Design of a fulfilment centre for an online grocer

Case study at Picnic Supermarkets

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by

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This thesis is confidential and cannot be made public

‘Physics is true, everything else is debatable. And even physics is questionable.’ Elon Musk
Opening Tesla Gigafactory, July 2016

Abstract

Grocery retail is lagging far behind in online shopping. Reasons for this are the economic and operational challenges of selling grocery products online directly to the customer. However, it has been predicted that the share of online grocery shopping will increase from the current 2% to 25% of total supermarket sales in 2030. Recently Picnic, the first online-only-grocer in the Netherlands, has entered the market. 'Online-only' means that the company does not own shops, that products can be bought online only, and that the company delivers at the customer directly. Picnic, active since September 2015, serving customers in Amersfoort, Soest, Leusden and Utrecht also distinguishes itself from other supermarkets by offering a lowest price guarantee and free delivery. Customers in other cities will be provided with the Picnic service soon.
Currently, Picnic is preparing customer orders in a fulfilment centre (FC) in Nijkerk. This FC (FC0) operates fully manual. The maximum capacity of 9K orders per week of FC0 is expected to be reached in December 2016. However, Picnic is aiming at a growth to 50K orders per week at the end of 2017 and 100K orders per week at the end of 2018. To facilitate expected growth, Picnic will have to expand FC capacity. For online retailers, FCs generate the main supply chain costs. Therefore, these centres should be highly efficient i.e. operational costs per item should decrease. Combined with the ambition of Picnic to continuously improve service levels, it is expected that a certain level of mechanization of FC processes is required.
In literature, a very limited number of studies can be found on the specific design of online grocer FCs. There is however, substantial literature on warehouse design. Considerable differences between online grocer FC- and warehouse design are the presence of multiple temperature zones, the order preparation in consumer units, the high number of items within one order, the high number of order lines within one order, the high variation of sizes and weights of products and the high variation in fragility constraints of products.

To explore the logistic design characteristics of online grocer FCs and to provide recommendations for the expansion of FC capacity of Picnic, the following research question is defined:

What are the logistic design characteristics of a (semi-) mechanized fulfilment centre of a fast growing pure play online grocer handling 20000 orders per day, taking into account operational and capital expenditure?

To answer this question, research is performed in different phases: an exploration, an analysis, a design, an assessment and an advice phase.
Based on the exploration and the analysis phase, it can be stated that an online grocer FC can vary on 11 major system functions within the design. These system functions are: *receiving*, *replenishing*, *product storage*, *picking of fast movers*, *picking of mid movers*, *picking of slow movers*, *order storage*, *consolidating*, *storing*, *transportation of products within the FC* and *the transportation of orders within the FC.* The picking process is split up for different product sales categories to assess if higher efficiencies can be reached when different pick strategies are installed. The main input variables for the design are: the number of stock keeping units (SKUs) within the ambient range, the number of ambient items in one order, the number of items per tote, the number of items per line, the average volume per SKU (in litres) and the percentage of orders which has to be consolidated.

Based on different manual and mechanized system solutions for the system functions, four design alternatives focussing on the ambient temperature zone are generated:

1. **Fully manual:** based on the current FC, pick circuit also includes pallet pick to scale the number of orders.
2. **Semi-mechanized:** manual picking with mechanized surrounding processes, splitting is performed with a sorter, replenishment with conveyor belts, pick cart preparation, consolidation and dispatch frame (DPF) storing is performed mechanically, a shuttle automatic storage and retrieval system (AS/RS) is installed to buffer order totes.
3. **Highly mechanized (product transport with conveyor belts):** three pick strategies (pallet pick, zone pick and goods to person (GTP) pick) to optimize pick productivity per sales category, shuttle AS/RS is installed to buffer and sequence order totes for a mechanized DPF frame loader.
4. **Fully mechanized (product transport with KIVAs)**: one pick strategy for all products, KIVAs transport products to GTP stations, order totes travel on conveyor belts, shuttle AS/RS is installed to buffer and sequence order totes for the mechanized DPF frame loader.

The alternatives are assessed in a deterministic model on the following criteria: all-in productivity, surface area, full time equivalent (FTE), capital expenditure (CapEx), operational expenditure (OpEx) and total fulfilment costs per year.

The main results of the assessment are presented in Table 1. It can be seen that alternative 3 results in the lowest fulfilment costs (€19.3 million per year) and the highest all-in productivity (153 items per hour). When alternative 3 is chosen, around 200 FTE and 18K square meters of surface area is required for the ambient temperature zone. There also has to be stated that the

assessment showed that when handling 20K orders, the obtained manual pick productivity for alternative 1 and 2, is 37% lower than the required pick productivity. This leads to order totes not being on time for further shipment and therefore, a decrease of the service level. When handling less than 15K orders, the required pick productivity can be reached within the manual alternatives.

Table 1: Results of the assessment when handling 20K orders

Design criteria	Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4
All-in productivity	[Item/hour]	54	81	153	132
FTE on site	[FTE]	641	327	198	245
Labour costs per item	[€/item]	0,28	0,20	0,11	0,13
Surface	[m^2]	14.6K	18.1K	17.8K	21K
CapEx	[€]	4.2M	9.8M	30.6M	67.4M
OpEx	[€/year]	37.6M	25.2M	14.4M	16.4M
Total costs per year	[€]	38.3M	27.3M	19.3M	27.8M

Tests with the model also showed that:

- When handling 5K orders, the semi-mechanized alternative becomes nearly as attractive as the fully mechanized alternative 3
- Order growth results in a higher increase of the total fulfilment costs per year for manual alternatives compared to order growth for mechanized alternatives
- Increase of the ambient range has a major effect on all-in productivity of manual alternatives, but a minor effect on the mechanized solutions
- Rental costs of FC housing have such a low share within operational costs per year that this does not have to be taken into account when choosing a location
- The 'Christmas' order profile scenario result in the largest increase of the total fulfilment costs and the largest decrease of all-in productivity for alternative 3

Based on the results of the assessment, it can be advised that to facilitate foreseen growth, Picnic should mechanize fulfilment processes. The assessment also showed that the highest all-in productivity and the lowest fulfilment costs can be reached when, together with an automatic storage and retrieval system and conveyor belts for internal transport, different pick strategies for fast fast moving, mid moving and slow moving articles are installed. This is because picking of least sold products with a high productivity, results in maximal operating efficiency.

Since the maximum capacity of FC0 is approaching rapidly, it is recommended to first realize a semi-mechanized FC (FC1), in which picking activities remain fully manual but surrounding activities are mechanized. Based on the growth forecast and the outcomes of the model, it can be concluded that the maximum optimal capacity of FC0 combined with FC1 will be reached around July 2017. Prior to reaching this capacity, the highly mechanized FC with three different pick strategies should be realized (FC2). Before realization of FC2, the assumption made regarding on-time performance of order totes should be investigated thoroughly. In consideration of depreciation costs, FC1, should remain operational for at least six years. After realization of FC2 however, FC0 can be shut down because of relatively high operational costs.

Terms and abbreviations

Terms:

Autostore	Automatic storage and retrieval system which makes use of robots to store and retrieve totes
Consumer unit	A single piece unit which can be bought by the consumer
Darkstore	English term for grocery FCs
Decanting	Unpacking of trading units to single items
Design approach	Method to design a fulfilment centre
Design mean	Solution for a design function
Dolly	Cart to transport crates
E-grocer	Grocer which sells products online directly to the customer
E-worker	Electrical vehicle at Picnic that is used to deliver the order to the customer
Fulfilment centre	Centre where orders are prepared for the customer
Hub	Station to cross-dock orders from a truck into an E-worker
KIVA	Name of the robot that is used by Amazone to transport products within the warehouse
Mini-load	Automatic storage and retrieval system which makes use of cranes to store and retrieve totes
Operating efficiency	Indicator for all-in productivity of a warehouse and the direct labour costs per article
Order completeness	Factor which indicates in how far the order includes all items requested by the customer
Order line	A unique product within an order
Order tote	Unit load to transport the order
Piece pick	The picking of consumer units
Personal shopper	Professional picking orders within Picnic
Product tote	Unit load to transport products that still have to be picked
System function	Process in system on which can be varied
Timeliness	Factor which indicates on-time readiness for shipment to the hub
Trading unit	A unit consisting of multiple single pieces of the same type
Unit load	Standardised equipment to transport goods

Abbreviations:

ABC	Activity based costing
AS/RS	Automatic storage and retrieval system
BBD	Best before date
CapEx	Capital expenditure
CE	Consumenten-eenheid (consumer unit)
DC	Distribution centre
DPF	Dispatch frame
e-FC	Electronic (commerce) fulfilment centre
FC	Fulfilment centre
FIFO	First in first out
FM	Fast mover
FTE	Fulltime equivalent
GTP	Goods to person
HE	Handels-eenheid (trading unit)
I/O-point	In-output point
I/O-rate	In-output rate
IDEF-0	Integration Definition for Function Modelling
JIT	Just in time
MM	Mid mover
OpEx	Operational expenditure
P2L	Pick to light
PC	Pick cart
RC	Roll container
RF-scanner	Radio frequency scanner
SKU	Stock keeping unit
SM	Slow mover
SC	Spiral conveyor
VSM	Value Stream Map
WOI	Waiting on inventory
WCS	Warehouse control system
WMS	Warehouse management system

Preface

This is the report of my research into the design of a fulfilment centre for an online grocer. The research was executed in collaboration with Picnic Supermarkets. The thesis is part of the Transport, Infrastructure and Logistics (TIL) master program of the Delft University of Technology. It was carried out from February 2016 until August 2016 in Nijkerk (location of the fulfilment centre of Picnic) and Amsterdam (Picnic headquarters).

By completing this thesis, I am also finalizing an amazing period as a student in Delft. First as a bachelor student at the faculty of Technology, Policy and Management and after as a TIL (Engineering track) master student, mostly connected to the faculty of Mechanical Engineering.

At first I would like to thank the committee of the Delft University of Technology. Professor Lodewijks, Mr. Beelaerts van Blokland and Mr. van Duin. Thank you for very much for your time and the feedback during the progress meetings.
Mr. van Duin, because of your critical notes regarding the model specification and validation, I could make big improvements.

