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Title: **Integration of a layer picking area with the OptilogX Sequencing Buffer**

Author: K.E. van Rooijen

Title (in Dutch) Integratie van een pallet-ombouwgebied met de OptilogX Sequencing Buffer

Assignment: Master thesis

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Initiator (university): Prof. dr. ir. G. Lodewijks

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Supervisor: Dr. ir. H.P.M. Veeke

Date: December 8, 2016

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Supervisor (ORTEC):	ir.M.R. Martens	Report number:	2016.TEL.8082
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			until: December 8, 2021

Subject: **Layer picking in an automated warehouse**

Usually, automated warehouses do not touch the layers on a pallet: pallets entering the warehouse will leave the system in the exact same configuration. Layer picking on pallets is executed outside the automated warehouse by hand or by machines, which is often very inefficient in terms of floor space usage. This leads to long walking/driving times, mistakes, safety issues, and lack of progress overview.

ORTEC Warehousing (located in Zoetermeer, the Netherlands) develops automated warehousing solutions (i.e., OptilogX Sequencing Buffer) to create highly dynamic buffering, sequencing and storage of pallets, roll cages, and custom size load units. ORTEC Warehousing wishes to offer an end-to-end logistic solution for clients by executing the layer picking inside the OptilogX. In that way, the automated warehouse will have single product pallets as input and a combination of single product pallets and mixed product pallets as output, in a certain sequence determined by the order or shipment.

The assignment should make an overview of the possibilities for a layer picking area, derive the characterization and performance indicators, create a generic model for a layer picking area, and use this model to identify the important lay-out variables. Furthermore, this thesis should deliver insights on the needs, possibilities and constraints for the layer picking area in combination with the OptilogX, delivering in particular:

- An analysis of the current situation, with the different layer picking needs and possibilities
- A system analysis to define the capabilities and possible improvements for the layer picking area
- A characterization of the required pallet flow within the system to be able to have a feasible solution
- An analysis on the effect of different input variables on the system performance

The report should be arranged in such a way that all data is structurally presented in graphs, tables, and lists with belonging descriptions and explanations in text. The report should comply with the guidelines of the section. Details can be found on the website.

The professor,

Prof. dr. ir G. Lodewijks

Layer picking

Integration of a layer picking area with the OptilogX Sequencing Buffer

by

K.E. van Rooijen

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday, December 8, 2016 at 10:00 AM.

Student number:	4011422	
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Thesis committee:	Prof. dr. ir. G. Lodewijks,	TU Delft, chairman
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This thesis is confidential and cannot be made public until December 8, 2021.

Preface

The research done within this report has been completed at ORTEC Zoetermeer and is used as the graduation project to complete the master Mechanical Engineering and to obtain the degree of Master of Science at the Delft University of Technology. The research shows a possibility for the integration of a new developed layer picking area with the OptilogX Sequencing Buffer.

I would like to thank Hans Veeke, my supervisor, for the interesting discussions and feedback throughout my thesis work. Professor G. Lodewijks and him both let me rethink everything I did, which helped to improve the final result. Furthermore, I would like to express my gratitude towards ORTEC for a warm welcome. Especially my daily supervisors, Lucas de M.Tostes and Martijn Martens, for always having the time to discuss problems and finding possibilities for improving the report. This certainly helped me throughout the project.

This thesis is the final step of my study Mechanical Engineering at the Delft University of Technology. I would like to give special thanks to Gerard & Anneke van Rooijen and Linda Giesselink for their endless support during these years. This support has been a great help for me.

K.E. van Rooijen
Delft, December 2016

Summary

ORTEC developed an automated warehousing solution to create a highly dynamic buffering, sequencing and storage of pallets. This solution, the ORTEC OptilogX Sequencing Buffer (OptilogX), sorts the pallets within the system to ensure a high output rate with a short response time. The OptilogX is currently only capable of handling order pallets without changing its layer configuration. However, a warehouse can be used to handle different order pallet types. An order pallet can contain of multiple stock keeping units (SKUs). A SKU is a unique identifier for a product within a specific packaging. For example, all 1 liter packing of an ice-cream flavor are equal to one SKU, while all 0.5 liter packing of the same ice-cream flavor equals a different SKU. Building order pallets with different SKU layers requires a layer picking area. This research focuses on developing a layer picking area which can be combined with the OptilogX.

Figure 1 shows the connection between the OptilogX and the layer picking area. In this way, the system has single product pallets as input and a combination of single product pallets and multiple product pallets as output, in a certain sequence determined by customer order. The layer picking system needs to be in line with the characteristics of the OptilogX to be able to be integrated. The system which suits best is a robot-based system. This system uses a small footprint, has a good mechanical flexibility and can be used within different warehouse types.

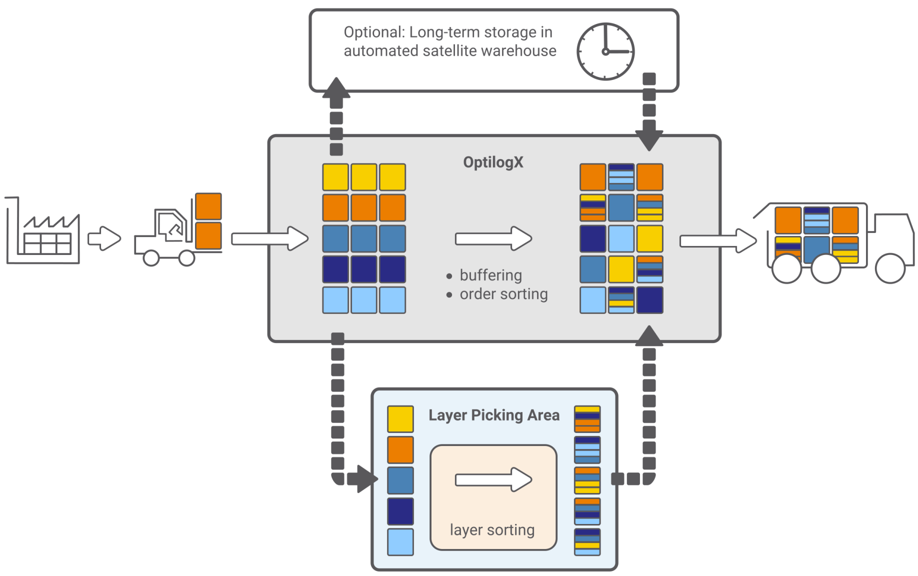

Figure 1: System representation of the connection between the OptilogX and the layer picking area

Building order pallets with assigned SKU layers requires multiple areas to store empty pallets and partially loaded pallets. Figure 2 shows a schematic view of the connection between these areas. The layer picking area needs a certain pallet flow to be able to use the full robot capacity. However, this required pallet flow is only possible to reach using a lot of equipment. A pallet scheduling method can be implemented to reduce the required equipment while maintaining a high layer picking throughput.

The layer picking area is simulated using a simulation model in DelphiXE6/TOMAS. Two basic scheduling methods are used to organize the pallet flow within the model: a reference method and a heuristic method.

- **Reference method**
  The reference method is based on an order oriented scheduling method. This method picks the first order pallet available, sends it to an order position at the robot and it will stay on its order position until

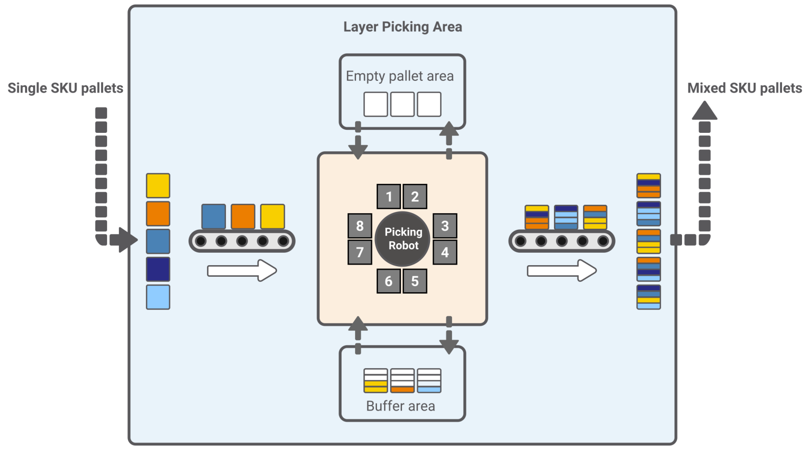

Figure 2: Schematic pallet flow within the system

it is completed. As such, no buffer area visit will be allowed for the order pallets. The supplying pallets will be called if necessary and sent away to the buffer area if no new picking action can be fulfilled.

- **Heuristic method**
  The heuristic method reacts on the current situation within the layer picking area. Its goal is to combine the supply- and order pallets at the robot to lower the pallet movements, while the layer picking throughput is maintained. It uses different priority rules to select each pallet.

The reference and heuristic scheduling methods are both tested in combination with fixed and non-fixed supply- and order positions. Fixed positions uses dedicated supply- and order positions, which results in the need of picking every layer from a supply pallet towards an order pallet. The non-fixed positions uses non-dedicated supply- and order positions, which gives the possibility to use the layers of a supply pallet directly as the first layers for an order pallet.

The scheduling methods have been tested with different experiments containing position variation, SKU influences, transfer time influences, batch size influences and due date influences. Together these five experiments showed the influence of the scheduling method and lay-out decisions for the layer picking area. The most important results from these experiments are:

- The heuristic method with non-fixed supply- and order positions shows the best overall results
- Use eight positions at the robot with at least three supply positions and three order positions
- Keep the pallet inter-arrival time from the buffer area short
- Keep the batch size preferably as big as possible
- Late batch arrival is possible but does have a small influence on the system

The overall results show a good performance of the heuristic method in combination with the non-fixed supply- and order positions. The method is capable of achieving a high pallet throughput if the buffer area pallet inter-arrival can be kept short. The number of required pallet movements is reduced to be able to achieve this situation.

Furthermore, this research shows the influences of the design decisions on a warehouse. This is important to know because each warehouse is different in terms of layer picking throughput, number of SKUs and available space. With this knowledge a decent choice in lay-out can be made.

Samenvatting

ORTEC heeft een magazijnoplossing ontwikkeld om een dynamische buffering, sortering en opslag van pallets mogelijk te maken. Deze oplossing, de ORTEC OptilogX Sequencing Buffer (OptilogX), is door middel van het sorteren van de pallets in staat om een hoge pallet uitvoer te genereren. Dit wordt gedaan met volledige pallets zonder hierbij de productsamenstelling van de pallet te veranderen. Echter, een magazijn kan ook worden gebruikt om verschillende type pallets te verzamelen en deze om te bouwen tot nieuwe samengestelde pallets. Een dergelijke pallet, ook wel orderpallet genoemd, kan uit meerdere voorraadbeheer eenheden (SKU) bestaan. Een SKU is een unieke identificatie voor een product in een specifieke verpakking. Bijvoorbeeld, alle 1 liter verpakkingen van een ijssmaak zijn gelijk aan een SKU, terwijl alle 0.5 liter verpakkingen van dezelfde ijssmaak gelijk zijn aan een andere SKU. Het opbouwen van deze orderpallets vereist een apart pallet-ombouw gebied. Binnen dit onderzoek ligt de focus op de ontwikkeling van een pallet-ombouwgebied welke in combinatie met de OptilogX gebruikt kan worden.

Figuur 3 geeft de verbinding tussen de OptilogX en het pallet-ombouwgebied weer. Hierdoor genereert het totale systeem pallets met een enkelvoudige SKU als invoer en een combinatie van pallets met enkelvoudige SKU's en gemengde SKU's als uitvoer. Om de systemen goed te kunnen combineren dienen de karakteristieken van het te gebruiken pallet-ombouwsysteem in lijn te liggen met die van de OptilogX. Door gebruik te maken van een grijprobot kan aan deze eis worden voldaan. Deze robot is in staat om met het gebruik van een klein vloeroppervlak toch een goede mechanische flexibiliteit en een hoge capaciteit te behalen.

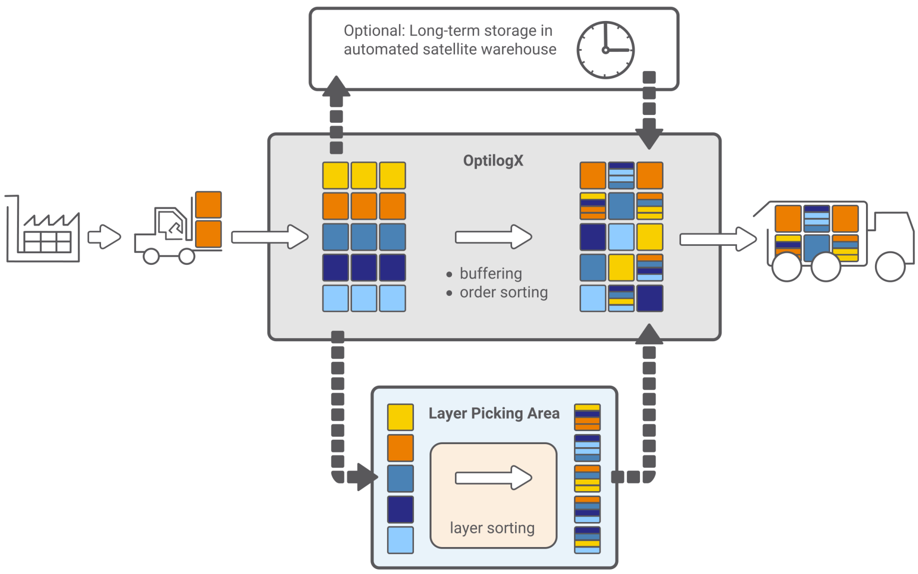

Figure 3: Systeem representatie van de OptilogX i.c.m. een pallet-ombouw gebied

Voor het bouwen van orderpallets met gemengde SKU's zijn verschillende opslaggebieden nodig om lege pallets en gedeeltelijk gevulde pallets op te slaan. Figuur 4 geeft een schematische weergave van de connectie tussen deze gebieden.

Om de volledige capaciteit van een grijprobot te kunnen benutten is een stroom van pallets binnen het systeem nodig. Echter, deze benodigde stroom van pallets is dusdanig hoog, dat het alleen mogelijk is om dit te behalen met het gebruik van veel materieel. Om met minder materieel toch een goede ombouwsnelheid te kunnen behalen is een planningsmethode nodig voor het verlagen van de benodigde stroom pallets.

Het pallet-ombouwgebied is gesimuleerd met een model in de simulatieomgeving DelphiXE6/TOMAS.

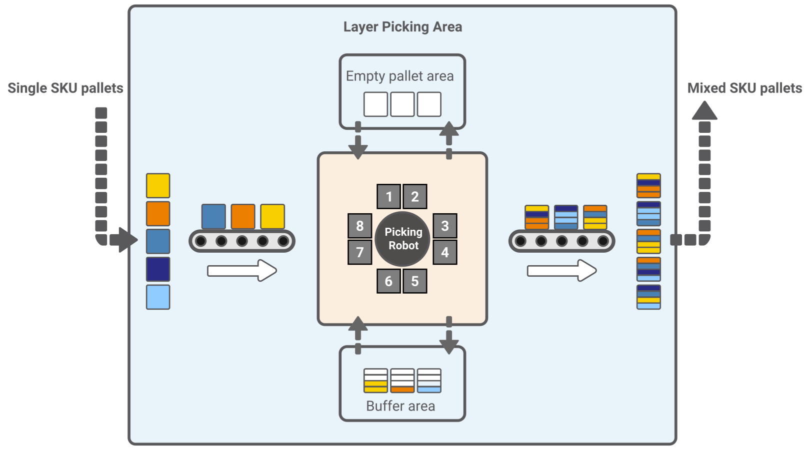

Figure 4: Schematische palletstroom in het systeem

Twee basis planningsmethoden zijn gebruikt om de stroom van pallets in het model te organiseren: een referentiemethode en een heuristische methode.

- **Referentiemethode**
  De referentiemethode kiest de eerst beschikbare orderpallet, stuurt deze naar een positie bij de robot en blijft hier vervolgens totdat de pallet compleet is. De aanvoer pallets worden opgehaald zodra ze nodig zijn en weggestuurd naar het gebied voor de gedeeltelijke pallets als er geen nieuwe laag meer kan worden gepakt.

- **Heuristische methode**
  De heuristische methode reageert op de huidige situatie in het pallet-ombouwgebied. Het doel hierbij is om de aanvoer- en orderpallets te combineren bij de robot om het aantal pallet bewegingen te verlagen.

De referentie- en heuristische planningsmethode zijn allebei getest in combinatie met vaste en niet-vaste aanvoer- en orderposities. De vaste posities maken gebruik van toegewezen aanvoer- en orderposities, welke resulteren in de noodzaak om elke SKU-laag te verplaatsen van een aanvoerpallet naar een orderpallet. De niet-vaste posities maken geen gebruik van toegewezen aanvoer- en orderposities, wat mogelijkheid geeft om de laatste SKU-lagen van een aanvoer pallet direct te gebruiken als de eerste SKU-lagen van een orderpallet.

De gecombineerde planningsmethoden zijn getest door middel van verschillende experimenten. Hierbij is gekeken naar de invloeden van de positie verdeling bij de robot, het aantal SKU's, de verplaatsingstijd van de pallets, het aantal orderpallets per bestelling en de invloed van verlate orders met een hoge prioriteit. Samen geven deze vijf experimenten de invloeden van de verschillende planningsmethoden weer, alsmede eisen aan de lay-out voor het pallet-ombouwgebied. De belangrijkste resultaten zijn:

- De heuristische methode met niet-vaste aanvoer- en orderposities geeft de meest stabiele en goede resultaten
- Gebruik acht posities bij de robot met daarbij minimaal drie aanvoer posities en drie orderposities
- Houdt de pallet tussen-aankomst tijd vanuit het buffer gebied klein
- Het aantal orderpallets per bestelling is bij voorkeur zo groot mogelijk
- Verlate orders zijn mogelijk, maar hebben wel een kleine invloed op het systeem

De resultaten laten een stabiele en goede prestatie zien voor de heuristische methode in combinatie met de niet-vaste aanvoer- en orderposities. Met behulp van deze methode is het aantal benodigde pallet bewegingen verlaagd om een goede pallet-ombouwsnelheid te kunnen behalen. Daarnaast zijn aan de hand van de resultaten belangrijke ontwerpkeuzes voor een pallet-ombouwgebied naar voren gekomen.

Nomenclature

λ	average pallet input flow rate
D	average pallet throughput time through the system
i	order pallet
L_1	robot position occupation time during first layer picking
L_s	robot position occupation time during succeeding layer picking
LR_i	layers remaining for order pallet i
M_p	pallet movements
M_b	pallet movements to/from buffer area
M_o	order pallet movements
M_s	supply pallet movements
N	average number of pallets in the system
p	pallet
$P(S)$	probability to pick a new layer without an extra pallet movement required
$P(S^c)$	probability to pick a new layer with an extra pallet movement required
P_L	probability to have a pallet with at a second SKU-layer available
$PP_{p,o}$	pallet position
PT	processing time for one layer
RH_p	pallet hold by robot
t_c	current time
t_l	time for the robot to pick or deliver a single SKU-layer
t_p	pallet change time
t_{dd}	due date
t_f	completion time
t_{pc}	full robot picking cycle time
t_{pm}	time for a single pallet movement
TT_{in}	pallet transfer time from an input area towards a robot position
TT_{out}	pallet transfer time from a robot position towards the output
v_a	pallet movement velocity
x	pallet position
x_p	pallet size to move
x_r	robot pallet position

List of Figures

List of Tables

Contents

1 Introduction

Chapter 1 gives an introduction to the research by describing the problem context and the research approach. First, the department ORTEC Warehousing will be introduced. Second, an insight in the normal flows within an automated warehouse will be given to show the opportunity for layer picking as a new development for ORTEC. Third, the research approach will be described.

1.1. ORTEC Warehousing

ORTEC is one of the worlds leaders in optimization software and analytic solutions with the goal to make businesses more efficient, more predictable and more effective. This is also done for warehousing development at the department ORTEC Warehousing. This means to automate material handling in situations where it has not been considered before. ORTEC Warehousing develops automated warehousing solutions to create highly dynamic buffering, sequencing and storage of pallets, roll cages and custom size load units.[11] These targets can be fulfilled using the patented ORTEC OptilogX Sequencing Buffer (OptilogX) for short-term pallet storage and sequencing. Sometimes also a long-term pallet storage, called ORTEC OptilogX Automated Shuttle Warehouse, is added to the system. ORTEC Warehousing performs the implementation and development of new software for the control of automated warehouses. At this moment, the systems can fulfill real-time control and management of all components within a warehouse. Figure 1.1 gives a schematic view of the system. As can be seen, pallets with goods are fed into the system on the left. Note that the pallet colors represent different goods. Consequently, the pallets are sorted before smart storing in the long-term warehouse or in the short-term buffer itself. Orders are sequenced in the buffer following the order schedule and when a truck actually arrives the system will pull the correct pallets out of the buffer. This is done with a high pallet throughput and thus a short turn around time for an arriving truck.

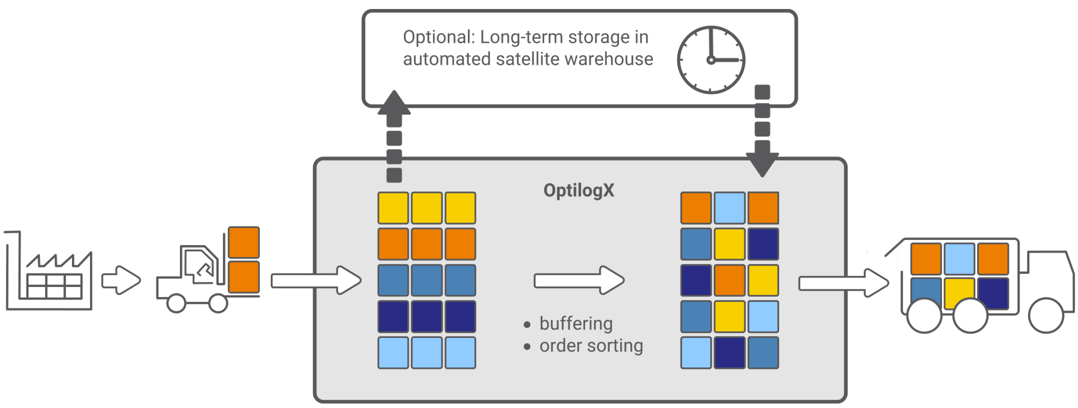

Figure 1.1: Schematic view of the OptilogX

1.2. Automated warehouse

Automated warehouses are widely used since their introduction in the 1950s. They are used for the storage and retrieval of products in both distribution and production environment. An automated warehouse system can be described as a storage system that uses fixed-path storage and retrieval machines running on one or more rails between fixed arrays of storage racks.[14] This basic idea of the system gives the ability to put pallets into a storage and also to retrieve these pallets from the storage to complete an order. These operations can be done fully automatic without an operator interrupting the process. A routing for the pallets can be determined based on the available space and the required internal movements. It creates the ability to sort, sequence, buffer and store a wide range of products using the full lay-out of the system.[8] This will result in multiple advantages over the use of a non-automated warehouse (e.g., labor cost reduction, floor space savings and higher reliability).

1.2.1. Warehouse types

Two different warehouse types can be distinguished by their location: a warehouse within a production facility and a warehouse within a distribution center.[15]

The main function for a warehouse within a production facility is to store raw material, work-in-process and finished products. Hereby, the raw materials and the finished products can sometimes be stored in a long-term storage while the work-in-process always needs to be stored in a short-term storage. The long-term storage is used to have a large storage capacity with low investment- and operational costs. The short-term storage is used for its quick system response time. This because the order is not always known at start of the process and the retrieval of the products needs to be fast in order to keep the production going.

