alpha_{02} = (1 + ELT) \cdot \left(\frac{DB+D02}{V} + TL\right) \tag{4.5}$$

The time reckoned for transport of a coated (Kit) pallet from Warehouse (1) brought to Hal 04. Pre-assembly (4), β_{04}, is given in formula 4.6 by the amount of travels, including empty travels, *ELT*, times the lift time per pallet, *TL*, added by travel distance *DB + 2 · D08 + D04* divided by average forklift speed *V*. The distance towards Coating, *D08,* is multiplied by two because parts are brought, but also need to be picked up after their treatment.

$$\beta_{04} = (1 + ELT) \cdot \left(\frac{DB+2\cdot D08+D04}{V} + TL\right) \tag{4.6}$$

The time reckoned for transport of a coated (Kit) pallet from Warehouse (1) brought to Hal 02. Final assembly (5), β_{02}, is given in formula 4.7 by the amount of travels, including empty travels, *ELT*, times the lift time per pallet, *TL*, added by travel distance *DB + 2 · D08 + D02* divided by average forklift speed *V*. The distance towards Coating, *D08,* is multiplied by two because parts are brought, but also need to be picked up after their treatment.

$$\beta_{02} = (1 + ELT) \cdot \left(\frac{DB+2\cdot D08+D02}{V} + TL\right) \tag{4.7}$$

Transportation time of pallets for one subassembly i from Warehouse (1) to Pre-assembly (4),$C_{tpt.kbn04}$, is given in formula 4.8 by the sum of the amount of the travel time needed for the amount of pallets needed for uncoated parts, UCP_i, and coated parts, CP_i. These travel times are given by the time reckoned for transport times the corresponding amount of pallets needed.

$$C_{tpt.kbn04} = \alpha_{04} \cdot \sum_i (UCP_i) + \beta_{04} \cdot \sum_i (CP_i) \quad (4.8)$$

The formulations, and corresponding parameters, of UCP_i and CP_i are described in 4.1.2.3 and 4.1.2.4.

Transportation time of pallets for one subassembly i from Warehouse (1) to Final assembly (5), $C_{tpt.kbn02}$, is given in formula 4.9 by the sum of the amount of the travel time needed for the amount of pallets needed for uncoated parts, UCP_i, and coated parts, CP_i. These travel times are given by the time reckoned for transport times the corresponding amount of pallets needed.

$$C_{tpt.kbn02} = \alpha_{02} \cdot \sum_i (UCP_i) + \beta_{02} \cdot \sum_i (CP_i) \quad (4.9)$$

The formulations, and corresponding parameters, of UCP_i and CP_i are described in 4.1.2.3 and 4.1.2.4.

Transportation time of kit pallets for one subassembly i from Warehouse (1) to Pre-assembly (4),$C_{tpt.kit04}$, is given in formula 4.10 by the sum of the amount of the travel time needed for the amount of pallets needed for uncoated parts, UCK_i, and coated parts, CK_i. These travel times are given by the time reckoned for transport times the corresponding amount of pallets needed.

$$C_{tpt.kit04} = \alpha_{04} \cdot \sum_i (UCK_i) + \beta_{04} \cdot \sum_i (CK_i) \quad (4.10)$$

The formulations, and corresponding parameters, of UCK_i and CK_i are described in 4.1.2.3 and 4.1.2.4.

Transportation time of kit pallets for one subassembly i from Warehouse (1) to Final assembly (5),$C_{tpt.kit02}$, is given in formula 4.11 by the sum of the amount of the travel time needed for the amount of pallets needed for uncoated parts, UCK_i, and coated parts, CK_i. These travel times are given by the time reckoned for transport times the corresponding amount of pallets needed.

$$C_{tpt.kit02} = \alpha_{02} \cdot \sum_i (UCK_i) + \beta_{02} \cdot \sum_i (CK_i) \quad (4.11)$$

The formulations, and corresponding parameters, of UCK_i and CK_i are described in 4.1.2.3 and 4.1.2.4.

A calculation example for usage of the above formulas is described in figure 24 below. Only 4.4, 4.6 and 4.8 are compared, because the other formulas are similar.

Consider the same example subassembly as the latter. A subassembly X consists of 100 part types and needs to be assembled in Hal 04. Pre-assembly. These 10 part types can be divided into 50 part types from Lift pick area, 30 from POD pick area and 20 from Heavy pick area.

The amount of pallets for Kanban replenishment needed per subassembly X is 1.5 for coated parts and 1 for uncoated parts. Thus $UCP_i = 1$ and $CP_i = 1.5$.

The fixed parameters, see table 2, are the parameters given by ELT, DB, D04, D02, D08, TL and V. With use of these parameters the time reckoned for uncoated pallets, α_{04}, and coated pallets, β_{04} can be determined.

$$\alpha_{04} = (1 + ELT) \cdot \left(\frac{DB + D04}{V} + TL\right) = 157.5\ seconds$$

$$\beta_{04} = (1 + ELT) \cdot \left(\frac{DB + 2 \cdot D08 + D04}{V} + TL\right) = 294.3\ seconds$$

Transportation time of pallets for one subassembly X from Warehouse (1) to Pre-assembly (4),$C_{tpt.kbn04}$, is then given by:

$$C_{tpt.kbn04} = \alpha_{04} \cdot \sum_i (UCP_i) + \beta_{04} \cdot \sum_i (CP_i)$$

$$C_{tpt.kbn04} = 157.5 \cdot 1 + 294.3 \cdot 1.5 = 599.0\ seconds$$

FIGURE 24 CALCULATION EXAMPLE FOR FORMULAS (4.4), (4.6) AND (4.3)

The total cost of transport is $C_{tpt.kbn04}$, $C_{tpt.kbn02}$, $C_{tpt.kit04}$ or $C_{tpt.kit02}$ times the operator cost per second, *OC*.

4.1.2.2 Parameters of time cost formulations

In the time cost formulations of the previous section multiple parameters are used. These parameters are either fixed or variable. The fixed parameters, see table 2, are the parameters given by PP_1, PP_2, $Pick_1$, $Pick_2$, $Pick_3$, $Pick_4$, *DB, D08, D04, D02, ELT, TL, V* and *CO*. Each of these parameters is determined by use of calculations, estimations of facts.

Fixed Parameters				
Parameter:		**Unit:**	**Value:**	**Source:**
PP_1	Average part placement time per (kit) pallet.	s	60	*Estimation.* This parameter, in accordance with Dewulf, is added to account for the time needed to place parts on a (kit) pallet in the main area of Warehouse (1).
PP_2	Average kit preparation time per kit pallet.	s	90	*Estimation.* This parameter, in accordance with Dewulf, is added to account for the time needed to prepare a kit for part placement in the main area of Warehouse (1).
$Pick_1$	Average picking time in Lift pick area per pick.	s	36	*Logistic management supplier.* Management of logistic operations is arranged by an external supplier, which claims

				that 100 Lift picks per hour are achievable.
$Pick_2$	Average picking time in POD pick are per pick.	s	72	*Logistic management supplier.* Management of logistic operations is arranged by an external supplier, which claims that 50 POD picks per hour are achievable.
$Pick_3$	Average picking time in Heavy pick area per pick.	s	225	*Logistic management supplier.* Management of logistic operations is arranged by an external supplier, which claims that 16 Heavy picks per hour are achievable.
$Pick_4$	Average picking time in Kanban far per pick.	s	72	*Estimation.* This parameter, in accordance with Dewulf, is added to account for the picking time in Kanban far. The value of 72 seconds is stated by Dewulf as the least amount of time needed for such a pick.
DB	Distance Warehouse (1) to Advanced warehouse (2).	m	130	*Fact.* Measurement of average travel distance from area to area.
D08	Distance Advanced warehouse (2) to Coating (3).	m	95	*Fact.* Measurement of average travel distance from area to area.
D04	Distance Advanced warehouse (2) to Pre-assembly (4).	m	25	*Fact.* Measurement of average travel distance from area to area.
D02	Distance Advanced warehouse (2) to Final assembly (5).	m	245	*Fact.* Measurement of average travel distance from area to area.
ELT	Ratio of empty to loaded travels.	%	0.20	*Estimation.* This parameter, in accordance with Dewulf, is added to account for the efficiency of transport operations. Dewulf states that in a good scenario 80% of the travels are loaded.
TL	Average lift time per pallet.	s	30	*Estimation.* This parameter, in accordance with Dewulf, is added to account for the height difference of Warehouse (1) and Advanced warehouse (2).

V	Average speed of a forklift truck.	m/s	2.22222	*Estimation.* This parameter, in accordance with Dewulf, is added to account for speed which is achieved by a forklift truck, including stoppages and accelerations.
CO	Operator cost per second.	€/s	0.00833	*Estimation*. An average cost of operators is assumed to be 30€ per hour.

TABLE 2 FIXED PARAMETERS OF TIME COST FORMULATIONS

The variable parameters given by $T_{1.i}$, $T_{2.i}$, UCP_i, CP_i, UCK_i, CK_i, $L_{1.i}$, $L_{2.i}$, $P_{1.i}$, $P_{2.i}$, $H_{1.i}$, and $H_{2.i}$ are calculated by use of the formulations in 4.1.2.3.

4.1.2.3 Additional formulations

Besides the values of the fixed parameters of the time cost formulations, additional formulations are used to find the variable parameters. These parameters are obtained from calculations with use of information retrieved from BOM lists and ERP database. An additional formulation is proposed for the *Amount of reckoned picks, Amount of (kit) pallets* and *Travel time*.

In order to describe the additional formulations, the below list clarifies the meaning of the extra symbols used. Symbol j states the BOM list row number.

Symbols:

- CAP_{ij} = Cumulative amount of the part on a BOM list row.
- PDL_{ij} = Largest dimension of the part on a BOM list row.
- PDS_{ij} = Smallest dimension of the part on a BOM list row.
- PS_{ij} = Utilised space of the part if placed in kit on a BOM list row.
- PV_{ij} = Volume of the part on a BOM list row.
- PW_{ij} = Weight of the part on a BOM list row.
- GPW_{ij} = Maximum grabbing potential in terms of weight of the part on a BOM list row.
- KOQ_{ij} = Kanban order quantity of the part type in the BOM list.
- OP_{ij} = Occurrence of part type in BOM list.
- SOP_{ij} = Sum of occurrence of part type in BOM list.
- $RQ_{k.ij}$ = Kanban replenishment quantity of part type on a BOM list row in terms of transport appliances considering symbol *k* representing a value for a Bito bin, Lager bin or Pallet/Ugly.
- GW = Maximum possible amount of weight grabbed if multiple parts are picked at once.
- GP_L = Maximum possible amount of parts grabbed at once considering Lift pick parts.
- GP_P = Maximum amount of parts grabbed at once considering POD pick parts.
- BR = Boundary box reduction.
- ER = Efficiency reduction of the maximum amount of SKU on travel piece.
- KMQ = Maximum Kanban replenishment quantity for a part in BOM list.
- MV_k = Maximum volume in transport/storage appliance, where symbol *k* can represent a value of a Bito bin, Lager bin or Pallet/Ugly.
- MS_P = Maximum square meter space on a kit pallet.
- CA_{LB} = Possible amount of Lager bin capacity on a pallet.
- CA_{BB} = Possible amount of Bito bin capacity on a pallet.
- l = Length of the storage rack in the Lift pick area.
- h = Length of the storage rack in the Heavy pick area.
- A = Amount of parallel aisles in the y-direction in the POD pick area.

- s = Amount of storage locations per aisle in the POD pick area.
- $N_{1.i}$ = Amount of different items to pick in an order in the POD pick area considering Kanban replenishment.
- $N_{2.i}$ = Amount of different items to pick in an order in the POD pick area considering Kit replenishment.
- y = Length of the storage rack along the aisle in the y-direction in the POD pick area.
- x = Length of the storage rack along the cross-aisle in the x-direction in the POD pick area.
- DL_i = Estimated travel distance in the aisle of the Lift pick area.
- $DP_{1.i}$ = Estimated travel distance in the aisles of the POD pick area considering Kanban replenishment.
- $DP_{2.i}$ = Estimated travel distance in the aisles of the POD pick area considering Kit replenishment.
- DH_i = Estimated travel distance in the aisle of the Heavy pick area.
- W_j = Help variable indicating the storage/transport appliances in BOM list row j.

In order to prepare the data, parts are filtered on their characteristics. The consideration of the filter values has arisen from discussion with Dewulf. The filter values are stated below.

The classification of parts is executed on:

- Bulk parts have a demand in a BOM list of 12 or more.
- Würth parts are the parts stated as such in the requirements planning from ERP.
- Lift pick parts are the parts that fit in a Bito bin and are not too heavy, meaning a maximum of 15 kilograms per part.
- POD pick parts are the parts that fit on a pallet, or Lager bin, and are not too heavy, meaning a maximum of 15 kilograms per part.
- Heavy pick parts are the parts which do not fit a regular Euro pallet.
- Single parts are the parts that do not fit on a kit pallet/ugly, and all parts that to do not fit in any of the profiles described above.

As described earlier Bulk, Single and Würth parts do not play a role in consideration of the least time costly material feeding principle. The only impact of these parts is the available space in assembly, but this will be addresses in this report later on. The Lift pick, POD pick and Heavy pick parts cause for the difference in time costs and are therefore examined.

Amount of reckoned picks

The amount of reckoned picks depends on the size, weight and occurrence of a part. These part characteristics are found by use of adapting a BOM list with part information from database. Limère et al. (2012) describe a possibility of picking multiple parts if the size allows it. However, the specification of the possible amount to pick corresponding to size is not stated. At Dewulf the warehouse layout differs for Lift, POD and Heavy parts.

Kanban replenishment is affected by the amount of reckoned picks due to the replenishment quantity. Large replenishment quantities may result in advantages for picking multiple parts at once and cause for less transportation. The replenishment quantity is depended on the maximum Kanban replenishment quantity for a part, *KMQ*, the sum of occurrence of the part type on a BOM list row, SOP_{ij}, the maximum volume of parts in transport appliance, *k*, and the part volume on a BOM list row, PV_{ij}. *k* represents a value for a BB (Bito bin), LB (Lager bin) or P (Pallet). It is assumed that there is a maximum of part capacity preferred in assembly, which is resembled by the value of *KMQ*.

When the bin or pallet can fit (more than) *KMQ* times the part type demand in BOM list, SOP_{ij}, than the Kanban order quantity for the warehouse, KOQ_{ij}, is given by multiplying the maximum Kanban replenish quantity, *KMQ*, with the sum of occurrence of the part type in BOM list, SOP_{ij}. Thus when the volume of the part, PV_{ij}, does not fit the volume of the transport appliance *k*, MV_k, as much as *KMQ* times SOP_{ij}, the Kanban order quantity, KOQ_{ij}, is given by dividing the volume of *k*, MV_k, by the part volume, PV_{ij}. This last value is rounded down, as no portion of a part can be fitted.

$$KOQ_{ij} = \begin{cases} KMQ \cdot SOP_{ij}, & \frac{MV_k}{PV_{ij}} \geq KMQ \cdot SOP_{ij} \\ \left\lfloor \frac{MV_k}{PV_{ij}} \right\rfloor, & \frac{MV_k}{PV_{ij}} < KMQ \cdot SOP_{ij} \end{cases} \tag{4.12}$$

For both Kanban and Kit, a potential to grab multiple parts is accounted for. The possibility to grab more parts at once, as described earlier, is also used in the research of Limère et al. (2012). The potential to pick multiple parts is assumed to be affected by size and weight of a part.