I would also very much like to thank Picnic for the opportunity to do scientific research in such an entrepreneurial and non scientific environment. Wybe-Jan, thank you for involving me in your visionary plans regarding the Picnic supply chain.
Hans, it means a lot to me that you always took the time to sit back and reflect when graduating seemed like climbing the Mount Everest. Frederik, often you go faster than lightening, but involving me in your plans for FC1 and taking me to your meetings with material handling suppliers, made me nearly as fast as you are.

At last I would like to thank my family. Pap, Mam en Connor: thank you for your unconditional love and support during my crazy Delft times. But remember: deliver the goods.

Amy Klein
Amsterdam, 2016

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1. Introduction

Over the last years, retail for slow-moving product categories such as books, electronics and fashion has gained a significant online share. Grocery retail, which involves fast-moving perishable products, lags behind on this growth (Syndy, 2015). In the Netherlands currently only 2% of online grocery shopping is done online (Rabobank, 2016). This is significantly less than the 30% share of online shopping in electronics. There are various logistic, operational and economic reasons for this, such as the complexity of organizing the distribution of fresh or cooled products, the small average order value and the low value per cubic meter. However, different initiatives have entered the online grocery market with the aim to provide this service. Online grocery shopping in the Netherlands is estimated to be around 25% in 2030 (Rabobank, 2016). The current on- and offline grocery shopping revenue in the Netherlands is around €35 billion, from which €0,6 billion is spent on online grocery (Rabobank, 2016). The UK, France and Germany have the biggest online grocery markets (Table 2). However, Table 2 also illustrates that of the countries listed, the Dutch online grocery market has recently shown the fastest growth.

Table 2: Online grocery revenues in different countries the EU (Rabobank, 2016)

Country	2012 (€ bn)	2016 (€ bn)
UK	7.1	13.7
France	5.0	10.6
Germany	1.1	2.5
Netherlands	0.6	1.6
Switzerland	0.7	1.1

It is considered to be difficult to organise the logistics of online grocery shopping in a costs effective way. An online grocer (e-grocer) has the advantage of comparatively low initial investment but needs to be very efficient, yet responsive, to be competitive in a price-sensitive grocery market. According to Pyke et al. (2001), supply chains for online retailers comprise processes in two main categories i.e. supply management and order fulfilment. Supply management deals with the management of the supply and the inventory of the grocery products, whereas order fulfilment includes all the processes from the point of a customers' buying decision until the moment when the products have been received. Different logistical processes will be triggered when a customer orders a product online.

1.1 Online grocery stores

Currently, more and more players in the Dutch grocery sector are changing their supply chain to provide customers the possibility of ordering groceries online. Online grocery stores can be divided in pure play stores and click and brick stores. Pure players only have online presence, click and brick stores combine on- and offline presence. Well known click and brick supermarkets are Jumbo and Albert Heijn. They provide the possibility of ordering groceries online and pick them up at pick up points or to deliver the groceries at home. One of the biggest pure play online grocer is Ocado. Ocado is active in Great Britain and fulfils and delivers over 250000 (250K) orders per week. Ocado has multiple mechanized warehouses (Ocado, 2015). Since February of last year, Ocado is gaining profit after 15 years of expanding and investing (Ocado,2015). The highest investments are done in the fulfilment centres where the orders are prepared. In general, for online retailers it is pivotal to aim for an agile (responsive to the market) and lean (eliminating all waste) supply chain to decrease the costs as much as possible.

1.2 Fulfilment centres

Fulfilment is the "processing of articles after a transaction via internet: retrieving, storage, picking, packing and sending to specified addresses (Agatz, Fleischmann, & van Nunen, 2008). The main supply chain costs for online retailers are generated by the fulfilment centres. Therefore, these centres should be highly efficient. Big online retailers like Amazon use advanced mechanized and automated systems to fulfil the orders. Because of the difficulty of the nonstandard characteristics of groceries (differences in sizes, temperature zones and freshness) it is more challenging to standardize grocer fulfilment centre processes than the processes in FCs that handle slow moving articles like electronics. However, different layout and process design methods that are used for FCs handling slow moving articles, can also be used for the design of FCs handling groceries.
Considerable differences between online grocer FCs and FCs handling slow moving articles are the presence of several temperature zones, the high number of items within one order, the high number of order lines within one order, the high variation of sizes of products and the high variation in fragility constraints of products.

1.3 Picnic Supermarkets

Picnic, an online-only supermarket, has entered the online grocery market of the Netherlands in September 2015 because of the foreseen growth of online grocery shopping. Picnic is a pure play online grocer, meaning that they have an online sales channel only. To successfully gain market share, Picnic offers lowest prices and free delivery. Picnic operates with a direct supply chain to omit unnecessary process steps and aims for a very high customer service level. Picnic is currently serving 6000 clients in Amersfoort, Leusden, Soest and Utrecht handling approximately 3000 orders per week and is growing every day.

Customers place orders in the Picnic app for a minimum of €25,-. An order can be placed until 22h00, the day before delivery. Picnic has prescheduled time frames for different areas in which the customer can receive the groceries. This is done to increase the order density per area. The orders are prepared in the FC. Picnic currently has one FC (FC0). This FC is operated manually. FC0 will reach the maximum capacity soon. To facilitate expansion, Picnic will have to increase fulfilment services by activating a new FC. To be able to keep providing lowest price warranty, operating efficiency of Picnic should increase. Besides this, it is pivotal to keep customer service level on the highest level while growing.

1.4 Problem description

Picnic is aiming at a growth to 50K orders per week at the end of 2017 and 100K orders per week at the end of 2018. To facilitate expected growth, Picnic will have to expand FC capacity. For online retailers, FCs generate the main supply chain costs. Therefore, these centres should be highly efficient i.e. operational costs per item should decrease. Combined with the ambition of Picnic to continuously improve service levels, it is expected that a certain level of mechanization of FC processes is required.

Manual processes should be transformed to mechanized processes. In this transition, operational efficiency has to be increased to minimize the total fulfilment costs per year and service levels have to be maintained at the highest level.

Therefore, the following problem is defined: to facilitate growth and to increase operating efficiency, Picnic will have to activate a new FC, which in full capacity should have the capacity of handling 20K orders per day, while optimizing the ratio between capital expenditure (CapEx) and operational expenditure (OpEx).

In this research, a conceptual design for a 20K (semi-) mechanized e-FC will be presented together with a transition strategy to scale the operation from 5K to 20K orders per day. To do this, it is important to understand the influence of the design characteristics of an online grocer FC.

1.5 Research question

The explore the logistic design characteristics of online grocer FCs and to provide recommendations for the expansion of FC capacity of Picnic, the following research question is defined:

What are the logistic design characteristics of a (semi-) mechanized fulfilment centre of a fast growing pure play online grocer handling 20000 orders per day, taking into account operational and capital expenditure?

1.6 Sub questions

The research question will be answered on the basis of the following sub questions:

Exploration

- What is known about the design of manual and mechanized processes in online grocer FCs?
- What is known about the effect of mechanization on the productivity, operational expenditure and capital expenditure?
- Which methodologies can be used to analyse, design and model a FC?

Analysis

- What is the design of FC0?
- What is the effect of the design of FC0 on operational- and capital expenditure?
- Which design variables have to be taken into account for the design of the new FC?

Design

- What are the design goals for the new FC and which design criteria follow from this?
- What are the design requirements that follow from the current FC and the growth perspective?
- Which system solutions can be defined for the system functions?
- Which design alternatives can be composed for the new FC?

Assessment

- What are the methods to assess the design alternatives?
- What are the effects of the alternatives and variables on the design criteria?

- Which alternative meets the requirements and the growth perspective of Picnic?

Advice

- Which transition strategy should Picnic follow to expand the FC capacities?
- Is the chosen research methodology appropriate for the development of the design of an online grocer FC?

1.7 Research scope

The presented logistic design characteristics do apply online-only grocer FCs. The assessed design alternatives will be conceptual design alternatives. Detailed design issues like operating parameters and material requirements will be excluded.
Within the fulfilment processes, there is a focus on the main activities within the ambient temperature zone. These main activities are: receiving, replenishing, picking, consolidating and storing. Supporting activities like quality checks, mirroring, stock counting and the transport of the orders to the hub will be excluded. The performance of the main activities is measured on the basis of operational costs. The operational expenditure (OpEx) will consist of the labour costs and the rent for housing. Energy costs and maintenance costs are excluded. The capital expenditure (CapEx) consists of the investment made in the building and the equipment. Information and communication technology like the warehouse management system (WMS) and the warehouse control system (WCS) are excluded from the research and the design.
The delivered design alternative includes equipment within the FC, the required number of FTE, the required number of FTE, the corresponding productivity and the costs per process.
The time dimensions differ within the research. The data used within the analysis phase, includes four months of operation. The model used in the assessment phase determines the effect on the criteria within one day. The OpEx and CapEx as an outcome of the model during the assessment are presented in euro per year.

1.8 Research structure & methodology

According to Beelaerts van Blokland (2013), a thesis research consists of the following generic components shown in Figure 1.

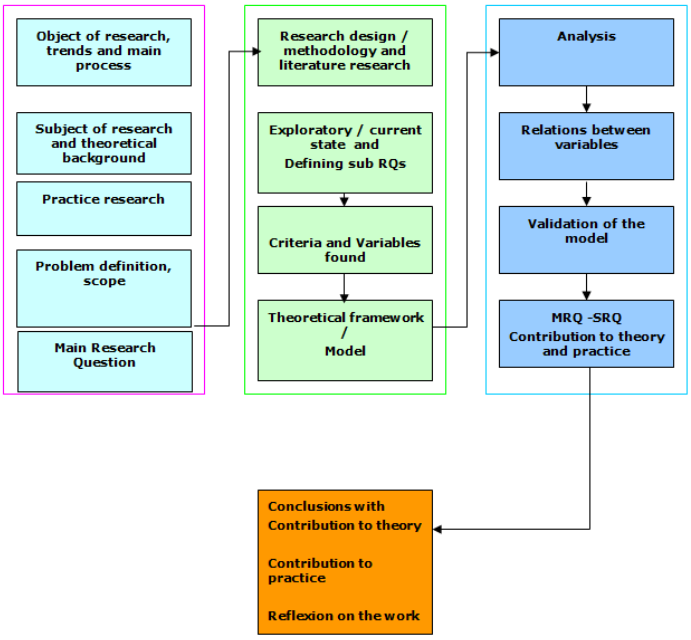

Figure 1: Generic research process (Beelaerts van Blokland, 2013)

Figure 1 shows that the research objectives and the main research question can be defined on the basis of the theoretical background. Thereafter, criteria and variables can be identified with a literature review and an exploration of the current state. At last, an analysis can be performed to find the relationship between variables. The answers of the main- and the sub questions, should contribute to theory and practice.
Inspired by the generic framework of Beelaerts van Blokland (2013), the research for this thesis is structured (Figure 2).