The distribution warehouse is used to have a large throughput capacity to be able to fulfill the customer orders. These orders usually contain a large number of different products which result in a complex order picking.

The current system used by ORTEC Warehousing is a high dynamic system and capable to deliver pallets with a short response time in combination with a high throughput. As such, this research will focus on the short-term storage for both a production facility as a distribution center.

1.2.2. Goods process

Order picking is the process of receiving goods from the storage and placing them towards shipment. This needs to be done with collecting goods in the correct quantities to fulfill the customer orders. Currently the OptilogX is only capable of performing order picking with full pallets; it does not touch the items on a pallet. It means that pallets entering the warehouse will leave the system in the exact same configuration. However, a warehouse can be used to handle different order types. An order can contain various quantities of one or more stock keeping units (SKUs). A SKU is a unique identifier for a product within a specific packaging. For example, all 1 liter packing of an ice-cream flavor are equal to one SKU, while all 0.5 liter packing of the same ice-cream flavor equals a different SKU. Figure 1.2 shows the order processing within a warehouse. This is done using the following main steps.[1]

1. *Receiving process*
   Collects the products that arrive from the production area or supplier. The products may be checked or transformed at this point.

2. *Storage process*
   Stores the incoming products in designated storage areas. The storage area mostly consist of two parts: reserve area and forward area. The reserve area is for an economical storage (e.g. bulk storage area) and the forward area is for the quick product retrieval by an order picker.

3. *Picking process*
   The requested products will be picked from the storage area. A distinction can be made between pallet picking, layer picking and case picking.

4. *Sorting or consolidation process*
   The picked product will be sorted and sequenced in the correct order. Products for the same order will be grouped.

5. *Shipping area*
   The products will be checked, packed and leave the warehouse in the correct sequence for shipment to the customer. This can be by truck, train or any other carrier.

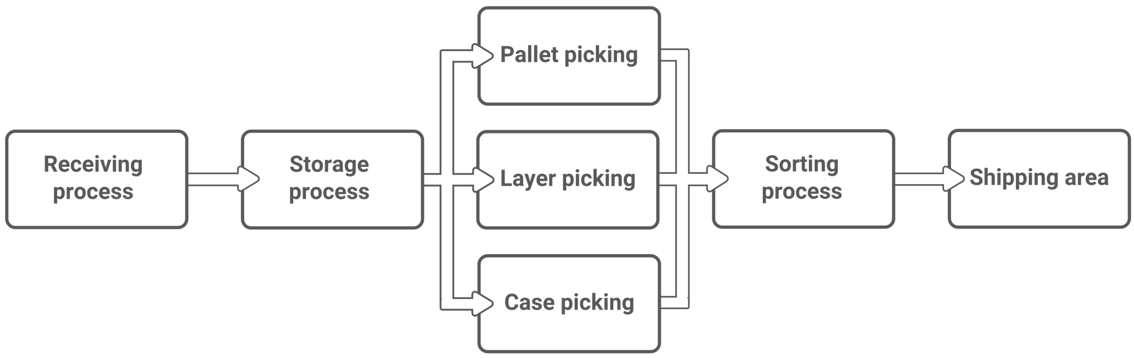

Figure 1.2: Regular process flow within a warehouse

Pallet volumes within different warehouses vary a lot. However, the Pareto principle can be applied for the distribution of order picking.[5] This means that 80% of the volume is transferred via pallet picking and 20% of the volume by layer or case picking. Within this 20% the rule can be applied again, resulting in a total of 16% volume transfers via layer picking and 4% volume transfers via case picking.

1.3. Research approach

Usually, automated warehouses do not touch the item content on a pallet. This while customers do have the opportunity to order products with smaller amounts than a full pallet. Creating these orders requires SKU-layer picking. Layer picking means creating new requested pallets consisting of different SKU-layers (i.e., SKU layers). Currently, this is for example done by hand or by machines. Layer picking gives customers the opportunity to order more specific quantities with the result of lowering their inventory. Layer picking is a high potential cost-reduction for companies that handle cubed packaged goods and that have a high level of less-than-pallet picking volume. This is in most times the case within food-retail and distribution customers.[18] Layer picking has become an important part to improve, because distribution managers are always looking to cut costs and to improve productivity within their warehouses.[7] Therefore, this research will focus on the integration of a layer picking area with the OptilogX Sequencing Buffer.

The first part of this research will focus on the system analysis to define opportunities for creating an automated layer picking area. This will be done using a description of the current situation and using the Delft Systems Approach to fulfill a system analysis. The following questions will be a guidance during the analysis.

- What does the current OptilogX system look like and how can it contribute to layer picking?
- Which conditions need to be used? (e.g. throughput times, mechanical possibilities)
- What are relevant KPIs?

The second part of this research will use the research question created within Chapter 4 as a guideline. This research question will be answered using experiments with a simulation model built in DelphiXE6/TOMAS.

2

Current situation

This chapter describes the current situation in the warehousing environment and the possibilities for layer picking within this environment. Section 2.1 shows the current system that is used by ORTEC Warehousing: the ORTEC OptilogX Sequencing Buffer. Some components will be explained in combination with the used scheduling methods and software structure. Section 2.2 focuses on the explanation and possibilities of a layer picking system. This is done with the market requirements and three layer picking system examples. Section 2.3 concludes this chapter with requirements from a current operating site.

2.1. OptilogX

The ORTEC OptilogX Sequencing Buffer is an automated warehouse which is capable to retrieve, store and sequence products in an optimized way to be able to deliver a high and fast output to the trucks. ORTEC Warehousing is performing the implementation and development of new software for the control of this system. Figure 2.1 shows an impression of the OptilogX.

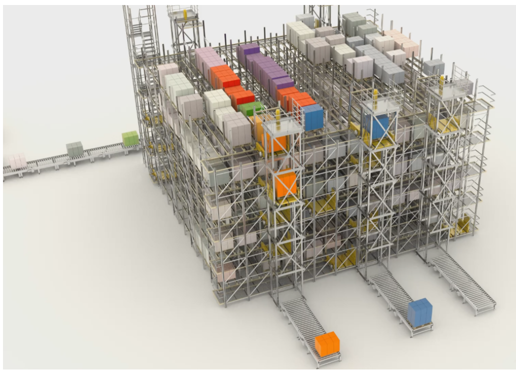

Figure 2.1: ORTEC OptilogX Sequencing Buffer [12]

Figure 2.2: Vertical transporter

2.1.1. Characteristics

The OptilogX is capable of handling and sorting pallets with products inside the system. By sorting the pallets in the buffer, a high output rate with a correct sequence can be delivered which reduces the handling time required to load the truck. The OptilogX is designed to be adjustable to the customer needs. Dimensions can be configured and the system is capable to deal with different temperatures. Also the routing decisions for the pallets can be changed according to the requirements. A difference with regular automated warehouses is the ability to re-order the pallets to create a high, reliable system output. The system is used for highly dynamic pallet buffering, storage and sequencing. Figure 2.3 shows a schematic view of the position of the OptilogX within a warehouse. The pallet enters from the production facility or a truck into the warehouse. From here the pallets are transferred towards the OptilogX. Inside the system, the pallets are temporarily stored at a long-term warehouse or directly sequenced and ready for delivery. If the destination truck arrives the corresponding pallets will be retrieved from the OptilogX and delivered at the truck.

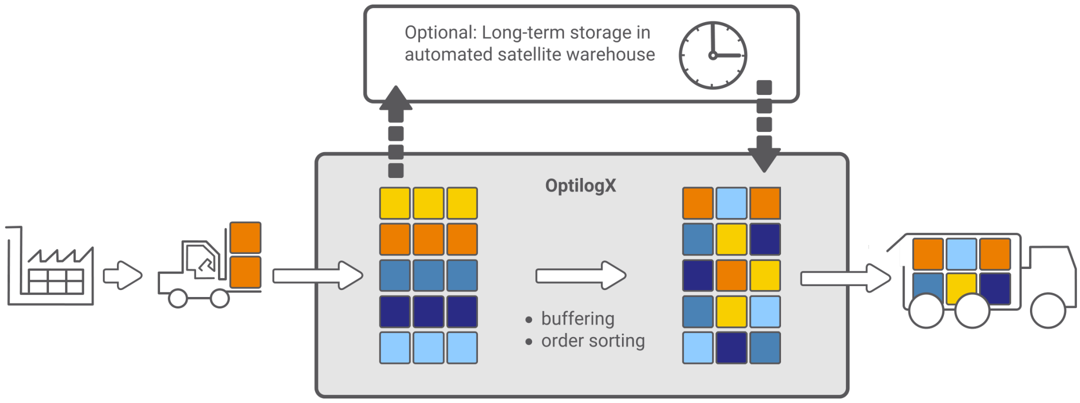

Figure 2.3: Schematic view of the OptilogX

The OptilogX is only used as a buffer to achieve a high pallet flow when the destination truck arrives. Therefore, the pallet content is not touched. Pallets leave the system in the same configuration as they entered. The OptilogX uses different components to transfer these pallets within the system. A short description of these components is given:

- **Vertical transporter (VT)** Figure 2.2 shows a vertical transporter. A vertical transporter (shuttle) is most commonly placed at the in-feed and out-feed of the system. It works as a lift to move pallets between the levels and uses three chain conveyors to transfer a pallet into and out of the shuttle. The capacity is 80-120 pallets/hour depending on the number of levels within the system.
- **Horizontal transporter (HT)** The horizontal transporter works similarly as the VT. However, a HT is responsible for horizontally moving the pallets across the OptilogX and placing/retrieving them from and to the VTs or buffer lanes. Each HT belongs to a specific level inside the OptilogX and is not capable of moving between the levels. The transfer capacity is up to 120 pallets/hour depending on the number of buffer lanes at one level.
- **Buffer lanes** Buffer lanes are places between the in-feed and out-feed side of the system. A buffer lane consist of three chain conveyors over the full length, which transfers the pallets forth and back. They are capable to use for short-term pallet storage, pallet transfers and the delivering and retrieving of pallets at both sides. The storage capacity of a single buffer lane is dependable on the pallet size, gap between the pallets and the buffer lane length. The pallets are stored next to each other over the length of the chains.

The system out-feed for most OptilogX systems is limited by the VT; all pallets needs to be transported via this system. Extra capacity can be created by using multiple VTs. Some OptilogX systems are able to use a HT to move pallets out of the system. Hereby it is difficult to create extra capacity due to physical limitations.

2.1.2. Scheduling method

The current pallet flow organization within the OptilogX is based on a heuristic approach. The system decides for each incoming pallet its destination lane by following priority rules. If the required pallet locations are determined by the system (specific lane or out-feed), then each pallet movement is calculated. These movements are defined by using a simple Dijkstra algorithm to calculate the shortest path for each case. So, the specific out-feed is ordered by the truck arriving and the movement order of these pallets is based on the Dijkstra algorithm. If there are multiple out-feed points, the system will take all pallets and requirements of the different trucks into account to decide the pallet movement order.

2.1.3. Software structure

The software structure of the OptilogX is developed by ORTEC and is called the ORTEC Warehouse Control System (OWCS). It controls the warehouse components and manages pallet flows by responding to incoming signals and sending out pallet movements, while managing the pallet inventory and interfacing with other information systems. The OWCS structure is a built of the Warehouse Planning and Management System (WPMS) in combination with the Connactive Processes (CP).

- **Warehouse Planning and Management System (WPMS)** WPMS is responsible for the planning of the OWCS software. It reacts on inventory changes, infed pallets, orders and on its own optimization routines. All signals are coming from the control layer which also manages the inventory. WPMS is stateless, meaning that it knows nothing about the systems lay-out nor the inventory until the information is sent from CP. WPMS does not maintain a database, except for internal databases used for calculations. In general, the objective for the WPMS pallet selection algorithm is to minimize the total out-feed time while taking the order constraints into account. Constraints can for example be blocked pallets, pallets in blocked areas or a required time inside the system (in case of deep-frozen products).

- **Connactive Processes (CP)** CP is the main software component which provides the actual warehouse control. It is used to execute the pallet movements by sending a signal to a Programmable Logic Controller (PLC). CP contains all information necessary for the warehouse control (e.g., all product information, warehouse lay-out and the current pallet positions inside the warehouse). WPMS will use this information to decide their actions. The information is updated directly if something changes in the system.

2.2. Layer picking

A layer picking area creates customer ordered pallets by picking a layer from an incoming pallet (containing one SKU per pallet) and placing this layer on the destination pallet (customer ordered pallet). Customer orders contain multiple products on a pallet with on each layer a specific SKU. This is normally the most labor-intensive operation in warehouses with manual systems, and a very capital-intensive operation in warehouses with automated systems.[3] This section will explain the different layer picking options to be able to set boundary conditions and requirements for this research.

2.2.1. Market development

Classic order picking systems use mostly the man-to-goods principle to fulfill layer picking. It means an employee walks or drives through the warehouse to the product to pick one or multiple cases. This manual layer picking is more and more replaced by semi-automated layer picking. An example of a semi-automated layer picking system is the combination of a forklift with an attachment which is specifically designed to handle layers of packaged goods. Using this eliminates the manual product handling, increases the process productivity and improves safety in the warehouse. However, still labor is required to drive the forklift. Another example of a semi-automated system is the goods-to-man system with automated storage and retrieval systems. This system is used to get the products towards the employee. The layer picking itself is still done manually.

Distribution managers change towards automated layer picking more and more. This is due to increasing case picking volumes and increasing cost-percentage for the total facility. Customers order in smaller, more frequent quantities to be able to better manage inventories.[7] The requirements for case picking solutions in a warehouse can be divided into five categories. Gilmore and Holste surveyed 210 managers and executives regarding case picking to create an overview of these categories. Case picking in this context can consist of a loose case or a full layer. Figure 2.4 shows the main survey results.

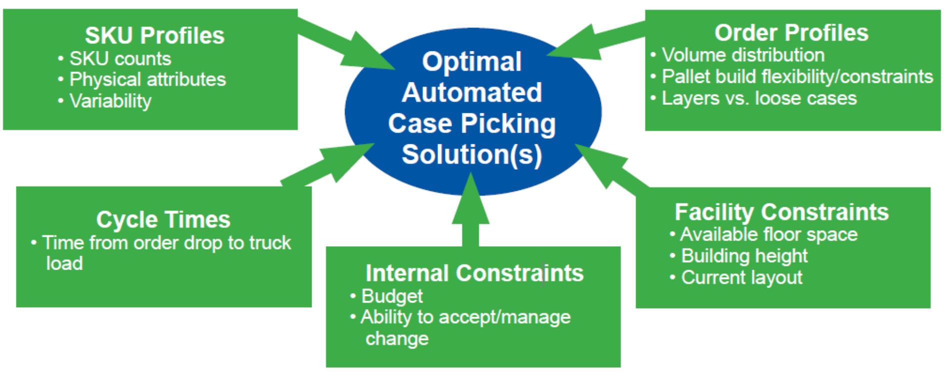

Figure 2.4: Drivers of case picking automation requirements [7]

2.2.2. Layer picking systems

Picking systems are often separately used as a palletizer or a de-palletizer. The picking system examples given in this section are possible to use for automated layer picking. The systems given are:

- Conveyor-based system
- Gantry robot-based system
- Robot-based system

Conveyor-based system

The conveyor-based automated layer picking system is a system which uses a separate storage unit for each product-layer. These storage units are located at possibly hundreds of conveyor lanes, each dedicated to just one SKU. Figure 2.5 shows an example of these storage units. The system flow starts with full pallets entering the pallet storage and if they are required by the SKU storage they will be transferred towards the automatic delayer machine. Subsequently, this machine will delayer the full pallet to single layers. Each layer is then transported on its own towards their appropriate SKU position. The layers will be released from the conveyor lanes based on the order pallets. In the end, the different layers will be palletized and shipped.[7] This full automatic system gives possibilities to use the software of the OptilogX system for transferring the different layers. However, the system needs very high volumes to be applicable, requires a large footprint to built the SKU conveyor lanes and needs two layer pick stations (in-feed and out-feed of the SKU storage). Therefore it is an expensive system to implement.

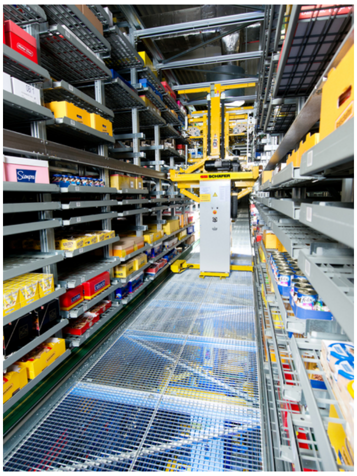

Figure 2.5: Example conveyor-based system [17]

Figure 2.6: Qubiqa layer picker Flex-R [13]

Gantry robot-based system

Figure 2.7 shows an example of a gantry robot-based system. The system uses a gantry which is able to move along a set of overhead tracks. This gantry contain a picking device (e.g., vacuum head) which is capable of picking a layer from the pallet. The layers are transported by the conveyor system to a dedicated inventory zone in the system. From here, the gantry will pick the layer and place it on their specific SKU column as tight as possible to ensure a high density storage. The gantry selects one or more layers from the inventory zone based on shipment orders and deposit them on the takeaway conveyor. The layers are then transported to the automated palletizing area.[7] Another gantry robot-based system is developed by RMT Robotics.[2] This system is ideally suited for facilities that pick more than 1,000 layers per day from 50-500 SKUs. Pallets are retrieved from the warehouse and stored underneath the gantry, creating an area which can include a pallet of every SKU the company offers. The gantry then picks a layer depending on order information, pallet building and inventory. The main disadvantage for using a gantry-based system is that it requires a large footprint because each SKU pallet needs its own storage-place.

Robot-based system

A robot-based system is the most used system in the palletizing and packaging industry.[4] A standard design can be a Cartesian robot with a cubic work space. This is ideal if the pallet arrangement is parallel or

Figure 2.7: Example gantry-based system [2]

rectangular to the conveyor. A Cartesian robot is able to move across its work space and reaches every position directly. Also more specialized solutions are increasing on the market. Figure 2.6 shows an example with the layer picker Flex-R created by Qubiqa [13]. This robot could use up to eight pallet positions with the ability to pick up to 200 layers/hour. An interesting part of using a robotic system is the high capacity in respect to the footprint. However, the warehouse needs to be capable to deliver the required high pallet flows for this robot.

With the available picking systems known it is possible to create an overview of the different systems. Table 2.1 provides the important characteristics of these layer picking systems. These characteristics will be used in Section 3.1 to choose the automatic layer picking system for this research.

2.3. Case: OptilogX with manual layer picking

An interesting OptilogX implementation is placed at a manufacturer near London.[10] This warehouse is used as a shipment buffer, which means that it is required to create a constant and high reactive pallet flow. It receives pallets from two different sections: a long-term storage system and a manual layer picking area. These flows are combined within the OptilogX, where they are sequenced. The pallets will be sent out the moment a truck arrives. The ideal situation for ORTEC would be to create a full automated warehouse. Fulfilling this would need an automated and integrated layer picking area with the OptilogX.

The KPIs set for this system and can be helpful for developing a layer picking area. The system KPIs concern the pallet throughput, the failure rate and the cycle time. Hereby, the cycle time is considered as the time between the last pallet arriving in the system and the last pallet out of the system. The KPIs used for the OptilogX with this case are:

- Nominal throughput needs to be 360 pallets per hour in and 360 pallets per hour out
- One hour every four hours, the throughput must be 400 pallets per hour in and 400 pallets per hour out
- The maximum failure rate is 3 pallet movements per 10.000 pallet movements; a pallet going in and out counts as 2 movements
- An order up to 52 pallets must be sent out within 15 minutes after activation

System measurements have been done to verify if the KPIs of the OptilogX have been achieved.[10] These measurement results are the only values available since the manufacturer is not willing to give specific data. However, the measured input pallet flow for the OptilogX can be used to define the required size for a layer picking area. The resulting capacity for this warehouse should be:

Nominal throughput:	180 picked layers/hour
Maximum throughput:	200 picked layers/hour

Table 2.1: Picking systems overview [7]

	Conveyor-based system	**Gantry-based system**	**Robot-based system**
Replenishment approach	Automatic depalletization charges SKU- specific conveyor lanes.	Full single SKU pallets are placed on the warehouse floor.	Usually used at end of conveyor divert lane.
Layer picking approach	System releasing the required supply pallets, usually in batches, to a takeaway conveyor that leads to an automatic sorter.	Gantry selects one or more layers and places them on a takeaway conveyor, where they are transported to a palletizing area.	Robot picks layers from a supply pallet using a mechanical grabber. Layers are then placed on the order pallet.
Recent advances	These systems have been around for many years; improvements in cost performance now changing the ROI picture for many companies.	Only recently have real, working systems of this type come to the market, aided by software advances and improved system engineering.	Speed and flexibility of robot mechanics; software to optimize pallet construction.
Incremental implementation	The increments would be large, such as a multiple levels of pick conveyors.	Could start with a single gantry and add more later.	Easy to start with one robot and add more later.
Footprint	Medium	Large	Small

3

System analysis

A system analysis will be done to be able to create the problem definition. The system used for this research consist of a layer picking area which can be combined with the current OptilogX. Currently there is some data available from non-combined layer picking systems. However, the combination of an integrated layer picking area with the OptilogX is still non-existing. Therefore, a system analysis is done using requirements set by ORTEC and data obtained within the case described in Section 2.3. The first part of this analysis contains the system overview with the objectives and requirements. The second part is used to quantify the flows required for the system to be able to operate.

3.1. Layer picking system

Usually, layer picking is executed outside the automated warehouse by hand or by machine. To be able to offer an end-to-end logistic solution, the wish is to execute the layer picking in combination with the automated warehouse. In this way the system has single product pallets as input and a combination of single product pallets and picked pallets as output, in a certain sequence determined by customer order. The current developed OptilogX ensures a high pallet throughput capable of sequencing and delivering pallets at the correct place and time. Chapter 2 showed an analysis of the current situation with layer picking systems. Possible options for a layer picking system to use in combination with the OptilogX would be a conveyor-based system, a gantry robot-based system or a robot-based system. These systems are all capable to perform the required capacity. However, the goal is to create a combination with the OptilogX. It means the influence on the important characteristics for the system needs to be minimized. These contain a dynamic and high-density system which is easy adjustable to different warehouses. The robot-based system is the system with the best suited characteristics. It has a small footprint, a good mechanical flexibility, is possible to use within different warehouse types and can be easy implemented with low investment costs. The required pallet flows for this system could be delivered using the OptilogX. This research will use the characteristics of the Qubiqa Layer Picker Flex-R [13] as a basis. A single layer picker is capable to pick 200 layers/hour to/from eight positions in total.

Figure 3.1 shows a combined OptilogX and layer picking flow. As can been seen, the system has single product pallets as input and a combination of single product pallets and multiple product pallets as output, in a certain sequence determined by customer order. The layer picking area in-feed is a single SKU pallet flow and the out-feed is a mixed SKU pallet flow.

3.2. System overview

The Delft Systems Approach will be used in order to create a structured system analysis on the different processes.[20] The basic system flow can be presented using a black box representing the transformation from the input flow to the output flow. This transformation is controlled by requirements from the customer and performance indicators towards the customer. Figure 3.2 shows the black box approach. Here can been seen that the system transforms single SKU pallets into mixed SKU pallets. The requirements for this system concern the pallet composition set by the customers. Each order contain an order pallet with its own specifications. These specifications are the number of layers, the SKU per layer and the order pallet due date.