The maximum grabbing potential in terms of weight, GPW_{ij}, is equally affecting parts from Lift and POD. The Heavy pick parts are assumed to be always picked per piece. As for Lift and POD pick parts the maximum possible amount of weight grabbed if multiple parts are picked at once, *GW*, limits the possibilities of grabbing multiple parts. When the part weight, PW_{ij}, has more weight than *GW*, the amount of parts to be picked at once equals one. Else dividing the weight limit, *GW*, by the part weight PW_{ij}, results in the maximum amount of parts picked at once in terms of weight, GPW_{ij}. This value is rounded down, as no portion of a picking action can be executed.

$$GPW_{ij} = \begin{cases} 1, & PW_{ij} \geq GW \\ \left\lfloor \frac{GW}{PW_{ij}} \right\rfloor, & PW_{ij} < GW \end{cases} \tag{4.13}$$

Consider parts which are filtered as Lift pick parts. The amount of reckoned lift picks when Kanban replenishment is used, $L_{1.i}$, is equal to the cumulative amount of the part on the BOM list row, CAP_{ij}, when the maximum amount of parts picked at once, GPW_{ij}, is equal to 1. If the maximum amount to be picked at once, GPW_{ij}, is larger than 1, the calculation is different. So multiple parts can be picked in terms of weight, but in terms of size, GP_L, is added to limit picking possibilities due to physical boundaries. The minimum of those values, GPW_{ij} and GP_L, denotes the possible amount of reckoned parts to be picked at once. The amount of picks needed to pick the Kanban order quantity, KOQ_{ij}, is given by dividing with the minimum of GPW_{ij} and GP_L. This result is divided by the occurrence of the part, OP_{ij}, in order to account for the multiple BOM list rows with the same part type. A maximum of 1 and the last resulting value causes for counting at least 1 pick, as the grab potential of parts can be higher as the Kanban order quantity, KOQ_{ij}. Multiplying this maximum value with the sum of occurrence, SOP_{ij}, divided by the Kanban order quantity, KOQ_{ij}, gives the amount of reckoned Lift pick parts when Kanban replenishment is used, $L_{1.i}$. The last multiplication yields the amount of picks per end product.

$$L_{1.i} = \sum_j \begin{cases} 0, & W_j \neq 1 \\ CAP_{ij}, & GPW_{ij} = 1 \\ \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot \frac{max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{GP_L, GPW_{ij}\}} \right\rceil \right\}}{OP_{ij}}, & GPW_{ij} > 1 \end{cases} \tag{4.14}$$

The amount of reckoned Lift picks when Kit replenishment is used, $L_{2.i}$, is equal to the cumulative amount of the part on the BOM list row, CAP_{ij}, when the maximum amount of parts picked at once, GPW_{ij}, is equal to 1. If the maximum amount to be picked at once, GPW_{ij}, is larger than 1, the calculation is different. So multiple parts can be picked in terms of weight, but in terms of size, GP_L, is added to limit picking possibilities due to physical boundaries. The minimum of those values, GPW_{ij} and GP_L, denotes the possible amount of reckoned parts to be picked at once. The amount of picks needed to pick the end product demand given by the sum of occurrence, SOP_{ij}, is given by dividing with the minimum of GPW_{ij} and GP_L. This result is divided by the occurrence of the part, OP_{ij}, in order to account for the multiple BOM list rows with the same part type. A maximum of 1 and the last resulting value causes for counting at least 1 pick, as the grab potential of parts can be higher as the sum of occurrence, SOP_{ij}. There is no multiplication with a replenishment quantity like with the reckoned picks for Kanban, because only the sum of occurrence facilitates Kit replenishment at assembly.

$$L_{2.i} = \sum_j \begin{cases} 0, \; W_j \neq 1 \\ CAP_{ij}, \; GPW_{ij} = 1 \\ \frac{max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{GP_L, GPW_{ij}\}} \right\rceil \right\}}{OP_{ij}}, \; GPW_{ij} > 1 \end{cases} \tag{4.15}$$

Consider parts which are filtered as POD pick parts. The calculation of the amount of reckoned POD picks when Kanban replenishment is used, $P_{1.i}$, is executed in the same way as the calculation of the amount of the reckoned Lift picks, when Kanban replenishment is used, $L_{1.i}$. The only difference is that the maximum amount of parts grabbed at once considering POD pick parts, GP_P, differs from the maximum amount of parts grabbed at once considering Lift pick parts, GP_L.

$$P_{1.i} = \sum_j \begin{cases} 0, \; W_j \neq 2 \\ CAP_{ij}, \; GPW_{ij} = 1 \\ \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot \frac{max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{GP_P, GPW_{ij}\}} \right\rceil \right\}}{OP_{ij}}, \; GPW_{ij} > 1 \end{cases} \tag{4.16}$$

The calculation of the amount of reckoned POD picks when Kit replenishment is used, $P_{2.i}$, is executed in the same way as the calculation of the amount of reckoned Lift picks, when Kit replenishment is used, $L_{2.i}$. The only difference is that the maximum amount of parts grabbed at once considering POD pick parts, GP_P, differs from the maximum amount of parts grabbed at once considering Lift pick parts, GP_L.

$$P_{2.i} = \sum_j \begin{cases} 0, \; W_j \neq 2 \\ CAP_{ij}, \; GPW_{ij} = 1 \\ \frac{max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{GP_P, GPW_{ij}\}} \right\rceil \right\}}{OP_{ij}}, \; GPW_{ij} > 1 \end{cases} \tag{4.17}$$

Consider parts which are filtered as Heavy pick parts. The amount of reckoned Heavy pick parts, $H_{1.i}$ and $H_{2.i}$, is the same as the sum of the cumulative amount of the part type on a BOM list row, CAP_{ij}. Due to the size of Heavy pick parts, multiple parts are not possible to be picked at once. The amount of reckoned picks for Kit and Kanban is therefore also the same.

$$H_{1.i} = H_{2.i} = \sum_j \begin{cases} 0, \; W_j \neq 3 \\ CAP_{ij}, \; W_j = 3 \end{cases} \tag{4.18}$$

Amount of (kit) pallets

The variables UCP_i, CP_i, UCK_i and CK_i are the amount of (kit) pallets needed in order to facilitate the assembly of one end product.

The amount of pallets needed for Kanban replenishment of one end product is derived from the amount transport appliances are needed on average. This value is influenced by the amount of pallets needed to be transported by the point-to-point transport of a forklift truck. Therefore the Bito bins and Lager bins are placed on pallets, whereas a capacity, CA_{BB} and CA_{LB}, is estimated. In literature the capacity is often denoted as the capacity of boxes on a tugger train and some larger parts for a point-to-point transport. However, the parts on pallets are already parts that are stored on pallets in their warehouse, so no combined transport on pallets is arranged.

Replenishment quantity of a part on a BOM list row, $RQ_{k.ij}$, for Bito bins, Lager Bins and Pallets is calculated in the same way. The Kanban replenishment quantity of part type on a BOM list row, $RQ_{k.ij}$, is given by dividing the sum of occurrence of the part type, SOP_{ij}, by the product of the Kanban order quantity of the part type, KOQ_{ij}, and the occurrence of the part type, OP_{ij}. Where symbol k represents a value for a Bito bin (BB), Lager bin (LB) or Pallet/Ugly (P). The sum of occurrence divided by the Kanban order quantity gives the replenishment amount, but as a part can appear multiple times in BOM, the ratio has to be divided by occurrence in BOM list.

$$RQ_{k.ij} = \frac{SOP_{ij}}{(KOQ_{ij} \cdot OP_{ij})} \tag{4.19}$$

Consider the amount of pallets needed for uncoated parts, UCP_i, and coated parts, CP_i. The calculation of these pallet amounts is the same. As said above, the replenishment is done by use of point-to-point transport, such that all transport appliances need to be translated to a pallet amount. This is achieved by use of a determined Bito bin and Lager bin pallet capacity, given by CA_{BB} and CA_{LB}. To accommodate for the stated efficiency reduction, ER, the capacity is reduced by this factor. Therefore the amount of pallets needed for either UCP_i or CP_i, can be given by the sum of the amount of replenishment Bito bins needed, $RQ_{BB.ij}$, divided by the pallet capacity of Bito bins, CA_{BB}, times the efficiency reduction, ER, the amount of replenishment Lager bins needed, $RQ_{LB.ij}$, divided by the pallet capacity of Lager bins, CA_{LB}, times the efficiency reduction, ER, and the amount of replenishment pallets needed, $RQ_{P.ij}$.

When final treatment of a part is not marked with the words "Wet Coating", the parts are accounted for in the amount of pallets needed for coated parts, UCP_i.

$$UCP_i = \sum_j \begin{cases} 0, & \text{Final treatment "Wet Coating"} \\ \left(\frac{RQ_{BB.ij}}{CA_{BB} \cdot ER} + \frac{RQ_{LB.ij}}{CA_{LB} \cdot ER} + RQ_{P.ij}\right), & \text{Final treatment is not "Wet Coating"} \end{cases} \tag{4.20}$$

When final treatment of a part is marked with the words "Wet Coating", the parts are accounted for in the amount of pallets needed for coated parts, CP_i.

$$CP_i = \sum_j \begin{cases} \left(\frac{RQ_{BB.ij}}{CA_{BB} \cdot ER} + \frac{RQ_{LB.ij}}{CA_{LB} \cdot ER} + RQ_{P.ij}\right), & \text{Final treatment "Wet Coating"} \\ 0, & \text{Final treatment is not "Wet Coating"} \end{cases} \tag{4.21}$$

The amount of Kit pallets needed for assembly of one end product, UCK_i and CK_i, are calculated differently. The Kit pallets have a maximum size and the parts need to be fit on those pallets. As described earlier, coated and uncoated parts are split up due to their route and treatment. The fitting of parts is assumed affected by the boundary box of parts, therefore the size of parts is reduced with a boundary box reduction, BR. In order to calculate the footprint of a part on the Kit pallet, PS_{ij}, the largest dimension of the part, PDL_{ij}, is multiplied with the smallest dimension, PDS_{ij}.

$$PS_{ij} = PDL_{ij} \cdot PDS_{ij} \tag{4.22}$$

Consider the amount of Kit pallets needed for uncoated parts, UCK_i, and coated parts, CK_i. The calculation of these Kit pallet amounts is the same. With use of the space per part, PS_{ij}, the total space needed on a Kit pallet can be calculated. The amount of Kit pallets needed can be given by the boundary box reduction, *BR*, divided by the maximum available space on a Kit pallet, MS_P, times the sum of the cumulative amount of parts on a BOM list row, CAP_{ij}, times space per part, PS_{ij}.

When final treatment of a part is not marked with the words “Wet Coating”, the parts are accounted for in the amount of pallets needed for coated parts, UCK_i.

$$UCK_i = \left\lceil \frac{BR}{MS_P} \cdot \sum_j \begin{cases} 0, & \textit{Final treatment "Wet Coating"} \\ (CAP_{ij} \cdot PS_{ij}), & \textit{Final treatment is not "Wet Coating"} \end{cases} \right\rceil \tag{4.23}$$

When final treatment of a part is marked with the words “Wet Coating”, the parts are accounted for in the amount of pallets needed for coated parts, CK_i.

$$CK_i = \left\lceil \frac{BR}{MS_P} \cdot \sum_j \begin{cases} (CAP_{ij} \cdot PS_{ij}), & \textit{Final treatment "Wet Coating"} \\ 0, & \textit{Final treatment is not "Wet Coating"} \end{cases} \right\rceil \tag{4.24}$$

Travel time in Warehouse

The variables, $T_{1.i}$ and $T_{2.i}$, are the amount of travel time in warehouse (1) for Kanban replenishment and respectively Kit replenishment. The travel time is build up by the amount of travel needed in the Lift, POD and Heavy pick areas, and the speed of the picker, *V*.

The travel distance needed for Lift pick parts is given by the needed travel distance in the aisle of the lift pick area. The average distance when a pick needs to be made is half the distance of the aisle length, *l*. However the pick route needs to end with traversing back to the beginning of the aisle, thus the total distance is two times a half distance which is the total length of the aisle, *l*.

$$DL_i = \begin{cases} 0, & L_{1.i} = 0 \\ l, & L_{1.i} > 0 \end{cases} \tag{4.25}$$

The travel distance needed for Heavy pick parts is given in the same analogous manner as Lift pick parts. Thus the travel distance when a Heavy pick needs to be made is given by the length of the Heavy pick area, *h*.

$$DH_i = \begin{cases} 0, & H_{1.i} = 0 \\ h, & H_{1.i} > 0 \end{cases} \tag{4.26}$$

The travel distance of POD pick parts is given by a milk-run through the layout of the aisles in the POD pick area. The travel distance can be estimated by the described estimation method of Schuur (2016). This distance approximation is build up by the amount of parallel aisles in the y-direction, *A*, the amount of available storage locations per aisle, *s*, the amount of different POD items to pick in an order, $N_{1.i}$ or $N_{2.i}$, the length of the storage rack along the aisle in the y-direction, *y*, and the length of storage rack along the cross-aisle in the x-direction, *x*.

The amount of different POD items to pick in an order, $N_{1.i}$ or $N_{2.i}$, differ. When using Kanban replenishment, the amount of different picks, $N_{1.i}$, is influenced by the replenishment quantity, $RQ_{k.ij}$, and the occurrence of parts, OP_{ij}. The amount of different picks, $N_{1.i}$, can be calculated by the replenishment quantity, $RQ_{k.ij}$, divided by the occurrence of the part in BOM list, OP_{ij}. Replenishment quantity is used because all POD pick locations do not need to be visited for each end product. The division of the occurrence accommodates the real number of different part locations, as parts can be present in the BOM list multiple times.

$$N_{1.i} = \sum_j \begin{cases} 0, & W_j \neq 2 \\ \frac{RQ_{k.ij}}{OP_{ij}}, & W_j = 2 \end{cases} \quad (4.27)$$

When using Kit replenishment all needed POD part locations have to be visited. Therefore only an accommodation for the part types that appear multiple times is present. The amount of different reckoned POD picks in Kit replenishment, $N_{2.i}$, can be calculated by dividing 1 by the occurrence of the part in BOM list, OP_{ij}.

$$N_{2.i} = \sum_j \begin{cases} 0, & W_j \neq 2 \\ \frac{1}{OP_{ij}}, & W_j = 2 \end{cases} \quad (4.28)$$

The actual travel distance approximation in the POD pick area can be given by the formula of Schuur (2016). The travel distance needed for picking POD parts, $DP_{1.i}$ and $DP_{2.i}$, is given by the distance travelled when making a milk-run in the aisles of the POD pick area. This distance is build up by the approximation in the x- and y-direction.

The travel distance in the POD pick area for Kanban replenishment is given by $DP_{1.i}$.

$$DP_{1.i} = \begin{cases} 0, & N_{1.i} = 0 \\ A \cdot y\left(1 - \frac{\left(\frac{(A-1)\cdot s}{N_{1.i}}\right)}{\left(\frac{A\cdot s}{N_{1.i}}\right)}\right) + \left(1 - \left(\frac{1}{2}\right)^{N_{1.i}-1}\right)\left(2x\left(\frac{N_{1.i}-1}{N_{1.i}+1}\right)\right) + \left(\frac{1}{2}\right)^{N_{1.i}-1} x\left(\frac{N_{1.i}}{N_{1.i}+1}\right), & N_{1.i} > 0 \end{cases} \quad (4.29)$$

The travel distance in the POD pick area for Kit replenishment is given by $DP_{2.i}$. Only the amount of possible part locations to be visited is differing due to the amount of different POD part types needed, $N_{1.i}$ or $N_{2.i}$.

$$DP_{2.i} = \begin{cases} 0, & N_{2.i} = 0 \\ A \cdot y\left(1 - \frac{\left(\frac{(A-1)\cdot s}{N_{2.i}}\right)}{\left(\frac{A\cdot s}{N_{2.i}}\right)}\right) + \left(1 - \left(\frac{1}{2}\right)^{N_{2.i}-1}\right)\left(2x\left(\frac{N_{2.i}-1}{N_{2.i}+1}\right)\right) + \left(\frac{1}{2}\right)^{N_{2.i}-1} x\left(\frac{N_{2.i}}{N_{2.i}+1}\right), & N_{2.i} > 0 \end{cases} \quad (4.30)$$

The estimated total travel time in Warehouse (1) when Kanban order quantities apply, $T_{1.i}$, is then given by the sum of the travel distances in the Lift pick area, DL_i, the POD pick area, $DP_{1.i}$, and the Heavy pick area, DH_i divided by the speed of the picker, V.

$$T_{1.i} = \frac{(DL_i + DP_{1.i} + DH_i)}{V} \quad (4.31)$$

The estimated total travel time in Warehouse (1) when Kit order quantities apply, $T_{2.i}$, is then given by the sum of the travel distances in the Lift pick area, DL_i, the POD pick area, $DP_{2.i}$, and the Heavy pick area, DH_i divided by the speed of the picker, V.

$$T_{2.i} = \frac{(DL_i + DP_{2.i} + DH_i)}{V} \quad (4.32)$$

4.1.2.4 Parameters of additional formulations

Fixed parameters are:

Fixed Parameters				
Parameter:		**Unit:**	**Value:**	**Source:**
ER	Efficiency reduction of the maximum amount of SKU on a travel piece.	%	0.90	Estimation.
BR	Boundary box reduction.	%	0.90	Estimation.