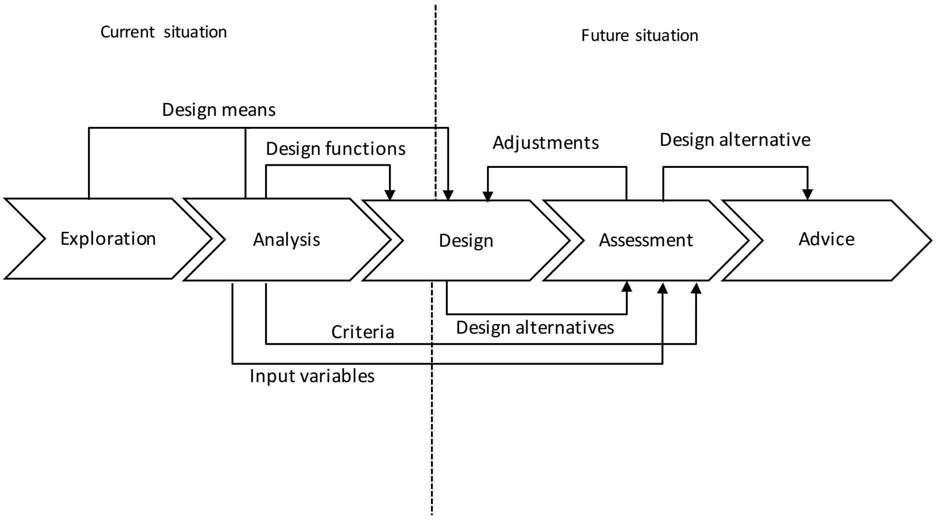

Figure 2: Research structure (Author, 2016)

Different phases will be run through to identify the logistic design characteristics. The phases will generate the design means (which can be varied on in the design), the criteria the design must meet, the design specifications, different design alternatives which will be assed, possible required adjustment in the designs a result of the assessment, the main design variables and the final design alternative. Below the different phases are explained. On the next page in Figure 3, the phases of the research are presented with the corresponding chapters and sub questions.

1.8.1 Exploration phase

In the current phase, the exploration phase, an introduction is presented on grocery supply chains, FC design and Picnic. In the literature study, previous outcomes of studies into FC design variables, the automation and mechanization of warehouse processes and methodologies to analyse, model and design a FC will be presented.

1.8.2 Analysis phase

In the analysis phase, the current FC (FC0) will be analysed on the basis of the processes, the layout, the equipment, the inventory, the range, order and tote characteristics. From these analyses the design criteria, variables and requirements for a new FC will be derived.

1.8.3 Design phase

The design phase will describe the design goals, the criteria, the requirements and the system functions. To compose design alternatives design means (solutions) for the functions will be defined. The design alternatives are constructed with the help of a Morphological chart.

1.8.4 Assessment phase

In the assessment phase the different alternatives will be assessed quantitatively. A deterministic flow model is constructed in Excel to assess the alternatives. In this phase, the model is validated and verified. The robustness is tested with the help of sensitivity analysis. The data required for the input of the model is gathered in the exploration and analysis phase.

1.8.5 Advice phase

In the advice conclusions will be drawn based on the outcomes of the assessment phase. During the recommendation an implementation strategy of the proposed alternative will be given. The research is finalized with discussion and reflection regarding the outcome of the research and the research methodology.

Exploration Ch. 2 Literature review

- What is known about the design of manual and mechanized processes in online grocer FCs?
- What is known about the effect of mechanization on the productivity, operational expenditure and capital expenditure?
- Which methodologies can be used to analyse, design and model an FC?

Analysis Ch. 3 Analysis current fulfilment centre

- What is the design of FC0?
- What is the effect of the design of FC0 on operational- and capital expenditure?
- Which design variables have to be taken into account for the design of the new FC?

Design Ch. 4 Generation of alternatives

- What are the design goals for the new FC and which design criteria follow from this?
- What are the design requirements that follow from the current FC and the growth perspective?
- Which system solutions can be defined for the system functions?
- Which design alternatives can be composed for the new FC?

Assessment Ch. 5 Assessment of alternatives

- What are the methods to assess the design alternatives?
- What are the effects of the alternatives and variables on the design criteria?
- Which alternative meets the requirements and the growth perspective of Picnic?

Advice Ch. 7: Recommendations and reflection

- Which transition strategy should Picnic follow to expand the FC capacities?
- Is the chosen research methodology appropriate for the development of the design of an online grocer FC?

Figure 3: Research phases with the corresponding chapters and sub questions (Author, 2016)

2. Literature review

To define the logistic design characteristics, an extensive literature review is performed. At first, general FC characteristics will be explained, subsequently, different analyses methods for the design of the FC will be discussed. A major part of the literature review will be dedicated to the automation and mechanization of warehouses. In the conclusion of the literature review answers will be given to the following sub questions:

- What is known about the design of manual and mechanized processes in online grocer FCs?
- What is known about the effect of mechanization on the productivity, operational expenditure and capital expenditure?
- Which methodologies can be used to analyse, design and model a FC?

2.1 FC characteristics

A FC has the same characteristics as a warehouse, however from a FC, the order is often directly sent to the customer. Typical warehouse operations include receiving, put away, internal replenishment, order picking, accumulating, sorting, packing, cross docking, and shipping (Tong & de Koster, 2011). In Figure 4, typical warehouse operations are presented. The main activities are explained below the figure. The online grocer FCs are also often called Darkstores. Kumar (2015) states that a Darkstore is a distribution centre that caters exclusively for online shopping. A dark store is generally a large warehouse that can either be used to facilitate a "click-and collect" service whereby a customer collects an article they have ordered online, or as an order fulfilment platform for online sales. According to Kumar (2015) a dark store is a highly automated warehouse with sophisticated carousels and conveyors for order picking, packing labelling and transporting.
The time and costs required to set up such a warehouse is extremely high (Kumar & Rajguru, 2015). In practice it can be seen that there are also Darkstores where all processes are performed manually.

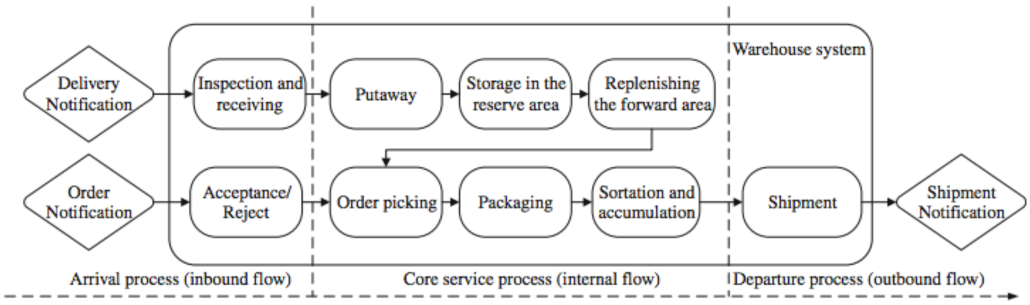

Figure 4: Typical warehouse operations from a stochastic process view (Tong & de Koster, 2011)

In Figure 4 the following main activities can be distinguished:
Inspecting and receiving: the receiving process is the first process encountered by an arriving product. Once products have arrived, they may be checked or transformed and wait for transportation to the next process.
Storing (and putaway): storage is concerned with the organization of articles held in the warehouse in order to achieve high space utilization and facilitate efficient material handling. Articles in storage can be organized into different departments. The drivers of department organization are classified into:

- Physical characteristics of the articles (e.g., pallet storage vs. case storage)
- Management considerations such as a dedicated storage area for a specific customer
- Material handling considerations such as a forward area for fast picking

Within a department or zone, articles are assigned to storage locations, and the storage location assignment has significant impact on storage capacity, inventory tracking, and order picking.
Replenishment: allocating products to the correct storage location for order picking.
Order Picking: order picking is triggered by an order notification and is generally recognized as the most expensive warehouse operation, as it tends to be either very labour intensive or very capital intensive (Frazelle & Frazelle, 2002). Furthermore, it refers to the retrieval of articles from their storage locations and can be performed manually or (partly) automated.
Packaging: within fulfilment, packaging is often performed to deliver the product directly to the customer.
Sortation and accumulation: sortation of orders is sometimes done for example for different freight operators.
Shipping: orders are eventually loaded in trucks, trains or any forms of transport.
In practice it can be seen that the before mentioned processes can be executed manually, mechanized or automated.

2.2 Automation and mechanization of FCs

Differences between mechanization and automation can be distinguished as follows. Mechanization is normally described as the replacement of a human task with a machine. However, true automation incorporates more than mechanization. Porter (2016) states that automation involves the entire process, including bringing material to and from the mechanized equipment. It normally involves integrating several operations and ensuring that the different pieces of equipment communicate with one another to ensure smooth operation. Often, true automation requires revaluating and changing current processes rather than simply mechanizing them (Porter, 2016). In this report there will be a focus on the mechanization of the processes. This is because practice has shown that atomizing grocer FCs is highly challenging and capital expensive because of the different temperature zones, the high number of unique products and the major difference between the sizes and volumes of products. In literature however, the terms are often used interchangeably.

Many studies are performed into automation and mechanization. One of the main studies which on the effects of mechanization is performed by Roodbergen (2008). He states that the following savings can be made because of mechanization:

1. Communication of locations to be visited (7% of time)
2. Walking of order picker to collect articles (50% of time)
3. Transportation of articles to other areas (7%)
4. Orientation to find the right location (7%)
5. Avoiding errors (3%)

To mechanize a FC, companies have to make different trade offs. Baker & Halim (2007) state that whilst both improved service and lower costs are significant reasons for companies to implement warehouse mechanization, it is the imperative of the need to accommodate growth that is found to be the main reason (Baker & Halim, 2007). They also issue that there can be real concerns about disruption to the ongoing operation in the short term and the degree of future flexibility in the longer term. One of the main challenges with equipment and technology is to find the balance between implementation cost and flexibility (Davarzani & Norrman, 2015). There also have been concerns expressed in literature as to whether automation can be sufficiently flexible to meet changing market requirements (Matthews, 2001) and (Allen, 2003).