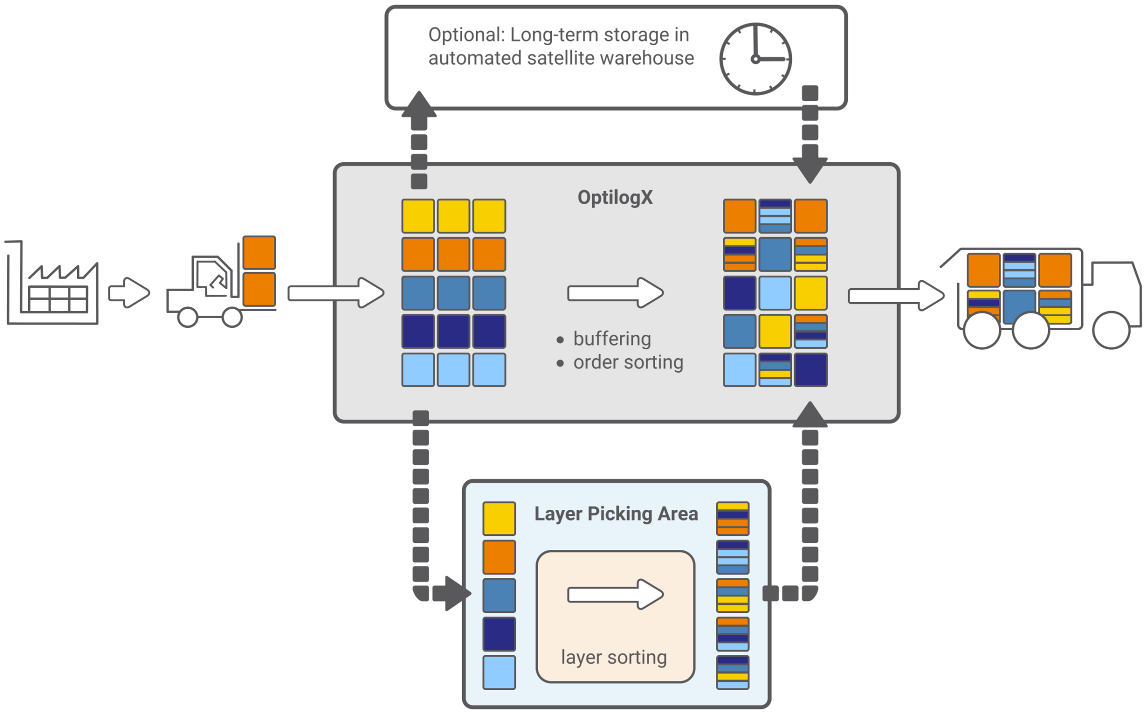

Figure 3.1: System representation of the combination between the OptilogX and the layer picking area

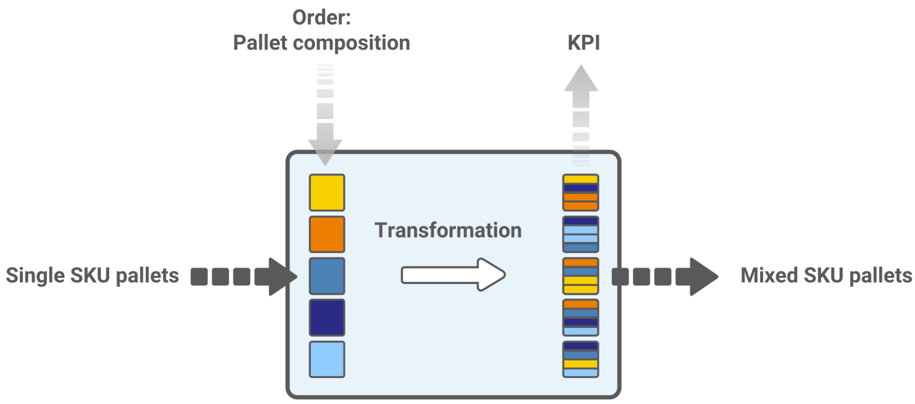

Figure 3.2: System representation using a black box

The transformation process for this layer picking area can be opened up to find the flows within the system. These flows can be described as a process performance (PROPER) model [20]. Figure 3.3 shows the PROPER model for the layer picking area. At least three aspects are included in the conceptual model:

1. The order flow; without customer orders no products will flow. In this flow, orders are transformed into handled orders.
2. The "product" as a transformation result
3. The "resources" (people and means) required to make the product. To make use of them, they must enter the system, and they will leave the system as used resources.

Order flow
The flow closest to the requirements is the order flow. This flow ensures an information flow which is

controlling the execution part of the process. The flow starts with customers sending the orders to the system, resulting in a specific order list. A scheduler will use this order list to create a pallet movement schedule for the system which will be sent towards the product flow. Following the results coming back from the product flow, the order list will be fulfilled and sent out of the system. The transformation that has been done within the system concerns orders towards handled orders.

Product flow
The product flow reacts on the movement schedule created by the order flow. All movements within the system are based on this schedule. If a pallet arrives at its required pallet position around the robot it gives a signal to the resource flow. After being handled, the single SKU pallet will be transitioned into a mixed SKU pallet. A feedback signal by the resource flow is given and the pallet will leave the system via the pallet out-feed. Transformation results are sent to the order flow while leaving the system. The transformation made within the product flow is from a single SKU pallet towards a mixed SKU pallet.

Resource flow
The resource flow is the most basic system flow. It is able to execute a required action and a to give feedback after completion. The resource flow within this research is the robot, with the possibility to transfer layers from a supply pallet towards an order pallet. These actions are triggered by a signal of the material flow and a verification will be given back after job completion. The robot will be transformed from a robot into a used robot.

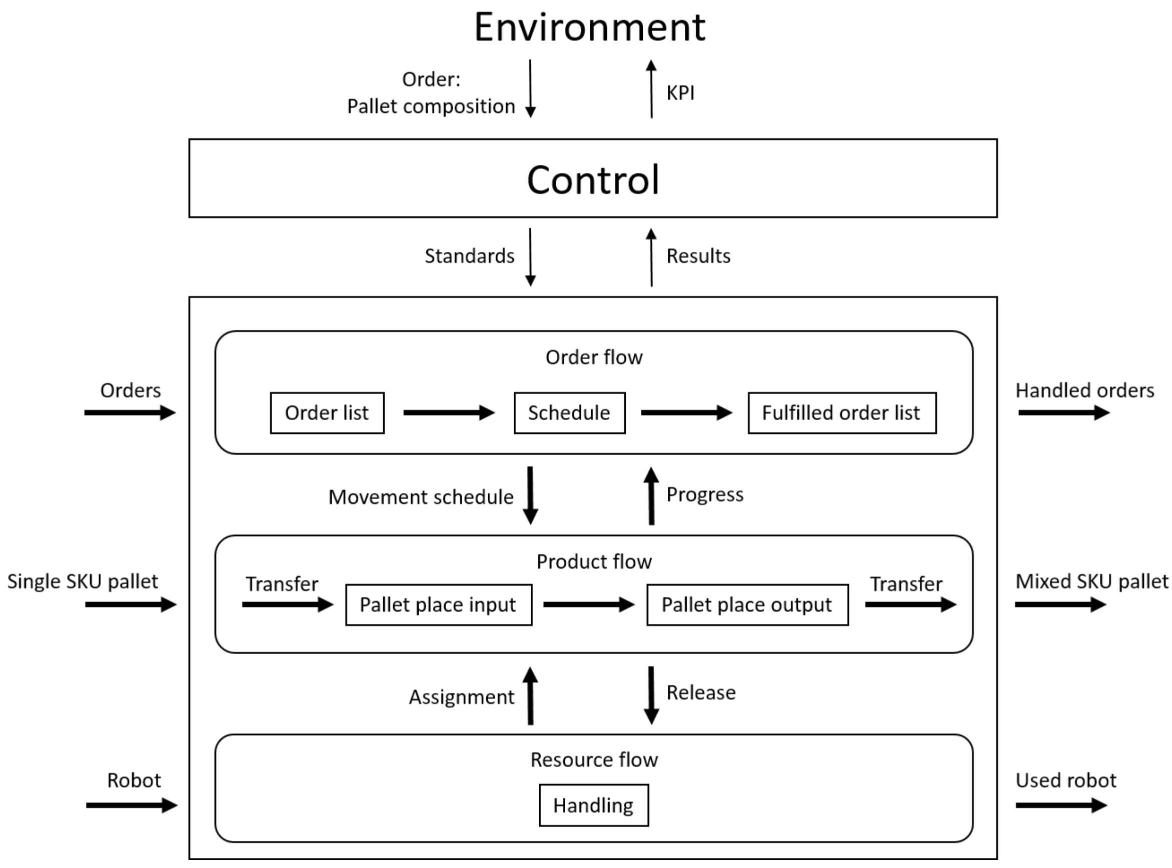

Figure 3.3: PROPER model

The described PROPER model will be used as a guideline for the system analysis. The flows can be separated into the vertical flows and the horizontal flows. The vertical flows represent the information flows through the system: the environmental conditions, objectives and requirements. The horizontal flows represent the pallet flows within the system.

3.3. Environment

The first analyzing step is setting the environmental conditions. This will be done by defining the preconditions and the system boundary.

3.3.1. Preconditions

Preconditions are used to set firm restrictions for the rest of the design trajectory. It means that they fall outside the system influence range. In this case the precondition is a warehouse which is handling pallets using an OptilogX and requires the opportunity to improve/create a layer picking area. Because the goal for ORTEC Warehousing is to offer an end-to-end automatic solution, the system needs to be able to use the current OptilogX as an in- and output. Besides the firm restrictions also a firm objective can be set: the layer picking solution needs to be applicable to be implemented at different (new) customers. So, the result needs to be a general solution.

3.3.2. System boundary

The system boundary can be set at different locations. It is important to choose the location with the least severed relationships and temporary elements which crosses the boundary. For this research, the decision needs to be made to include or exclude the OptilogX. Including the OptilogX would give the possibility to reintroduce partially loaded pallets which has been sent away from the layer picking area. However, this would give a complicated system since the other pallet activities of the OptilogX need to be taken into account as well. Therefore, a separate buffer area is created to keep the system simple. This buffer area is capable to accommodate the partially loaded pallets. Using this gives the possibility to keep the OptilogX outside the system boundary. The system input flow will be full single SKU pallets from the OptilogX and the system output flow will be completed mixed SKU pallets towards the OptilogX.

3.4. Objectives

The second analyzing step is to define the objectives. The system needs to be adjustable to different warehouses and therefore able to cope with changes. These changes can be used to create the final objectives required for describing the system. The influencing variables are the order pallets volume, the order completion time, the system reliability, the price/quality compared with competitors, different layouts and the required movements per picked layer. Using these variables it is possible to create the objectives for a layer picking system. The main objectives that will be used are:

- Minimize completion time
- Minimize pallet movements

Since the system needs to be adjustable to different warehouses, it is required to create a flexible system. This flexibility concern differentiation in lay-out, number of SKU, SKU distribution, pallet throughput variation and environmental influences.

3.5. Requirements

The third analyzing step is to set the requirements for the system using the chosen objectives. Two requirement types will be used: functional requirements and operational requirements.

3.5.1. Functional requirements

The functional requirements can be set using the research done in Chapter 2. The resources required for a robot-based layer picking system concern the picking robot, the transport systems, the buffer area and the empty pallet area. The different resources can be combined with their operations:

- The robot transfers a layer from a supply pallet towards an order pallet
- The transport system (shuttles and conveyor belts) moves the pallets through the system
- The buffer area receives, stores and sequences pallets for temporary storage
- The empty pallet area supplies and receives empty pallets for the layer picking area

Given these combinations it is possible to define the pallet flow required within the system. Therefore, assumption need to be made. These assumptions can change during implementation and therefore it is important to check the validity on a regular basis. The following assumptions will be done:

- The order arrival rate is equal to 40 order pallets per hour
- An order consist of one pallet, each with 2-8 product-layers per pallet
- In total there will be 100 SKUs which can be used to create the orders
- The layer configuration on an order pallet is fixed
- All ordered SKUs are available at an input pallet inside the OptilogX (no shortage)
- No changes can be made after order arrival
- The picking robot is capable of picking 180-200 layers/hour
- The OptilogX is capable of supplying 80-120 pallets/hour per VT

3.5.2. Operational requirements

Operational requirements are focused on the mechanical part of the system and therefore important for achieving a feasible solution. These requirements are set using mechanical component restrictions in combination with assumptions done before. The operational requirements that needs to be fulfilled can be formulated:

- n robot(s) with m pallet positions will be used
- The transport system will use conveyor belts and horizontal transporters
- A pallet size of 1200mm x 1000mm is used

3.6. Pallet flow

The main aspect for the layer picking system is the product flow, in this case the pallet flow. The system area will be defined step by step using this pallet flow. The start is a basic layer picking area with single SKU pallets coming in and mixed SKU pallets going out. These pallets will be transferred using conveyor belts to/from the robot area. Figure 3.4 shows this procedure using conveyor belts with a robot area.

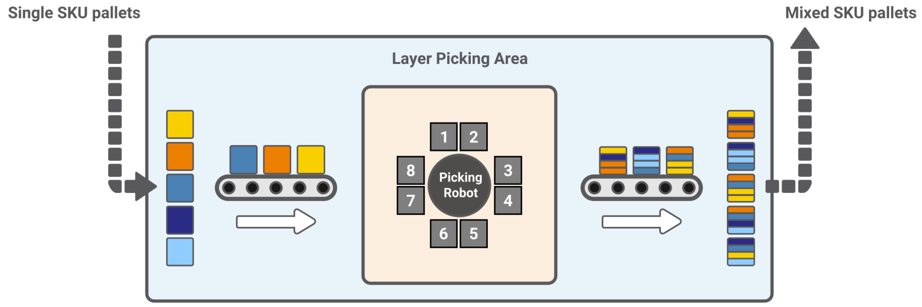

Figure 3.4: Pallet flow with robot area

Combining single SKU pallets towards a mixed pallet will create more pallet types. Figure 3.5 shows the extra pallet types that occur using this process. It shows that empty pallets are required to built the pallet and the result is completed mixed SKU pallet, but also partially loaded single SKU pallets. These pallets also need to be moved and stored within the system. Therefore, a buffer area and an empty pallet area need to be added within the flow.

So, the layer picking area uses different areas to be able to create mixed SKU pallets. These areas are the layer picking area, the empty pallet area, the buffer area and the robot area. They are connected with transport systems for moving the pallets through the system. Figure 3.6 shows the different areas which are used within the pallet flow. These areas are flexible in size and capabilities because the system needs to be able to be implemented at different lay-outs, different SKUs and different layer picking throughput.

Figure 3.5: Building a mixed SKU pallet

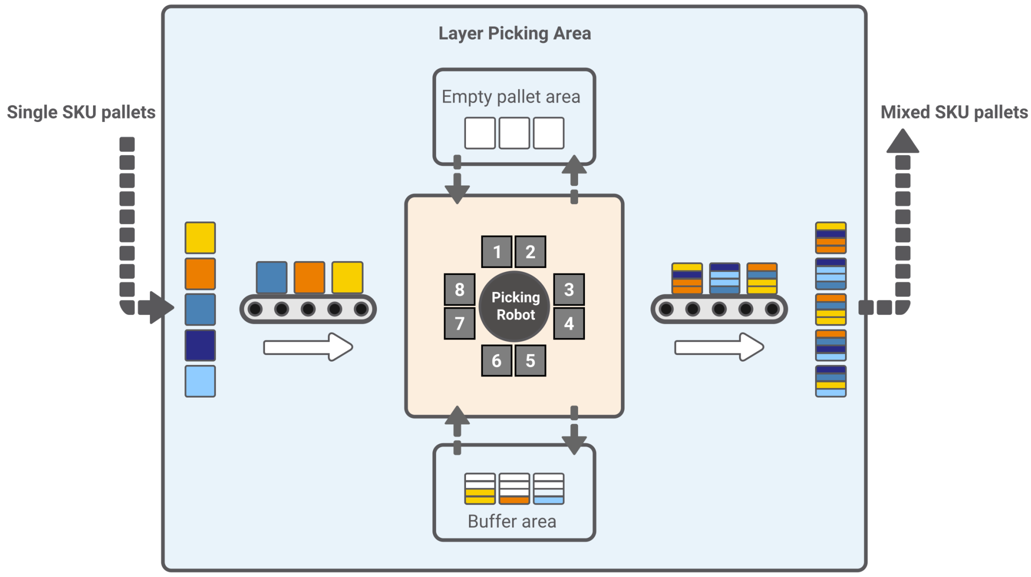

Figure 3.6: Schematic flow within the system

Buffer area
The buffer area receives partially loaded pallets from the layer picking area and temporarily stores them. Each pallet gets its own position in the system and sequencing is not necessary. The storage capacity is dependable on the warehouse lay-out. However, for this research an unlimited capacity is set.

Empty pallet area
The empty pallet area is used as a queue for empty pallets and supplies an empty pallet if that is required by the system. Empty pallets coming from the layer picking area are placed in the end of the queue, so this will not have influences on the delivery rate of the system. The empty pallet inventory is satisfying the orders and therefore no shortage will take place.

Pallet transfers
A pallet transfer is a pallet movement between different areas. Six transfers are possible to make within the system boundary. Each flow will have its own transfer time which will be estimated using data from a current operating OptilogX system. An accurate estimation will create a realistic situation to simulate. The six possible transfers are:

1. Pallet from the OptilogX towards a robot position
2. Pallet from a robot position towards the OptilogX
3. Pallet from the empty pallet area towards a robot position
4. Pallet from a robot position towards the empty pallet area
5. Pallet from the buffer area towards a robot position
6. Pallet from a robot position towards the buffer area

3.7. Flow calculation

A flow calculation is done to provide an insight in the different pallet flows within the system. The calculations are based on estimated averages. Furthermore, each input layer will be assigned to an output layer. First, the robot capacity will be calculated which will be used as the basis for the pallet flow. Second, the required pallet flow will be quantified.

3.7.1. Robot capacity

A capacity calculation will be made with the use of the robot characteristics from the Qubiqa Layer Picker Flex-R.[13] Figure 3.7 shows the standard robot position lay-out used for this analysis. Each robot side is given a number S1 to S4, with pallet positions 1 to 8. A normal robot cycle is divided into four different steps. These steps are:

1. Horizontal movement to the supply pallet position
2. Vertical movement to pick the layer(s) and going up again
3. Horizontal movement to the order pallet position
4. Vertical movement to deliver the layer(s) and going up again

Figure 3.8 shows the average movement times between the different robot-arm position. These movement times result in an average 2.5 seconds horizontal movement time and a 6.6 seconds vertical movement time. Following the normal robot cycle would give an average of 18.2 seconds per cycle. This leads to a capacity of 197.8 layers/hour for one robot.

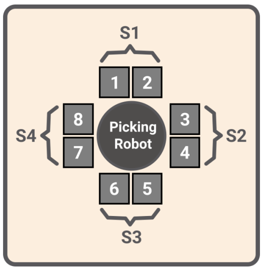

Figure 3.7: Robot position lay-out

Movement	Time [s]
Layer picking/layer delivery	6.6
Single side change (S1-S2, S2-S3, S3-S4, S4-S1)	2.4
Double side change (S1-S3, S2-S4)	3.9
Same side position change (1-2, 3-4, 5-6, 7-8)	0.5

Figure 3.8: Average movement times for a picking robot

With the average robot cycle time known it is possible to determine the required pallet flows to be able to reach the robot capacity. Three picking action scenarios will be calculated without the use of a scheduling method. This means that for each picked layer a new pallet is required. Characteristics of the different layers are not taken into account. The three situation are:

- **Minimum cycle time: 1-2, 1-2, 1-2, 1-2, 1-2**
  A maximum capacity for the picking robot can be reached using a minimum single cycle time. This can be done using pallet positions at the same side which result in movements between two neighbor pallet positions. Hereby, the average robot cycle time required to complete a single layer is 14.2 seconds. Using just one supply position gives the system few time to change the used supply pallet to a new supply pallet. This to prevent waiting time for the robot for picking the next layer. This is the time it takes for the robot to deliver the layer to the order pallet (two movements, one delivery), 7.6 seconds.

- **Average cycle time: 18,2 seconds per cycle**
  The average robot cycle time can be used to check the system feasibility concerning the maximum robot usage. A picking robot picks or delivers one layer from the same position on average each four picked layers. This to equally divide the picking actions over the positions. It means a pallet has an average waiting time of 66.2 seconds between the picking of two successive layers. This is the available time for a specific pallet to be changed to a new pallet. With four pallets that needs to be changed within a full cycle, every 18.2 seconds a pallet need to be fed into the system.

- **Maximum cycle time: 1-5, 2-6, 3-7, 4-8, 1-5**
  The maximum time between two successive pallet layers concern picking and delivering at the opposite side. This gives the system the most time to change a specific pallet. It leads to a time interval of 73.8 seconds before the robot arrives at the same pallet spot. The system needs a single SKU pallet in-feed each 20.1 seconds, because the robot visits all four order pallet spots.

Table 3.1 shows the results of the described situations above. The result show a high required in-feed capacity for all three situations. This is because a 100% robot utilization is used in combination with a pallet change for each picked layer, a combination which gives the highest possible flow demand for one robot.

Table 3.1: Robot capacity

	Single robot cycle time [s]	**Maximum pallet change time [s]**	**Required in-feed [layers/hour]**
Minimum cycle time	14.2	7.6	253.5
Average cycle time	18.2	66.2	197.8
Maximum cycle time	20.1	73.8	179.1

3.7.2. Required pallet flow

The pallet flow for the layer picking system can be calculated using the required in-feed for a single layer picking robot. This analysis will use the full robot capacity with an average cycle time: 200 layers/hour. This throughput capacity is the basis for the system. However, this system will use pallet movements instead of layer movements. Therefore, an average number of layers on a single pallet and the number of SKUs needs to be determined to be able to calculate the required pallet flow. For this research the used variables are:

- 40 pallets/hour
- 5 layers/pallet
- 100 SKU

Achieving a stable system requires an equal supply- and order pallet flow. The supply pallet flow contains full single SKU pallets which will be delayered until no layer is left. The order pallet flow contains empty pallets and will be layered to an average of five layers. Both flows can be calculated using an order oriented scheduling method. The order oriented scheduling method uses the order pallets as the leading pallet type. Figure 3.9 shows the required movement for this scheduling method. As can been seen, the order pallet is sent towards a position at the robot area. The movement order results in a single pallet movement for the order flow and five pallet movements for the supply flow. Notably, the layer picking area has four supply pallet positions and a pallet has on average five layers (with potentially five different SKU layers). In that case, the system will need to sent one supply pallet to the buffer area to enable all five different SKU supply pallets to be positioned at a supply pallet position. The following movements take place:

1. Order pallet towards robot, containing an order of five SKU-layers
2. Supply pallet with first required SKU-layer sent towards robot, first SKU-layer transferred from the supply pallet towards the order pallet
3. Supply pallet with second required SKU-layer sent towards robot, second SKU-layer transferred from the supply pallet towards the order pallet
4. Supply pallet with third required SKU-layer sent towards robot, third SKU-layer transferred from the supply pallet towards the order pallet
5. Supply pallet with fourth required SKU-layer sent towards robot, fourth SKU-layer transferred from the supply pallet towards the order pallet
6. Supply pallet with fifth required SKU-layer sent towards robot, fifth SKU-layer transferred from the supply pallet towards the order pallet

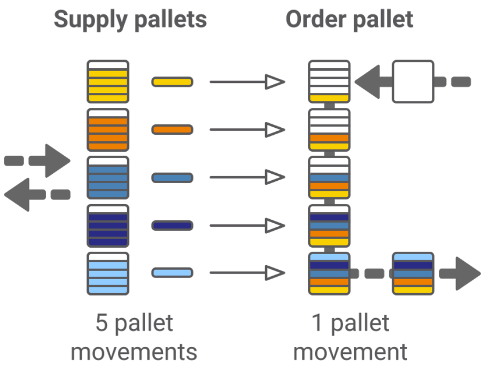

Figure 3.9: Order oriented pallet flow

The order oriented scheduling method exists of a required order pallet flow and a required supply pallet flow. Both will be shown separately, with a combined flow afterwards.