MS_P	Maximum square meter space on a kit pallet.	m^2	3.24	Fact.
CA_{BB}	Possible amount of Bito bin capacity on a pallet.	pieces	20	Estimation.
CA_{LB}	Possible amount of Lager bin capacity on a pallet.	pieces	4	Estimation.
MV_k	Maximum volume in transport/storage appliance, where symbol *k* can represent a value of a Bito bin, Lager bin or Pallet/Ugly.	m^3	BB: 0.0205 LB: 0.0300 P: 2.4300	Fact.
KMQ	Maximum Kanban replenishment quantity for a part in BOM list.	pieces	6	Estimation.
GW	Maximum possible amount of weight grabbed if multiple parts are picked at once.	kg	5	Estimation.
GP_L	Maximum possible amount of parts grabbed at once considering Lift pick parts.	pieces	5	Estimation.
GP_P	Maximum amount of parts grabbed at once considering POD pick parts.	pieces	2	Estimation.
l	Length of the storage rack in the Lift pick area.	meter	11.5	Fact.
h	Length of the storage rack in the Heavy pick area.	meter	36.0	Fact.
A	Amount of parallel aisles in the y-direction in the POD pick area.	pieces	8	Fact.
s	Amount of storage locations per aisle in the POD pick area.	pieces	45	Fact.
y	Length of the storage rack along the aisle in the y-direction in the POD pick area.	meter	40	Fact.
x	Length of the storage rack along the cross-aisle in the x-direction in the POD pick area.	meter	2.4	Fact.
W_j	Help variable indicating the storage/transport appliances.	N/A	0: Not assigned 1: Lift 2: POD 3: Heavy	Calculation.

TABLE 3 FIXED PARAMETERS OF ADDITIONAL FORMULATIONS

The remainder of the variable parameters for the additional formulations are gathered from BOM list and their values are depended on the characteristics of the parts.

4.2 Identifying preference conditions

With use of the previous section condition can be found where one policy is preferred in terms of time costs. As mentioned earlier, the identification of preference conditions is done in steps.

First scenario 1 and 4 are compared, in section 4.2.1, in order to find the preferences for either a pure Kit replenishment policy or line stocking with Kanban replenishment policy. The preferences for a pure policy are on subassembly level. Subassembly level means that all parts in a lower level of BOM are accounted for in the calculation. When considering the BOM list example of table 4, the preference conditions are found for subassembly 11 and 12 that are each built up by all underlying parts.

When these conditions are found, the preferences are found on part level. Part level means that the preference conditions are found for each distinct part used in an assembly. Some parts may best be treated differently, under certain conditions, as opposed to the pure policy. This means that scenarios 1 and 2 and scenarios 3 and 4 are compared. In the BOM list example of table 4 the preference conditions are found for part 11A, 11B and 11B and 12A. If kitting is best for Subassembly 11, Part 11A, 11B and 11C are fed by use of a kit, with the exception of conditions where one of these parts are least time costly in Kanban close. Then such a part can be excluded from the kit and is stored in Kanban close.

Number	Name	Level
0100	Product 1	0
0110	Subassembly 11	1
0111	Part 11A	2
0112	Part 11B	2
0113	Part 11C	2
0120	Subassembly 12	1
0121	Part 12A	2

TABLE 4 BOM LIST EXAMPLE

4.2.1 Preference conditions for a pure policy

Firstly conditions are found wherefore a pure policy is best. The pure policy stands for a gross advantage of either kit or Kanban far, and therefore either dock or line assembly. Scenarios 1 and 4 are compared in order to find the conditions where dock or line is in favour, see figure 25.

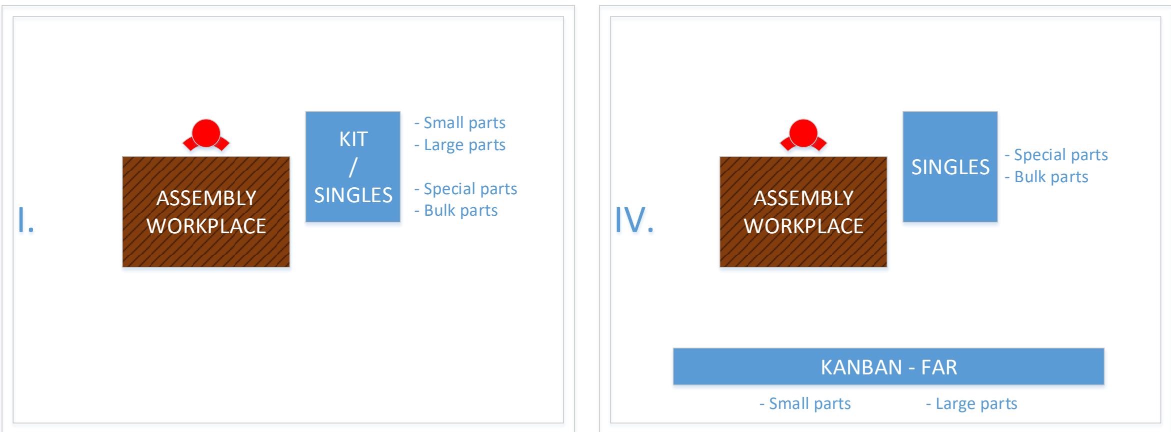


FIGURE 25 SCENARIO 1 VERSUS 4

The time cost formulations in section 4.1 are used to find a time difference for parts supplied by use of kit or line stocking with Kanban. These time cost formulations are used to evaluate two distinct subassemblies from the Dewulf 3060. In order to make use of the time cost formulations the BOM lists are edited. Part characteristics are added by use of information from ERP.

The adjusted BOM is filtered on the parts which are relevant for comparison. Only parts that are actually used in assembly are allocated to a material feeding principle. Which is accommodated by finding the parts in BOM that are part of a higher level assembly step and have no remaining assembly steps. These parts cause for a so called "stop explosion" once moving through a BOM list. Meaning, that al underlying parts of a (higher level) stop explosion characterisation are not considered.

Among the marked parts, with a stop explosion, there are still parts which are not considered in this research or have no influence on the comparison. These parts are mainly small parts, like nuts and bolts, from a certain supplier named Würth. These Würth parts are considered to be present in assembly. Singles and bulk part types are also considered to be present in assembly and the replenishment operations are the same for all feeding policies. However, Würth, single and bulk parts do consume space in assembly.

At last the additional formulations of 4.1.2.3 are used on the remaining parts. The resulting parameters which are determined by use of the adjusted BOM lists are visualised in table 5.

		Subassembly: Bunker 3060	*Subassembly: Egelband 3060*	*Unit:*
Parameter:		**Value:**	**Value:**	
KANBAN				
$T_{1.i}$	Travel time in Warehouse (1) when Kanban order quantities apply.	55.89	29.23	seconds
UCP_i	Amount of pallets needed for uncoated parts.	1.29	0.65	pieces
CP_i	Amount of pallets needed for coated parts.	2.38	1.55	pieces
$L_{1.i}$	Amount of reckoned Lift picks when Kanban order quantities apply.	29.98	22.33	pieces
$P_{1.i}$	Amount of reckoned POD picks when Kanban order quantities apply.	12.00	2.50	pieces
$H_{1.i}$	Amount of reckoned Heavy picks when Kanban order quantities apply.	12.00	10.00	pieces
KIT				
$T_{2.i}$	Travel time in Warehouse (1) when Kit order quantities apply.	129.65	59.18	seconds
UCK_i	Amount of kits needed for uncoated parts.	1.00	1.00	pieces
CK_i	Amount of kits needed for coated parts.	1.00	1.00	pieces
$L_{2.i}$	Amount of reckoned Lift picks when Kit order quantities apply.	52.00	41.00	pieces
$P_{2.i}$	Amount of reckoned POD picks when Kit order quantities apply.	12.00	3.00	pieces
$H_{2.i}$	Amount of reckoned Heavy picks when Kit order quantities apply.	12.00	10.00	pieces

TABLE 5 PARAMETER VALUES OF TWO SUBASSEMBLIES

As can be seen in table 5:

- The travel time in Warehouse (1) for Kitting, $T_{2.i}$, is higher than the travel time for Kanban, $T_{1.i}$, for both subassemblies.
- The combined amount of reckoned pallets, UCP_i and CP_i, for both subassemblies are larger than the amount of kits, UCK_i and CK_i, needed.
- The amount of reckoned Lift picks for Kitting, $L_{2.i}$, are almost twice as large as the amount of reckoned picks for Kanban, $L_{1.i}$.
- The amount of POD picks, $P_{1.i}$ and $P_{2.i}$ is somewhat the same for Kanban and Kitting for both subassemblies.
- The amount of reckoned heavy picks are somewhat the same for both subassemblies.

The found parameters were expected to be different in terms of composition of Heavy, POD and Lift parts. The *Bunker 3060,* one of the largest subassemblies, is much larger than the *Egelband 3060*. The needed time in assembly is approximately four times longer for *Bunker 3060*. Hence the amount of pallets needed, UCP_i and CP_i, is indeed much larger. Although the total amount of needed kit pallets is still 2. In addition, the amount of Heavy picks was expected to be much higher for the *Bunker 3060*, but this can be explained by the fact that 8 bulk and 4 single part types are filtered out. While such parts are not found in *Egelband 3060*. At last, the amount of kits, UCK_i and CK_i, is rounded to whole kits, but the possibility to combine parts efficiently leads to less kit pallets in comparison with the needed amount of Kanban pallets, UCP_i and CP_i.

Results of time cost formulations using the above parameters are given in table 6 below. The parts are both subassemblies which are made in Pre-assembly (4).

	Subassembly: Bunker 3060	*Subassembly: Egelband 3060*
Time cost:	**Value:**	**Value:**
KANBAN		
$C_{pick.kbn1}$	4919.36	3395.32
$C_{pick.kbn2}$	5472.00	3888.00
$C_{tpt.kbn04}$	683.29	422.65
Total time cost in seconds	**11074.65**	**7705.97**
KIT		
$C_{pick.kit}$	5865.65	4301.21
$C_{tpt.kit04}$	342.00	342.00
Total time cost in seconds	**6207.65**	**4643.21**
Advantage of KIT	44%	40%

TABLE 6 RESULTING TIME COSTS OF TWO SUBASSEMBLIES

The total time costs for Kanban replenishment are according to Dewulf representing reality in a sufficient way. The results of the calculations show a convincing advantage of Kitting over Kanban far. Namely 44% and 40% less time for respectively *Bunker 3060* and *Egelband 3060*. The greatest time difference is due to the picking activity from Kanban far in assembly. However, against all expectations, the amount of travelling pallets per end product is also higher than the required amount of kits. So the transport timess are higher. The main favour of Kanban over kitting is the ability to pick efficiently in Warehouse (1).

With use of the found results the preference conditions can be found more easily. Some scenarios can be excluded beforehand. These scenarios are not likely to happen, thus can be left out of the possible solution space. These scenarios are reflected by the following statements:

- The travel distances in warehouse $T_{1.i}$ and $T_{2.i}$ are depended on the amount of lift, POD and heavy picks per subassembly. Or better said, whether or not there are lift or heavy picks to be made and the amount of different aisle locations in POD storage need to be visited. The maximum amount of travel distance is approximately 167.5 seconds. Therefore the travel distances are limited by this value.
- The amount of kits needed is most certainly 2, as is needed for one of the largest subassemblies *Bunker 3060*. However the scenarios which are examined consist of a maximum of 3 kits in total. Thus two kits for coated parts and one for uncoated parts or one kit for coated parts and two kits for uncoated parts.
- The amount of picks and Kanban pallets are variable, although there is often a dependence of picks towards needed pallet amount.

Experiments

A few experiments can be carried out with the above statements in mind. The conditions where Kanban far is better as kit replenishment are searched by use of the solver of Microsoft Excel. The goal is to find the break-even where the time costs for both feeding principles are the same. This actually means that all time costs corresponding with Kanban minus all time costs corresponding with Kit is equal to zero.

The goal is given by:

$$\left(C_{pick.kbn1} + C_{pick.kbn2} + C_{tpt.kbn04}\right) - \left(C_{pick.kit} + C_{tpt.kit04}\right) = 0 \tag{4.33}$$

This objective function is subject to the below constraints:

$$L_{1.i} \leq L_{2.i} \tag{4.34}$$

$$P_{1.i} \leq P_{2.i} \tag{4.35}$$

$$H_{1.i} = H_{2.i} \tag{4.36}$$

$$T_{1.i} \leq T_{2.i} \tag{4.37}$$

$$T_{2.i} \leq 167.5 \tag{4.38}$$

$$UCK_i + CK_i \leq 3 \tag{4.39}$$

$$UCK_i, CK_i \geq 1 \tag{4.40}$$

$$UCK_i, CK_i = integer\ value \tag{4.41}$$

$$T_{1.i}, T_{2.i}, L_{1.i}, L_{2.i}, P_{1.i}, P_{2.i}, H_{1.i}, H_{2.i}, UCK_i, CK_i \geq 0 \tag{4.42}$$

The experiments are based on the statements of the results described above. Reckoned lift picks considering Kanban replenishment cannot be higher than those reckoned for Kit replenishment (4.34). Reckoned POD picks considering Kanban replenishment cannot be higher than those reckoned for Kit replenishment (4.35). Reckoned Heavy picks are the same for both feeding policies (4.36). The amount of travel time in Warehouse (1) considering Kanban replenishment cannot be higher than the travel time reckoned for Kit replenishment (4.37). Maximum travel time in Warehouse (1) is 167.5, which corresponds with at least one pick from Lift, at least one pick from Heavy and picking from all locations in POD (4.38). To accommodate for an advantage of Kanban, there is a possibility that one extra Kit is needed to feed by use of Kit replenishment (4.39). At least one Kit is needed for coated parts and at least one Kit is needed for uncoated parts (4.40). As Kits feed one end product the amount of Kit pallets needed can only be an integer value (4.41). All parameters need to be a positive value (4.42).

Experiment 1:

If the above goal is searched with the solver, by changing all variables, the result is as shown in table 7.

Parameter:	Value:	Unit:
$T_{1.i}$	0	seconds
$T_{2.i}$	0	seconds
UCP_i	0	pieces
CP_i	2.274176	pieces
UCK_i	1	pieces
CK_i	1	pieces
$L_{1.i}$	0	pieces
$L_{2.i}$	0	pieces
$P_{1.i}$	0	pieces
$P_{2.i}$	0	pieces
$H_{1.i} = H_{2.i}$	0	pieces

TABLE 7 RESULT OF EXPERIMENT 1

A solution for the goal is found. When examining the result of the first experiment iteration, the following is marked as an issue:

- The amount of travel time is zero. This is actually true as there are no parts picked, but then there would be no replenishment at all.
- The fact that no parts are picked is not realistic, as the point of gathering the (kit) pallets has no purpose.