Kamarainen & Punakivi (2002) have written about the inflexible capacity issues in the online grocer market. They state that over-investment in 'picking' automation was identified as the main weakness of the business models. Hackman, et al. (2001) discuss that warehouse automation projects can negatively effect service levels in the short term, with "burn-in" difficulties being experienced. This can lead to a "service level dip" (Naish & Baker, 2004). Reasons for the difficulties encountered in warehouse automation projects are not always clear (Baker & Halim, 2007). The projects are often very complex, involving a number of different systems that need to be designed and developed in parallel, including the equipment itself, the software and the building in which it will be housed (Drury & Falconer, 2003).

However, in practice fairly successful mechanized FCs have been developed. The Ocado FCs in the United Kingdom reach an all-in productivity of 155 items per hour and are fulfilling orders for 0,11 cents per item (Ocado, 2016). In Appendix 1 examples of current mechanized online grocer FCs are described. It can be seen that per temperature zone and sales volume group different pick strategies are realized. In frozen areas often no mechanization is applied. This is due to the difficulties which arise because of the low temperatures.

Dematic (2015) a material handling supplier, has visualised the different processes which can be mechanized in a FC in Figure 5. It can be seen that it is possible to mechanize the receiving processes, the storage & buffering procedures, the replenishment, the picking and the shipping. However, the main mechanized processes (from which other processes are often dependent) are the storage & buffering and the picking (circled in bleu in Figure 5). In the figure it can be seen that case pick can be mechanized also. However, within Picnic and other pure play grocer FCs there is only piece pick, because of order fulfilling with consumer units (CEs). The mechanisation options for the different processes are explained below Figure 5.

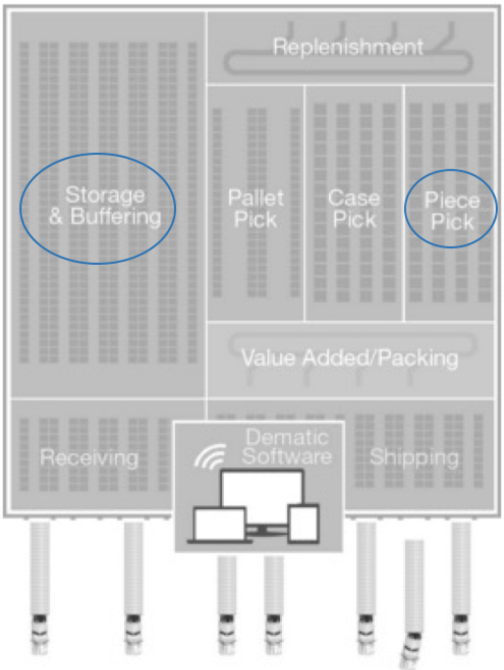

Figure 5: Possible processes which can be mechanized (Dematic, 2014)

2.2.1 Picking

Mechanized or automated picking can be done in several matters. Dallari, Marchet & Melacini (2009) have written about the design and automation of order pick systems. They have classified order picking systems as shown in Figure 6. It can be seen that a distinction can be made between a human or a machine picking the articles. Even in the mechanized grocer FCs 'manual' picking is still required, because of the different shapes and sizes of the products. Therefore, the mechanisation of the picking stands for the movement of the goods to the picker (Parts-to- picker)(Figure 6).

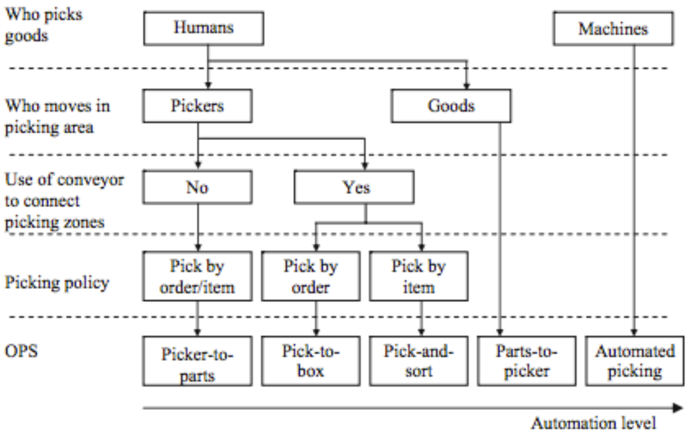

Figure 6: Classification of order picking systems (Dallari, Marchet, & Melacini, 2009)

With the help of mechanized pick strategies up to 600 picks per hour can be reached. This is done with goods to person (GTP) stations. An other frequently used method within the parts-to-picker strategy is the pick-and-pass method. Within this method, pick rates up to 450 picks per hour can be achieved. More information on mechanized picking will be given in Paragraph 4.3.

2.2.2 Storage and buffering

Mechanized storage and buffering can be done for products and (completed) orders. The storage and buffering of the orders is also called dispatching. Mechanized storage and buffering can result in less space usage for storage in the warehouses and the optimization of sequencing of the order totes for consolidation. Consolidation is last minute adding of products to a tote.
For the storage of the products and orders, Automated Storage and Retrieval systems (AS/RSs) are realized. These systems are used in both distribution and production environments (Roodbergen & Vis, 2009). An AS/RS usually consists of racks served by cranes running through aisles between the racks. An AS/RS is capable of handling unit loads (pallets, crates, totes) without the

interference of an operator, thus the system is fully automated (Roodbergen & Vis, 2009). At the end of the aisles an AS/RS pick and deposit stations are installed to transfer loads in and out of the AS/RS.

The AS/RS can be classified on the type of crane, handling and rack. An important measure of system performance is the throughput capacity of the system. The throughput capacity for a single aisle AS/RS is the inverse of the mean transaction time, which is the expected number of time required for the S/R machine to store and/or retrieve a transport unit load (Potrc, 2004). True performance of the AS/RS is typically influenced by other systems as are the other systems' performances influenced by the AS/RS (Roodbergen & Vis, 2009). This is most visible at, but not restricted to, the interplay of systems at the AS/RS' (in- and output points) I/O-points. Loads are picked up and dropped off at an I/O-point by the AS/RS. It is the task of, for example, a conveyor system or a set of vehicles to make the connection from the I/O-point to the rest of the warehouse. Delays in one system can cause delays in the other system. More information on AS/RSs will be given in Chapter 4.3.

2.2.3 Receiving

Receiving can be done in multiple ways. A mechanized sorter can be used to sort trading units (HEs) to transport them to the right aisle (Distrisort, 2016). Decanting is the process of unpacking HEs into CEs and placing them in unit loads (bins or totes) to be replenished into an AS/RS or to be transported into a picking circuit. Decanting is done with the help of a decanting station. The productivity of a decanting station is dependent on the required procedures of the decanter and the on time availability of the products and order tote (Buijsen, 2016).

2.2.4 Replenishing

Replenishment of AS/RSs is integrated in the system. Transport to AS/RSs is done with the help of conveyor belts. Conveyor belts transport the product totes from the decanting station to the AS/RS. The replenishment productivity is therefore highly dependent on the speed of the conveyor belts and the number of I/O-points of the AS/RS and the number of shuttles (Wolters, 2016).

The replenishment of racks for manual picking can also be done with the help of a conveyor belt. Induction points will be required to insert HEs on the conveyor belts. When replenishing the HEs on to the racking, unwrapping is needed to facilitate order picking of CEs.

2.2.5 (Un)loading of equipment

The loading and unloading of equipment can be done with automatic loading and unloading systems. This is often seen for the (un)loading of trucks and equipment to handle and transport products and orders within FCs (Wolters, 2016). There are also options for the loading and unloading of DPFs and pick carts (PCs) (Wolters, 2016). More information on these systems is presented in Paragraph 4.3

2.2.6 Internal transport

The internal transport within the warehouse (excluding the AS/RSs) can be divided into horizontal and vertical transport. Horizontal transport can be performed with conveyor belts (Wolters, 2016). Conveyor belts are frequently used in warehouses as a first mechanization step to decrease the movement of the personnel. The last couple of years, new ways of horizontal transport arose. Amazone was one of the first companies to use robots (KIVAs) for the horizontal transportation of products (Amazone, 2015). Vertical transport is often performed by lifts and can easily become a bottleneck in a warehouse because of capacity constraints due to lower transport speed (Schoonderwoerd, 2016). Vertical transport is sometimes replaced by diagonal transport with the help of conveyor belts. However, diagonal transport uses a high amount of surface area (Schoonderwoerd, 2016).

2.3 FC analyses, design and modelling methodologies

Different methodologies can be used to analyze, design and model a FC. The methodologies used in this research are explained below.

2.3.1 Activity based costing

Activity based costing (ABC) is a method to differentiate costs of a logistic system. Cooper & Kaplan developed the method in 1988. They stated that one of the main problems of companies is, that they make important decisions based on distorted cost information (Cooper & Kaplan, 1988). Christopher (2011) states that in logistics management, companies seem to suffer from a lack of visibility of costs in the logistics pipeline. With ABC, indirect costs are assigned to specific categories, products or services. In this way a clear sight on costs per activity is presented (Griendt, Wezenbeek, Balder, & Bos, 1997). In multiple papers regarding warehouse systems and order picking, the ABC method is used to determine costs and cost savings (Özbayraka, Akgünb, & Türkerc, 2004; Gunasekaran & Sarhadi, 1998).

ABC enables to separately account for each customer's unique characteristics in terms of order behaviour and distribution requirements. An example is that instead of the average costs per order the costs of order picking can be calculated by the number of lines per order (Christopher, 2011).