Order pallet flow

The order pallet flow is the determining flow for the order oriented scheduling method. As shown before, the order pallet flow of this solution starts with an order pallet (empty pallet) entering the robot area at which it will be layered. The pallet leaves the system when the order pallet is completed. Figure 3.10 shows this single order pallet flow. As can been seen, no extra pallet changes occur within the system. Therefore, the required pallet flow for the robot is equal to the order pallet flow. Figure 3.11 shows the order pallet flow required for a maximum utilization for a single robot.

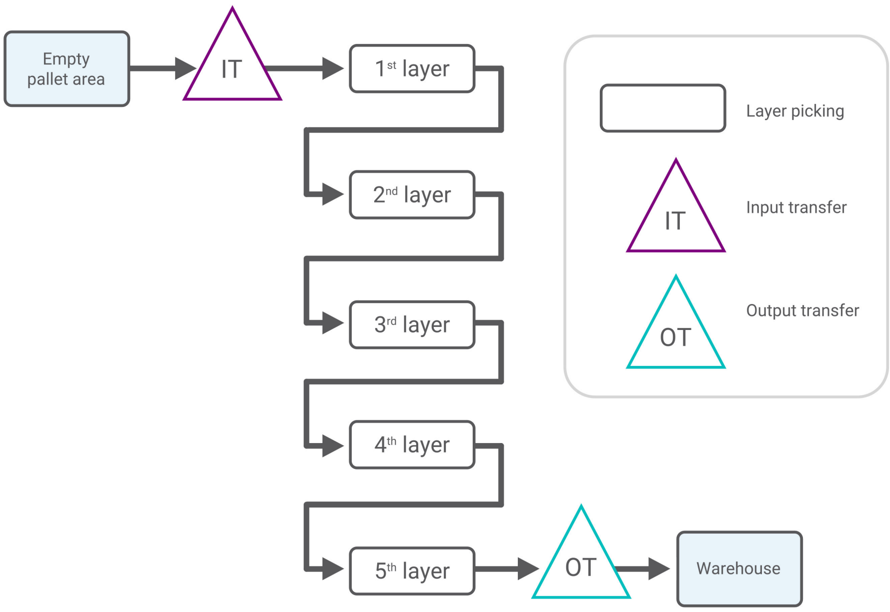

Figure 3.10: Single order pallet flow through the layer picking area

Supply pallet flow

The supply pallet flow for this order oriented system is more complicated. As shown before, a specific supply pallet is sent towards the robot area, depending on the order pallet needs. After delivering the first layer to the order pallet, the supply pallet moves towards the buffer area. From here, the supply pallet is called again if required by an order pallet. The supply pallet will be sent towards the empty pallet area when all layers are picked. Figure 3.12 shows this single supply pallet flow. As can been seen, it takes in total four buffer area visits per supply pallet. A supply pallet flow of 40 pallets/hour into system will lead to a total 160 pallets/hour supply pallet flow through the buffer area.

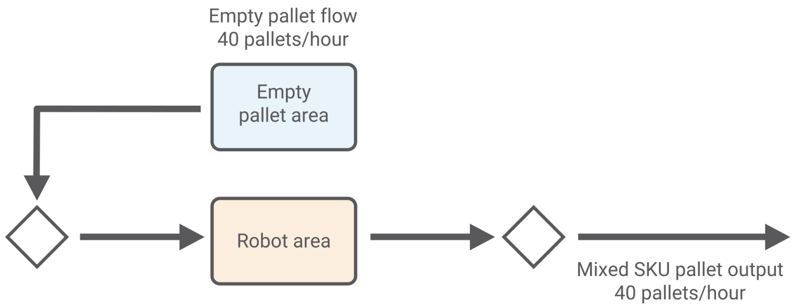

Figure 3.11: Order pallet flow

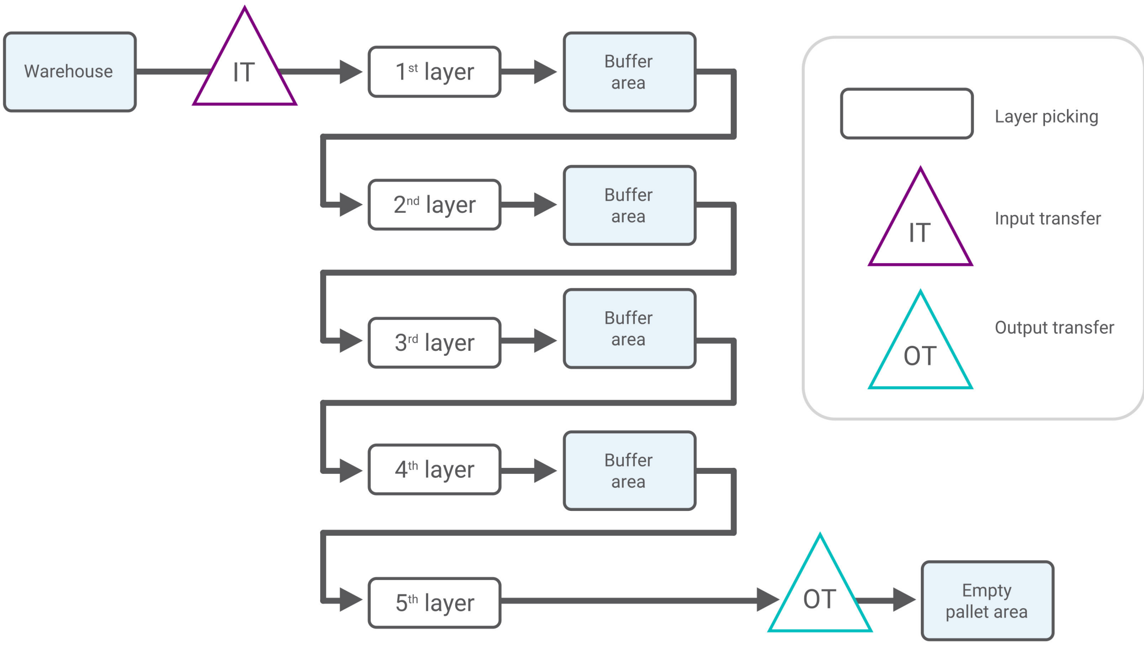

Figure 3.12: Single supply pallet flow through the layer picking area

However, the supply pallet flow is influenced by the number of SKUs and the pallet positions available. A standard lay-out of eight pallet positions with equal divided supply- and order positions will be used for this situation. The system will use 100 SKUs, with each supply layer specifically assigned to a position on an order pallet. So, the following steps occur within the robot area:

1. Three supply positions and four order positions are taken with respectively supply pallets and order pallets
2. A new supply pallet enters the robot area and takes the fourth supply position, the first layer of this supply pallet equals a required layer by an order pallet
3. The first layer is picked by robot and transferred towards the order pallet. The supply pallet still has SKU-layers available.

Figure 3.13 shows the result of the first situation. The goal is to calculate the probability for a supply pallet to directly deliver a second layer to an order pallet. Having 100 SKUs available in the system, a single order pallet has the probability of $\frac{1}{100}$ to need the specific SKU-layer. When there are four order pallets at the robot area, the total probability that a supply pallet can directly deliver a next layer to one of those four order pallets is $P_1(S^c)$:

$$\begin{aligned} P_1(S^c) &= (1 - P_1(S))^4 \\ &= 0.99^4 \end{aligned} \tag{3.1}$$

With

$P(S)$	probability to pick a new layer without an extra pallet movement required
$P(S^c)$	probability to pick a new layer with an extra pallet movement required

Figure 3.14 shows the second situation. Since a new order layer is revealed within the system, it is also possible that one of the other supply pallets is capable to deliver this SKU-layer. Combining the three supply pallets for delivering a next layer results in $P_2(S^c)$:

$$\begin{aligned} P_2(S^c) &= (1 - P_2(S))^3 \\ &= 0.99^3 \end{aligned} \tag{3.2}$$

Figure 3.15 shows the third situation. Besides the change of a supply pallet, it is also possible for an order pallet to be changed. This occurs when an order pallet is completed. A new opportunity arises with four supply pallets at the robot. All four are possibly capable to deliver the first layer for this order pallet. It also results in an extra layer picking action without an extra pallet movement. This results in the next probability $P_3(S^c)$:

$$\begin{aligned} P_3(S^c) &= (1 - P_3(S))^4 \\ &= 0.99^4 \end{aligned} \tag{3.3}$$

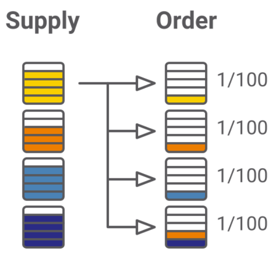

Figure 3.13: Situation for P_1

Figure 3.14: Situation for P_2

Figure 3.15: Situation for P_3

These three situations can be combined and processed within the expected supply pallet flow for the system. Thereby, P_1 and P_2 occurs each time a supply pallet is changed and P_3 occurs each time an order pallet is changed. This is only possible if a succeeding layer is available, which is the case with 4 layers/pallet. Combining these probabilities for delivering an extra layer without a pallet movement leads to the following required flow:

$$\begin{aligned} M_b &= 160 - (1 - P_1(S^c)P_2(S^c)) * P_L M_s + (1 - P_3(S^c)) * P_L M_o \\ &= 160 - (1 - P_1(S^c)P_2(S^c)) * \frac{4}{5} * 200 + (1 - P_3(S^c)) * \frac{4}{5} * 40 \\ &= 147.9 \text{ movements} \end{aligned} \tag{3.4}$$

With

M_b	pallet movements to/from buffer area
M_s	supply pallet movements
M_o	order pallet movements
P_L	probability to have a pallet with at a second SKU-layer available

Figure 3.16 shows the full supply pallet flow. The combined pallet flow for the single SKU input and the buffer area is able to deliver the required layers by the layer picking robot.

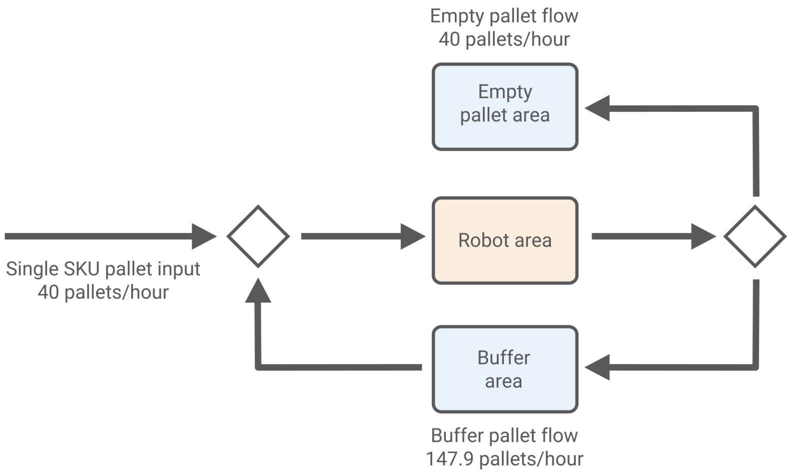

Figure 3.16: Supply pallet flow

Combined pallet flow
Figure 3.17 shows the combined required pallet flow within the system to be capable to use a single robot for its full capacity. However, no pallet transfer times are taken into account which could further increase the required flow (e.g., pallet collisions due to high required flows).

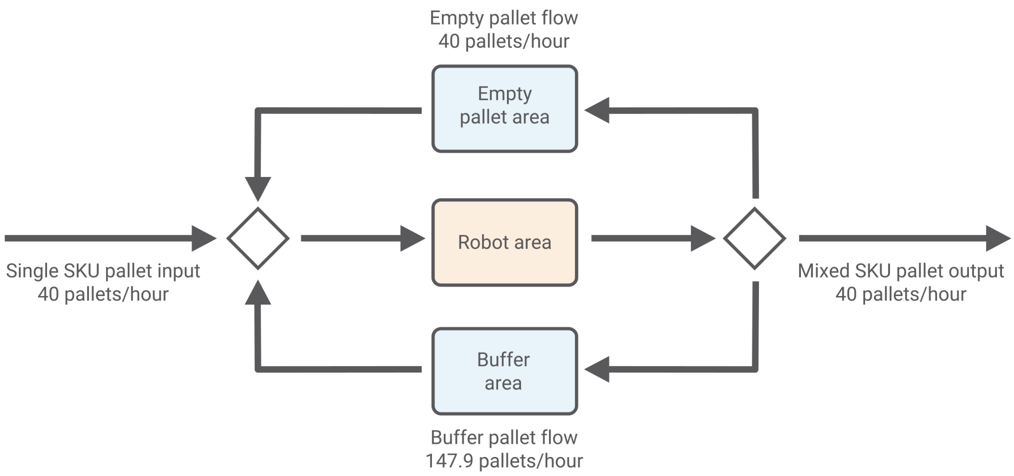

Figure 3.17: Combined supply- and order pallet flow

3.7.3. Littles Law
The previous shown pallet flows can be used to do a calculation for the average number of pallets present within the robot area. This can be done using Little's Law (eq. 3.5).[9]

$$N = \lambda * D \tag{3.5}$$

With
N average number of pallets in the system
λ average pallet input flow rate
D average pallet throughput time through the system

Supply pallets
First, the supply pallets within the system. Figure 3.16 shows the supply pallet flow which is used for the system. As can been seen, the input pallet flow rate is the combination of the single SKU pallet input and the buffer area input. Combined it gives the average input flow rate: $\lambda = 187.9$ pallets/hour. This input flow rate

is capable to supply 200 layers/hour for the layer picking robot. So, each incoming supply pallet will supply 1.0646 layers per robot area visit. The average throughput time (D) for a supply pallet can be determined with the required picking time at a robot position.

Picking the first layer or the second layer does differ in time. The time for the first layer of a pallet consist of a pallet change time at a robot position and a layer picking time. In this case, the pallet is directly sent away after usage. The second layer does not need the pallet change time at a robot position, but it has to wait during the time the layer picking robot picks and delivers layers to/from other pallets within the robot area. A full robot cycle concerns the usage of two robot positions, a supply position and an order position. This leads to three full robot picking cycles before the robot is with the same position again. Together, it result in equation 3.6.

$$D = L_1 + 0.0646 L_2 \tag{3.6}$$

$$L_1 = t_p + t_l$$
$$L_s = 4 t_{pc}$$

With

t_p	pallet change time
t_l	time for the robot to pick or deliver a single SKU-layer
t_{pc}	full robot picking cycle time
L_1	robot position occupation time during first layer picking
L_s	robot position occupation time during succeeding layer picking

Section 3.7.1 has given values for t_l and t_{pc}, but t_p is not determined yet. Figure 3.18 shows the required movements for changing a single pallet at a robot position. In total six movements with a pallet and two re-position movements without a pallet need to be made to fulfill this cycle. The pallet change cycle time can be determined using the time for both movements.

$$v_a = 0.15 m/s$$
$$x_p = 1.2 m$$

$$t_{pm} = v_a * x_p \tag{3.7}$$

With

v_a	pallet movement velocity
x_p	pallet size to move
t_{pm}	time for a single pallet movement

Equation 3.7 results in $t_{pm} = 8s$. The time for movement without a pallet is set to $t_m = 4s$, because shuttle needs to be re-positioned to pick the next pallet and does not have to travel a big distance. The average number of supply pallets within the robot area (N_s) can be calculated using the known transfer times.

$$t_p = 6 t_{pm} + 2 t_m$$
$$t_l = 6.6 s$$
$$t_c = 18.2 s$$

$$N_s = \lambda * D$$
$$= 3.51 \text{ supply pallets}$$

Order pallets

Second, the order pallets within the system. Figure 3.11 shows the order pallet flow which is used for the system. As can been seen, the input pallet flow rate is set to λ = 40 pallets/hour. Each order pallet arrives

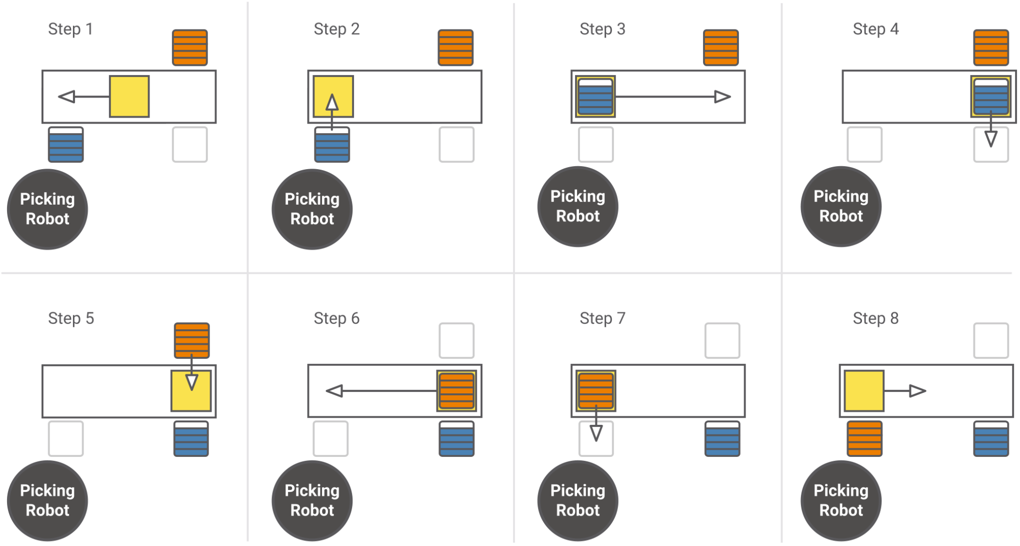

Figure 3.18: Required steps for the pallet change at a robot position

empty and leaves the system when completed. This means each pallet is at a single pallet position during the picking of all layers. Equation 3.8 shows the average throughput time for an order pallet. The average number of order pallets within the robot area (N_o) can be set determined using the known transfer times.

$$D = L_1 + 4L_s \tag{3.8}$$
$$\lambda = 40 \text{ pallets/hour}$$

$$N_o = \lambda * D$$
$$= 3.93 \text{ order pallets}$$

Applying Little's Law to the robot area leads to an average presence of $N_s + N_o = 7.44$ pallets at the same time. This calculation is based on an average robot cycle time with 100% utilization. The available space within the robot area will be sufficient with eight pallet spots around the robot.

4

Problem definition

This chapter describes the conclusions from the research done in Chapters 2 and 3. The main research question will be set using these conclusions. Sub-questions will be added to guide the research further.

4.1. Analysis

Chapter 2 has shown the need for an automatic layer picking addition to the current OptilogX. Furthermore, it showed the different components, possibilities and software structure of the OptilogX. This system is able to supply or receive pallets in an ordered sequence with a capacity of 80-120 pallets per VT. Possible additional required capacity for the layer picking area can be achieved by adding more VTs. However, it is preferred to minimize the VTs required for the system to keep the OptilogX small and operational. A robot layer picker will pick the layers from a supply pallet towards an order pallet. This robot is able to pick on average 200 layers per hour to/from eight pallet positions around.

Chapter 3 used the robot characteristics to do a system analysis. The basic system flow concerns the transformation of supply pallets into order pallets. This flow is researched to be able to set the conditions that need to be used for the system. Requirements, set within Section 3.5, are used for defining the different required areas, their connections and the required flows. A high pallet flow in the system is required to be able to use the full capacity of a single robot. Table 4.1 shows the different pallet flows as well as the combined pallet flow at the robot area. As can been seen, the static calculation lead to a total pallet flow into the robot area of 227.9 pallet movements/hour. Creating a feasible system for this high pallet flow could be possible with two options. First, it is possible to add more infrastructure by adding more VTs and conveyors. Second, it is possible to lower the required pallet flow by reducing the required pallet movements within the system. The preferred method to create a feasible system is reducing the required pallet flow. This because it is important to minimize the equipment usage for the system to suit the characteristics of the OptilogX and the robot-based layer picking system.

Besides the pallet flow, a high and reliable output is important to be able to met the requirements. Achieving this requires a sufficient layer picking robot throughput. So, lowering the pallet movements will need to be done while keeping a high layer picking throughput possible.

Table 4.1: Pallet flow within the layer picking area

	Robot in [pallet movements/hour]	**Robot out [pallet movements/hour]**
Warehouse	40	40
Empty pallet area	40	40
Buffer area	147.9	147.9
Combined	**227.9**	**227.9**

At the moment, the required pallet flows are too high to be able to integrate an automated layer picking area within the OptilogX. Therefore, a scheduling method is required for minimizing the pallet movements and at the same time maintaining the layer picking throughput. Two KPIs result from this analysis:

- **Pallet movements**
  Pallet movements within the system should be minimized, this can be achieved by combining supply pallets with order pallets.

- **Layer picking throughput**
  The layer picking throughput for the system should be maximized up to a single robot's capacity.

4.2. Research question

The goal for this research is to create a solution for adding a layer picking area to the OptilogX. The focus for this solution is the pallet flow organization within the layer picking area. Important for the pallet flow is to check the feasibility of the proposed solution. In this case, it means the ability of delivering a required pallet flow in combination with a high layer picking throughput. The solution needs a scheduling method which is able to minimize the pallet movements, to maintain the layer picking throughput and to be adjustable for different warehousing environments. The main research question is therefore:

What is a feasible scheduling method for minimizing pallet movements, while maintaining the layer picking throughput?

Different sub-questions can be formed to find an answer for this research question. The sub-questions that will be investigated are:

1. Which scheduling methods can be used?
2. How to connect the scheduling methods with the requirements?
3. What is the influence on the scheduling method of different layer picking area layouts, different arrival times, SKU differentiation and changing orders over time?

5
Simulation model

The environment DelphiXE6 is used to build the simulation model with an object oriented system. The simulation package TOMAS[19] is added to the environment to be able to use a discrete process simulation. This gives the opportunity to create different elements which will be tasks from their own viewpoint. An element will be activated if the its own requirements are fulfilled. The specific choices made by the elements are specified with the use of separate functions. The model structure will be described following the assumptions, the elements within the system, the different functions available, the scheduling methods, model input, the model output and the model verification.

5.1. Assumptions

Assumptions are used to be able to create a generic simulation model. The most important assumptions are related to the robot area, the warehouse and the buffer area.

Robot area

The robot area does not use a specific lay-out. This is done because each warehouse has its own characteristics and requirements. Using a generic system creates the possibility to find the influence of different position distributions. Therefore, each position has the same characteristics concerning the pallet change time, the transfer time to a position and a layer picking time between the positions. These different times are set constant within this research to leave the specific lay-out influence out.

Warehouse

A constant pallet inter-arrival time (i.e., the time between pallet A passing location X and pallet B passing that exact same location) from the warehouse is used within this simulation model. This is done because the specific flow within the warehouse is not known throughout the simulation.

Buffer area

A constant pallet inter-arrival time from the buffer area is used within this simulation model. A buffer area is a complex area which is influenced by the lay-out of the full warehouse, design criteria and the pallet scheduling within this area. This simulation model is built as a generic model to show the different influences and requirements for a layer picking area. So, a constant performing buffer area is used instead of creating a specific lay-out for each situation. Therefore, the pallet inter-arrival time between the buffer area and a robot positions is set constant.

Experiments will be used to show the influence of varying transfer times and varying pallet inter-arrival times from and to the different areas. Using these results, will give an insight into the requirements for creating a layer picking area.

5.2. Elements

Figure 5.1 shows the model lay-out which is used for creating the simulation structure. This lay-out is similar to the lay-out used in Chapter 3. The different elements used within the system are the order generator, the warehouse (OptilogX), the transfer units, the picking robot and the buffer area. The figure also shows the used queues (Q) and the flow directions.