A next step is executed in order to reduce the latter issues.

First a few help variables, *b*, *c* and *d*, are added to accommodate the possible range of the travel time that is assigned to a feeding principle.

If $L_{1.i} > 0$ then $b = 1$, if $L_{2.i} > 0$ then $c = 1$ and if $H_{1.i} = H_{2.i} > 0$ then $d = 1$.

To overcome the issue with the travel time the following constraints are added or adjusted:

$$T_{1.i} \geq 11.5 \cdot b + 36 \cdot d \tag{4.43}$$

$$T_{2.i} \geq 11.5 \cdot c + 36 \cdot d \tag{4.44}$$

$$L_{2.i} \leq 0.6 \cdot L_{1.i} \tag{4.45}$$

$$P_{2.i} \leq 0.8 \cdot P_{1.i} \tag{4.46}$$

$$UCK_i = UCP_i \tag{4.47}$$

$$CK_i = CP_i \tag{4.48}$$

The transporting time costs of the Lift pick area and Heavy pick are represented by (4.43) and (4.44). When a help variable is one the corresponding expected travel time in that area is accounted for. To accommodate for the fact that when Lift picks in Kit are considered, there are also picks for the Kanban equivalent. The values of 60% and 80% percent in (4.45) and (4.46) are very favourable for Kanban replenishment. These percentages are assumed for this experiment, because the advantageous picking amount of Kanban will not be extremely large in practice. The amount of pallets is set to the same value as kits in (4.47) and (4.48), however in reality the amount of pallets tends to be more than the needed amount of Kit pallets.

Experiment 2:

If the goal is searched with the solver, by changing all variables and implementing the new constraints, the result is as shown in table 8.

Parameter:	Values:	Unit:
$T_{1.i}$	47.5	seconds
$T_{2.i}$	167.5	seconds
UCP_i	1	pieces
CP_i	2	pieces
UCK_i	1	pieces
CK_i	2	pieces
$L_{1.i}$	4.057292	pieces
$L_{2.i}$	6.762153	pieces
$P_{1.i}$	0	pieces
$P_{2.i}$	0	pieces
$H_{1.i} = H_{2.i}$	8.07E-09	pieces

TABLE 8 RESULT OF EXPERIMENT 2

The result shows that there is a maximum possible picks where Kanban far is best. However this is with less than 7 picks in total. Less than 7 reckoned lift parts cannot fill up 3 kit pallets. In practice there is not a subassembly with such low amount of parts. If more picks are forced with a constraint no feasible solution can be found. Also the reckoned amount of Kit pallets, pallets and travel distance is very farfetched in this result. There are no reckoned POD pick parts, but the travel distance for Kit is set to the maximum, which is not possible when no POD pick parts are needed. When POD picks would be reckoned the total amount of parts is even lower than the current result. At last the amount of (Kit) pallets needed is too high for the amount of reckoned picks.

From the above statements can be concluded that another experiment will not result in a plausible solution. Thus the conclusion is then as follows:

"***All subassemblies and their corresponding part types can best be placed in Kit, when Kanban far is the alternative solution.***"

4.2.2 Preference conditions for a hybrid policy

The next step, is to find conditions where parts are better allocated to Kanban close instead of the pure policy of Kitting or Kanban far. Result is a hybrid policy with two material feeding principles used for one Final (5) or Pre-assembly (4).

For the stated conditions in the previous section where scenario 4, thus line assembly, is least time costly the transition of scenario 4 to 3 could be compared. The transition is given by figure 26. However the Kanban far solution is not found to be better in all possible cases, thus this transition is not examined.

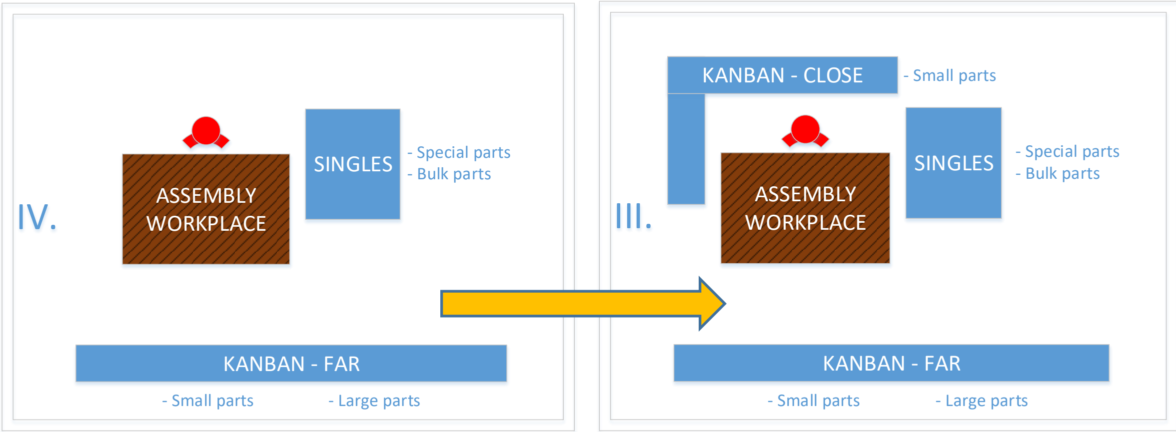


FIGURE 26 TRANSITION FROM KANBAN FAR TO KANBAN FAR WITH KANBAN CLOSE

For the stated conditions in the previous section where scenario 1, thus dock assembly, is least time costly is the transition of scenario 1 to 2 compared. The transition is given by figure 27. Then the conditions are stated for which small parts can be left out from Kit and can be placed in Kanban close such that the time costs are lowered.

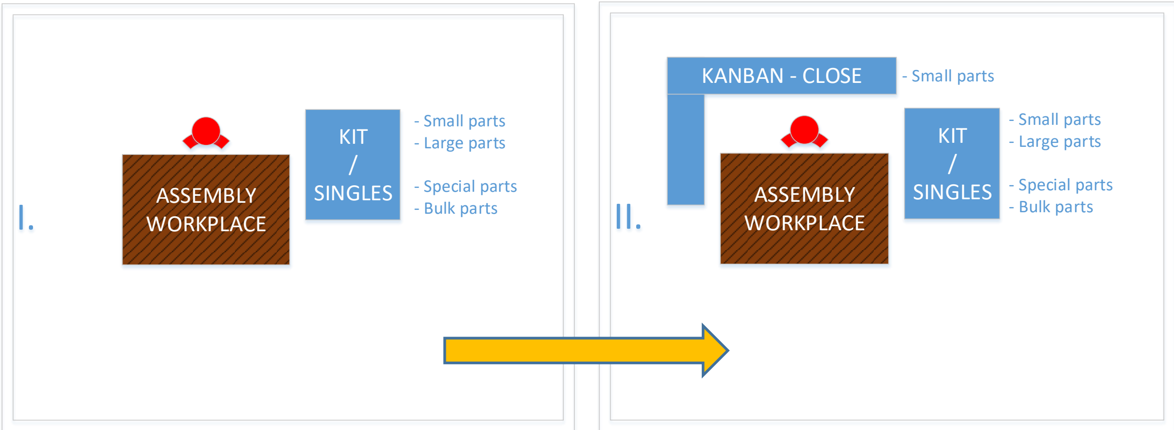


FIGURE 27 TRANSITION FROM KIT TO KIT WITH KANBAN CLOSE

When considering Kanban close, the time costs for Kanban far given by $C_{pick.kbn2}$ can be neglected. The time costs for some parts are now lower when not in Kit, but put into Bins along Kanban close. The preference conditions for these cases are presented below. The parts which are considered to be Lift pick parts, POD pick parts and Heavy pick parts are examined separately.

4.2.2.1 Lift pick parts

To find the preference conditions for parts stored in Vertical lift, the time costs for the part which is already allocated to Kit are compared to the time for Kanban close.

Lift pick parts are characterized by:

- Smaller than or equal to 368 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Bito bin size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

The cases where weight and size are causing for a switch in material feeding principle are examined for Lift pick parts below.

Coated Lift pick parts

Firstly the preference conditions are determined for the Lift pick parts which need coating and have Hal. 04 or Hal. 02 as a final destination. The notation of part occurrence, OP_{ij}, is not used in the below formulas as the BOM list rows are not of influence. It is assumed that the time cost of the part in Kit is only represented by the amount of picks, because the Kit time costs for transport and preparation are already made. The time cost of the part in Kanban is given by the amount of pallets needed for transport and the amount of picks made considering a Kanban order quantity. The travel time in the Lift pick area in Warehouse (1) is not accounted for as this is the same for Kanban and Kit. The equation which needs examination is given below:

$$L_{2,i} \cdot Pick_1 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+2 \cdot D08+D04}{V} + TL + PP_1 \right) \right) + L_{1,i} \cdot Pick_1$$

Now all known parameter values are filled in:

$$L_{2,i} \cdot 36 = (1 + 0.20) \cdot \left(CP_i \cdot \left(\frac{130+2 \cdot 95+25}{2.2222} + 30 + 60 \right) \right) + L_{1,i} \cdot 36$$

Simplify the above equation into the following:

$$36\, L_{2,i} = 294.3\, CP_i + 36\, L_{1,i}$$

Then $L_{2.i}$, $CP_{1.i}$ and $L_{1.i}$ are replaced by their underlying formulations:

$$36 \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{GP_L, GPW_{ij}\}} \right\rceil \right\} = 294.3 \left(\frac{RQ_{BB.ij}}{CA_{BB} \cdot ER} \right) + 36 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{GP_L, GPW_{ij}\}} \right\rceil \right\}$$

Again all known parameter values are filled in to finalise the equation for examination:

$$36 \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\} = 294.3 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{20 \cdot 0.90} \right) + 36 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\}$$

The Kanban order quantity, KOQ_{ij}, is influenced by the part volume which is multiplied by the sum of part occurrence in an end product, SOP_{ij}, whilst fitting a Bito bin. To come up with conditions where Kanban close is better than Kit the average advantage of a part characteristic is examined. It is therefore assumed that sum of occurrence in one end product is not taken into account, but the size of a part which has impact on the possible amount of parts in a Bito bin. This amount has impact on the Kanban order quantity. Besides the part size also part weight has impact, as this can result in picking multiple parts at once. To take both impacts into account the values of GPW_{ij} and KOQ_{ij} are varied. The average advantage is taken over the different values of SOP_{ij} whereas the amount of parts are assumed to be fitting in a Bito bin.

The average advantage of a part that can be picked up with 5 parts at a time, considering a weight which allows that. And, the size of the part should be small enough to fit the corresponding Kanban order quantity in the Bito bin. The result of this examination is given in table 9.

Sum of occurrence	**Kanban order quantity**	**Potential grab of multiple parts**	**Kit picking time**	**Kanban picking time**	**Advantage in seconds**	**Average advantage in seconds**

1	6	5	36	9.925	26.075	11.675
2	12	5	36	17.125	18.875	
3	18	5	36	24.325	11.675	
4	24	5	36	31.525	4.475	
5	30	5	36	38.725	-2.725	
6	36	5	72	45.925	26.075	
7	42	5	72	53.125	18.875	
8	48	5	72	60.325	11.675	
9	54	5	72	67.525	4.475	
10	60	5	72	74.725	-2.725	
11	66	5	108	81.925	26.075	
12	72	5	108	89.125	18.875	
13	78	5	108	96.325	11.675	
14	84	5	108	103.525	4.475	
15	90	5	108	110.725	-2.725	

TABLE 9 RESULTS OF CALCULATING THE ADVANTAGE OF KANBAN CLOSE OVER KIT BY CHANGING KANBAN ORDER QUANTITY AND THE POTENTIAL OF GRABBING MULTIPLE PARTS AT ONCE

The time difference of the part example of table 9 is visualised in the graph below:

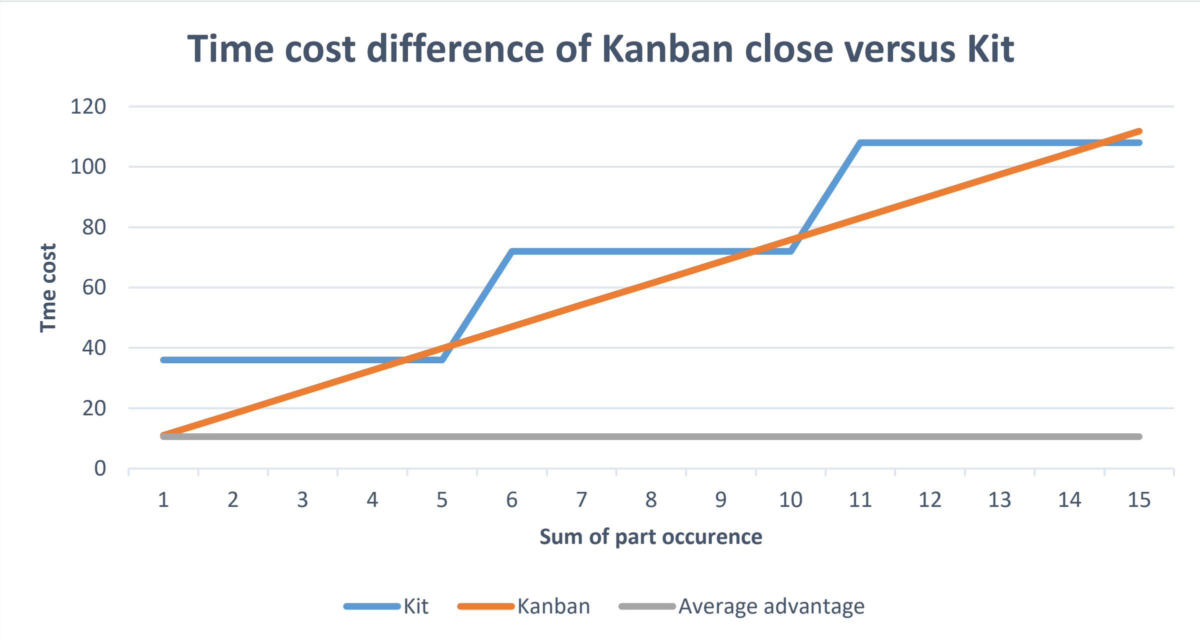


FIGURE 28 TIME DIFFERENCE OF KANBAN CLOSE VERSUS KIT

From table 9 and the graph 28 can be concluded that the amount of parts that are picked at once have great effect on time cost difference. When the amount of parts needed in an end product is a plurality of the grab potential, the time cost difference will favour Kit. Else Kanban close is greatly favoured. However this picking parameter is a way to approximate this potential and when examining the average advantage of Kanban close over Kit, Kanban close is less time costly.

Such tables and graphs are also made for lower values of Kanban order quantity, KOQ_{ij}, in combination with varying levels of grab potential, GPW_{ij}. All these graphs show the same pattern. The average advantages of each variation are stated in table 10. The last column states whether the advantages are large as opposed to the lowest disadvantage. When this disadvantage is lower than the average advantage, it is consider safe. This is done in order grade the relative size of the advantage.