2.3.2 ABC product analysis

The analysis of the assortment handled by a FC can be performed with the help of an ABC product analysis (Rushton, 2009). This technique is also known as Pareto analysis and is furthermore referred to as the 80/20 rule. The results of this analysis more often than not show that roughly 20 percent of the stock range accounts for roughly 80 percent of the total inventory, 80 percent of the sales and 80 percent of the picking effort. This enables to define the important stock keeping units (SKUs) in the product range, and also to identify different characteristics for different sections of the product range. This can help to choose appropriate storage and handling methods for the different product groups (Rushton, 2009). A simple example of the ABC analysis is shown in

Table 3. In practice, other factors such as throughput would also have to be superimposed on this analysis in determining the storage systems to be adopted for the different part of the product range. In Paragraph 3.7.1 an ABC product analysis will be performed with the sales volumes and the number of SKUs in the range.

Table 3: Example ABC product analysis (Rushton, 2009)

Product Group	Percentage of Product Range	Percentage of Total Stock	Suitable Storage Methods
A	20%	80%	block stack, drive-in, push back, live, double deep, very narrow aisle
B	30%	15%	VNA,APR
C	50%	5	APR, mobile

2.3.3 Approaches to design a FC

In literature there is no extensive research on FC design and especially not on FCs handling groceries. However, extensive research can be found on warehouse design. Even though warehouse design has been studied for years, Rouwenhorst (2000) writes that the overwhelming majority of scientific papers address well-designed isolated problems and are typically of an analytical nature. This is in contrary with the often problems in warehouses which cannot be reduced to multiple isolated sub-problems. The design therefore requires a mixture of analytical skills and creativity. Therefore, he concludes that research aiming at an integration of various models and methods is badly needed in order to develop a methodology for systematic warehouse design & Canessa (2009) also write about the absence of systematic approaches for warehouse design. Baker & Canessa (2009) have combined different methods and tools to develop a structured approach to design a warehouse. The list contains eleven steps, which present a structured, validated view on the development of a warehouse:

1. Define system requirements and design constraints
2. Define and obtain data
3. Analyse data
4. Establish what unit loads will be used
5. Postulate basic operations and methods
6. Consider possible equipment types for storage and handling
7. Calculate equipment quantities
8. Calculate staffing levels
9. Prepare possible building and site layouts
10. Evaluate the design against system requirements and constraints
11. Identify the preferred design

Rouwenhorst (2000), states that warehousing models can be classified into a strategic, tactical or operational level. Strategic stands for the system type selection, tactical for the dimensioning and operational for the models that fine-tune the design of a warehouse. This research will focus on the strategic warehouse design (the system selection) and will partly address the tactical level (dimensioning). Koster, Le- Duc & Roodbergen (2006) add to Rouwenhorst's (2000) conclusion regarding the classification that decisions to be taken regarding picking methods at tactical and operational level are:

- Layout design and dimensioning of the storage system (tactical level)
- Assigning products to storage locations (tactical and operational level)
- Assigning orders to pick batches and grouping aisles into work zones (tactical and operational level)

- Order picker routing (operational level)
- Sorting picked units per order and grouping all picks of the orders (operational level)

In this research the decisions taken regarding the picking method, will be done on a tactical level.
Inspired on the design steps of Baker & Canessa (2009) and the classification of de Koster, Le- Duc & Roodbergen (2006), the following steps will be taken in this research during the design and the assessment phase of this research:

- Define system requirements and design constraints
- Define system functions
- Define possible system solutions for the system functions
- Choose suitable combinations of the system elements with the help of a Morphological chart
- Outline the expected results of the alternatives on the design coals and criteria
- Assess the alternatives on the basis of a deterministic model

In the same research de Koster, Le- Duc & Roodbergen (2006) conclude that objectives of a warehouse design are often the following:

- Minimising the throughput time of an order
- Minimising the overall throughput time (e.g. to complete a batch of orders)
- Maximise the use of space
- Maximise the use of equipment
- Maximise the use of labour
- Maximise the accessibility to all articles
- The design objectives within this research will be discussed in Paragraph 4.1.

2.3.3 Modelling

There are different ways systems can be studied. Kelton & Law (1991) describe that the two main methods are experiments with an actual system (in real life) or experiments with a model of a system. The installation of a mechanized FC has a major impact on processes and comes together with high investments. Therefore, a model is used to experiment with the system and specify the design characteristics. Kelton & Law (1991) explain that a model can be a physical model or a mathematical model. A physical model can be for example a train simulator. To simulate a FC in real life will be very challenging and costly. Therefore, a mathematical model is constructed. In a mathematical model the system is represented in terms of logical and quantitative relationships which can be altered to see how the model and thus the system reacts (Vorst, Tromp, & Zee, 2009). Van der Vorst, Tromp, & van der Zee (2009) distinguish analytical models where relationships between elements are expressed with the help of mathematical equations and simulation for real-world systems that are too complex to allow for analytical modelling. Due to the deterministic character of the data and the need for ABC (explained in Paragraph 2.3.1), the model constructed in the assessment, will be a deterministic analytical model. Multiple studies can be found in literature on analytical warehouse models. Park & Webster (1989) explain that a main analytical warehouse cost model includes: land costs, building costs, equipment costs, storage rack facility costs, labour costs, maintenance costs and operating costs. In this research the building and maintenance costs will not be taken into account. The model, constructed in the assessment phase, is made in Excel and includes the quantification of the main processes with the corresponding logic between the processes and variables for the different alternatives.

2.4 Conclusions exploration

In the exploration answers where found for the following sub questions:

Sub question 1: What is known about the design of manual and mechanized processes in online grocer FCs?
FCs are designed based on the order, assortment and SKU characteristics. Picking is the main activity and during the design of the FC different manual or mechanized pick strategies can be taken into account. The processes within a FC, which are often mechanized, are picking (bringing the product to the picker) and the storage of product or orders. The performance of the mechanized processes is dependent on the combination of the systems. In grocer FCs it can be seen that the mechanization of the storage and picking is organized differently for products in different temperature groups (ambient and chilled) and sales volume groups. Frozen pick processes are not mechanized due to temperature challenges. Storage functions are mechanized with AS/RSs and picking is often mechanized with the help of zone-picking and GTP stations.

Sub question 2: What is known about the effect of mechanization on the productivity, service level, operational expenditure and capital expenditure? Mechanization can increase pick productivity up to 600 picks per hour, resulting in a decrease of the required FTE and direct labour costs. Ocado has a highly mechanized grocer FC with an all-in productivity of 155 items per hour and variable costs of 0,11 cents per item. There are no quantified known effects of mechanization on service level. However, it decreases flexibility and on the short term it can have a negative effect because of start-up procedures. On the long term it can increase service level because of the decrease in picking mistakes and the increase in flow. The CapEx put into FCs are often not published. However, through data from material handling suppliers it is possible to retrieve the costs for different equipment.

Sub question 3: Which methodologies can be used to analyse, design and model a FC?
To analyze the assortment characteristics and the costs of a FC, the ABC product analysis and Activity based costing analysis can be used. For the design of a warehouse Koster, Le- Duc & Roodbergen (2006) have defined several decisions that should be taken on a strategic, operational and tactical level. Besides these decisions, there are multiple frameworks in literature. The method used in this research is inspired on the framework of Baker & Canessa (2009). FC modelling can be performed with the help of simulation or analytical models. Due to the deterministic character of the data and the need for ABC, the model constructed in the assessment, will be a deterministic analytical model.

Analysis

‘Let the data speak.’ Wybe-Jan Bleeker
Progress meeting, May 2016

3. The current FC (FC0)

To fully understand the required processes for the new FC, processes of the current FC (FC0), used for the fulfilment of the orders for Picnic, will be analysed.
In this chapter the following sub questions will be answered:

- What is the design of FC0?
- What is the effect of the design of FC0 on operational- and capital expenditure?
- Which design variables have to be taken into account for the design of the new FC?

The analysis of FC0 is performed in a qualitative and quantitative matter. The qualitative analysis is performed with the help of process drawings (IDEF-0, Proper model and Value Stream Mapping). Integration Definition for Function Modelling (IDEF-0) is a common modelling technique for the analysis, development, re-engineering, and integration of information systems; business processes; or software engineering analysis (Leonard, 1999). A Proper model is an approach where processes and performance are combined (Veeke, Ottjes, & Lodewijks, 2008). It describes the general functional relationship among components of a system. Value Stream Mapping is a tool for analysing the current state and designing a future state for a (manufacturing) process from beginning to end (Rother & Shook, 2003). In this research VSM is used to calculate the time used for the main processes.
A quantitative analysis is performed with data extracted from the Data Warehouse from Picnic covering the 1st of December until the 31st of March, using the ABC analysis and the ABC product analysis method. To fully understand the processes within the FC, the overall supply chain of Picnic should also be understood. Therefore, at first a description of the up- and downstream activities of the FC will be presented.

3.1 Up- and downstream activities

The current supply chain of Picnic is shown in Figure 7. Suppliers deliver goods on pallets to Boni. Boni is a supermarket active in the North of Holland and close to FC0. When Boni receives an order from Picnic, it is prepared on roll containers (RCs) in trading unit quantities (HEs). In the FC the trading units are unpacked and consumer units are replenished on to the shelves. The orders are picked and put into plastic bags in totes. The totes are stored in dispatch frames (DPFs) which can be directly stored into a truck. A truck transports the DPFs from the FC to a hub. At the hub the DPFs are cross-docked into smaller electrical vehicles (E-workers). The E-workers can carry 2 DPFs (one for ambient products and one for chilled and frozen products). The two DPFs store articles for around 13 households. The E-workers deliver the orders to the customer. The customer receives the groceries in plastic bags.

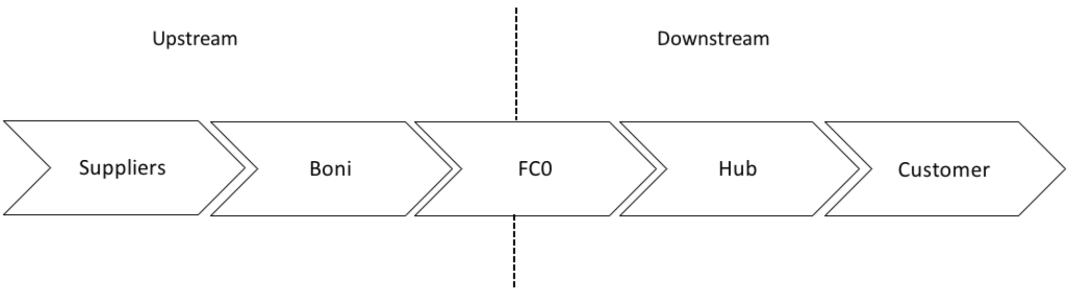

Figure 7: Up- and downstream of Picnic supply chain (Author, 2016)

3.2 FC process analysis

In Figure 8, the main processes of the FC are shown. Like expected, they match the warehouse processes described in the exploration phase. The FC handles around 4500 stock keeping units (SKUs). Orders are fulfilled in three temperature zones: an ambient, chilled and frozen zone. The FC is operated manually and different unit-loads are used to prepare the order. To minimize waste due to over-date products and to minimize the space usage, there is a minimal amount of stock in the FC. The FC is currently (April, 2016) handling around 500 orders per day.