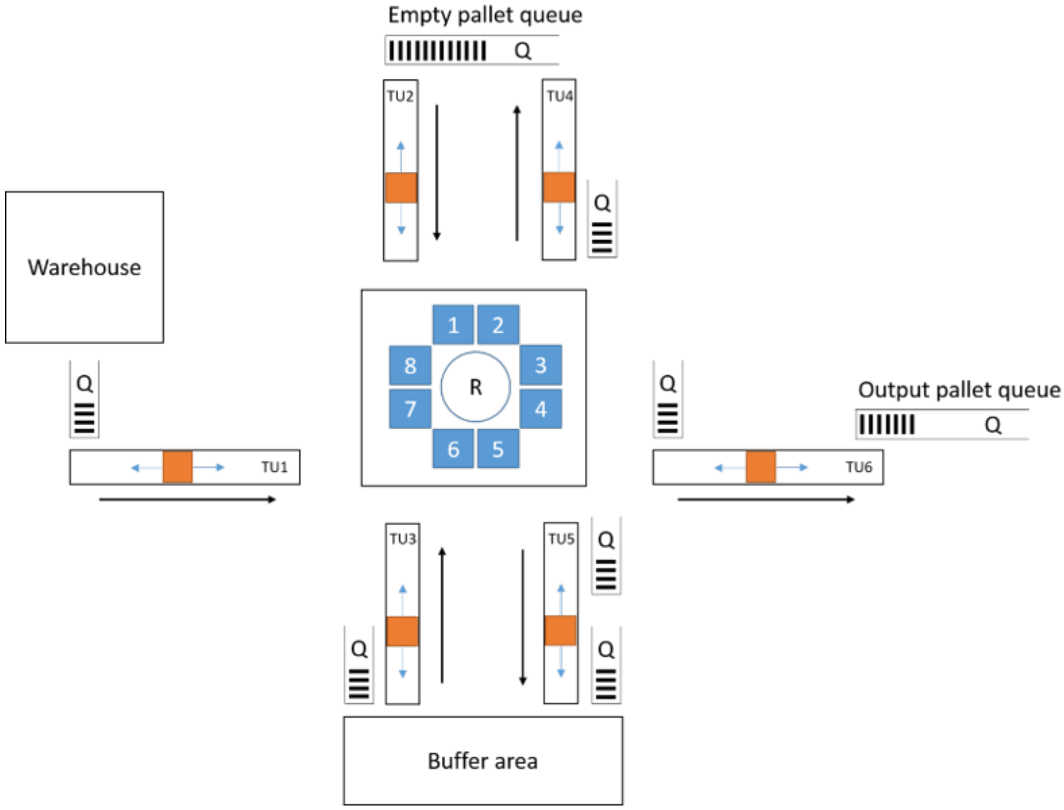

Figure 5.1: Model structure

The model is built using different elements which will operate independent from each other. The elements react on the current situation within the system and therefore are able to react on changes within the system. Each element will be given a short description in combination with "Plain English", which is used as a basis for the programming code.

5.2.1. Order generator

The model starts with the order generator. The order generator is the input for the system and creates orders in batches, with a continuous arrival time or using XML-files. Each order contain a single pallet with a number of assigned SKU layers. The created order pallet uses stacking restrictions, so no layers will be interchangeable. The order generator will follow the distributions set at the input file. The different processing steps for the order generator will be given in the framework.

Order generator
Repeat
    For number of orders
        Create order pallet
        Add number of layers
        Add an SKU to each layer
    Put pallet in order queue

For batch arrival time:
    Wait batch inter-arrival time

For continuous arrival time:

Wait order inter-arrival time

For XML-file:
Wait for next arrival

5.2.2. Warehouse

The warehouse is activated at the moment an order pallet arrives within the order queue. It starts with a check if each ordered SKU-layer is available in the system. The required supply pallet will be prepared within the warehouse and will be set available for the transfer unit to pick.

Warehouse
Repeat
Wait while no SKU is required
Create pallet with required SKU layers
Wait for retrieval time warehouse
Put pallet into transfer unit queue (1)

5.2.3. Transfer units

A transfer unit is an element with the function of transferring a pallet from position A to position B. This is the basic function which is valid for all transfer units, but for each transfer unit (six in total) a different position A and B is available. The transfer units will be separated into two different functionality since there is a single pallet flow direction: transfer units used for the in-feed and transfer units used for the out-feed of the robot area.

Transfer unit in-feed

The transfer units which are used to transport pallets towards the positions around the robot are TU1, TU2 and TU3. Figure 5.1 shows these transfer units. They are pending between their own in-feed queue and the robot area. They wait at the in-feed queue at the moment they are standby for operation. When a pallet is available and at the same time the corresponding position at the robot is also available, then the specific transfer unit will be activated. It will choose a pallet from its queue and reserves the robot position. Then the pallet transfer will be performed. The framework below shows the basic steps for this element.

Transfer unit in (warehouse, empty pallet area and buffer area)
Repeat
Wait while TransferUnitQueue (1, 2, 3) is empty or no correct robot position is available
Pick pallet from queue (warehouse, empty pallet queue or buffer area)
Reserve robot position
Move to robot position
Put pallet on position
Move back to original position

Transfer unit out-feed

Figure 5.1 shows the out-feed transfer units TU4 , TU5 and TU6. They are pending between their dedicated robot out-feed queue and their destination queue. Activation will take place if a pallet becomes available within their robot out-feed queue. This pallet is then directly transported towards its destination, respectively the empty pallet queue, the buffer area queue or the output pallet queue (OptilogX).

Transfer unit out (output, empty pallet area and buffer area)
Repeat
Wait while TransferUnitQueue (4, 5a, 6) is empty
Pick pallet from TransferUnitQueue

Move to new position
Put pallet in new queue
Move back to original position

5.2.4. Robot

The robot will fulfill the main model activity: transferring SKU-layers from a supply pallet towards an order pallet. It will be activated when a supply layer and an order layer with the same SKU are available at the robot. At this moment, the robot moves to the supply position, picks the layer from the pallet, moves to the order position and then delivers the layer at the order pallet. The robot will stay above the last position when waiting for a new action. The robot process also checks if a supplying pallet is empty or an order pallet is full. If this is the case, then the pallet will be sent towards the specific output queue depending the situation. These steps will be done within the robot process because their status only changes after a layer is picked. The main processing steps for the robot are given in the framework below.

Robot process
Repeat
Wait while SKU from supply- and order layer are not equal
Go to supply position
Pick layer
Go to order position
Deliver layer
If the order pallet is full, sent it to the out-feed transfer unit (TU6)
If the supply pallet is empty, sent it to the empty pallet area transfer unit (TU4)

5.2.5. Buffer Area

The buffer area stores the partially (de)loaded pallets. It has two main functions; moving pallets from the incoming TU5 queue towards a buffer position and moving pallets from its buffer position towards the outgoing TU3 queue. Hereby, the outgoing activities are preferred above the incoming activities. This because it is important to keep the robot busy, so pallets need to be delivered as fast as possible. The processing steps are shown in the framework below.

Buffer area
Repeat
Wait while no pallet is requested by the robot and no pallet is within the buffer input queue

If a layer from a pallet is requested by the robot
Pick requested pallet from the buffer position
Move pallet to buffer output queue
Put pallet in buffer output queue

If pallet is within the buffer input queue and no pallet is requested by the robot
Pick pallet from queue
Move to buffer position
Put pallet on buffer position

5.3. Functions

The elements are the basis for the simulation model; they perform the actions. However, they do not decide the actions themselves. This is done using functions which contain the different scheduling method decisions. The functions that will be used are listed below.

- *Scheduler*
  The scheduler is activated when an order pallet arrives. It will assign this order to an empty pallet and

activates the warehouse to create the missing SKU. This is done by checking the layer availability within the system.

- *Select pallet*
  The transfer units 1, 2 and 3 need to choose a pallet from their own queue. This is done following the priority rules set with the scheduling method. For each transfer unit there is a specific function to decide which pallet needs to be picked.
- *Robot position control*
  The robot position control prevents a deadlock at the robot. A pallet is sent away towards the buffer area when the robot is not able to pick a new layer. This can be either a supplying pallet or an order pallet, dependent on the scheduling method. The robot position control is activated if the robot is not capable to pick three more layers. This because the robot needs to be utilized during the pallet change time (t_p).
- *Check layer*
  This function is used to count the remaining available layer combinations at the robot and activates the robot position control if required.

5.4. Scheduling method

This research will use a reference method and a heuristic method. Both methods will be explained within this section. Equation 5.1 shows the objective for the scheduling methods. The equations 5.2, 5.3 and 5.4 are set as constraints to ensure the model is a representation of the real situation. These will be processed throughout the model. Equation 5.5 is set as a constraint to deliver all pallets before their due date. This is an important characteristic for the system.

$$minimize \sum_{p \in P} M_p \tag{5.1}$$

s.t.

$$\sum_{p \in P} PP_{p,x} = 1 \qquad \forall\ x \in X \tag{5.2}$$

$$\sum_{x \in X} PP_{p,x} = 1 \qquad \forall\ p \in P \tag{5.3}$$

$$\sum_{p \in P} RH_p \leq 2 \tag{5.4}$$

$$t_{f,i} \leq t_{dd,i} \qquad \forall\ i \in N \tag{5.5}$$

With

$p\ = 1,..,P$	pallet
$i\ = 1,..,n$	order pallet
$x\ = 1,..,X$	pallet position
$x_r = 1,..,X_R$	robot pallet position
M_p	pallet movements
$PP_{p,o}$	pallet position
RH_p	pallet hold by robot
t_f	completion time
t_{dd}	due date

5.4.1. Reference method

The modeled system is a system without available performance results. Therefore, a reference scheduling method will be used to be able to compare the results. Two options can be chosen as a reference method: a supply oriented method and an order oriented method. Both are basic selection methods and will not take intelligent decisions into account.

Supply oriented scheduling
The supply oriented scheduling method is based on the idea that supply pallets are sent to a position at the robot and are only able to leave when they are empty (or no assigned layers are left). An exception is made when there is no order pallet remaining in the system which requires one of the available specific layers. So, only when no other option a buffer area visit will be allowed for the supply pallets. The order pallets will be called if required and sent away to the buffer area if no new picking action can be fulfilled. From here they can be called again.

Order oriented scheduling
The order oriented scheduling method is based on the idea that order pallets are sent to a position at the robot and will be sent away after finishing. So, no buffer area visit will be allowed for the order pallets. The supplying pallets will be called if required and sent away to the buffer area if no new picking action can be fulfilled. From here they can be called again.

Both scheduling methods are the same under the condition that no stacking restrictions are involved. However, this will not be the case in a realistic scenario with order pallets having stacking restrictions. The result from this non-ideal situation is a negative influence on the supply oriented scheduling method due to the increasing possibility a supply pallet cannot be picked completely before moving out. In some cases an order pallet first need another (multiple) layers before picking the layer already there. During a process simulation it occurred that a supplying pallet, still containing layer(s), is sent away to be able to complete the order pallets. The result will be extra movements in the system, since a supply pallet needs to pass the buffer area as well. This possible extra movements make the order oriented scheduling method at least as good as the supply oriented method, but in most cases better. The reference method for this research will therefore be the order oriented scheduling method. A static analysis for this method is already performed in Section 3.7.2. The following priority rules will be used within this method:

Order pallet positions

- When an order pallet position is available, sent the first available order pallet towards this position.
- When an order pallet is completed at the robot then sent it away to the output.

Supply pallet positions

- When a supply pallet position is available, sent the first required supply pallet from the buffer area towards this position.
- If no required supply pallet is available at the buffer area, sent the first required supply pallet from the warehouse.
- If all pallet positions are full and no layers can be transferred from an available supply pallet towards an order pallet, then sent a supply pallet towards the buffer area.

The system will be able to operate using these priority steps. However, performance improvements will be possible using decisions which will take the KPIs into account and which fulfill the requirements. Performance results of this reference method will be used as a basis for analyzing the process simulation model.

5.4.2. Heuristic method

A heuristic method will be used as an improvement of the reference method. This method is suitable to use in a dynamic system subjected to delays and disruptions. The system consist of multiple processes which interact with each other and need to be able to react on the current situation. The order oriented scheduling method will be used as a basic solution with small steps improving the system performance. Using a heuristic method gives the possibility to show the influences of the different decisions on the system performance. Different decisions at different locations need to be made within the model. These decisions are based on two possible actions which can be fulfilled with both a supply- and order pallet:

- A pallet can be sent from the warehouse, buffer area or empty pallet area to a pallet position at the robot area
- A pallet can be sent away from the robot area towards the output, the buffer area or the empty pallet area

The first action can be divided into a choice between a supply pallet selection or an order pallet selection. The pallets to choose for a supply pallet are available at the warehouse or the buffer area, while for the order pallet it can be found in the empty pallet area or the buffer area. The second action can pick one of the pallets available on a specific pallet position at the robot. The possible pallet selections will be explained; the order pallet selection, the supply pallet selection and the robot pallet selection.

Order pallet selection
A priority rule is required to ensure each order pallet is complete before its due date. This will be done using a pallet selection for choosing the next pallet to handle. The first step for this selection is to sequence all order pallets on due date. The second step is to check for each order pallet in the system if it is possible to create this pallet before their due date. This is including the time required to fulfill all pallets in front of them and also the time it takes for a pallet to be overtaken by one pallet. Once a pallet cannot be completed within their due date (including overtaking), then this will be the last pallet in the list to choose from. A specific decision for an order pallet will be made using this list, which will be redefined when a new pallet needs to be chosen. It can be summarized using equation 5.6 with the goal to maximize i.

$$\sum_{i=1}^{n}(LR_i * PT) + LR_{i_{max}} * PT + 2 * TT_{in_{max}} + TT_{out_{max}} \leq t_{dd_i} - t_c \tag{5.6}$$

With

PT	processing time for one layer
LR_i	layers remaining for order pallet i
TT_{in}	pallet transfer time from an input area towards a robot position
TT_{out}	pallet transfer time from a robot position towards the output
t_{dd}	due date
t_c	current time

A new pallet can be chosen using the order pallet list made available with equation 5.6. The following priority rules will be used to determine the specific pallet to choose.

1. Select the order pallet with the most consecutive layers available at the robot
2. If equal then select the order pallet which has the most total layers already at the robot
3. If equal then select the pallet with all order layers already at the robot.
4. If equal then select the pallet with the lowest due date

Supply pallet selection
A new supply pallet need to be chosen when a supply position is empty. Supply pallets do not contain a due date, so all pallets can be chosen. The priority rules that will be used are:

1. Select the pallet which is directly required for an order pallet if its due date does not allow delays anymore
2. Select the pallet with the most layers directly required by order pallets available at the robot
3. If equal select the pallet with the most layers required by order pallets available at the robot
4. If equal select a pallet available in the buffer area above a pallet from the warehouse

Robot pallet selection
When all positions at the robot are full and no layers can be picked, a pallet has to be sent away to the buffer area. Therefore, a decision to sent a supply- or an order pallet has to be made. The following priority will be used for this decision:

1. If the remaining time until an order pallet due date is low, then a supply pallet will be changed to be able to fulfill the due date of this order pallet.
2. If a supply pallet is able to match with most layers already available at the robot, a supply pallet will be sent away
3. If an order pallet is able to match with most layers already available at the robot, an order pallet will be sent away
4. If equal, sent a supply pallet away

5.4.3. Changing supply- and order positions

The model starts with fixed supply- and order positions at the robot. A big influence on the scheduling method could be to make these positions non-fixed. In this way the system is able to choose between a supply- and order pallet. An advantage of this system is the ability to change a supply pallet into an order pallet. This can be done when the remaining supply layer(s) are equal to the first layer(s) for an order pallet. This will save the need of picking these layers from one pallet to another. The result from this change leads to less robot picking movements and therefore a higher system performance. Performing a change from a supply pallet into an order pallet also changes the number of supplying positions and order positions. Therefore a limitation will be set for the availability to change pallets. It will only be required as long as the lower-bound for the supply positions is not reached yet. The order positions will be changed towards supply positions when one of them becomes available. In this way a balance between supply positions and order positions will kept. The specific balance criteria will be found using simulation. So, non-fixed position do not only create the opportunity to choose between the need of a supply- or order pallet, it also directly reduces the number of layers required to be picked by the robot and reduces the number of pallet movements between the empty pallet area and the robot area.

5.4.4. Scheduling methods used

A combination between the different scheduling methods will be used. The reference method and the heuristic method will be the basis with both using fixed and non-fixed supply- and order positions. It results in the use of the following scheduling methods:

1. Reference method with fixed supply- and order positions (ref)
2. Reference method with non-fixed supply- and order positions (ref+p)
3. Heuristic method with fixed supply- and order positions (heur)
4. Heuristic method with non-fixed supply- and order positions (heur+p)

5.5. Model input

The model input contain all variables which will be used within the model. They are are located in a separate text-file and adjustable for each case that will be tested. The variables that define the initial model state are:

- Scheduling method
- Number of initial supply positions
- Number of initial order positions
- Number of orders
- SKU distribution
- Layer distribution

- Discrete or continuous order arrival
- Inter-arrival time distribution for continuous order arrival
- Transfer times for each transfer unit
- Pallet inter-arrival time for each transfer unit
- Pallet change time for a robot position

The order input can also be given using XML-files containing data for each single pallet (entry time, number of layers, SKU-type and due date). This is data provided by ORTEC to validate the model with real data. However, the system will be analyzed using the generated data given in the input text-file. This because only one real data set is available.

5.6. Model output

The model result will be written to several .csv-files. The main file gives the performance results for the model. Furthermore, files are written containing information about the pallet occurrence within the warehouse, buffer area and robot. Also the robot activity will be logged to a file. Important information is the delivery and receiving time for specific pallets at the warehouse and output. This is the connection with the OptilogX, so using this information would give the opportunity to test the influence of the layer picking on the current system. The different files with their most important information are given below. Appendix B gives examples of the used files, including the model visual and the input-file.

General results
Completion time
Utilization robot
Buffer area: mean length, max length, mean waiting time, max waiting time
Pallet output/hour
Layers handled/hour
Pallet movements/hour: TU1 till TU6

Pallets required at warehouse
Pick-up time
Pallet number

Pallet delivered to warehouse
Delivery time
Pallet number
Due date achieved yes/no

Robot position usage
Position
Pallet number
Time arrival
Time leave

Layer picked file
Supply position
Pallet number
Order position
Order pallet
Picking time

5.7. Verification

Verification and validation are concerned with determining whether a model and its results are correct for a specific use. Model verification is often defined as "ensuring that the computer program of the computerized model and its implementation are correct."[16] Performing the verification will therefore focus on the model correctness. Model validation can be defined as: "the process of determining that the model on which the simulation is based is an acceptably accurate representation of reality."[6] This validation cannot be fulfilled because the model is not available in reality yet. Therefore, only verification will be used to determine the model correctness.

The model verification will be done using three steps. The first step is shown in section 5.2 which contain the description of each separate element. Following this structure gives an insight in the different steps that will be taken within the model. The second step is done during the model development using the TOMAS trace function. This is a function which shows all steps taken during simulation. It is used to check if each added model part is following the expected actions. Appendix C shows the trace of a supply pallet. These first two steps are the basis for the model verification. However, a third step is required which uses a comparison between hand calculations and model results. This final verification step will be accomplished with using the pallet movements, transfer times and Little's Law [9].

Pallet movements

The first test concerns the pallet movements through the system. Table 5.1. shows the input values used for this test. Small transfer times are used to achieve a 100% robot utilization. This utilization is also used within the calculated results in Section 3.7.2. A big number of orders is used to minimize the start-up influence for the system (start from an empty model).

Table 5.1: Input values for verification

Variable	Value
Runs	20
Orders	10.000
SKU	100, uniform distribution
Layers per pallet	2-8, uniform distribution
Supply positions at robot	4
Order positions at robot	4
Pallet transfer times	0.1 [s]

Table 5.2 shows the results of both the calculated results and the model results. As can be seen, a small difference between the calculated results and the model results occurred. This can be explained by the fact the warehouse created more supply pallets due to the non-ideal uniform distribution that has been used. This distribution varies a little bit, resulting in creating 40 supply pallets too much and a supply flow (warehouse - robot area and robot area - empty pallet area) which differs a little bit from the calculated ideal flow. The buffer area flow is also a little different than the calculated flow. This can also be explained by the small variation in the layer distribution.

Table 5.2: Movements in the system

Movement	Calculated results [movements/hour]	Model results [movements/hour]
Warehouse - robot area	40.0	40.1
Robot area - Warehouse	40.0	40.0
Empty pallet area - robot area	40.0	40.0
Robot area - empty pallet area	40.0	39.8
Buffer area - robot area	147.9	148.0
Robot area - buffer area	147.9	148.4

Transfer times

The second test will be used to check the different transfer times within the system. This is done using the pallet transfer times measured at a current OptilogX. Table 5.3 shows the used transfer times. The inter-arrival time is based on the VT capacity. A VT delivers 100 pallets/hour, equal to 36 seconds/pallet. This is the pallet-interval time for the warehouse and buffer area, which both will use a VT to deliver or retrieve a pallet in the basic situation. The empty pallet area is a less complicated area at which the system will be able to deliver pallets directly after each other. A pallet inter-arrival time will be used to avoid collisions, this is equal to 15 seconds. Also the pallet removal time can be determined. This concerns the time it takes to remove an old pallet and to place a new pallet at a single robot position. Section 3.7.3 shows the result, $t_p = 56s$. Using these inter-arrival times will avoid collisions and at the same time create a high pallet throughput.

Besides the pallet inter-arrival time, also the transfer time between the different areas need to be defined. This time is calculated using averages, since the exact placing at the robot area is not taken into account in this model. The influence of these travel times will be tested within the experimental plan. In this way it will be possible to show the lay-out requirements for the system.

Table 5.3: Pallet transfer times

Inter-arrival time	**Time**	**Transfer time**	**Time**
Warehouse	36 s	Warehouse - robot area	200 s
Empty pallet area	15 s	Empty pallet area - robot area	100 s
Buffer area	36 s	Buffer area - robot area	200 s
Pallet change at robot position	56 s		

Little's Law

The third test will be using Little's Law[9]. The average model results, obtained with TOMAS, will be compared with calculated results. This law can be described with:

$$N = \lambda * D \tag{5.7}$$

Used values:

N = 79.39 pallets
λ = 40.14 pallets/hour

Results:

$D_{calculated}$ = 7120 seconds
D_{model} = 7141 seconds

The result of $D_{calculated}$ and D_{model} differ just 0.3%. This is fulfilling the requirements due to a small error margin. With this final comparison the model has completed all verification steps. It fulfills the correct steps and produces the expected results. Therefore, the model can be seen as verified.

6
Experiments

Chapter 6 describes the experiments done with the simulation model. The first paragraph explains the experimental plan. The second and subsequent paragraphs will show different test cases. A differentiation in position usage, number of SKUs, transfer times, batch sizes, and due dates will be made.

6.1. Experimental plan

Four scheduling methods will be used during the experiments. It is possible to show the influences of the used priority rules on the system performance and the most important lay-out influences with these four methods. Section 5.4 explained the different used scheduling methods:

1. Reference method with fixed supply- and order positions (ref)
2. Reference method with non-fixed supply- and order positions (ref+p)
3. Heuristic method with fixed supply- and order positions (heur)
4. Heuristic method with non-fixed supply- and order positions (heur+p)

The impact of each scheduling method will be shown using test cases with differentiation in important variables. The influence of each changing variable on the scheduling method is important to be able to deliver a satisfying solution to the customer and to show whether a suggested solution is feasible. The following variables are most important for the system design and will be used as test cases:

- Position variation
- SKU influence
- Transfer time influence
- Batch size influence
- Due date influence

The experiments will be performed using a basic data-set. The different tested variables will be varied to able to show the individual influences. Using an individual approach will filter the most important variables which can be used for multiple warehouse types. This is done because each warehouse has its own requirements (e.g., number of SKUs, throughput and available space). Table 6.1 gives the basic situation used for the experiments.