Kanban order quantity	Potential grab of multiple part	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
6	5	11.675	11	-2.725	Safe
5	5	11.130	11	-3.270	Safe
4	5	10.313	10	-4.088	Safe
3	5	8.950	8	-5.450	Safe
2	5	6.225	6	-8.175	
1	5	-1.950	-1	-16.350	
6	4	10.775	10	-2.725	Safe
5	4	10.230	10	-3.270	Safe
4	4	9.413	9	-4.088	Safe
3	4	8.050	8	-5.450	Safe
2	4	5.325	5	-8.175	
1	4	-2.850	-2	-16.350	
6	3	9.275	9	-2.725	Safe
5	3	8.730	8	-3.270	Safe
4	3	7.913	7	-4.088	Safe
3	3	6.550	6	-5.450	Safe
2	3	3.825	3	-8.175	
1	3	-4.350	-4	-16.350	
6	2	6.275	6	-2.725	Safe
5	2	5.730	5	-3.270	Safe
4	2	4.913	4	-4.088	Safe
3	2	3.550	3	-5.450	
2	2	0.825	0	-8.175	
1	2	-7.350	-7	-16.350	
6	1	-2.725	-2	-2.725	
5	1	-3.270	-3	-3.270	
4	1	-4.088	-4	-4.088	
3	1	-5.450	-5	-5.450	
2	1	-8.175	-8	-8.175	
1	1	-16.350	-16	-16.350	

TABLE 10 RESULTS OF TIME DIFFERENCES FOR COATED LIFT PICK PARTS IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 04

As a result from the above examination the following preference conditions are apparent for coated Lift pick parts that are needed in Hal 04. Pre-assembly:

1. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
2. *If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Besides coated Lift pick parts that are needed in Pre-assembly, coated Lift pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for coated Lift pick parts that are needed in Hal 02. Final assembly:

3. *If at least a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
4. *If a Kanban order quantity of 6 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Uncoated Lift pick parts

Then the preference conditions are determined for the Lift pick parts which do not need coating and have Hal 04. or Hal 02. as a final destination. The calculation steps are the same as with the coated parts. However, the notation of the equation is slightly different as the distance to Hal 08. Coating is not of impact. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for uncoated Lift pick parts that are needed in Hal 04. Pre-assembly:

5. *If at least a Kanban order quantity of 2 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Besides uncoated Lift pick parts that are needed in Hal 04. Pre-assembly, uncoated Lift pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for uncoated Lift pick parts that are needed in Hal 02. Final assembly:

6. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
7. *If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

4.2.2.2 POD pick parts

To find the preference conditions for parts stored in POD racks, the time costs for the part type which is already allocated to Kit are compared to the time costs for Kanban close. These parts are stored in either a Lager bin or on a pallet. First the preference conditions for Lager bins are determined and secondly the conditions for the pallets.

POD pick parts stored in Lager bin are characterized by:

- Smaller than or equal to 500 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Lager bin or Euro pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

POD pick parts placed on a pallet are characterized by:

- Smaller than or equal to 1200 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Lager bin or Euro pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

The cases where weight and size are causing for a switch in material feeding principle are examined for POD pick parts below. Travel time in the POD pick area in Warehouse (1) is not accounted for as this is the same for Kanban and Kit.

Coated POD pick parts from Lager bin

This examination of preference conditions is done in analogous manner like with the Lift pick parts. Thus the full description is in appendix C

As a result the following preference conditions are apparent for coated POD pick parts from Lager bin that are needed in Hal 04. Pre-assembly:

8. *If at least a Kanban order quantity of 6 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Besides coated POD pick parts that are needed in Hal 04. Pre-assembly, coated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for coated POD pick parts from Lager bin that are needed in Hal 02. Final assembly:

9. *If at least a Kanban order quantity of 13 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Uncoated POD pick parts from Lager bin

Then the preference conditions are determined for the POD pick parts from Lager bin which do not need coating and have Hal 04. or Hal 02. as a final destination. The calculation steps are the same as with the coated parts. However, the notation of the equation is slightly different as the distance to Hal 08. Coating is not of impact. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 04. Pre-assembly:

10. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Besides uncoated POD pick parts that are needed in Hal 04. Pre-assembly, uncoated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 02. Final assembly:

11. *If at least a Kanban order quantity of 10 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Coated POD pick parts from pallet

This examination of preference conditions is done in analogous manner like with the Lift pick parts. Thus the full description is in appendix C.

As a result from the above examination the following preference conditions are apparent for coated POD pick parts that are needed in Hal 04. Pre-assembly:

12. *If at least a Kanban order quantity of 33 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Besides coated POD pick parts that are needed in Hal 04. Pre-assembly, coated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for coated POD pick parts that are needed in Hal 02. Pre-assembly:

13. If at least a Kanban order quantity of 46 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Uncoated POD pick parts from pallet

Then the preference conditions are determined for the POD pick parts from pallet which do not need coating and have Hal 04. or Hal 02. as a final destination. The calculation steps are the same as with the coated parts. However, the notation of the equation is slightly different as the distance to Hal 08. Coating is not of impact. This examination of preference conditions is again done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 04. Pre-assembly:

14. If at least a Kanban order quantity of 18 times the part type demand can fit on a pallet and the grab potential is at least 2.

Besides uncoated POD pick parts that are needed in Hal 04. Pre-assembly, uncoated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. Thus the full description is in appendix C.

As a result the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 02. Final assembly:

15. If at least a Kanban order quantity of 35 times the part type demand can fit on a pallet and the grab potential is at least 2.

4.2.2.3 Heavy pick parts

To find the preference conditions for parts stored in Heavy racks, the time costs for the part type which is already allocated to Kit are compared to the time costs for Kanban close.

Heavy pick parts are characterized by:

- Smaller than or equal to 2700 millimetre. (Maximum length)
- Smaller than or equal to Ugly pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

In the calculations of the Lift and POD pick preference conditions are no cases for which one part can only be picked at once be more advantageous for Kanban close. This is easily seen as the time costs for a pick in Kit and Kanban are both reckoned as whole picks, while there are extra transportation time costs for Kanban close. The part is already travelling in Kit and needs to be transported by another forklift truck movement. Thus there are no preference conditions for Heavy pick parts relocated to Kanban close.

"All Heavy parts, uncoated and coated, are best replenished to Hal. 04 or Hal. 02 by use of Kit".

4.2.3 Sensitivity analysis

In this section the sensitivity of the results of sections 4.2.1 and 4.2.2 are examined. This sensitivity should support the robustness of the conclusions above. Sensitivity is tested on subassembly level and part level. The effect of changing fixed parameters, which are ought to have a large impact, are examined. And, in case of the results on part level, preference conditions are studied.

4.2.3.1 Sensitivity on subassembly level

The search for preference conditions on assembly level resulted in preference for Kit replenishment in all plausible cases of Dewulf. The sensitivity of parameters which are ought to have the most impact are enumerated and discussed below. Tests are done on a subassembly example as this will roughly be representative. If a very sensitive result is found, then this approach will not be sufficient.

The time for a pick in Kanban far.

The largest influencing factor of the time cost of Kanban far is the picking activity in Kanban far. All parts are brought from Warehouse (1) to a large and distant storage rack in assembly. The time to pick from these racks is estimated at 72 seconds, which is the same time as pick in POD pick area. 72 seconds is already considered as low value for Kanban far, as POD picking is most likely to be more efficient. Orders will in practice be pooled and the travel time is minimised in Warehouse (1).

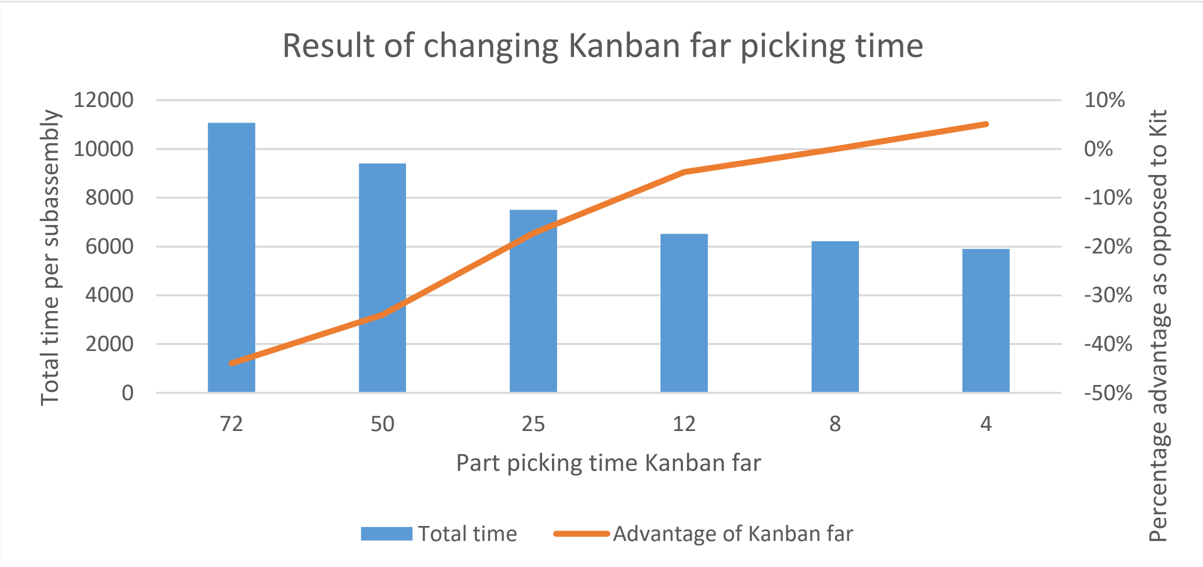


FIGURE 29 RESULT OF CHANGING KANBAN PICKING TIME FOR SUBASSEMBLY: BUNKER 3060

Figure 29 above shows the effect of changing the part picking time from Kanban far for the subassembly Bunker 3060. The effect of the picking activity in Kanban far is very large, but the time is seen as reasonable by Dewulf. When the part picking time is set to 8 seconds or less it will cause for an advantage for Kanban far in this example. However, this is not really plausible as an efficient pick in the Lift pick area is already consuming 36 seconds.

Thus, this parameter is not making the result sensitive.

Time to travel in Warehouse (1).

The time needed to travel in Warehouse (1) is accounted for by formulation of expected S-shape routing in the aisles. This calculation is somewhat **Pro-Kanban**, because in practice the orders will be pooled during a picking route. This would mean that the relative difference between reckoned travel distances will be closer than assumed in the calculation on subassembly level.

Thus, this parameter is not making the result sensitive.

Speed of the picker.

The speed of the picker is of influence in the transporting time cost for (kit) pallets and for the travel time in Warehouse (1). The impact is most on the amount of pallets, but marginally with respect to the total time cost of replenishment. When the speed of the picker is changed both Kanban far and Kit are affected.

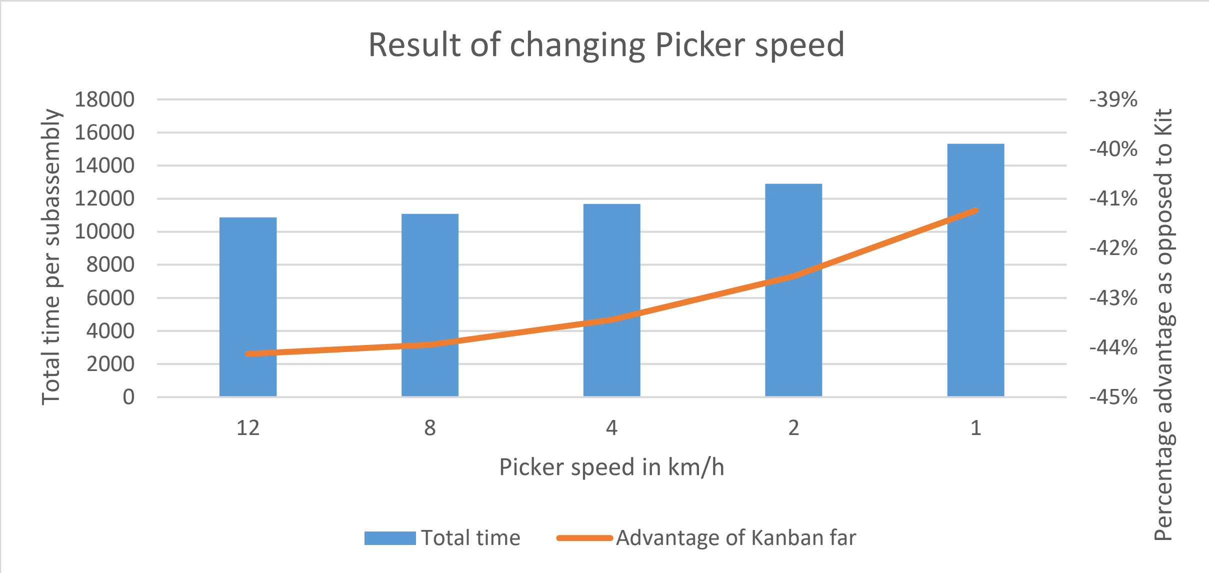


FIGURE 30 RESULT OF CHANGING PICKER SPEED FOR SUBASSEMBLY: BUNKER 3060

Figure 30 above shows the effect of changing the picker speed for the subassembly Bunker 3060. The effect of the picking speed is large. When the part picking speed is very low it will cause for a smaller disadvantage for Kanban far in this example. However, this speed of 1 km/h is too low and not changing the final judgement.

Thus, this parameter is not making the result sensitive.

Pallet capacity calculation.

The amount of capacity of Bito bins and Lager bins which is used for Kanban replenishment amounts to respectively 20 and 4. The amount of Bins needed impacts the amount of pallets which are needed on average to replenish assembly of an end product. Changing the bin capacity of a pallets is only of influence on Kanban replenishment.

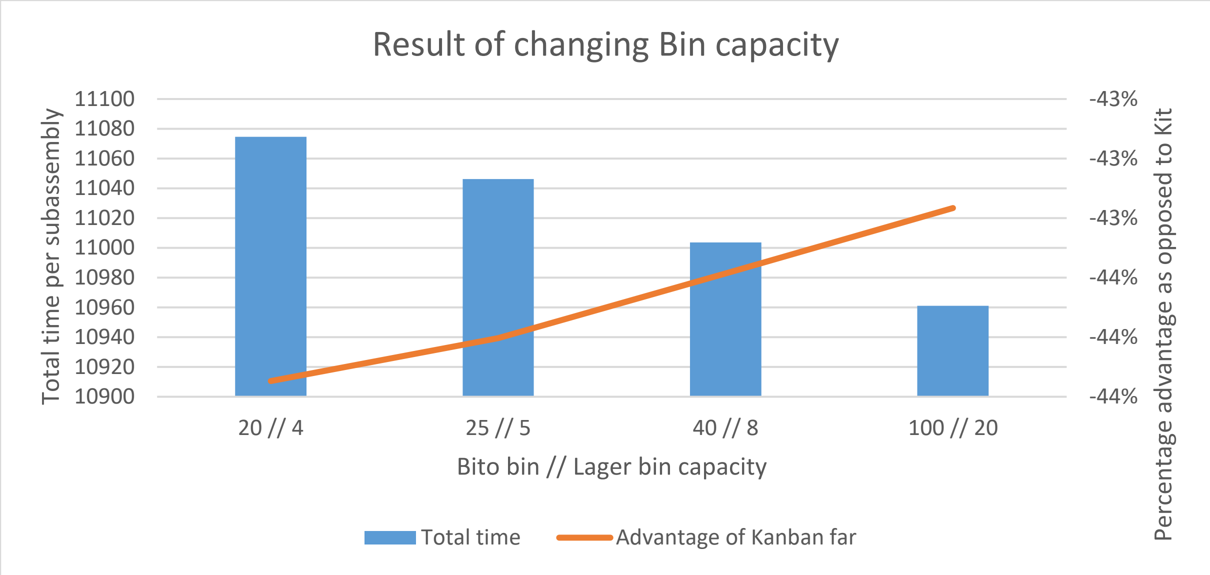


FIGURE 31 RESULT OF CHANGING BIN CAPACITY ON A PALLET FOR SUBASSEMBLY: BUNKER 3060

Figure 31 above shows the effect of changing the bin capacity on a pallet for the subassembly Bunker 3060. The effect appears to be very low. When the bin capacity of a pallet is very high it will cause for a smaller disadvantage for Kanban far in this example. However, this difference is almost nothing and not changing the final judgement.

Thus, this parameter is not making the result sensitive.

The other fixed parameters are ought to have a low impact and/or are values which are facts or acquired from an external source.

4.2.3.2 Sensitivity on part level

The search for preference conditions on part level resulted in a series of preference conditions based on size and weight. The sensitivity of the corresponding parameters which are ought to have the most impact are enumerated and discussed below. Tests are done on part formulations used in the previous section.