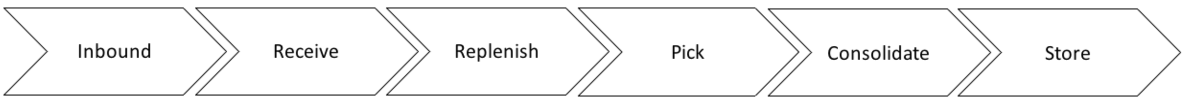

Figure 8: Main processes in the FC (Author, 2016)

All processes in the FC are steered by the business control of the FC. According to Veeke (2003) a business system consists of business processes and their relation with the environment. The Proper conceptual model is used to describe the business system of the FC. A Proper model is an approach where processes and performance are combined (Veeke, 2003). It describes the general functional relationship among components of a system. This model makes a distinction in three parallel transformations, namely the transformation of orders into handled orders (perform), products into delivered products (operate) and resources into used resources (use). The Proper conceptual model for Picnic is presented in Figure 9.

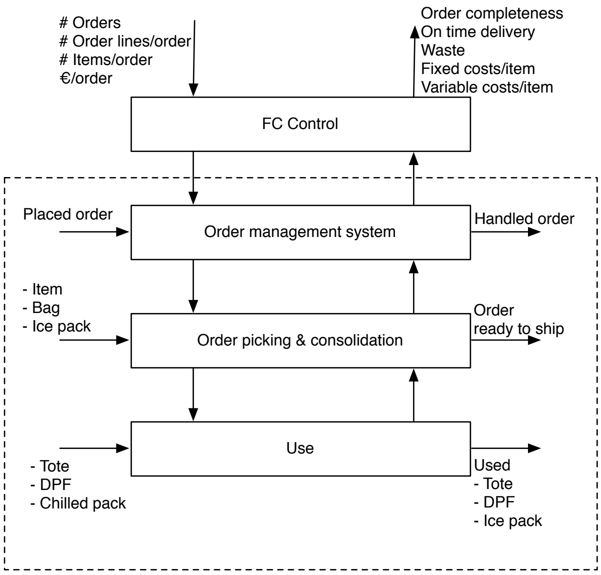

Figure 9: Proper model FC (Author, 2016)

To give a structured overview of all processes, IDEF-0 diagrams are depicted. IDEF-0 is used to describe processes based on activities (the block), input (the ingoing arrow), output (the outgoing arrow), resources (bottom arrows), and steering/controlling factors (top arrows) (Ross, Dickover, & McGowan, 1977). IDEF-0 diagrams give the opportunity to describe the processes in different levels of details. In Figure 10, the processes in FC0 on the highest level of detail are given. This is called the A0 diagram. The input is the customer orders; the output is the shipped orders. The main controllers of the FC operations are costs per item, on time delivery rate and order completeness. The main function (the A0 of the IDEF-0) can be split up in main processes. These processes can be seen in Figure 11. Below Figure 11 explanations are presented of the different processes.

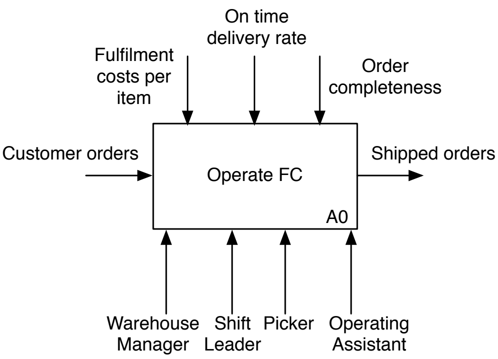

Figure 10: IDEF-0 A0 (Author, 2016)

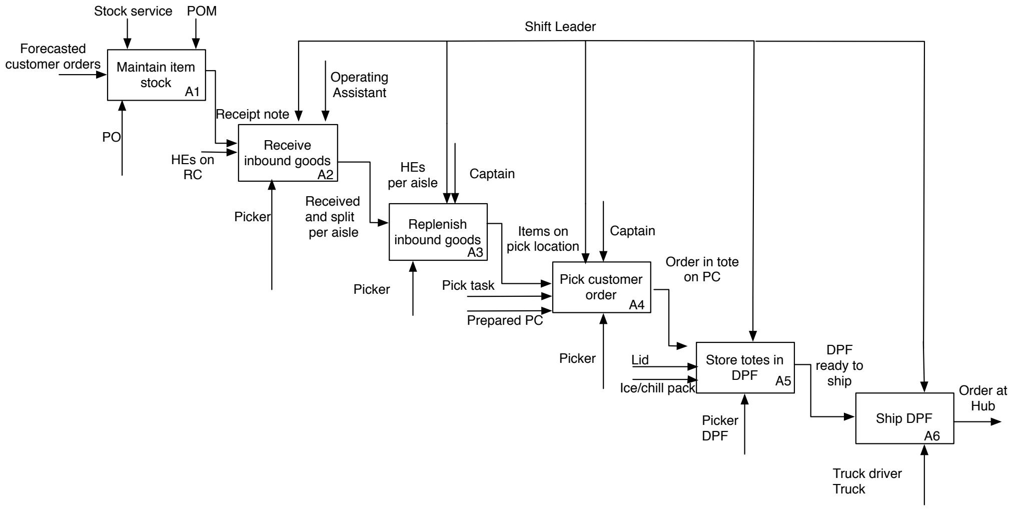

Figure 11: IDEF-0 A1-A6 (Author, 2016)

A1 Maintain article stock
To prepare the orders, the stock in the FC has to be maintained. To maintain the stock, orders have to be placed by the 'purchase orderers' (POs). This is done on the basis of the forecasted number of customer orders and the content of the orders.

A2 Receive inbound articles
The receiving process of inbound articles is performed in different receiving areas per temperature zone. During the receiving process, the expected inbound of articles (based on the receipts of suppliers) is checked with the actual inbound of articles. In the ambient zone, the articles are split into RCs per aisle. The inbound articles from the suppliers are combined in RCs which do not correspond to the deviation of SKUs per aisle in FC0. Splitting is performed to increase the replenishment productivity. For chilled and frozen products, the articles are not split per aisle and directly replenished.

A3 Replenish inbound articles
The replenishing of articles is the filling of the articles on the shelves. In ambient, the filling is done from the back of the shelves to establish a FIFO picking system and to keep the aisles free for the order picking. In the chilled area some shelves have to be filled from the front. Therefore, the filling in this area is done before or after picking. For the frozen articles, freezer containers are used which are opened from the top. Therefore, the replenishment of the frozen articles can also not be done during picking. During the replenishment, the HEs have to be unpacked so that pickers can pick CEs directly.

A5 Pick customer order
The picking of the order is the main activity within the FC. The picking of the orders is done separately per temperature zone. A more detailed analysis of picking is given in the next paragraph.

A6 Store totes in DPF
In this activity the order is prepared to ship by combining, stocking and assigning the totes from the picking cart into a DPF (Appendix 3, Figure 55). This process is also called storing. During the storing process it is also possible to consolidate orders. Within the chilled and frozen temperature zones, storing also included the addition of chilled or frozen packs and lids to the totes, to ensure the temperature of the products does not increase.

A7 Ship customer order
When the totes are assigned to a DPF, the frames are ready to be shipped. DPFs can be stacked on to each other to optimize space usage of the truck. The DPFs are shipped to the hub where they are directly cross-docked into E-workers.

3.3 Pick process analysis

As stated before, picking is the main, often most time consuming process in a warehouse. During the literature review, different picking methods where specified. Picnic operates with a Picker-to-Parts strategy. Articles are picked in batches and sorted while picked. The assisting technology is a Radio Frequency (RF) scanner, which is connected to the WMS. De Koster (2006) has visualised the complexity of picking on strategic and policy level, inspired on Goetschalckx and Ashayeri (1989). In Figure 12, this visualisation is shown. The used methods for Picnic are circled in blue.

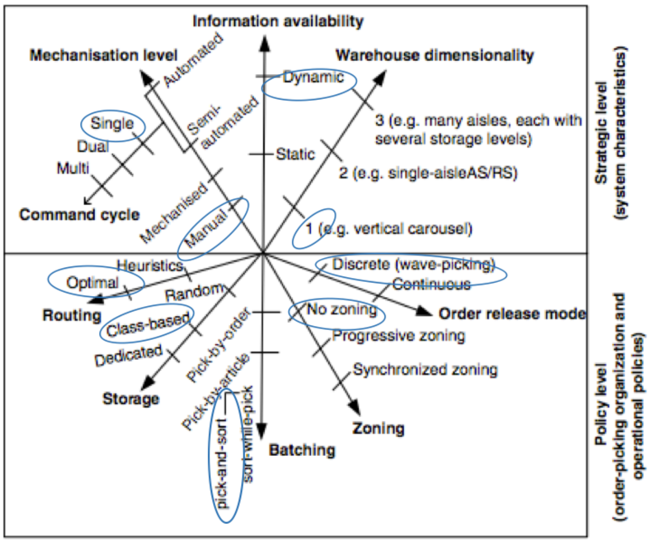

Figure 12: Complexity of order picking at Picnic (de Koster, 2016)

Figure 13 shows that the picking is a manual process with a multi command cycle (different articles in a pick round). The routing is optimal per temperature zone (defined by the WMS). The storage of the articles is dedicated. The articles are picked as a single piece and sorted while picked into different totes.
The picking tasks are released in waves and the FC only has one floor. However, the shelves in the aisles have multiple storage levels. The picking is done with the help of a pick cart (PC) (Appendix 3, Figure 54). The PC can transport twelve totes, which are filled with three bags. Before using the PC, the totes have to be assigned to a dedicated place on the PC.
The chilled temperature zone has a shorter PC to simplify the picking on a smaller surface area. However, the PC contains the same number of totes. For each temperature zone the tote has to be bagged and assigned to the picking cart. This process is also shown in the IDEF-0 dedicated to picking (Figure 13). With the help of an RF-scanner the articles are picked in batches. Meaning that the same articles of multiple orders on the picking cart are picked at ones. The orders from the customer are split up into order lines. The order lines are the input for the generated picking tasks given buy the WMS. One order line can consist of multiple items of one SKU.
The picker reads the picking task from the RF-scanner. The RF-scanner displays the product name, the location, the quantity to pick and the number of the place of the tote of the picking cart. The picker has to search for the location, scan the article, put the article in the tote and scan the tote see Figure 14. When the article or tote is incorrect, the RF-scanner will give an error message. When the article and tote is correct, the picker will receive a new picking task. When the picking round is complete, the picker stores the picking cart in the outbound area. So that the totes can be stored into a DPF.