Table 6.1: Basic input values experiments

Variable	**Value**
Runs	20
Setting time	equal to building 200 pallets
Order batch	500
Number of SKUs	100, uniform distribution
Layers per pallet	2-8, uniform distribution
Supply positions at robot	4
Order positions at robot	4
Warehouse: *Inter-arrival time pallets* *Travel time to robot position*	 36 [s] 100 [s]
Buffer area: *Inter-arrival time pallets* *Travel time to robot position*	 36 [s] 200 [s]
Empty pallet area: *Inter-arrival time pallets* *Travel time to robot position*	 15 [s] 200 [s]
Pallet change time at a robot position (t_p)	56 [s]
Due date	none

6.2. Position variation

Varying the robot positions directly influences the system lay-out. Different decisions can be made regarding these positions. The first decision is the number of positions that can be used. Table 6.2 shows the results from a position variation. The position distribution is given in supply positions (S) and order positions (O). As can been seen, the system performance increases when more positions are used. This is due to the fact that the robot has the same layer picking times regardless the number of positions. Using this assumption, having as much as possible positions available at the robot is preferred. At the moment, a layer picking robot is capable of using eight positions but in the future this number of positions possibly increases (with the same layer picking time). Interesting is the huge performance difference between S3,O3 and S4,O4. This is caused by the pallet change time. In the case of three positions the robot will need to wait until the new pallet arrives. Section 3.7.1 showed that a robot needs 18.2 seconds to pick a layer. As such, there should be a new layer (i.e., a new SKU pallet) available every 18.2 seconds to ensure that the order pallet will be layered as fast as possible and does not need to wait for a new SKU pallet to arrive at the robot. Once the robot has picked a layer, the system needs 56 seconds to replace the supply pallet with another SKU pallet. Because each layer picking action takes 18.2 seconds, the system needs minimal four supply pallet positions (18.2 x 4 = 54.8 sec) to ensure there is a constant layer picking flow (i.e., the first supply pallet is replaced and ready for layer picking when a layer is picked from the fourth supply pallet).

Table 6.2: Position number influence, layer picking throughput (reference scheduling method)

Positions	**10 SKU [layers/hour]**	**100 SKU [layers/hour]**	**200 SKU [layers/hour]**
S3, O3	106.9	91.3	89.5
S4, O4	142.9	107.3	105.4
S5, O5	161.7	109.4	106.3
S6, O6	173.7	111.3	107.3

Using the maximum eight positions at the robot gives the possibility to change the distribution for the number of supply- and order positions. Table 6.3 shows the results from this experiment done with the reference scheduling method. As can been seen, the results are not constant for all different distributions. To be as constant as possible and to prevent extra waiting times for the robot, it is required to have at least four supply and three order positions available. There are just three order positions required because multiple layers can be placed on an order pallet directly after each other. However, some order pallets just need one or two layers. Therefore, a minimum of three order positions is required to prevent extra waiting times for the robot due to order pallet changes.

The limitation in supply- and order positions is implemented with the varying positions (ref+p and heur+p). These scheduling methods will use a minimum number of supply- and order positions during operation. The minimum is set to three supply position and three order positions. Experiments showed the best results using this position distribution. Since both scheduling methods decrease the number of required pallet movements, and thus pallet changes at the robot, the system can operate with less required supply positions than the reference method.

Table 6.3: Position distribution influence, layer picking throughput (reference scheduling method)

Positions	10 SKU [layers/hour]	100 SKU [layers/hour]	200 SKU [layers/hour]
S2, O6	89.9	79.3	79.2
S3, O5	120.3	93.5	91.8
S4, O4	142.9	107.3	105.4
S5, O3	143.6	106.0	103.9
S6, O2	130.3	94.4	89.4

6.3. SKU influence

A SKU is a specific product which is available for creating order pallets. Therefore, increasing the number of SKUs results is an increase of possible products that can be used to create the order pallets. The order generator creates the same differentiation in number of layers for each order, but the number of SKUs assigned to each layer will be different. Therefore, an increase in the number of SKUs will decrease the probability that two equal layers occur within one single order pallet. The results from varying the number of SKUs will be shown using the two KPIs: pallet movements to/from the buffer area and the system layer picking throughput.

Figure 6.1 shows the total pallet movements to/from the buffer area. As can be seen, the individual results show a fast decrease with a few SKUs for all methods. This is because the system is influenced by the probability to have two equal SKU-layers on a single order pallet. Equation 3.4 shows the required pallet movements for the reference method, including this probability. Each time a supply pallet arrives at a supply position at least one SKU-layer can be picked by the robot. The supply pallet then has a probability $P(S)$ that a following layer can be picked without an extra pallet movement.

The heuristic method improves the reference method for all number of SKUs. However, the influence by the number of SKUs is the same because the priority rules are based on local optimization and, therefore, based on the probability of occurring SKU-layers. The position change improves both the reference method and the heuristic method for all number of SKUs. This improvement is expected because a position change means a supply pallet will be transferred into an order pallet directly. This transformation results in one layer pick (and transfer) per change less. However, the system performance is also slightly affected due to a temporarily different used position distribution.

Figure 6.2 shows the total pallet movements for the combination of the buffer area and the empty pallet area. As can been seen, the non-fixed supply- and order positions also have an influence on the empty pallet area usage. This is because it occurs that a supply pallet directly becomes a order pallet, without moving to or from the empty pallet area. As a result, the improvement from the heur+p method compared with the reference method is between 37.1% (10 SKUs) and 22.5% (300 SKUs) lowering in pallet movements (10 SKUs).

Figure 6.3 shows the system layer picking throughput. As can be seen, the influence of the non-fixed supply- and order positions is important with few SKUs. This can be explained with the probability of more equal SKU-layers at the bottom of one order pallet. For example, it can lead to a direct pallet transformation containing three layers. Having this opportunity will save the need of picking three layers by the robot as well as saving an empty pallet movement to and from the empty pallet area. The positive influence in the system performance will be less as the number of SKU increases. This because the chance of having a direct pallet change reduces. As such, the robot will need to pick a higher layer percentage. The heur+p method showed a layer picking throughput increase between 19.3% and 27.8% compared with the reference method.

A stable buffer area length is required to be able to design a system which is capable of handling varying conditions. Besides the full system lay-out, the buffer area size also influences the buffer area pallet inter-

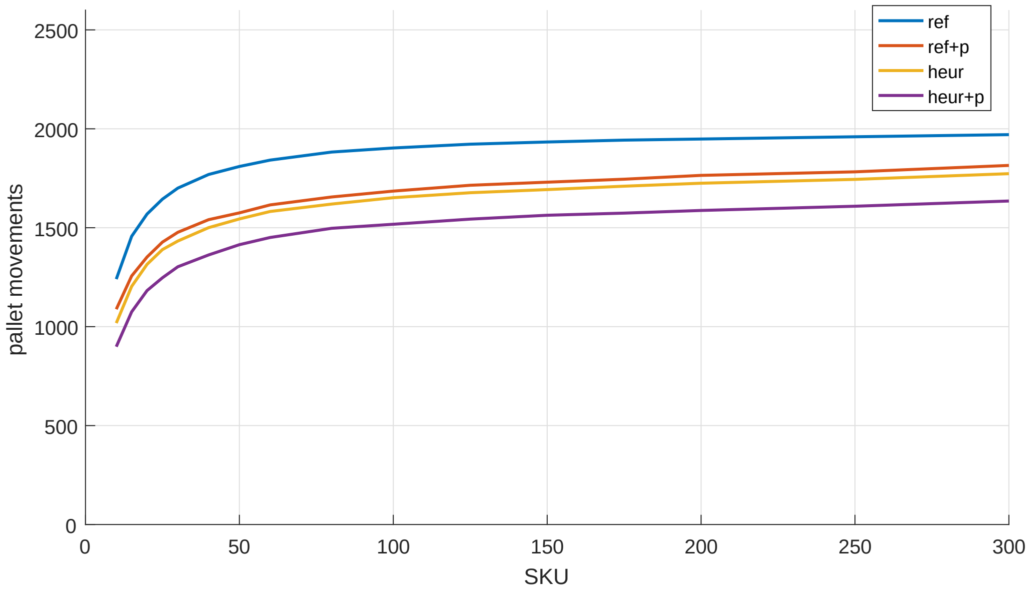

Figure 6.1: SKU influence, pallet movements to/from buffer area

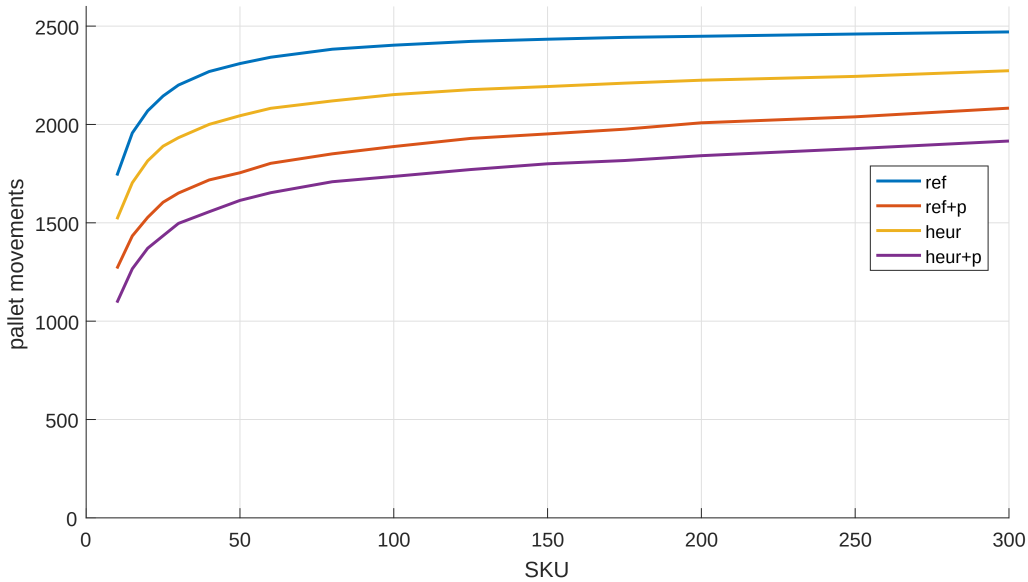

Figure 6.2: SKU influence, combined pallet movements to/from buffer area and empty pallet area

arrival time. An increasing required buffer area will create less stable delivery times, is more sensitive to delays and more sensitive to changing orders. Therefore, a small (preferably constant) buffer area is required to keep a simple system. The mean buffer length is equal to about 80% of the number of SKUs available. The maximum buffer area size is linear between 20 positions (10 SKU) and 250 positions (300 SKU). The buffer area is only influenced by the number of SKUs available in the system.

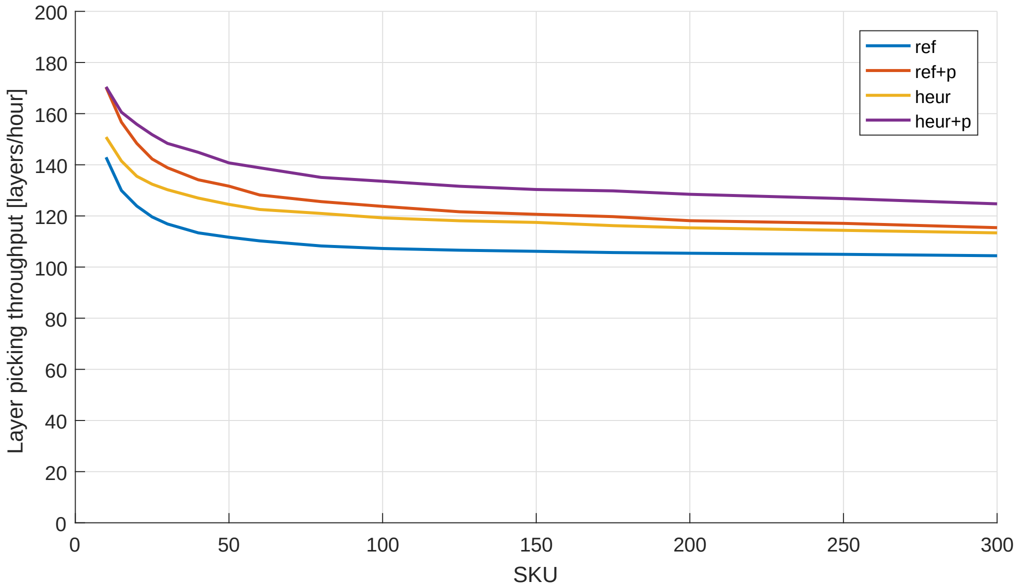

Figure 6.3: SKU influence, layer picking throughput

6.4. Transfer time influence

The transfer time influence can be separated into the transfer times and the pallet inter-arrival times to/from the separate areas. Both are important for the final system lay-out.

The pallet transfer time is the time it takes for a pallet to be transferred between two locations, in this case from a specific area towards a robot position or from a robot position towards a specific area. In total three different pallet transfer times are used: to/from the warehouse, to/from the buffer area and to/from the empty pallet area. Figure 6.4 shows the influence of these three transfer times. As can be seen, the transfer time to/from the warehouse and to/from the empty pallet area do not influence the state because they do not depend on pallets coming back from the robot area; their inventory is satisfying the requests. However, a longer transfer time means the system has to determine its pallet decisions earlier. This does not influence the system directly assuming constant delivery times but the system will be less robust to changes. On the other hand, the transfer time to/from the buffer area has a small influence because the inventory is not satisfying the request. A pallet is not available to choose during its transfer time. Therefore, increasing the transfer time will lead to less choices at the robot and, therefore, to a slightly decreasing system performance. However, this influence is limited because the required SKU-layers can also be supplied by the warehouse. In total, this leads to more pallets within the system and, therefore, a bigger required buffer area. These small influences on the system performance are important conclusions for the system lay-out. It can give freedom in creating the total layer picking area lay-out. The transfer time to/from the warehouse and empty pallet area does not influence the system performance directly but it matters for the system flexibility. The system has to decide the upcoming actions earlier, which means the system will be less robust to last minute changes or disruptions.

The pallet inter-arrival time is the time between the front of two succeeding pallets and can be determined by the pallet arrival rate from the different areas. For example, the pallet arrival rate for the warehouse is equal to its VT capacity. The simulation model just uses one VT at each area. Consequently, each pallet inter-arrival rate is equal to 36 seconds per pallet. The influences of the differentiation in inter-arrival times are different for each location. Figure 6.5 shows the results using the reference method. As can been seen, the buffer area inter-arrival time is the most important to control because the total number of pallet movements is the largest from/to this area. Therefore, this will also have the biggest influence on the system performance.

At the moment, the buffer area pallet inter-arrival time is a bottleneck for the system. The robot is able to pick a single SKU-layer each 18.2 seconds. However, the buffer area is only able to deliver a single pallet each 36 seconds. Therefore, decreasing the buffer area pallet inter-arrival directly improves system performance. This improvement can be made as long as the pallet inter-arrival time is the bottleneck. The bottleneck changes towards a different part of the layer picking area below 18.2 seconds (the time for the robot to pick a layer).

As such, the layer picking throughput can be improved by decreasing the pallet inter-arrival time from the buffer area. Possibly, this pallet inter-arrival time decrease can be done using a buffer area on the same level as the robot, or by using two VTs as a pallet in-feed and two VTs as a pallet out-feed. However, adding two VTs at both sides of the OptilogX would lead to complications within the OptilogX. The preferred solution would be to place the buffer area at the same level as the robot. A problem that occurs with lowering the pallet inter-arrival time is the increasing possibility for pallet collisions within the robot area. Therefore, the lay-out for delivering and retrieving pallets from the robot area should be adjusted to a new pallet inter-arrival time.

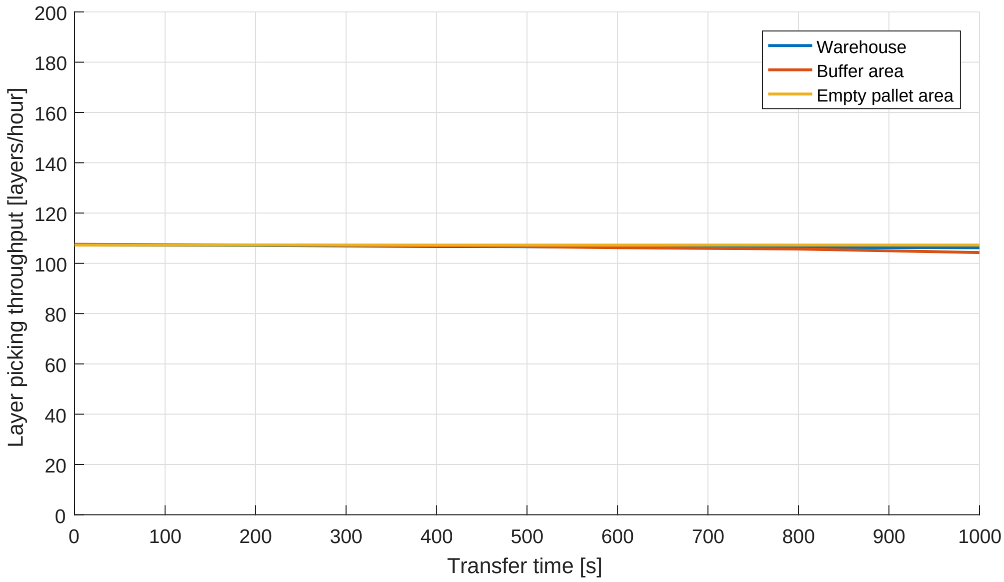

Figure 6.4: Transfer time influence, layer picking throughput (reference method)

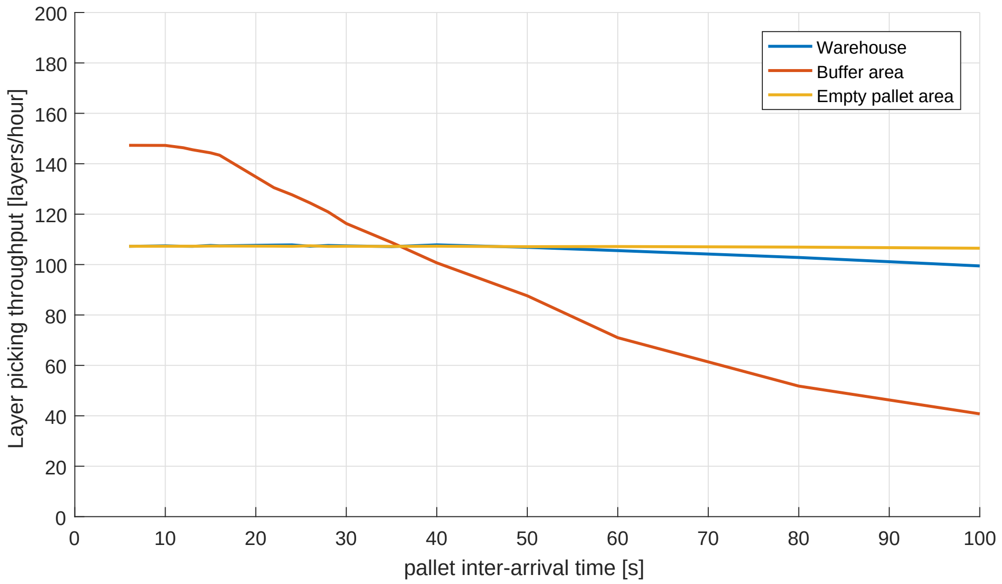

Figure 6.5: Pallet inter-arrival time influence, layer picking throughput (reference method)

6.5. Batch size influence

An order batch consists of multiple order pallets which arrive at the same time. Varying these order batch sizes shows the influence in pallet choice possibility for the different scheduling methods. This experiment uses 500 orders in total, with a new order batch arriving when a previous batch is completed. Figure 6.6 shows the combined pallet movements for the buffer area and the empty pallet area. As can be seen, the order batch size does not influence the reference method because it uses the same pallet order with all batch sizes. However, all three other scheduling methods are influenced by the order batch size.

The scheduling methods using the non-fixed supply- and order positions are influenced because they do not have the same opportunity to find a comprehensive order pallet for the final layer(s) of the supply pallet. The batch size of 10 order pallets shows an interesting point. The reference method with non-fixed supply- and order positions uses more pallet movements than the reference method with fixed supply- and order positions. This result is caused by the temporarily worse position distribution which occurs after a direct position change from a supply position towards an order position. This temporarily state exists of three supply positions and five order positions. Section 6.2 shows the negative performance influence for being in this state. However, a possibility to choose from a bigger order batch reduces this negative performance influence. This can been seen with a bigger order batch where the scheduling methods using the non-fixed positions perform better than the scheduling methods using the fixed positions. This situation is caused by using an operational system without looking a couple steps ahead.

The heuristic scheduling method is influenced because it chooses a preferred pallet from all pallets available. Therefore, having more pallets available can result in an improvement in the pallet selection.

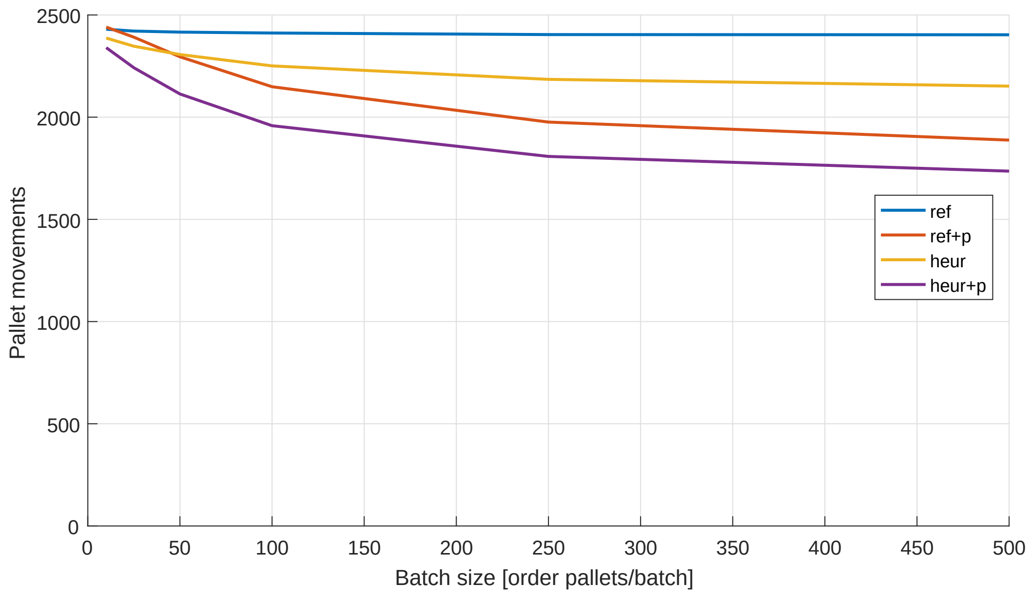

Figure 6.6: Batch size influence, combined pallet movements to/from buffer area and empty pallet area

6.6. Due date influence

A requirement for the model is creating all orders before their due date. This requirement is implemented in the heuristic scheduling method. Section 5.4.2 shows this implementation using equation 5.6. It states each time a pallet needs to be chosen, an order pallet selection is made which contains all order pallets possible to be able to complete before their due date. This is calculated using the due date of each order pallet and then check if it is possible to finish it in time, including all order pallets with a lower due date. The pallets resulting in this list can be chosen as a next order pallet. This method fulfills its main task; creating each pallet before their due date. However, it is also important to check the robustness for this method.