Multiple parts picking.

From the found preference conditions can be concluded that the amount of parts which can be picked at once is of great impact on advantage of Kanban close. This amount is influenced by the possibility to pick an amount based on size and on weight. When the possibility to grab more at once is higher the advantage will be higher. Obviously the cases where only one part can be picked at a time are already rejected. When the maximum amount of parts to pick are instead of 5, 4, the same preference conditions hold. If a condition is a combination with a potential grab of 5, it will no longer occur. This solution can be seen as somewhat sensitive, but for the decision framework as a whole not so much.

Thus, this parameter is not making the total result sensitive.

Kanban order quantity.

Kanban order quantity has impact on the amount of transport appliances per end product. When really high numbers of this Kanban order quantity are needed, the result is somewhat sensitive. However, in the latter section is already a “Safe” statement in corporate that only advantages which are large enough count. If on average an advantage of 2 seconds can be realised, but one of the disadvantages is 8 seconds within the same condition, the advantage does not seem very solid.

Thus, this parameter is sensitive, but already compensated by the “Safe” statement. Besides that, the average advantage is taken so the lowest (dis)advantages can be cancelled out with the highest advantage.

Distance Warehouse (1) to assembly.

The distance travelled between Warehouse (1) and assembly has great impact. However this is roughly incorporated in the decision rules. If the decision rules of Hal 02. Final assembly (5) are used for the complete facility, these rules will be more than safe enough. Hal 02 is the location which is farthest from Advanced warehouse (2). To choose more parts for Kanban close, closer final destinations have preference conditions which are appropriate for more types of parts. Apart from the amount of travel distance, the distance are a fact, thus will not appear very different in practice.

Thus, this parameter is not making the total result sensitive.

4.3 Resulting decision rule

The found preference conditions of the latter section are translated to a decision rule in this section.

4.3.1 Decision rule on subassembly level

There are no preferred conditions for Kanban far on subassembly level found. This has resulted in the following: “***All subassemblies and their corresponding part types can best be placed in Kit, when Kanban far is the alternative solution.”***

4.3.2 Decision rule on part level

The decision rule on part level is split into three parts, namely the preference conditions for Lift pick parts stored in Bito bin, POD pick parts stored in Lager bin and POD pick parts stored on pallets. All preference conditions found are enumerated in appendix D. For heavy parts holds the following: ***“All Heavy parts, uncoated and coated, are best replenished to Hal. 04 or Hal. 02 by use of Kit.”***

The preference conditions are put into a structured framework. With the framework, the amount of conditions which need to be checked are reduced. Each check can cause for allocation of a part to a preferred material feeding principle. For instance, when a part type is more than a certain weight it will always be better off in Kit. The framework is meant to work like a pinball box. Where each step further holds a different check on preference.

In the previous section is described that part type size and weight are used to determine the preference conditions. The interpretation in the decision rule is as follows:

- The size is accounted for by the possibility to fit the amount of needed parts of a part type times the Kanban order quantity. The maximum possible volume of a Bito bin, Lager bin or Pallet divided by the part volume gives the possible amount of parts which fit, $\left\lfloor \frac{MV_k}{PV_{ij}} \right\rfloor$. A preference condition with respect to size is thus influenced by the needed amount of the part type, per kit, times the part volume times the preferred total Kanban order quantity.
- The weight is accounted for by the possibility to pick multiple parts at once. This possibility is determined by the maximum possible weight, where multiple picking is likely to happen, divided by the part weight. However, within this possibility the size of the part is also accounted for, GP_L. Bulky part dimensions will not invite the picker into picking multiple parts at once. The pick possibility is given by: $min\{GP_k, GPW_{ij}\}$.

Decision rule for Lift pick parts stored in Bito bin

Lift pick parts are characterized by:

- Smaller than or equal to 368 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Bito bin size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

For parts which fulfil the above characteristics, the decision rule in figure 32 is cast into a pinball box structure.

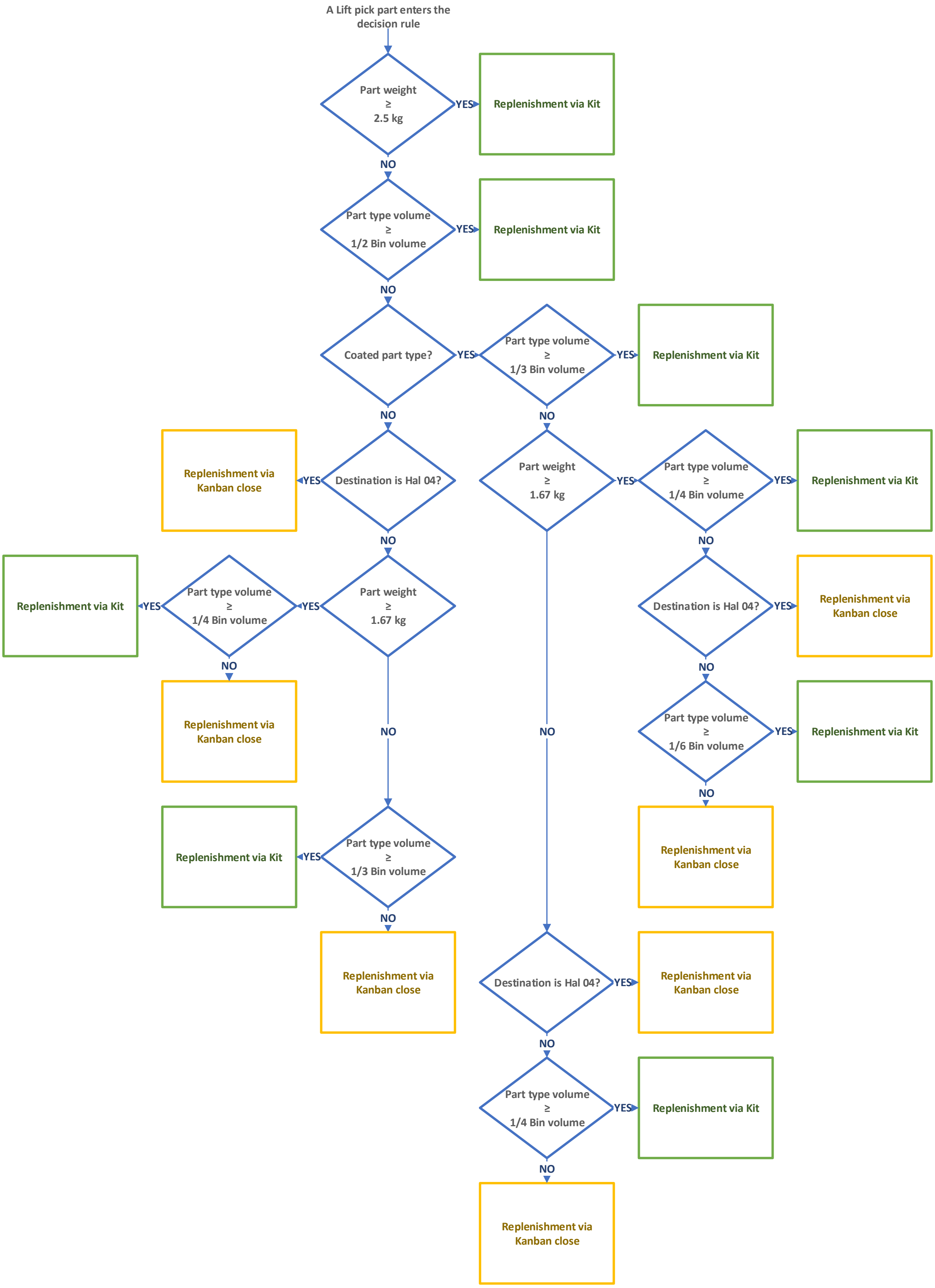


FIGURE 32 DECISION RULE FOR LIFT PICK PARTS

Decision rule for POD pick parts stored in Lager bin

POD pick parts stored in Lager bin are characterized by:

- Smaller than or equal to 500 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Lager bin or Euro pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

For parts which fulfil the above characteristics, the decision rule in figure 33 is cast into a pinball box structure. The values for *W*, *X*, *Y* and *Z* are varying for POD lager bin parts and POD pallet parts. For POD lager bin parts W = 3, X = 6, Y = 10 and Z = 13.

Decision rule for POD pick parts stored on pallet

POD pick parts placed on a pallet are characterized by:

- Smaller than or equal to 1200 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Lager bin or Euro pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

For parts which fulfil the above characteristics, the decision rule in figure 33 is cast into a pinball box structure. The values for *W*, *X*, *Y* and *Z* are varying for POD lager bin parts and POD pallet parts. For POD pallet parts W = 18, X = 33, Y = 35 and Z = 46.

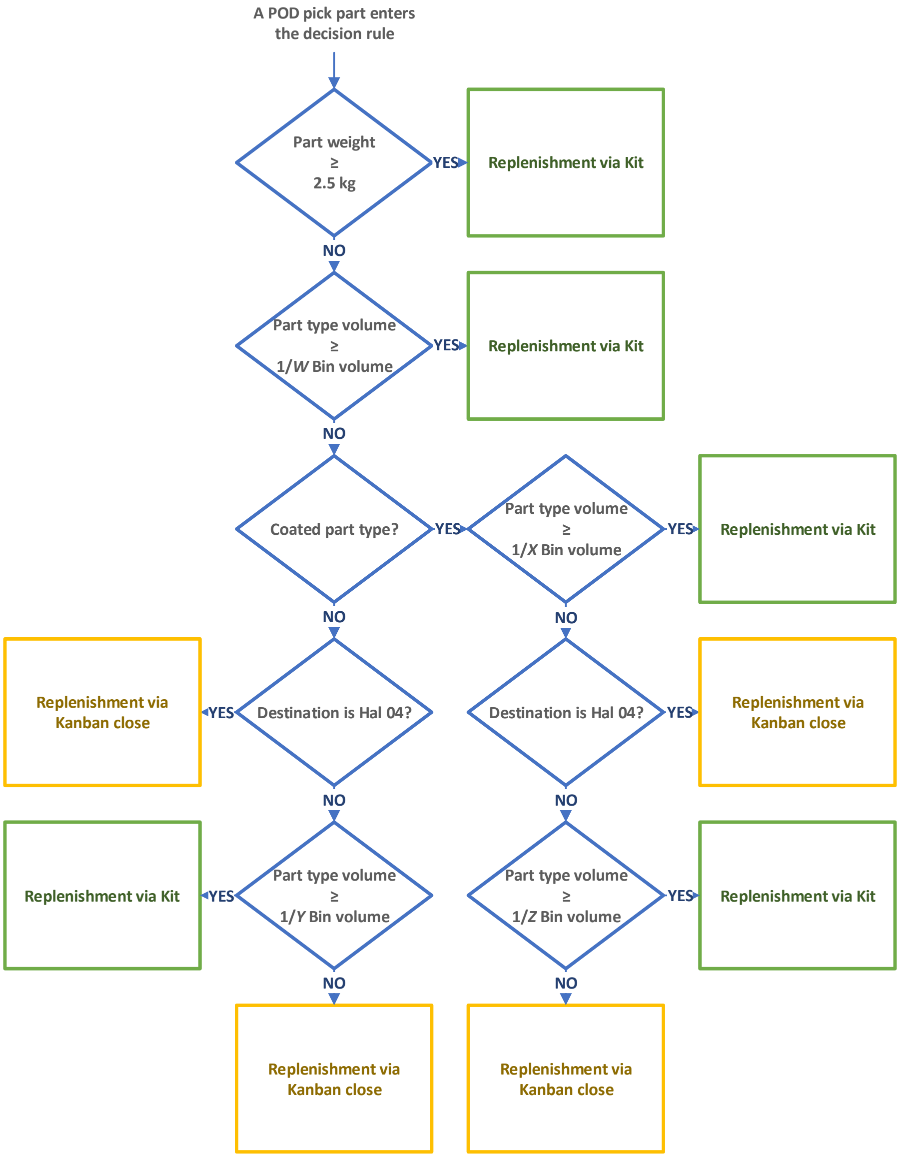


FIGURE 33 DECISION RULE FOR POD PICK PARTS

Based on the above decision structures a material feeding principle can be allocated to each part of the end products at Dewulf. The single and bulk part allocations are not apparent in this decision rule structure. This is done in order to find the decision values for the Lager bin and Pallet parts. However, it can be questionable to hold 15, 25 or even 50 times the part demand per kit in storage.

Now that the latter questionable fact is raised, the importance and advantage of allocating a part to Kanban close are examined. The division arisen from usage of the decision rule is based on limit values of parts size and weight. The possibility to fit a lot of parts in a bin or pallet is not always the best solution either, as this would lead to unnecessary stock alongside assembly. Therefore, the average advantage is taken of a part type which is allocated based on a respective limit value. This average is taken, where possible, over levels reaching to 6 times the part demand, because 6 times an end product demand in stock is often sufficient according to Dewulf.

This gives the following advantages when a part type satisfies a preference condition favouring Kanban close over Kit:

Lift pick parts Bito bin			
1.	*Hal 04 Coated*	*If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*	9.4 seconds
2.	*Hal 04 Coated*	*If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*	5.6 seconds
3.	*Hal 02 Coated*	*If at least a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*	8.6 seconds
4.	*Hal 02 Coated*	*If a Kanban order quantity of 6 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*	5.2 seconds
5.	*Hal 04 Uncoated*	*If at least a Kanban order quantity of 2 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*	9.7 seconds
6.	*Hal 02 Uncoated*	*If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*	9.2 seconds
7.	*Hal 02 Uncoated*	*If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*	5.5 seconds
POD pick parts Lager bin			
8.	*Hal 04 Coated*	*If at least a Kanban order quantity of 6 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	4.4 seconds
9.	*Hal 02 Coated*	*If at least a Kanban order quantity of 13 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	9.2 seconds
10.	*Hal 04 Uncoated*	*If at least a Kanban order quantity of 3 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	7.6 seconds
11.	*Hal 02 Uncoated*	*If at least a Kanban order quantity of 10 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	9.4 seconds
POD pick parts pallet			
12.	*Hal 04 Coated*	*If at least a Kanban order quantity of 33 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	9.1 seconds
13.	*Hal 02 Coated*	*If at least a Kanban order quantity of 46 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	9.0 seconds
14.	*Hal 04 Uncoated*	*If at least a Kanban order quantity of 18 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	9.3 seconds
15.	*Hal 02 Uncoated*	*If at least a Kanban order quantity of 35 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*	9.1 seconds

TABLE 11 TIME ADVANTAGE OF A PART TYPE PLACED IN KANBAN CLOSE AS OPPOSED TO KIT WITH RESPECT TO A PREFERENCE CONDITION

It can be concluded, from advantage pattern corresponding with the above values, that parts that fit in a bin/pallet in very large numbers are more advantageous. However this is paired with the usage of the part per kit. If the part is also not used that often, then it is even more advantageous in Kanban close. This phenomenon is caused by the resulting amount of transports to assembly, which is then very low.

It is best when the decision rule is used, that the parts are then sorted from most advantageous to least advantageous. After this sortation, the parts which tie should be compared on occurrence per kit. If a part is needed in very large numbers per kit and satisfies one of the preference conditions, the available meters in assembly are best utilised. The chances that multiple end products consume the specific parts are also more likely.

4.4 Conclusion

It can be concluded that the impact of material feeding principles and the way of storage alongside assembly can be determined. The impact of transportation, picking and preparation activities have been addressed in this chapter.

The constructed formulas represent the truth, as the pilot subassemblies show trustworthy values of replenishment time needed per subassembly. Therefore the decision rules could be made with use of preference conditions. The preference conditions are depended on part size, part weight, finish and destination. Parameters that are needed come from BOM list, are estimated, retrieved from measurement or retrieved from an external source.