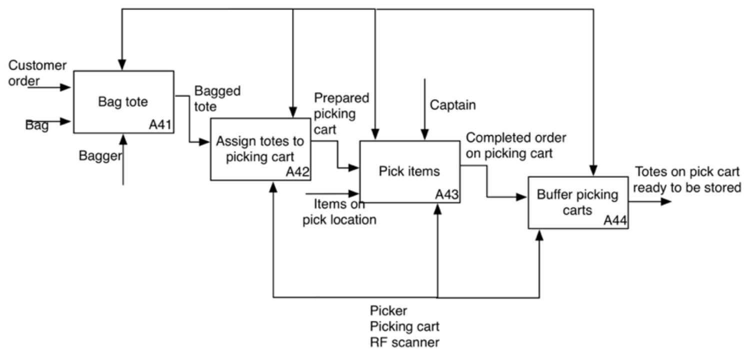

Figure 13: IDEF-0 Picking A41-A44 (Author, 2016)

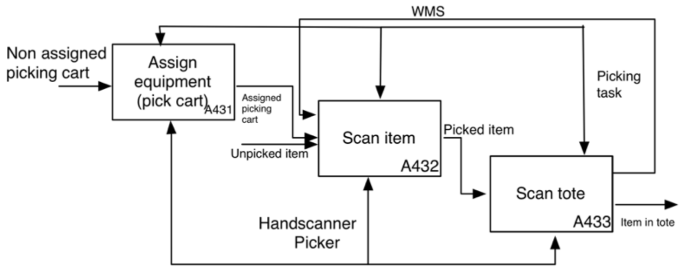

Figure 14: IDEF-0 A431-A433 Picking of an article (Author, 2016)

Picnic aims to use a Z-picking walking method to increase productivity. Meaning that the picker should walk a 'Z' around the PC while picking the articles to minimize the walking distance and maximize productivity.
To make use of the Z-picking method in an optimal way, the PC has to be static in the areas where the articles have to be picked. However, it regularly occurs that a PC is taken over by another PC. In this case the PCs are not optimally located for Z-picking. A quantified productivity analysis of the picking is presented in Paragraph 3.8.1.

3.4 Layout analysis

According to de Koster, Le-Duc & Roodbergen (2007), layout design and especially the layout design of order picking, entails two problems: the layout of the facility containing the order-picking system and the layout within the order-picking system. The first problem is usually called the facility layout problem; it concerns the decision of where to locate various departments (receiving, picking, storage, sorting, and shipping, etc.). According to de Koster, Le-Duc & Roodbergen (2007) it is often carried out by taking into account the activity relationship between the departments. He states that the common objective is minimising the handling cost, which in many cases is represented by a linear function of the travel distance. The second problem is the internal layout design of the picking area. De Koster, Le-Duc & Roodbergen (2007) state that this concerns the determination of the number of blocks, and the number, length and width of aisles in each block of a picking area. The common goal is to find a 'best' warehouse layout with respect to a certain objective function among the layouts which fit a given set of constraints and requirements.
Again, the most common objective function is the travel distance. In Appendix 2 the layout analysis of the order-picking system is presented. From the results it can be concluded that the major part is used for processes related to the ambient temperature zone and the the FC is designed in a U-flow. (The layout within the order-picking system is excluded from the research.)

3.5 Transport equipment analysis

In the FC, the order is prepared with the help of different equipment and unit loads. The inbound articles enter the FC on RCs per temperature zone. The articles are picked with the help of a PC and stored in totes per order. The totes are stored in DPFs. The current amount of equipment is to prepare 800 orders per day. The amount of equipment increases with the number of orders. For the current calculations of the required amount of equipment, safety factors are included to allow for the fact that DPFs and totes are still at the Hubs. At the moment there are two different kinds of DPFs (with 3 and 4 layers). In the future Picnic aims for the use of the 4 layered DPFs only. However, currently the biggest share of the E-workers can only transport 3 layered DPFs. There are two different types of totes. Plastic ambient totes and Styrofoam isolation totes with lids for chilled and frozen articles. The number of articles in a tote is dependent on the volume and weight of the products. Dependent on the volume and weight, the WMS calculates the maximum number of articles that can be assembled into a tote. The numbers and types of equipment used in FC0 is listed in Appendix 2.

3.6 Stock inventory analysis

Picnic aims to minimize stock inventory. However, to decrease the chance of not delivering a product, Picnic operates with an inventory system which ensures that there will always be stock for one day extra than required. Besides the extra day of stock, there is a safety margin of around 30% per product dependent on the sales volume of the product. Dependent on the day of delivery and the lead-time, the purchase order management system defines how many articles should be in stock. The shelving in the FC is organized in such a way that all inventory can be stocked on the shelf. In theory no buffer areas are required. However, practice has shown that buffer areas are used when stock does not fit on the shelf. This can for example be a result of daily peak in demand.

3.7 Range and order characteristic analysis

As already stated in the literature study, the design of a FC is highly dependent on the range (assortment) offered by the grocer. Because of the fact that there is a focus on the ambient category, only the ambient range will be discussed. The analyses for the other temperature zones are presented in Appendix 4 (Table 26). Ambient products will be categorized based on sales volume and fragility. The categorisation of sales volumes is based on fast, slow and mid movers. The FMs are the articles most frequently ordered. These articles represent 20% of the total sales volume (in number of articles). The mid movers (MMs) are articles which represent the next 30% sales volume. The slow movers (SMs) represent the 50% sales volume of least sold articles. For this analysis an ABC product analysis (explained in the exploration phase) will be performed to calculate the ratio between volume and the number of unique SKUs. After the ABC analysis, an order and tote characteristics analysis is performed.

3.7.1 ABC product analysis

The ABC analysis is performed in Excel. In Figure 15 it can be seen that 20% of the volume is represented by less than 2% of the SKUs. Within the analysis these products are the A-products (the FMs). The B-products (the MMs) represent the next 50% of the volume. In the graph it can be seen that this is represented by around 10% of SKUs. The C-products (SMs) are the SKU that represent the rest of the volume. They account for around 88% of the SKUs.

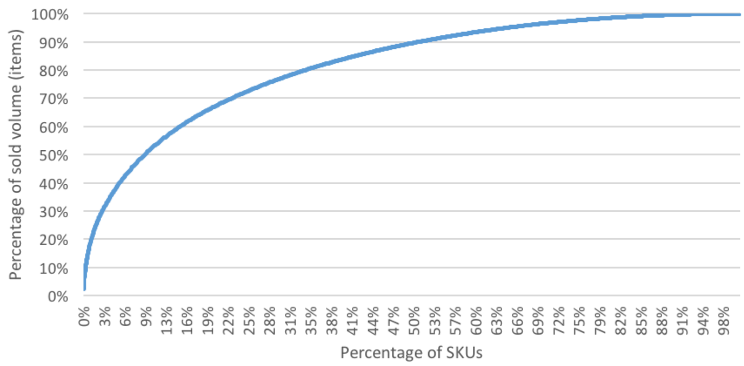

Figure 15: ABC analysis ambient (Author, 2016)

The products can also be categorised on the basis of fragility. Fragility stands for the probability of damaging the product. One can imagine that the most fragile products have to be positioned in the top layer of the tote and the least fragile products can be positioned on the bottom of the tote. At the moment the shelving in the FC is classified in such a way that pickers at first pick the heavy products and at the end the lightest and most fragile products. This is classified manually on the basis of product families.
Because of the fact that at the moment fragility is classified manually, the classification of fragility is based on pick locations. The classification per aisle is presented in Appendix 4 (Table 30).
The volume within the ABC analysis is based on the number of items. The analysis can also be performed with the number of lines. Lines are unique items within an order. An order can have multiple items (the same product) within one line.
In Table 4 a matrix of the categorisation of the range over fragility and volume characteristics is shown. It is shown that the category of slow movers includes the highest number of SKUs with a high fragility (1188 SKUs). These products represent 19% of the sales in items and 21% of the sales in lines. As explained in the Exploration phase, it is important to understand the product range to successfully design a FC. The outcomes of the analysis will be taken into account during the assessment.

Table 4: Range categorized over volume and fragility in number of SKUs, units and lines (ambient)

	FM	***MM***	***SM***	
High-frag	22	84	1188	# SKUs
	1%	3%	37%	% SKUs
	15%	11%	19%	% units
	15%	11%	21%	% lines
Med- frag	7	88	1094	# SKUs
	0%	3%	34%	% SKUs
	2%	9%	23%	% units
	2%	9%	23%	% lines
Non- frag	8	72	676	# SKUs
	0%	2%	21%	% SKUs
	3%	10%	8%	% units
	2%	8%	9%	% lines

3.7.2 Order and tote characteristics

The activities within the FC are highly dependent on the number and characteristics of the orders. The number and characteristics of orders also determine the number and characteristics of totes within the FC. Therefore, an analysis is performed on the order and tote characteristics. The quantitative output of this and the above analysis will be used as an input for the model during the assessment. Below, the outcomes for ambient products are presented. The average order characteristics from the other temperature zones are presented in Appendix 4 (Table 28 and Table 29). Table 6 shows that the average number of ambient items per order is 21. They are divided over 17 order lines and constitute 30 litres of volume in average. The full tote analysis is shown in Appendix 4. From the results of the tote analysis it can be concluded that 65% of the orders contain one ambient tote (Figure 56), the number of items in the tote is also highly dependent on the number of totes in the order (Figure 57). When an order has multiple totes, at first the first tote is totally filled and thereafter the remaining items are put in to the second tote (Figure 58). This means that the products are not evenly spread over the totes. In Table 7 the standard deviations of the main order and tote characteristics are depicted. From the standard deviations it can be concluded that overall the frozen category results in the least spread of the characteristics. Besides this, the table shows that the volume (in liters) from the ambient and chilled SKUs is not normally distributed (the standard deviation is bigger than the mean). Within ambient temperature zone category, this could be a result of for example high sales volumes (due to promotions) of big items like detergents.