This due date test uses different order batches with different due dates. It means priority is important throughout the simulation and the system needs to be capable of dealing with order changes. Figure 6.7 shows the order batch arrival used within this test. It uses a basic order batch which arrives at the start. A new (small) order batch arrives during the processing time of the basic order batch. The new order batch has a due date which is before the basic order batch due date. The tests are performed using late-arriving order batches with the size of 10, 20 and 30 order pallets. These order batches are implemented one, two or three times during the processing of the basic order batch. The due date used for the implemented order batch is equal to five minutes per pallet. Using this will give the system the possibility to create all pallets before their due date. At the same time, the influence of the incoming pallets still needs to be taken into account. The reference method is based on picking the next order in the order queue, which is sorted on due date. Therefore, the reference method system performance will not be influenced by a late batch arrival. Consequently, only results from the heuristic scheduling method in combination with the non-fixed supply- and order position will be shown.

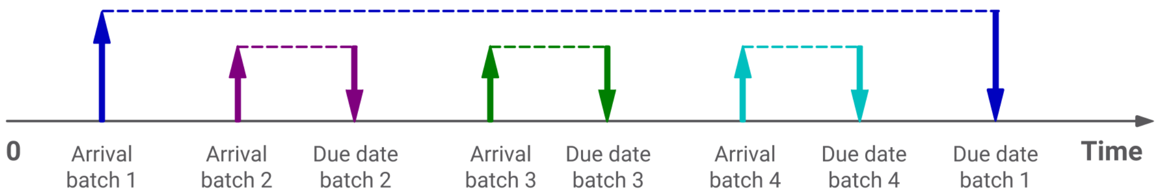

Figure 6.7: Experiment with three small order batches arriving late (heuristic with non-fixed positions scheduling method)

The results can be divided into the two system KPIs. Table 6.4 shows the first KPI: pallet movements. A basic situation is created with the number of pallet movements to/from the buffer area and the empty pallet area required to complete the 500 orders without a late-arriving order batch. Logically, this number of pallet movements increases due to the unexpected batch arrival. The influence of this arrival is that current order pallets at the robot will be sent towards the buffer area and will be replaced by new orders. The normal operating process continues after completion of the late arrived orders. This process repeats itself with each late batch arrival. The result shows the number of implementations does not have a big influence. However, this does not count for the total implemented pallets. For example, the difference in pallet movements between 1x 30 pallets (1791 movements) and 3x 10 pallets (1784 movements) is small, while the difference between 1x 30 (1791 movements) and 1x 10 (1759 movements) is bigger. Section 6.5 can be used to explain this result. It shows that using small order batches will not create scheduling possibilities because of the low pallet choice availability within the system.

Table 6.4: Buffer area movements (heuristic with non-fixed positions scheduling method)

Implementations	**0x [movements]**	**1x [movements]**	**2x [movements]**	**3x [movements]**
10 pallets	1736	1759	1775	1784
20 pallets	1736	1776	1811	1835
30 pallets	1736	1791	1841	1890

Table 6.5 shows the second KPI: layer picking throughput. The system is able to keep a constant layer picking throughput. However, there is a slight decrease in performance. This is caused by the tight due date, which results in less direct pallet transformations from a supply pallet into an order pallet and in more idle time at the robot because of the extra waiting time for a new pallet.

Table 6.5: Layer picking throughput (heuristic with non-fixed positions scheduling method)

Implementations	**0x [layers/hour]**	**1x [layers/hour]**	**2x [layers/hour]**	**3x [layers/hour]**
10 pallets	133.6	132.8	131.8	131.3
20 pallets	133.6	131.3	130.0	129.1
30 pallets	133.6	131.0	128.6	126.3

Overall, the due date results show the ability to fulfill the high priority orders in time. However, it has to deal with an increase in the number of movements in the system and a slight decrease in layer picking throughput. This influence is due to the temporarily situation with just a few order pallets to choose.

7 Conclusion and recommendations

Chapter 7 shows the conclusion and recommendations from this research. The results from the five experiments will be combined to show the possibilities with this research and together they will give an answer to the research question. Furthermore, the recommendations for further research will be given.

7.1. Conclusion

The current OptilogX is not capable of creating order pallets with different SKU layers. Building such a layer picking area requires an organized system to minimize the pallet movements and to create a high layer picking throughput. Chapter 6 shows the results of the experiments done with four different pallet scheduling methods. Together, these results will show restrictions, goals and possibilities for the system.

The first experiment shows the importance of the different pallet positions at the robot. The system requires at least three supply positions and three order positions at all times to ensure a stable performance of the system.

The second experiment shows the mutual differences in performance between the different scheduling methods. The heur+p scheduling method shows an improvement in pallet movements up to 37.1%. Furthermore, the non-fixed supply- and order positions show a gain using a few SKUs. Increasing the number of SKUs decreases the non-fixed supply- and order positions' influence. Therefore, especially with a few SKUs it is important for the system to use the non-fixed supply- and order positions.

The third experiment determines the lay-out requirements for the system. The transfer times between the different areas do not show big influences. However, the pallet inter-arrival time does. The most influencing part is the pallet inter-arrival time between the buffer area and the robot area. The system performance will improve significantly if the pallet inter-arrival time from the buffer area is small. This can be achieved using a buffer area on the same level as the robot area. Furthermore, a small buffer area is required to be able to deliver a constant small pallet inter-arrival time.

The fourth experiment shows the batch size influence. Small batches will lead to less improved results due to the lack of scheduling possibilities. The larger the batch size, the more choices to organize the pallet flow can be made.

The fifth experiment shows the influence of late order batch arrivals. It shows that a late order batch arrival is possible but also has a small influence to the system performance.

Together these five experiments showed the influence of the scheduling methods and lay-out decisions for the layer picking area. The most important results from these experiments are:

- The heuristic method with non-fixed supply- and order positions shows the best overall results
- Use eight positions at the robot with at least three supply positions and three order positions
- Keep the pallet inter-arrival time from the buffer area short
- Keep the batch size preferably as big as possible
- Late batch arrival is possible but does have a small influence on the system

Therefore, this research gives an answer to the research question:

What is a feasible scheduling method for minimizing pallet movements, while maintaining the layer picking throughput?

The overall results show a good performance of the heuristic method in combination with the non-fixed supply- and order positions. The method is capable of achieving a high pallet throughput if the buffer area pallet inter-arrival can be kept short. The number of required pallet movements is reduced to be able to achieve this situation.

Furthermore, this research shows the influences of the design decisions on a warehouse. This is important to know because each warehouse is different in terms of layer picking throughput, number of SKUs and available space. With this knowledge a decent choice in lay-out can be made.

7.2. Recommendations

This research shows the capabilities of adding a layer picking area to the OptilogX. Several assumptions have been made to create a simulation model adaptable to different warehouse types and, as such, more research needs to be done before the system can be implemented. Specifically, the following four recommendations have been identified:

1. Finding the buffer area influence. For this research, a constant pallet inter-arrival time from the buffer area was assumed. However, this is difficult to achieve with large buffer area sizes. Furthermore, it occurs that pallets have to be "dug out" from the buffer area.

2. Integrated buffer area with OptilogX. In some warehouses it might be beneficial to integrate the buffer area within the currently available pallet spots of the OptilogX. In such a situation, the warehouse needs to operate with full pallets and partially loaded pallets within one buffer lane. It could be interesting to research whether integrating the buffer area with OptilogX is feasible and to find the operational influence on the OptilogX.

3. Multiple layer picking robots. This research used one robot to fulfill the operation. However, two or more robots might be required for a higher capacity and to cover for a malfunctioning robot. This is an interesting topic to research because of the extra lay-out possibilities and, thereby, new scheduling possibilities.

4. Quick scan possibility for different warehouses. Due to the variety in warehouses no specific lay-out has been built. Differences in lay-out, throughput requirements and number of SKUs will occur. Therefore, for each client a specific lay-out will need to be built. This is possible with the simulation model built within this research. However, a tool could be developed which is capable to show the results directly, instead of running through simulation again.

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A
Scientific paper

Integration of a layer picking area with the OptilogX Sequencing Buffer

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***Abstract*— The current automated warehousing solution from ORTEC is handling order pallets without changing its layer configuration. However, a warehouse can be used to handle different order pallet types. This paper shows the requirements for and the feasibility of integrating a layer picking area with the automated warehousing solution. A layer picking area gives the possibility to have an automated warehouse with single product pallets as input and a combination of single product pallets and mixed product pallets as output, in a certain sequence determined by the order or shipment. The system analysis shows the required pallet flow within this system. Scheduling methods are developed to reduce this required pallet flow to be able to create a feasible solution.**

***Index Terms*— Automated warehouse, layer picking, pallet scheduling.**

I. Introduction

ORTEC (located in Zoetermeer, the Netherlands) developed an automated warehousing solution to create a highly dynamic buffering, sequencing and storage of pallets. This solution, the ORTEC OptilogX Sequencing Buffer, sorts the pallets within the system to ensure a high pallet output rate with a short response time. Currently, the OptilogX is only capable of handling order pallets without changing its layer configuration. However, a warehouse can be used to handle different order pallet types. Distribution managers change towards automated order pallet picking more and more due to increasing picking volumes and increasing cost-percentage for the total facility. Customers order in smaller, more frequent quantities to be able to better manage inventories.[1] An order pallet can contain various quantities of one or more stock keeping units (SKUs). A SKU is a unique identifier for a product within a specific packaging. For example, all 1 liter packing of an ice-cream flavor are equal to one SKU, while all 0.5 liter packing of the same ice-cream flavor equals a different SKU. This research focuses on developing a layer picking area which is capable to build order pallets with different SKU layers. This layer picking area should be combined with the OptilogX in order to create an end-to-end solution for the customer. Figure 1 shows the combination of the OptilogX with the layer picking area. Using this would give the capability to have single product pallets as input and a combination of single product pallets and mixed product pallets as output, in a certain sequence determined by the order or shipment.

The current developed OptilogX ensures a high pallet throughput capable of sequencing and delivering pallets at the correct place and time. Possible options for a layer picking system to use in combination with the OptilogX would be a conveyor-based system, a gantry robot-based system or a robot-based system. These systems are all capable of performing the required capacity. However, the characteristics of the layer picking system should be in line with the important characteristics of the OptilogX. These characteristics contain a dynamic and high-density system which is easy adjustable to different warehouses. The robot-based system is the layer picking system with the best suited characteristics. It uses a small footprint, a good mechanical flexibility, is possible to use within different warehouse types and can be easy implemented with low investment costs. A single robot layer picker is capable to pick 200 layers/hour to and from eight pallet positions around.

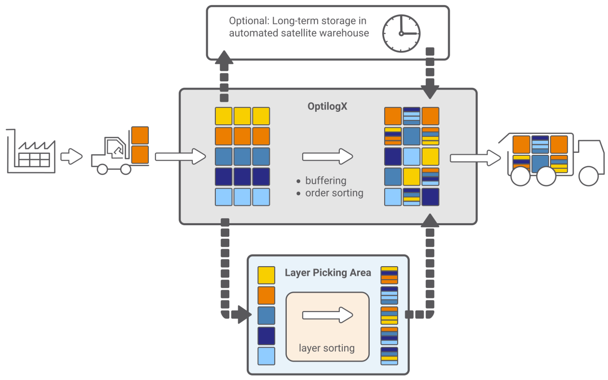

Fig. 1: System representation of the connection between the OptilogX and the layer picking area

II. Method

The first part of this research will focus on the system analysis to define opportunities for creating an automated layer picking area. This will be done using the Delft Systems Approach.[2] The second part of this research will use a simulation model built in DelphiXE6/TOMAS. It is used to identify opportunities and requirements for improving the layer picking area and to show the system feasibility. Experiments with different input variables will be done to show their influence towards the system performance.

III. System analysis

The layer picking area is developed as a separate area which uses an in-feed and out-feed connection with the OptilogX. The transformation of single SKU pallets towards mixed SKU pallet is done using a layer picking robot. This transformation will create more pallet types which need to be stored within the layer picking area. Therefore, a buffer area and an empty pallet area will be added within the pallet flow. Furthermore, transfer units are required to be able to move the pallets from a specific area towards a robot position, or from a robot position towards a specific area. Figure 2 shows the schematic flow within the layer picking area.

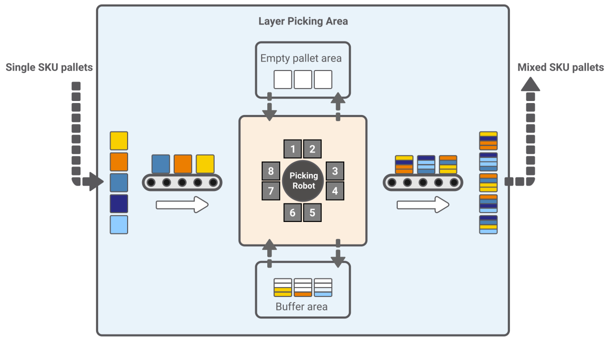

Fig. 2: Schematic pallet flow within the system

A flow calculation is done to provide insight in the requirements for an improved scheduling method. This is done using an order oriented scheduling method. This method uses the order pallets as the leading pallet type. It means an order pallet is sent towards the robot area. At this point, the required supply pallet will be called towards the robot area and delivers a SKU-layer. This will be done until the order pallet is completed. It will lead to a single robot area visit for an order pallet, and a multiple robot area visit for a supply pallet. The used input parameters are a 200 layer/hour throughput capacity, an average of 5 layers/pallet and 100 SKUs. Figure 3 shows the results from this flow analysis. As can been seen, the static calculation lead to a total pallet flow into the robot area of 227.9 pallet movements/hour. Creating a feasible system for this high pallet flow could be possible with two options. First, it is possible to add more infrastructure by adding more VTs and conveyors. Second, it is possible to lower the required pallet flow by reducing the required pallet movements within the system. The preferred method to create a feasible system is reducing the required pallet flow. This because it is important to minimize the equipment usage for the system to suit the characteristics of the OptilogX and the robot- based layer picking system. Besides the pallet flow, a high and reliable layer picking throughput is important to be able to met the requirements. So, lowering the pallet movements will need to be done while keeping a high layer picking throughput possible.

At the moment, the required pallet flows are too high to be able to integrate an automated layer picking area within the OptilogX. Therefore, a scheduling method is required for minimizing the pallet movements and at the same time maintaining the layer picking throughput. Two KPIs result from this analysis:

- *Pallet movements*
  Pallet movements within the system should be minimized, this can be achieved by combining supply pallets with order pallets.
- *Layer picking throughput*
  The layer picking throughput for the system should be maximized up to a single robot's capacity.

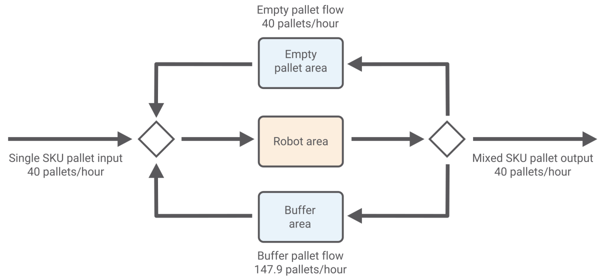

Fig. 3: Combined supply- and order pallet flow

IV. Model

The environment DelphiXE6/TOMAS is used to build a simulation model for the layer picking area. The pallet flow within this mode is determined using different scheduling methods. The goal is to combine the supply- and order pallets at the robot to lower the pallet movements, while the layer picking throughput is still acceptable. Equation 1 shows this goal within a mathematical formulation. The basic scheduling methods used are a reference method and a heuristic method.

$$minimize \sum_{p\in P} M_p \tag{1}$$

s.t.

$$\sum_{p\in P} PP_{p,x} = 1 \qquad \forall\ x \in X \tag{2}$$

$$\sum_{x\in X} PP_{p,x} = 1 \qquad \forall\ p \in P \tag{3}$$

$$\sum_{p\in P} RH_p \leq 2 \tag{4}$$

$$t_{f,i} \leq t_{dd,\,i} \qquad \forall\ i \in N \tag{5}$$

With

$p \;= 1, .., P$	pallet
$i \;= 1, .., n$	order pallet
$x \;= 1, .., X$	pallet position
$x_r = 1, .., X_R$	robot pallet position
M_p	pallet movements
$PP_{p,o}$	pallet position
RH_p	pallet hold by robot
t_f	completion time
t_{dd}	due date

A. Reference method

The reference method is based on an order oriented scheduling method. This method picks the first order pallet available, sends it to an order position at the robot and it will stay on its order position until it is completed. As such, no buffer area visit will be allowed for the order pallets. The supplying pallets will be called if necessary and sent away to the buffer area if no new picking action can be fulfilled.

B. Heuristic method

The heuristic method reacts on the current situation within the layer picking area. The decisions within the heuristic scheduling method are based on two possible actions which can be fulfilled with both a supply- and an order pallet:

- A pallet can be sent from the warehouse, buffer area or empty pallet area to a pallet position at the robot area
- A pallet can be sent away from the robot area towards the output, the buffer area or the empty pallet area

The used priority rules chooses the best pallet for the current situation. This means selecting a pallet to match the most layers already available at the robot. It ensures a high robot utilization and a robust scheduling method. Equation 6 is used to check if each order pallet in the system is possible to create before its due date. This is an important constraint for the system and will be implemented using a pallet selection for choosing the next pallet to handle.

$$\sum_{i=1}^{n}(LR_i * PT) + LR_{i_{max}} * PT + 2 * TT_{in_{max}} + TT_{out_{max}} \leq t_{dd_i} - t_c \quad (6)$$

With

PT	processing time for one layer
LR_i	layers remaining for order pallet i
TT_{in}	pallet transfer time from an input area towards a robot position
TT_{out}	pallet transfer time from a robot position towards the output
t_c	current time

The reference and heuristic scheduling methods are both tested in combination with fixed and non-fixed supply- and order positions. Fixed positions uses dedicated supply- and order positions, which results in the need of picking every layer from a supply pallet towards an order pallet. The non-fixed positions uses non-dedicated supply- and order positions, which gives the possibility to use the layers of a supply pallet directly as the first layers for an order pallet. The four different scheduling methods tested are:

1) Reference method with fixed supply- and order positions (ref)
2) Reference method with non-fixed supply- and order positions (ref+p)
3) Heuristic method with fixed supply- and order positions (heur)
4) Heuristic method with non-fixed supply- and order positions (heur+p)

V. Results

Experiment are used to show the impact of each scheduling method towards the system performance. The influence of the variables to the scheduling method is important to be able to deliver a satisfying solution to the customer. In this way, it can be proven if a suggested solution is feasible. Table I shows the basic data-set used for the experiments. The variables tested contain the position variation, the SKU influences, the transfer time influences, the batch size influences and the due date influences.

TABLE I: Basic input values experiments

Variable	**Value**
Runs	20
Setting time	equal to building 200 pallets
Order batch	500
Number of SKUs	100, uniform distribution
Layers per pallet	2-8, uniform distribution
Supply positions at robot	4
Order positions at robot	4
Warehouse: *Inter-arrival time pallets* *Travel time to robot position*	 36 [s] 100 [s]
Buffer area: *Inter-arrival time pallets* *Travel time to robot position*	 36 [s] 200 [s]
Empty pallet area: *Inter-arrival time pallets* *Travel time to robot position*	 15 [s] 200 [s]
Pallet change time at a robot position (t_p)	56 [s]
Due date	none

The first experiment shows the importance of the different pallet positions at the robot. Using the maximum eight positions at the robot gives the possibility to change the distribution for the number of supply- and order positions. Table II shows the results from this experiment done with the reference scheduling method. As can been seen, the results are not constant for all different distributions. To be as constant as possible and to prevent extra waiting times for the robot, it is required to have at least four supply and three order positions available. There are just three order positions required because multiple layers can be placed on a single order pallet directly after each other. However, some order pallets just need one or two layers. Therefore, a minimum of three order positions is required to prevent extra waiting times for the robot due to order pallet changes.

The limitation in supply- and order positions is implemented with the varying positions (ref+p and heur+p). These scheduling methods will use a minimum number of supply- and order positions during operation. The minimum is set to three supply position and three order positions. Experiments showed the best results using this position distribution. Since both scheduling methods decrease the number of required pallet movements, and thus pallet changes at the robot, the system can operate with less required supply positions than the reference method.

The second experiment shows the mutual differences in performance between the different scheduling methods. Figure 4 shows the total pallet movements to/from the buffer area. As can be seen, the individual results show a fast decrease with a few SKUs for all methods. This is because the system is

TABLE II: Position number influence, layer picking throughput (reference scheduling method)

Positions	10 SKU [layers/hour]	100 SKU [layers/hour]	200 SKU [layers/hour]
S2, O6	89.9	79.3	79.2
S3, O5	120.3	93.5	91.8
S4, O4	142.9	107.3	105.4
S5, O3	143.6	106.0	103.9
S6, O2	130.3	94.4	89.4

influenced by the probability to have two equal SKU-layers on a single order pallet. Each time a supply pallet arrives at a supply position at least one SKU-layer can be picked by the robot. The supply pallet than has a probability $P(S)$ that a next layer can be picked without an extra pallet movement.

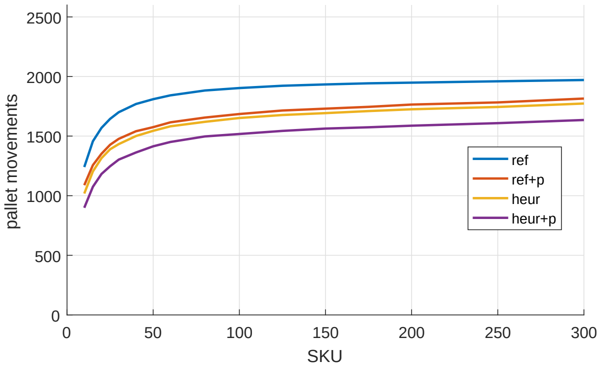

Fig. 4: SKU influence, combined pallet movements to/from buffer area and empty pallet area

Figure 5 shows the system layer picking throughput. As can be seen, the influence of the non-fixed supply- and order positions is important with few SKUs. This can be explained with the probability of more equal SKU layers at the bottom of one order pallet. For example, it can lead to a direct pallet transformation containing three layers. Having this opportunity will save the need of picking three layers by the robot as well as saving an empty pallet movement to and from the empty pallet area. The positive influence in system performance will be less as the number of SKU increases. This because the chance of having a direct pallet change reduces. As such, the robot will need to pick more layers.

The third experiment is an experiment to show the lay-out requirements for the system. Figure 6 shows the influence of the pallet inter-arrival time from the different areas. The pallet inter-arrival time is the time between the front of two succeeding pallets. As can been seen, the buffer area pallet inter-arrival time is a bottleneck for the system. The robot is able to pick a single SKU-layer each 18.2 seconds. However, the buffer area is only able to deliver a single pallet each 36 seconds. Therefore, decreasing the buffer area pallet inter-arrival directly improves system performance. This improvement can be made as long as the pallet inter-arrival time is the bottleneck. The bottleneck changes towards a different part of the layer picking area below 18.2 seconds (the time for the robot to pick a layer).