A layout in terms of presentation meters usage can be filled in using the decision rule and the general visualisation of the dock assembly layout. As Kit is always superior over Kanban far, the dock layout appearance for workstations is most appropriate at Dewulf. It is concluded that Kit replenishment is always the best solution when Kanban far is the alternative. However the decision rules on part level show that a hybrid policy is best. This hybrid policy is a combination of Kitting and Kanban close.

When a part is allocated to a Kanban close, the advantage can be given as an average value, however parts turn out to be equally advantageous with this method. Therefore parts which have a tied advantage should be compared on the utilisation per Kit.

5. Result in practice

Kit replenishment in combination with Kanban close is most appropriate at Dewulf, therefore an assembly layout will likely consist of multiple docks. To choose whether or not a part should be placed in Kanban close, the decision rule is put to the test in this chapter. Each part could be allocated to Kanban close, however space is not limitless.

In the first section, 5.1, the usage of the decision rule on a BOM list is examined. Section 5.2 concludes this chapter.

5.1 Result on BOM list

The usage of the decision rules on a BOM list example is examined as an example result. The BOM list of Bunker 3060 is used again. The pinball box structures of chapter 4 are transformed for usage with this BOM list.

Within this BOM list 75 different part types can be allocated by use of the decision rules. The other part types are better off in Kit or are treated as single parts. The result of applying the rules is that 44 of the 75 different part types are more time efficient when placed in Kanban close. While Bunker 3060 will be made in Hal 04. Pre-assembly, the same amount of part types are nominated for Kanban close when considering assembly of Bunker 3060 in Hal 02.

In consultation with Dewulf is chosen for the amount of reckoned space is consumed by a Bito bin, Lager bin or Pallet. It is assumed that both types of bins are placed with a maximum of 6 bins above each other in the racks. Pallets are assumed to be stacked with a maximum of 2, because of the nature of a Kanban close rack. Picking is less easy and the layout should not exceed the picking time needed with a Kit. The Kanban close rack should resemble a narrow bin layout, see chapter 3. The resulting presentation meter usage is 1.98 meters for Bunker 3060.

The above results are summarised in the table below, table 12.

Bunker 3060	
Number of different part types allocated	75
to Kit	31 (41%)
to Kanban close	44 (59%)
Presentation meters needed	1.98 meter

TABLE 12 ALLOCATION RESULT ON BUNKER 3060

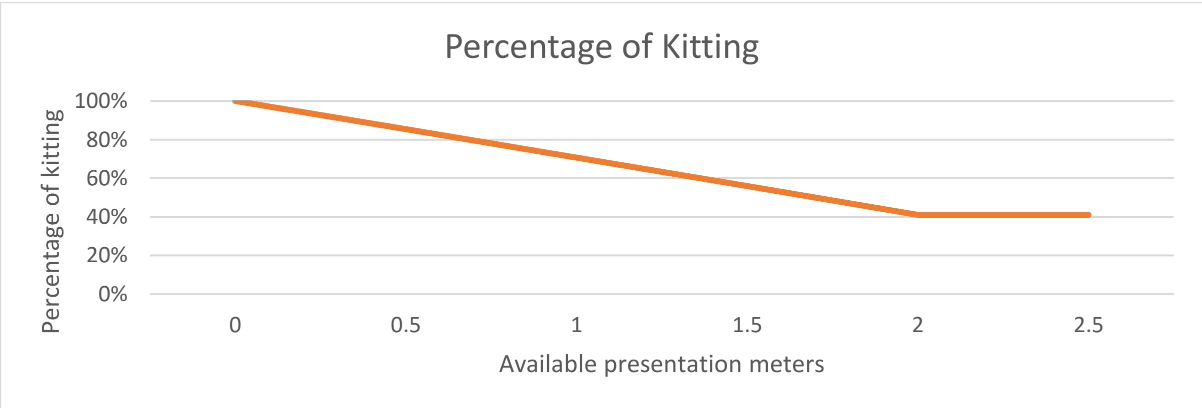


FIGURE 34 PERCENTAGE OF KITTING AS OPPOSED TO AVAILABLE PRESENTATION METERS

Figure 34 presents the relation of presentation meters as opposed to the percentage of kitting. The line decreases in a straight line because only 2 POD Lager bin parts are more advantageous in Kanban close, while 42 Lift Bito bin parts are more advantageous. The increase of presentation meters is thus very constant for the same size bins. However within Bunker only 3 different part types are reckoned as Lager bin, which could have made it a little less constant.

The bar chart below, figure 35, shows that a pure Kit policy is 44% better as a pure policy with Kanban far. A Hybrid policy is even 47.5% better. This Hybrid policy consists for 59% of Kanban close and is 6.3% better as a pure Kit policy. Thus the amount of parts which are needed in Kanban close is very high, while the advantage as opposed to a pure Kit policy (3.5%) and the pure Kanban far policy is meagre.

The improvement from Kanban far to Kitting is largely due to transportation, as the Kits used are very large and the amount of transports for Kanban far pallets will exceed those of Kit transports. If parts are added to a Kit it will often still fit, which does not lead to an increased transportation cost. The travel distance of the Warehouse (1) to assembly has thus a great impact.

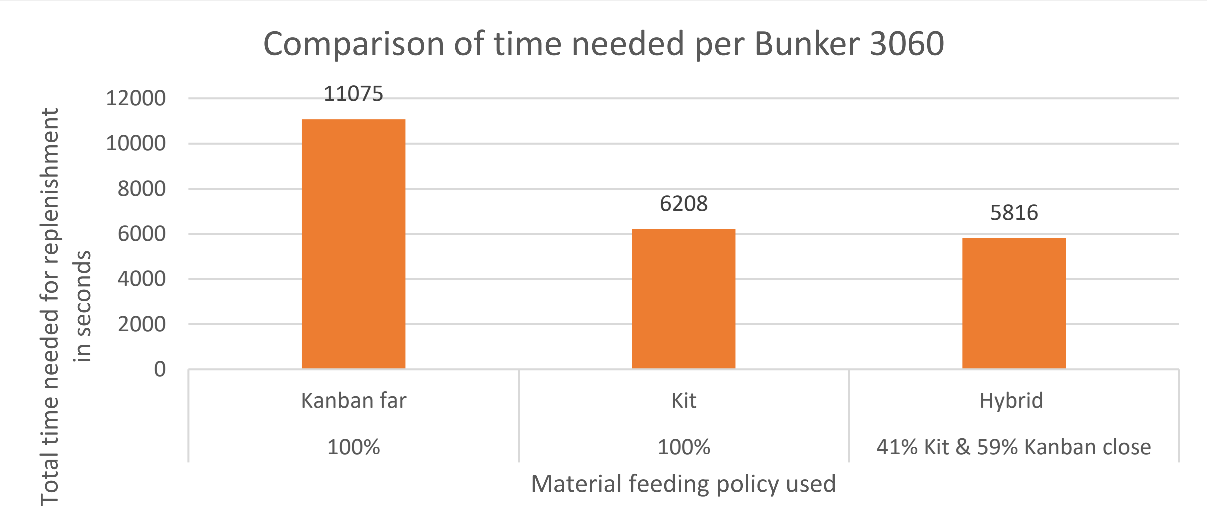


FIGURE 35 COMPARISON OF TIME NEEDED PER SUBASSEMBLY BUNKER 3060

In this case it will lead to a lot of stock keeping units on the floor, although this will most likely look like a narrow bin layout. The narrow bin layout also mentions a big improvement for parts which can be presented in small and narrow bins.

When the decision rules are used on other subassemblies, it will most likely be with similar results. The improvement of Lift pick parts is generally higher as for POD pick parts, thus a lot of different parts can be allocated in few presentation meters, but the advantage will be very little as opposed to pure kitting. The rules can be used for BOM list examples, but if part demand and purpose from a complete work cell is adapted, it could be useful on a broader perspective. Then different end products are occupying presentation meter space, which will most likely cause for a shortage in meter. This shortage will have an impact on the advantage of the Hybrid over the pure Kitting policy.

5.2 Conclusion

The usage of the decision rules is used on a BOM list and shows interesting results. The rules can be used to examine all types of BOM lists and after some data preparation, even used on a work cell. The results show that the biggest improvement is on subassembly level, from Kanban far to Kitting. The statement that Kitting is always superior to Kanban far, is a powerful one. The improvement from

Kanban far to Kitting is mostly due to transportation. Transportation is reduced by adding a lot of parts to one kit pallet, while Kanban keeps parts separated and has to stack bins on that transportation pallets if possible.

When the hybrid policy is introduced another improvement can be realized, however this will not be with the same order of magnitude. The improvement results in case of the example subassembly is in line with the narrow bin layout. It shows that lift pick parts are great candidates for Kanban close due to their size and weight. The weight is important because the rules in chapter 4 already show that only light parts can be picked in plural.

The improvement on one BOM list will be higher than on dock assembly workstation or work cell as the presentation meters have to be shared in the latter case. These presentation meters are then likely to be insufficient.

6. Recommendations

In this chapter the recommendations are presented. It is apparent that an improvement can be made by use of the decision rules. Besides the rules, it can already be interesting to see at placing Lift (and POD Lager bin) pick parts in Kanban close first. In order to test this, we suggest using a pilot work station in which is tested how storing parts in Kanban close can have impact. The parts are best stored in a narrow bin layout, where the VASA model is kept in mind. All most advantageous parts need to be placed in the most ergonomic place.

To start with selecting the parts which need to be placed in Kanban close, the following action plan is proposed:

1. Choose a work cell were part consumption of all parts is known and the amount of kits needed on average.
2. Calculate the occurrence of a part type on an average kit.
3. Calculate the Kanban close advantage per part.
4. Translate costs to improvement per presentation meter.
5. Sort the parts with their advantages per meter from high to low.
6. Resort parts which tied on an advantage by sorting at the utilisation per presentation meter. If the advantage for different part types ties per kit, we suggest that the most parts needed per Kit is favourable for a Kanban close position.
7. Assign all parts which fit the available presentation meters of the work cell.

It should be taken into account that parts are divided into three part groups, while in practice this may change.

7. Discussion

This chapter briefly mentions some points of discussion.

1. **The presentation in assembly**.

The way parts are presented can be done in a different way as the conventional racks in assembly. It was mentioned during the process that a horizontal carousel or vertical lift could be interesting if the Lift pick parts are indeed superior for placement in Kanban close. However this comes with a cost, a horizontal carousel is for instance very expensive. According to Bastian solutions, a horizontal carrousel will cost 1,200 to 1,500 dollar per bin. (Bastian solutions, 2017)

2. Bin size.

For further research it is interesting to look at a complete work cell. If all parts can be allocated properly, the bin size is of importance. When it is known that mostly Lift picks parts are best placed in Kanban close, then how large may this bin be?

3. Personnel.

Personnel is affected by the use of Kitting as opposed to Kanban far. The material handling in terms of transportation, picking, preparation and assembly can be affected. Besides that a large amount of time is currently needed for picking in assembly executed by assembly personnel, while with use of kitting the total time consumption of logistic personnel may increase.

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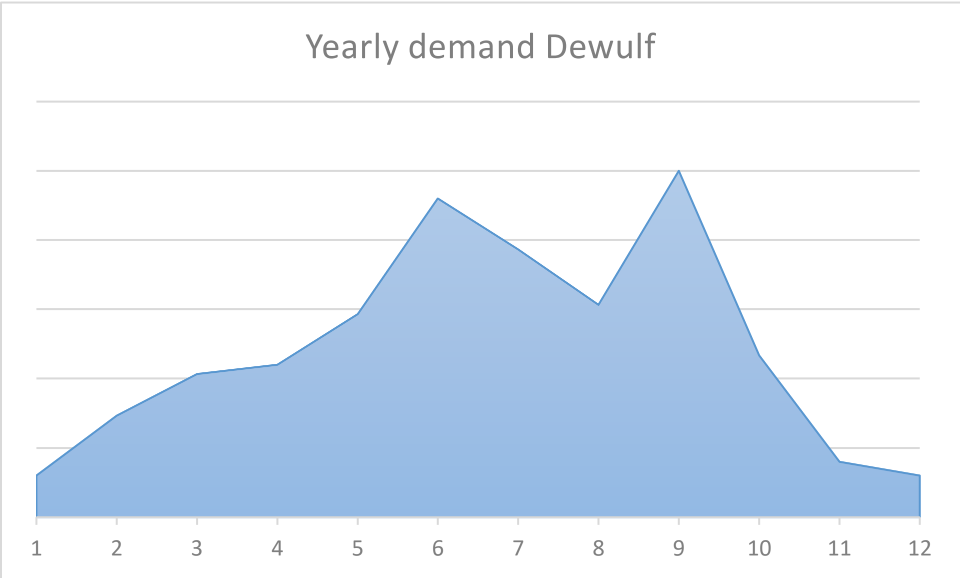
Appendix A. Transport appliances

List of stock and transport appliances mentioned by Dewulf is visualised below:

			Lengte	Breedte	Hoogte	gewicht
Liften	LS	Small bin	160	110	132	15
Liften	LM	Medium bin	260	155	132	20
Liften	LL	Large bin	368	268	208	20
Rekken	COL	Collie	1200	400	250	20
Rekken	EUL	Euro pallet - low	1200	800	350	650
Rekken	EUM	Euro pallet - medium	1200	800	750	650
Rekken	EUH	Euro pallet - high	1200	800	1050	650
Rekken	UDL	Ugly dubbel - low	1700	1200	350	650
Rekken	UDM	Ugly dubbel - medium	1700	1200	750	650
Rekken	UDH	Ugly dubbel - high	1700	1200	1050	650
Rekken	UTL	Ugly triple - low	2700	1200	350	650
Rekken	UTM	Ugly triple - medium	2700	1200	750	650
Rekken	UTH	Ugly triple - high	2700	1200	1050	650
Liften	SLL	Semi lang liften	2750	250	100	7
Draagarm	CAN	Draagarm	4000	750	300	125
Grond	GRO	Ground	10000	10000	3500	4500

Appendix B. Yearly demand

A visualisation of an average historic demand over a year is shown below. The amount of machines is not specified.



Appendix C. Determine preference conditions

Remainder of Lift pick parts

Besides coated Lift pick parts that are needed in Pre-assembly, coated Lift pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. The equation is as follows:

$$L_{2,i} \cdot Pick_1 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+2 \cdot D08+D02}{V} + TL+PP_1 \right) \right) + L_{1,i} \cdot Pick_1$$

The latter equation is simplified to:

$$36 \ \cdot max \left\{ 1, \left\lceil \frac{SOP_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\} = 413.1 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{20 \cdot 0.90} \right) + 36 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max \left\{ 1, \left\lceil \frac{KOQ_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 11 below.

Kanban order quantity	Potential grab of multiple part	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
6	5	10.575	10	-3.825	Safe
5	5	9.81	9	-4.59	Safe
4	5	8.6625	8	-5.7375	Safe
3	5	6.75	6	-7.65	
2	5	2.925	2	-11.475	
1	5	-8.55	-8	-22.95	
6	4	9.675	9	-3.825	Safe
5	4	8.91	8	-4.59	Safe
4	4	7.7625	7	-5.7375	Safe
3	4	5.85	5	-7.65	
2	4	2.025	2	-11.475	
1	4	-9.45	-9	-22.95	
6	3	8.175	8	-3.825	Safe
5	3	7.41	7	-4.59	Safe
4	3	6.2625	6	-5.7375	Safe
3	3	4.35	4	-7.65	
2	3	0.525	0	-11.475	
1	3	-10.95	-10	-22.95	
6	2	5.175	5	-3.825	Safe
5	2	4.41	4	-4.59	
4	2	3.2625	3	-5.7375	
3	2	1.35	1	-7.65	
2	2	-2.475	-2	-11.475	
1	2	-13.95	-13	-22.95	
6	1	-3.825	-3	-3.825	
5	1	-4.59	-4	-4.59	

4	1	-5.7375	-5	-5.7375	
3	1	-7.65	-7	-7.65	
2	1	-11.475	-11	-11.475	
1	1	-22.95	-22	-22.95	

TABLE 11 RESULTS OF TIME DIFFERENCES FOR COATED LIFT PICK PARTS IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 02

As a result from the above examination the following preference conditions are apparent for coated Lift pick parts that are needed in Hal 02. Final assembly:

3. *If at least a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*

4. *If a Kanban order quantity of 6 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Uncoated Lift pick parts

Then the preference conditions are determined for the Lift pick parts which do not need coating and have Hal. 04 or Hal. 02 as a final destination. The calculation steps are the same as the coated parts. However, the notation of the equation is slightly different as the distance to Hal 08. Coating is not of impact. The equation which needs examination is given below:

$$L_{2,i} \cdot Pick_1 = (1 + ELT) \cdot \left(UCP_i \cdot \left(\frac{DB+D04}{V} + TL + PP_1 \right) \right) + L_{1,i} \cdot Pick_1$$

The latter equation is simplified to:

$$36 \ \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\} = 157.5 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{20 \cdot 0.90} \right) + 36 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 12 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
6	5	12.94166667	12	-1.458333333	Safe
5	5	12.65	12	-1.75	Safe
4	5	12.2125	12	-2.1875	Safe
3	5	11.48333333	11	-2.916666667	Safe
2	5	10.025	10	-4.375	Safe
1	5	5.65	5	-8.75	
6	4	12.04166667	12	-1.458333333	Safe
5	4	11.75	11	-1.75	Safe
4	4	11.3125	11	-2.1875	Safe
3	4	10.58333333	10	-2.916666667	Safe
2	4	9.125	9	-4.375	Safe
1	4	4.75	4	-8.75	

6	3	10.54166667	10	-1.458333333	Safe
5	3	10.25	10	-1.75	Safe
4	3	9.8125	9	-2.1875	Safe
3	3	9.083333333	9	-2.916666667	Safe
2	3	7.625	7	-4.375	Safe
1	3	3.25	3	-8.75	
6	2	7.541666667	7	-1.458333333	Safe
5	2	7.25	7	-1.75	Safe
4	2	6.8125	6	-2.1875	Safe
3	2	6.083333333	6	-2.916666667	Safe
2	2	4.625	4	-4.375	Safe
1	2	0.25	0	-8.75	
6	1	-1.458333333	-1	-1.458333333	
5	1	-1.75	-1	-1.75	
4	1	-2.1875	-2	-2.1875	
3	1	-2.916666667	-2	-2.916666667	
2	1	-4.375	-4	-4.375	
1	1	-8.75	-8	-8.75	

TABLE 12 RESULTS OF TIME DIFFERENCES FOR UNCOATED LIFT PICK PARTS IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 04

As a result from the above examination the following preference conditions are apparent for uncoated Lift pick parts that are needed in Hal 04. Pre-assembly:

5. *If at least a Kanban order quantity of 2 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Besides uncoated Lift pick parts that are needed in Hal 04. Pre-assembly, uncoated Lift pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. The equation is as follows:

$$L_{2,i} \cdot Pick_1 = (1 + ELT) \cdot \left(UCP_i \cdot \left(\frac{DB+D02}{V} + TL+PP_1 \right) \right) + L_{1,i} \cdot Pick_1$$

The latter equation is simplified to:

$$36 \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\} = 310.5 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{20 \cdot 0.90} \right) + 36 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{5, GPW_{ij}\}} \right\rceil \right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 13 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
6	5	11.525	11	-2.875	Safe
5	5	10.95	10	-3.45	Safe
4	5	10.0875	10	-4.3125	Safe

3	5	8.65	8	-5.75	Safe
2	5	5.775	5	-8.625	
1	5	-2.85	-2	-17.25	
6	4	10.625	10	-2.875	Safe
5	4	10.05	10	-3.45	Safe
4	4	9.1875	9	-4.3125	Safe
3	4	7.75	7	-5.75	Safe
2	4	4.875	4	-8.625	
1	4	-3.75	-3	-17.25	
6	3	9.125	9	-2.875	Safe
5	3	8.55	8	-3.45	Safe
4	3	7.6875	7	-4.3125	Safe
3	3	6.25	6	-5.75	Safe
2	3	3.375	3	-8.625	
1	3	-5.25	-5	-17.25	
6	2	6.125	6	-2.875	Safe
5	2	5.55	5	-3.45	Safe
4	2	4.6875	4	-4.3125	Safe
3	2	3.25	3	-5.75	
2	2	0.375	0	-8.625	
1	2	-8.25	-8	-17.25	
6	1	-2.875	-2	-2.875	
5	1	-3.45	-3	-3.45	
4	1	-4.3125	-4	-4.3125	
3	1	-5.75	-5	-5.75	
2	1	-8.625	-8	-8.625	
1	1	-17.25	-17	-17.25	

TABLE 13 RESULTS OF TIME DIFFERENCES FOR UNCOATED LIFT PICK PARTS IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 02

As a result from the above examination the following preference conditions are apparent for uncoated Lift pick parts that are needed in Hal 02. Final assembly:

6. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
7. *If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

POD pick parts

To find the preference conditions for parts stored in POD racks, the time costs for the part type which is already allocated to Kit are compared to the time costs for Kanban close. These parts are stored in either a Lager bin or on a pallet. First the preference conditions for Lager bins are determined and secondly the conditions for the pallets.

POD pick parts stored in Lager bin are characterized by:

- Smaller than or equal to 500 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Lager bin or Euro pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

The cases where weight and size are causing for a switch in material feeding principle are examined for POD pick parts below. Travel time in the POD pick area in Warehouse (1) is not accounted for as this is the assumed to be very similar for Kanban and Kit. The reckoned difference in travel time from Kanban far as opposed to Kit did not take into account that order picking can be pooled. In practice, both Kit and Kanban order picking will be done in pooled picking routes.

Coated POD pick parts from Lager bin

The equation which needs examination is given below:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+2\cdot D08+D04}{V} + TL+PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \ \cdot max\left\{1, \left\lceil\frac{SOP_{ij}}{min\{2,GPW_{ij}\}}\right\rceil\right\} = 294.3 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{4\cdot 0.90}\right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot max\left\{1, \left\lceil\frac{KOQ_{ij}}{min\{2,GPW_{ij}\}}\right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 14 below. The result of examining results with a potential grab of 1 are not visualised here, as these are no advantageous scenarios.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
6	2	4.375	4	-2.725	Safe
5	2	1.65	1	-3.27	
4	2	-2.4375	-2	-4.0875	
3	2	-9.25	-9	-5.45	
2	2	-22.875	-22	-8.175	
1	2	-63.75	-63	-16.35	

TABLE 14 RESULTS OF TIME DIFFERENCES FOR COATED POD PICK PARTS FROM LAGER BIN IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 04

As a result from the above examination the following preference conditions are apparent for coated POD pick parts from Lager bin that are needed in Hal 04. Pre-assembly:

8. *If at least a Kanban order quantity of 6 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Besides coated POD pick parts that are needed in Hal 04. Pre-assembly, coated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. The equation is as follows:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+2\cdot D08+D02}{V} + TL+PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{2, GPW_{ij}\}} \right\rceil\right\} = 413.1 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{4 \cdot 0.90} \right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{2, GPW_{ij}\}} \right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 15 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
13	2	9.173076923	9	-8.826923077	Safe
6	2	-1.125	-1	-19.125	

TABLE 15 RESULTS OF TIME DIFFERENCES FOR COATED POD PICK PARTS FROM LAGER BIN IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 02

As a result from the above examination the following preference conditions are apparent for coated POD pick parts from Lager bin that are needed in Hal 02. Final assembly:

9. If at least a Kanban order quantity of 13 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Uncoated POD pick parts from Lager bin

The equation which needs examination is given below:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(UCP_i \cdot \left(\frac{DB + D02}{V} + TL + PP_1 \right) \right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{2, GPW_{ij}\}} \right\rceil\right\} = 157.5 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{4 \cdot 0.90} \right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}} \right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{2, GPW_{ij}\}} \right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 16 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
6	2	10.70833333	10	-1.458333333	Safe
5	2	9.25	9	-1.75	Safe
4	2	7.0625	7	-2.1875	Safe
3	2	3.416666667	3	-2.916666667	Safe
2	2	-3.875	-3	-4.375	
1	2	-25.75	-25	-8.75	

TABLE 16 RESULTS OF TIME DIFFERENCES FOR UNCOATED POD PICK PARTS FROM LAGER BIN IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 04

As a result from the above examination the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 04. Pre-assembly:

10. If at least a Kanban order quantity of 3 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Besides uncoated POD pick parts that are needed in Hal 04. Pre-assembly, uncoated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. The equation is as follows:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(UCP_i \cdot \left(\frac{DB+D02}{V} + TL + PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \ \cdot max\left\{1, \left\lceil \frac{SOP_{ij}}{min\{2,GPW_{ij}\}} \right\rceil \right\} = 310.5 \left(\frac{\frac{SOP_{ij}}{KOQ_{ij}}}{4 \cdot 0.90} \right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot max\left\{1, \left\lceil \frac{KOQ_{ij}}{min\{2,GPW_{ij}\}} \right\rceil \right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 17 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
10	2	9.375	9	-8.625	Safe
6	2	3.625	3	-14.375	

TABLE 17 RESULTS OF TIME DIFFERENCES FOR UNCOATED POD PICK PARTS FROM LAGER BIN IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 02

As a result from the above examination the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 02. Final assembly:

11. If at least a Kanban order quantity of 10 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Coated POD pick parts from pallet

POD pick parts placed on a pallet are characterized by:

- Smaller than or equal to 1200 millimetre. (Maximum length)
- Less than or equal to 15 kilograms. (Maximum weight)
- Smaller than or equal to Lager bin or Euro pallet size when the sum of part type occurrence times the part volume times the boundary box reduction is taken. (Total volume of part type)

The equation which needs examination is given below:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+2 \cdot D08+D02}{V} + TL + PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \cdot max\left\{1, \left\lceil\frac{SOP_{ij}}{min\{2, GPW_{ij}\}}\right\rceil\right\} = 294.3 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot max\left\{1, \left\lceil\frac{KOQ_{ij}}{min\{2, GPW_{ij}\}}\right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 18 below. The outcome of examining results with a potential grab of 1 are not visualised here, as these are no advantageous scenarios. In addition, there are no advantageous scenarios for a Kanban order quantity of 6 or lower. The table shows the limit level, and as a comparison the result for a Kanban order quantity of 6 is shown.

Kanban order quantity	**Potential grab of multiple parts**	**Average advantage (sec)**	**Rounded average advantage (sec)**	**Largest disadvantage (sec)**	
33	2	9.081818182	9	-8.918181818	Safe
6	2	-8.25	-8	-49.05	

TABLE 18 RESULTS OF TIME DIFFERENCES FOR COATED POD PICK PARTS FROM PALLET IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 04

As a result from the above examination the following preference conditions are apparent for coated POD pick parts that are needed in Hal 04. Pre-assembly:

12. *If at least a Kanban order quantity of 33 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Besides coated POD pick parts that are needed in Hal 04. Pre-assembly, coated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. The equation is as follows:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+2 \cdot D08+D02}{V} + TL+PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \cdot max\left\{1, \left\lceil\frac{SOP_{ij}}{min\{2, GPW_{ij}\}}\right\rceil\right\} = 413.1 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot max\left\{1, \left\lceil\frac{KOQ_{ij}}{min\{2, GPW_{ij}\}}\right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 19 below.

Kanban order quantity	**Potential grab of multiple parts**	**Average advantage (sec)**	**Rounded average advantage (sec)**	**Largest disadvantage (sec)**	
46	2	9.019565217	9	-8.980434783	Safe
6	2	-50.85	-50	-68.85	

TABLE 18 RESULTS OF TIME DIFFERENCES FOR COATED POD PICK PARTS FROM PALLET IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 02

As a result from the above examination the following preference conditions are apparent for coated POD pick parts that are needed in Hal 02. Pre-assembly:

13. *If at least a Kanban order quantity of 46 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Uncoated POD pick parts from pallet

The equation which needs examination is given below:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+D04}{V} + TL + PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \cdot max\left\{1, \left\lceil\frac{SOP_{ij}}{min\{2,GPW_{ij}\}}\right\rceil\right\} = 157.5 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot max\left\{1, \left\lceil\frac{KOQ_{ij}}{min\{2,GPW_{ij}\}}\right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 20 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	
18	2	9.25	9	-8.75	Safe
6	2	-8.25	-8	-26.25	

TABLE 20 RESULTS OF TIME DIFFERENCES FOR UNCOATED POD PICK PARTS FROM PALLET IN KANBAN CLOSE VERSUS IN KIT WHEN TRANSPORTED TO HAL 04

As a result from the above examination the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 04. Pre-assembly:

14. *If at least a Kanban order quantity of 18 times the part type demand can fit on a pallet and the grab potential is at least 2.*

Besides uncoated POD pick parts that are needed in Hal 04. Pre-assembly, uncoated POD pick parts are also needed in Hal 02. Final assembly. This examination of preference conditions is done in analogous manner. The equation is as follows:

$$P_{2,i} \cdot Pick_2 = (1 + ELT) \cdot \left(CP_i \cdot \left(\frac{DB+D02}{V} + TL + PP_1\right)\right) + P_{1,i} \cdot Pick_2$$

The latter equation is simplified to:

$$72 \cdot max\left\{1, \left\lceil\frac{SOP_{ij}}{min\{2,GPW_{ij}\}}\right\rceil\right\} = 310.5 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) + 72 \cdot \left(\frac{SOP_{ij}}{KOQ_{ij}}\right) \cdot max\left\{1, \left\lceil\frac{KOQ_{ij}}{min\{2,GPW_{ij}\}}\right\rceil\right\}$$

Similar tables and graphs like, table 9 and figure 28 are constructed for the latter equation, and lead to the same conclusions. The graphs show the same patterns. So the advantages are best taken from the different scenarios where the sum of occurrence of a part type is varied. The results of all these similar tables are summarised in table 21 below.

Kanban order quantity	Potential grab of multiple parts	Average advantage (sec)	Rounded average advantage (sec)	Largest disadvantage (sec)	

35	2	9.128571429	9	-8.871428571	Safe
6	2	-33.75	-33	-51.75	

Table 21 Results of time differences for uncoated POD pick parts from pallet in Kanban close versus in Kit when transported to Hal 02

As a result from the above examination the following preference conditions are apparent for uncoated POD pick parts that are needed in Hal 02. Final assembly:

15. If at least a Kanban order quantity of 35 times the part type demand can fit on a pallet and the grab potential is at least 2.

Appendix D. Preference conditions on part level

Preference conditions for Kanban close when the part is initially placed in Kit:

Lift pick parts

Hal 04 coated:

1. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
2. *If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Hal 02 coated:

3. *If at least a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
4. *If a Kanban order quantity of 6 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Hal 04 uncoated:

5. *If at least a Kanban order quantity of 2 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

Hal 02 uncoated:

6. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Bito bin and the grab potential is at least 3.*
7. *If a Kanban order quantity of 4 times the part type demand can fit in a Bito bin and the grab potential is at least 2.*

POD pick parts Lager bin

Hal 04 coated:

8. *If at least a Kanban order quantity of 6 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Hal 02 coated:

9. *If at least a Kanban order quantity of 13 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Hal 04 uncoated:

10. *If at least a Kanban order quantity of 3 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

Hal 02 uncoated:

11. *If at least a Kanban order quantity of 10 times the part type demand can fit in a Lager bin and the grab potential is at least 2.*

POD pick parts pallet

Hal 04 coated:

12. If at least a Kanban order quantity of 33 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Hal 02 coated:

13. If at least a Kanban order quantity of 46 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Hal 04 uncoated:

14. If at least a Kanban order quantity of 18 times the part type demand can fit in a Lager bin and the grab potential is at least 2.

Hal 02 uncoated:

15. If at least a Kanban order quantity of 35 times the part type demand can fit in a Lager bin and the grab potential is at least 2.