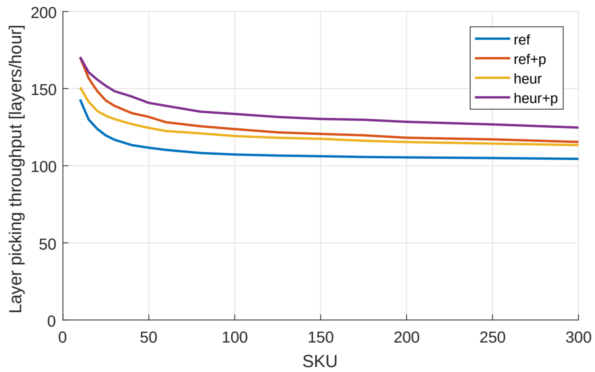

Fig. 5: SKU influence, layer picking throughput

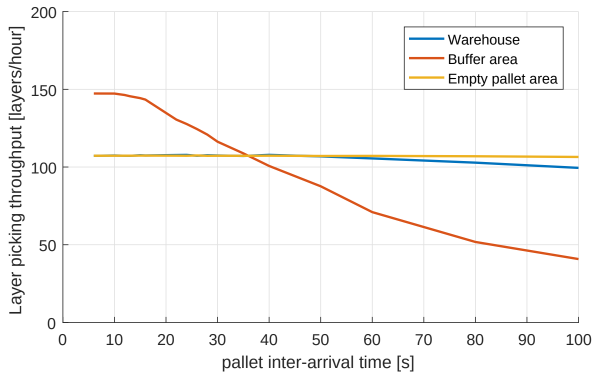

Fig. 6: Pallet inter-arrival time influence, layer picking throughput (reference method)

The fourth experiment shows the batch size influence. Figure 7 shows the results for the different scheduling methods. As can been seen, the scheduling methods using the non-fixed supply- and order positions are most influenced because they do not have the same opportunity to find a comprehensive order pallet for the final layer(s) of the supply pallet. The batch size of 10 order pallets shows an interesting point. The reference method with non-fixed supply- and order positions uses more pallet movements than the reference method with fixed supply- and order positions. This result is caused by the temporarily worse position distribution which occur after a direct position change from a supply position towards an order position. This temporarily state exists of three supply positions and five order positions. Table II showed the negative performance influence for being within this state. However, a possibility to choose from a bigger order batch reduces this negative performance influence. This can been seen with a bigger order batch where the scheduling methods using the non-fixed positions perform better than the scheduling methods using the fixed positions. This situation is caused by using an operational system without looking a couple steps ahead.

The fifth experiment shows the influence of late-arriving order batches. The tests are performed using late-arriving order batches with the size of 10, 20 and 30 order pallets.

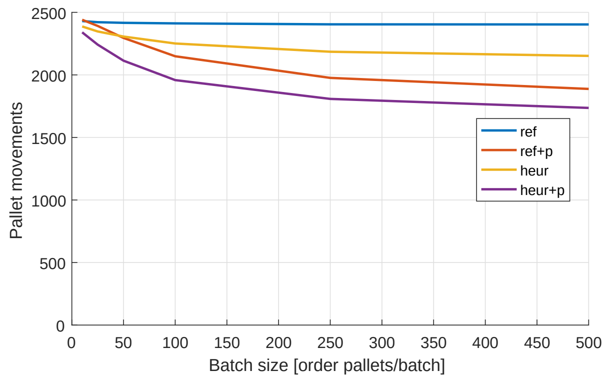

Fig. 7: Batch size influence, combined pallet movements to/from buffer area and empty pallet area

These order batches are implemented one, two or three times during the processing of the basic order batch. The due date used for the implemented orders is equal to five minutes per implemented pallet. Using this will give the system the possibility to create all pallets before their due date. Table III shows the results from the late order batch arrivals. As can been seen, there is a slight decrease in performance. This is caused by the tight due date, which result in less direct pallet transformations from a supply pallet into an order pallet and in more idle time at the robot because of the extra waiting time for a new pallet.

TABLE III: Buffer area movements (heuristic with non-fixed positions scheduling method)

	0x [layers/hour]	**1x [layers/hour]**	**2x [layers/hour]**	**3x [layers/hour]**
10 pallets	133.6	132.8	131.8	131.3
20 pallets	133.6	131.3	130.0	129.1
30 pallets	133.6	131.0	128.6	126.3

VI. Conclusions

The experiments showed the influence of the different scheduling methods and lay-out decisions for the layer picking area. The most important results from these experiments are:

- The heuristic method with non-fixed supply- and order positions shows the best overall results
- Use eight positions at the robot with at least three supply positions and three order positions
- Keep the pallet inter-arrival time from the buffer area short
- Keep the batch size preferably as big as possible
- Late batch arrival is possible but does have a small influence on the system

The overall results show a good performance of the heuristic method in combination with the non-fixed supply- and order positions. The method is capable of achieving a high pallet throughput if the buffer area pallet inter-arrival can be kept short. The number of required pallet movements is reduced to be able to achieve this situation.

Furthermore, this research shows the influences of the design decisions on a warehouse. This is important to know because each warehouse is different in terms of layer picking throughput, number of SKUs and available space. With this knowledge a decent choice in lay-out can be made.

References

[1] Gilmore, D., & Holste, C. (2009). *Automated Case Picking 2009: The Next Frontier in Distribution Center Management.* Springboro, Ohio.

[2] Veeke, H. P. M., Ottjes, J. A., & Lodewijks, G. (2008). *Delft Systems Approach: analysis and design of industrial systems.* Delft: Springer.

B

Model files

input - Notepad

File Edit Format View Help

```
2016-04-01T06:30:00.00  {StartTimeString}
4       {SupplyPositionsSet}
4       {OrderPositionsSet}
3       {OrderPositionsStart; this is the limit: supplypos stays supplypos and orderpos stays demand pos}
5       {OrderPositionsMax}
700     {NrOfOrders}
1       {DiscreteContinuousXML 1=discrete, 2=continuous, 3=XML}
1       {SelectionMethodRefHeur 1= reference, 2=heuristic}
1       {SelectionMethod Supply 1= first pallet/first layer, 2= heuristic
1       {SelectionMethod Order 1= first order pallet, 2= Select order pallet with first layer available, 3= OrderPalletSelection}
1       {SelectionMethodPosControl 1= first supply pallet, 2= heuristic}
1       {SelectionMethod_Fixed_nonFixed  1= fixed, 2= non-fixed}
3       {RobotMovementsLeftAllowed}
100     {SKUunit}
700     {EmptyPalletAtStart}
36      {TT_TransferUnit_WH_In, 100 pallets per hour for 1 VT}
36      {TT_TransferUnit_BA_In}
15      {TT_TransferUnit_Empty_In}
36      {TT_TransferUnit_Out_Empty}
36      {TT_TransferUnit_Out_Buffer}
36      {TT_TransferUnit_Out}
.5      {HoldForStartTime}
56      {PositionControlPalletRemoveTime}
937472  {SKU seed}
1       {SKUlowerbound}
582125  {LAYER seed}
2       {LAYER lowerbound}
9       {LAYER upperbound}
1       {IATseed}
40      {IATlowerbound}
50      {IATupperbound}
100     {TU1_traveltime}
200     {TU24_traveltime}
200     {TU35_traveltime}
100     {TU6_traveltime}
50      {TU3_Traveltime}
50      {TU5_Traveltime}
0       {SKUexponential, 0=uniform and 1=exponential}
200     {OrderBatch1}
0       {OrderBatch1ArrivalTime}
1000000 {OrderBatch1DueDate}
500     {OrderBatch2}
60000   {OrderBatch2ArrivalTime}
1000000 {OrderBatch2DueDate}
10000   {Buffer area limit}
1500    {HoldBetweenBatches}
1       {DueDateFactor}
3000    {DueDateStep}
```

Figure B.1: Example of the text-input file used

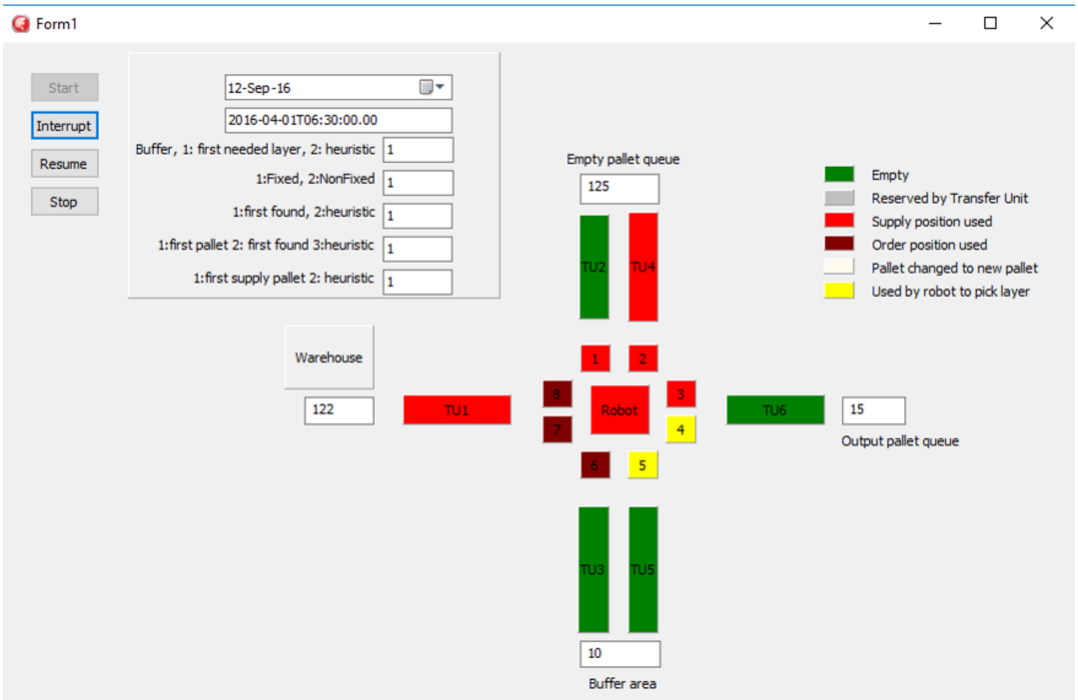

Figure B.2: Used visual for simulation model, created in DelphiXE6/TOMAS

	A	B	C
1	**Warehouse pick up time**	**PalletNr**	**Time from start**
2	06:30:36	S 1	136
3	06:31:13	S 4	173
4	06:31:50	S 8	210
5	06:32:26	S 2	246
6	06:34:41	S 3	381
7	06:35:18	S 6	418
8	06:37:31	S 5	551
9	06:39:00	S 7	640
10	06:39:36	S 9	676
11	06:40:13	S 10	713
12	06:41:11	S 21	771
13	06:41:50	S 16	810
14	06:42:48	S 13	868
15	06:44:04	S 11	944
16	06:44:41	S 14	981

Figure B.3: Example output-file: SystemIn

	A	B	C	D
1	**Pallet finished time**	**DueDate**	**Order pallet**	**Finished Before Due Date**
2	06:38:40	07:00:00	O 1	yes
3	06:40:14	07:00:00	O 3	yes
4	06:41:31	07:00:00	O 2	yes
5	06:42:59	07:00:00	O 4	yes
6	06:43:36	07:00:00	O 5	yes
7	06:48:04	07:00:00	O 6	yes
8	06:49:17	07:00:00	O 9	yes
9	06:49:53	07:00:00	O 7	yes
10	06:53:40	07:00:00	O 8	yes
11	06:54:16	07:45:00	O 12	yes
12	06:55:32	07:45:00	O 10	yes
13	06:59:20	07:45:00	O 15	yes
14	06:59:56	07:45:00	O 13	yes
15	07:00:32	07:45:00	O 14	yes
16	07:01:08	07:45:00	O 11	yes

Figure B.4: Example output-file: SystemOut

	A	B	C	D
1	**Buffer in**	**PalletNr**	**Current Buffer Area position**	**Time from start [s]**
2	06:37:11	S 4	1	431
3	06:40:22	S 8	1	622
4	06:42:27	S 3	1	747
5	06:43:41	S 5	1	821
6	06:44:20	S 7	2	860
7	06:45:18	S 9	2	918
8	06:46:34	S 10	3	994
9	06:47:10	S 16	4	1030
10	06:47:46	S 21	5	1066
11	06:48:22	S 13	5	1102
12	06:48:58	S 11	6	1138
13	06:49:58	S 14	7	1198
14	06:50:34	S 17	7	1234
15	06:51:52	S 12	7	1312
16	06:53:08	S 22	7	1388

Figure B.5: Example output-file: BufferIn

	A	B	C	D	E	F	G
1	Buffer out	PalletNr	Position in BufferAreaQueue	Current length BufferAreaQueue	Time in Buffer Area	Time in Buffer Area [s]	Current time from start [s]
2	06:38:52	S 4	1	1	00:01:41	151	532
3	06:48:18	S 10	6	6	00:01:44	154	1098
4	06:48:55	S 8	1	6	00:08:33	563	1135
5	06:49:32	S 3	1	6	00:07:05	474	1172
6	06:50:12	S 13	6	6	00:01:50	160	1212
7	06:51:29	S 16	4	6	00:04:19	309	1289
8	06:53:02	S 21	4	7	00:05:16	366	1382
9	06:54:56	S 22	8	8	00:01:48	158	1496
10	06:56:32	S 12	7	7	00:04:40	330	1592
11	07:01:13	S 19	10	11	00:02:22	192	1873
12	07:04:03	S 7	2	12	00:19:43	1233	2043
13	07:04:40	S 22	9	12	00:05:13	362	2080
14	07:05:16	S 28	11	11	00:02:23	193	2116
15	07:07:12	S 15	6	10	00:12:30	800	2232
16	07:07:48	S 23	10	10	00:02:05	175	2268

Figure B.6: Example output-file: BufferOut

	A	B	C	D	E
1	Position	PalletNr	TimeArrival	TimeLeave	TimeDifference
2	4	S 2	246	379.1	133.1
3	2	S 4	173	381	208
4	5	O 1	136.5	399.3	262.8
5	7	O 3	167.5	492.8	325.3
6	4	S 6	417.5	530.2	112.7
7	6	O 2	152	569.6	417.6
8	3	S 8	209.5	571.5	362
9	1	S 1	136.5	619	482.5
10	3	S 4	582	637.7	55.7
11	8	O 4	183	658.4	475.4
12	5	O 5	420	695.1	275.1
13	2	S 3	381	697	316
14	4	S 5	551	771	220
15	1	S 7	640	810	170
16	3	S 9	676.5	868	191.5

Figure B.7: Example output-file: Robot position occupation

	A	B	C	D	E	F	G
1	Position	IPalletNr	Position	OPalletNr	SKU	Starttime	EndTime
2	1	S 1	5	O 1	2	136.5	154.7
3	1	S 1	5	O 1	2	155.2	173.4
4	2	S 4	6	O 2	1	173.9	192.1
5	2	S 4	7	O 3	1	192.6	210.8
6	1	S 1	5	O 1	2	211.3	229.5
7	3	S 8	8	O 4	2	230	248.2
8	4	S 2	6	O 2	3	248.7	266.9
9	2	S 4	7	O 3	1	267.4	285.6
10	4	S 2	5	O 1	3	286.1	304.3
11	4	S 2	8	O 4	3	304.8	323
12	4	S 2	6	O 2	3	323.5	341.7
13	1	S 1	7	O 3	2	342.2	360.4
14	4	S 2	8	O 4	3	360.9	379.1
15	2	S 3	5	O 1	4	381.1	399.3
16	2	S 3	6	O 2	4	399.8	418

Figure B.8: Example output-file: Layers picked by robot

C
TOMAS trace

This appendix shows the TOMAS trace for a supply pallet. This is used for the model verification. All steps for a specific supply pallet are given within the boxes using the time (seconds from start) and the specific action.

136.00 Warehouse is current now
136.00 InputPallet1 created
136.00 Input pallet 1, Layers created
136.00 Input Layer1_1_(1) created
136.00 Input Layer1_1_(1) to tail of Input pallet 1, Layers
136.00 Input Layer1_2_(1) created
136.00 Input Layer1_2_(1) to tail of Input pallet 1, Layers
136.00 Input Layer1_3_(1) created
136.00 Input Layer1_3_(1) to tail of Input pallet 1, Layers
136.00 Input Layer1_4_(1) created
136.00 Input Layer1_4_(1) tail of Input pallet 1, Layers
136.00 Input Layer1_5_(1) created
136.00 Input Layer1_5_(1) to tail of Input pallet 1, Layers
136.00 Order Layer1_1_(1) out of LayerMissingQueue
136.00 InputPallet1 to tail of TransferQueue1_Warehouse
136.00 InputPallet1 to tail of AllSupplyPalletsQueue
136.00 Warehouse holds until 137.00

137.00 TransferUnit_WH_In is current now
137.00 InputPallet1 out of TransferQueue1_Warehouse
137.00 Position1 out of SupplyPositionsEmpty
137.00 Position1 to tail of SupplyPositionsUsed
137.00 InputPallet1 to tail of SupplyPalletsInSystemQueue
137.00 TransferUnit_WH_In holds until 173.00

137.00 Robot is current now
137.00 Position5 out of OrderPositionUsed
137.00 Position5 to tail of OrderPositionRobot
137.00 Position1 out of SupplyPositionsUsed
137.00 Position1 to tail of SupplyPositionRobot
137.00 Robot holds until 155.0

```
155.00 Robot is current now
155.00 Input Layer1_1_(1) out of Input pallet 1, Layers
155.00 Order Layer1_1_(1) out of Order pallet 1, OrderLayers
155.00 Order Layer1_1_(1) to tail of Order pallet 1, HandledLayers
155.00 Input Layer1_1_(1) to tail of Order pallet 1, Layers
155.00 Position5 out of PositionRobot
155.00 Position5 to tail of OrderPositionUsed
155.00 Position1 out of SupplyPositionRobot
155.00 Position1 to tail of SupplyPositionsUsed
155.00 Robot holds until 156.00
```

```
249.00 Robot is current now
249.00 Position8 out of OrderPositionUsed
249.00 Position8 to tail of OrderPositionRobot
249.00 Position1 out of SupplyPositionsUsed
249.00 Position1 to tail of SupplyPositionRobot
249.00 Robot holds until 267.00
```

```
267.00 Robot is current now
267.00 Input Layer1_2_(1) out of Input pallet 1, Layers
267.00 Order Layer4_4_(1) out of Order pallet 4, OrderLayers
267.00 Order Layer4_4_(1) to tail of Order pallet 4, HandledLayers
267.00 Input Layer1_2_(1) to tail of Order pallet 4, Layers
267.00 Position8 out of OrderPositionRobot
267.00 Position8 to tail of OrderPositionUsed
267.00 Position1 out of SupplyPositionRobot
267.00 Position1 to tail of SupplyPositionsUsed
267.00 Robot holds until 268.00
```

```
360.00 TransferUnit_Out_Buffer is current now
360.00 InputPallet1 out of TransferQueue5a_RobotBuffer
360.00 InputPallet1 to tail of Hold_BA_TravelQueue
360.00 TransferUnit_Out_Buffer holds until 396.00
```

```
561.00 TravelTimeCheck is current now
561.00 InputPallet1 out of Hold_BA_TravelQueue
561.00 InputPallet1 to tail of BufferAreaSupplyQueue
561.00 TravelTimeCheck holds until 562.00
```

```
2672.00 TransferUnit_BA_In is current now
2672.00 Position1 out of SupplyPositionsEmpty
2672.00 Position1 to tail of SupplyPositionsUsed
2672.00 InputPallet1 out of BufferAreaSupplyQueue
2672.00 TransferUnit_BA_In holds until 2708.00
```

```
2673.00 Robot is current now
2673.00 Position8 out of OrderPositionUsed
```

```
2673.00 Position8 to tail of OrderPositionRobot
2673.00 Position1 out of SupplyPositionsUsed
2673.00 Position1 to tail of SupplyPositionRobot
2673.00 Robot holds until 2691.00
```

```
2691.00 Robot is current now
2691.00 Input Layer1_3_(1) out of Input pallet 1, Layers
2691.00 Order Layer20_20_(1) out of Order pallet 20, OrderLayers
2691.00 Order Layer20_20_(1) to tail of Order pallet 20, HandledLayers
2691.00 Input Layer1_3_(1) to tail of Order pallet 20, Layers
2691.00 Position8 out of OrderPositionRobot
2691.00 Position8 to tail of OrderPositionUsed
2691.00 Position1 out of SupplyPositionRobot
2691.00 Position1 to tail of SupplyPositionsUsed
2691.00 Robot holds until 2692.00
```

```
3102.00 TransferUnit_Out_Buffer is current now
3102.00 InputPallet1 out of TransferQueue5a_RobotBuffer
3102.00 InputPallet1 to tail of Hold_BA_TravelQueue
3102.00 TransferUnit_Out_Buffer holds until 3138.00
```

```
3303.00 TravelTimeCheck is current now
3303.00 InputPallet1 out of Hold_BA_TravelQueue
3303.00 InputPallet1 to tail of BufferAreaSupplyQueue
3303.00 TravelTimeCheck holds until 3304.00
```

```
7036.00 TransferUnit_BA_In is current now
7036.00 Position1 out of SupplyPositionsEmpty
7036.00 Position1 to tail of SupplyPositionsUsed
7036.00 InputPallet1 out of BufferAreaSupplyQueue
7036.00 TransferUnit_BA_In holds until 7072.00
```

```
7036.00 Robot is current now
7036.00 Position8 out of OrderPositionUsed
7036.00 Position8 to tail of OrderPositionRobot
7036.00 Position1 out of SupplyPositionsUsed
7036.00 Position1 to tail of SupplyPositionRobot
7036.00 Robot holds until 7054.00
```

```
7054.00 Robot is current now
7054.00 Input Layer1_4_(1) out of Input pallet 1, Layers
7054.00 Order Layer48_48_(1) out of Order pallet 48, OrderLayers
7054.00 Order Layer48_48_(1) to tail of Order pallet 48, HandledLayers
7054.00 Input Layer1_4_(1) to tail of Order pallet 48, Layers
7054.00 Position8 out of OrderPositionRobot
7054.00 Position8 to tail of OrderPositionUsed
7054.00 Position1 out of SupplyPositionRobot
```

```
7054.00 Position1 to tail of SupplyPositionsUsed
7054.00 Robot holds until 7055.00
```

```
8034.00 TransferUnit_Out_Buffer is current now
8034.00 InputPallet1 out of TransferQueue5a_RobotBuffer
8034.00 InputPallet1 to tail of Hold_BA_TravelQueue
8034.00 TransferUnit_Out_Buffer holds until 8070.0
```

```
8235.00 TravelTimeCheck is current now
8235.00 InputPallet1 out of Hold_BA_TravelQueue
8235.00 InputPallet1 to tail of BufferAreaSupplyQueue
8235.00 TravelTimeCheck holds until 8236.00
```

```
12315.00 TransferUnit_BA_In is current now
12315.00 Position4 out of SupplyPositionsEmpty
12315.00 Position4 to tail of SupplyPositionsUsed
12315.00 InputPallet1 out of BufferAreaSupplyQueue
12315.00 TransferUnit_BA_In holds until 12351.00
```

```
12316.00 Robot is current now
12316.00 Position7 out of OrderPositionUsed
12316.00 Position7 to tail of OrderPositionRobot
12316.00 Position4 out of SupplyPositionsUsed
12316.00 Position4 to tail of SupplyPositionRobot
12316.00 Robot holds until 12334.00
```

```
12334.00 Robot is current now
12334.00 Input Layer1_5_(1) out of Input pallet 1, Layers
12334.00 Order Layer73_73_(1) out of Order pallet 73, OrderLayers
12334.00 Order Layer73_73_(1) to tail of Order pallet 73, HandledLayers
12334.00 Input Layer1_5_(1) to tail of Order pallet 73, Layers
12334.00 Position7 out of OrderPositionRobot
12334.00 Position7 to tail of OrderPositionUsed
12334.00 Position4 out of SupplyPositionRobot
12334.00 Position4 to tail of SupplyPositionsUsed
12334.00 Position4 out of SupplyPositionsUsed
12334.00 Position4 to tail of Hold_RSE_TravelQueue
12334.00 Robot holds until 12335.00
```

```
12355.00 TransferUnit_Out_Empty is current now
12355.00 InputPallet1 out of TransferQueue4_RobotEmpty
12355.00 InputPallet1 out of AllSupplyPalletsQueue
12355.00 InputPallet1 out of SupplyPalletsInSystemQueue
12355.00 InputPallet1 to tail of Hold_EP_TravelQueue
12355.00 TransferUnit_Out_Empty holds until 12391.00
```

```
12506.00 TravelTimeCheck is current now
12506.00 InputPallet1 out of Hold_EP_TravelQueue
12506.00 InputPallet1 to tail of Empty pallet Queue
12506.00 TravelTimeCheck holds until 12507.00
```