Table 5: Order characteristics per sales volume and fragility category (ambient)

	FM	MM	SM	Units
High-frag	3,20	2,34	4,08	# items
	2,49	1,93	3,55	# lines
	7,53	4,71	5,26	# vol. (l)
Med-frag	0,49	1,99	4,86	# items
	0,29	1,47	3,91	# lines
	0,22	1,53	4,97	# vol. (l)
Non- frag	0,63	2,11	1,78	# items
	0,40	1,38	1,49	# lines
	1,58	4,87	3,39	# vol. (l)

Table 6: Averages of most important order and tote characteristics

Temp zone	Item /line	SKU volume (l)	Item/order	Line/order	Items /tote	Volume (l)/tote
Ambient	1,27	1,41	21,46	16,92	14,82	29,16
Chilled	1,30	1,16	14,54	11,15	13,00	18,36
Frozen	1,19	1,68	2,82	2,38	6,68	11,83

Table 7: Standard deviations of most important order and tote characteristics

Temp zone	Item /line	SKU volume (l)	Item/order	Line/order	Items /tote	Volume (l)/tote
Ambient	0,82	1,85	12,07	8,67	7,76	12,91
Chilled	0,83	1,22	8,37	5,91	7,05	9,75
Frozen	0,60	0,93	2,35	1,73	3,94	6,42

3.8 Performance analysis

Warehouse performance has multiple dimensions. Often, performance is measured in terms of ratios of output and input factors. Output factors include production (shipped orders, lines and units), quality (order completeness, error-free and on-time delivery), flexibility (possibility to cope with changes in customer demand), agility (process adaptation to changed environment) and innovativeness (use of new supply-chain concepts yielding competitive advantage). Inputs are the resources used to achieve the outputs. These include the number of FTE, investment in systems, buildings and IT infrastructure, process organization (i.e. the management), or the assortment carried (Rouwenhorst, et al., 2000). Within this research the CapEx and OpEx are main performance measures. The OpEx is highly influenced by productivity. Therefore, at first a productivity analysis is performed. Within the cost analysis, the CapEx will be defined.

3.8.1 Productivity analysis

Currently (April 2016) the all-in productivity in the FC is 65 articles per hour. The all-in productivity is calculated by dividing the total handled number of items by the hours spent on direct labour. According to the estimated fulfilment model of FC0, this could be 85 articles per hour when the FC operates the most efficient.

When an analysis is performed on al the recorded main process tasks, the overall productivity in the warehouse is 85 articles per hour. However, when the hours of non-recorded (by the WMS) tasks are also included, the FC has an overall productivity of 65 articles per hour. These hours are for example extra hours worked by the captain, hours spent on side activities like searching for articles on demand of the shift leader and quality checks. The all-in productivity is calculated by dividing the daily picked articles from all the orders by the total daily number of worked hours in the FC. It can be seen that pick productivity in the chilled area is the highest. This is because the pick area is smaller, resulting in smaller distances to travel. The productivity per activity in the FC is presented in Appendix 5. The current deviation of the workload is shown in Figure 16. It can be seen that 40% of the direct labour hours are spent on picking. These calculations are done with the number of worked hours in 2016. To decompose what the productivity per process are, a Value Stream Map (VSM) is drawn. A VSM is used to identify waste in a process or side activities (which do not add direct value). The VSM is presented in Appendix 6. One of the main conclusions that can be drawn from the VSM is that 68% of the total hours are spent on the main activities (described in the process analysis) and 32% on side activities.

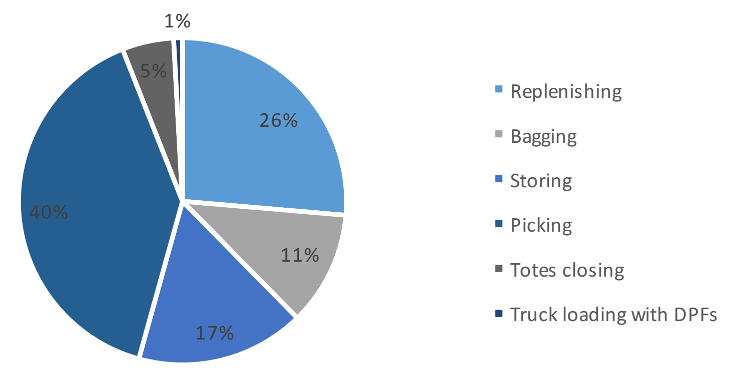

Figure 16: Workload deviation (percentage of total hours) FC0 (Author, 2016)

3.8.2 Cost analysis

The total fulfilment costs can be divided in CapEx and OpeX. The CapEx is based on the investments and the Opex are the variable costs based on direct and indirect labour and facility costs.

The variable costs are mainly based on the direct labour costs (the pickers), but also the costs for the used plastic bags and the freeze packs. If all costs are decomposed it can be seen that 57% is due to the direct labour (pickers).

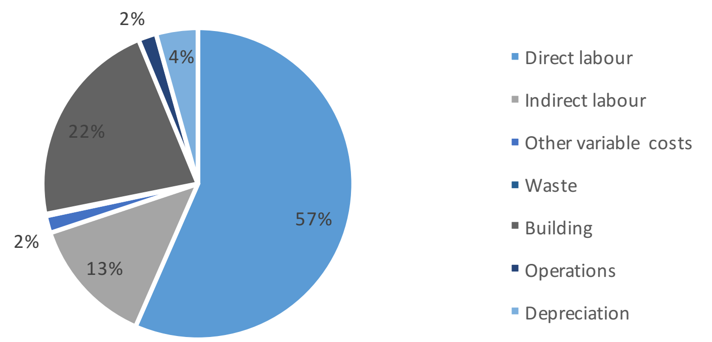

Figure 17: Allocation of costs current situation (Author, 2016)

In Table 8 it can be seen that the target of the current direct labour costs is approximately the half of the current direct labour costs. This can be achieved by handling more articles with the same number of spent hours, or handling the same number of articles with an increase of the required number of direct labour hours. Therefore, productivity of the different processes should increase.

Table 8: Fulfilment costs per article P1 2016 (Picnic, 2016)

	Current [€ ct]	Target [€ ct]
Total fixed costs per item	26,9	6,7
Indirect labour costs per item	8,8	2,1
Building costs per item	9	2,1
Depreciation costs per item	3	0,6
Total variable costs per item	38,8	26,2
Direct labour costs per item	38	17,6

The operational costs within this research are the direct labour costs summed with the building costs (49 cents per item). The capital expenditure are the depreciation costs. At the moment this is 3 cents per handled item.

3.8.3 Service level analysis

Picnic quantifies the provided service-level, with the help quality key performance indicators (KPIs). The main quality KPIs are:

- Out of stock
- Order completeness
- On-time delivery
- Complaints/errors

Out of stock is the percentage of items which where not delivered to the customer. Order completeness stands for the fact that the order is complete when it's delivered to the customer. Order incompleteness can be caused by many factors. Among others, it can be a result of products being out of stock or because of picking mistakes. On-time delivery within the FC stands for the on time readiness for delivery to the hub. Currently (April '16) around 97% of the orders are ready on time. The number of complaints is also a KPI to track the service level. The main complaints are regarding quality issues (often due to fragility challenges) and wrong or missing items due to pick errors. During the design of the new FC, service level will be a constraint and not a criteria. Meaning that the design should be able to deliver a certain level of service. Because of the fact that it is hard to predict the effect of the designs on the service level, the main constraint will be that the orders should be fulfilled within the provided schedule to be on time for the delivery to the Hub.

3.9 Conclusions analysis

In the analysis phase the next sub questions were answered:

Sub question 4: What is the design of FCO?

FC0 is designed to fulfil the orders fully manual within three temperature zones. The FC has a surface area of 3250 square meters from which the major part is used for the ambient zone. Different unit loads are used to fulfil the order (e.g. PCs, totes and DPFs). Picking is 40% of the workload and is carried out in batches and sorted while picked. The assisting technology which is used during picking is the RF-scanner. The main processes within the FC are receiving, replenishing, picking, consolidating and storing. 73% of the SKUs are within the ambient temperature zone. From all articles, 81 SKUs represent 20% of the volume. Within ambient, 37 SKUs represent 20% of the volume. Differences in the pick strategy for SMs, MMs and FMs are not taken into account. Fragility of products is taken into account by strategically slotting the products.

Sub question 5: What is the effect of the design of FC0 on operational- and capital expenditure?

The current all-in productivity is 65 items per hour (excluding surrounding activities: 98 items per hour). 68% of the time is spent on main processes. The current direct labour costs are 38 cents per item. The aim of Picnic Supermarkets is to nearly half these direct labour costs for FC0. The current depreciation costs (CapEx) per item is 3 cents and the current on time delivery rate is 97%. From the productivity analysis it can be seen that pick productivity is reasonably good. The productivity of splitting HEs and storing ambient orders is relatively low.

Sub question 6: Which design variables have to be taken into account for the design of the new FC?

The main design variables which have to be taken into account are the input variables related to the order, range and tote characteristics. These variables are: the number of SKUs within the ambient range, the number of ambient items in one order, the number of items per tote, the number of items per line, the average volume per SKU (in litres) and the percentage of orders which has to be consolidated.

Design

‘Good design is good business.’ Thomas Watson Jr.
IBM president 1952-1962

4. Design alternatives

The design of the new FC will focus on the ambient temperature zone. Like already stated in the literature review, Baker & Canessa (2009) have developed a framework for warehouse design. Based on this framework the following steps have been constructed:

1. Define system requirements and design constraints
2. Define system functions
3. Define possible system solutions for the system functions
4. Choose suitable combinations of the system elements with the help of a Morphological chart
5. Outline the expected results of the alternatives on the design coals and criteria

The design phase will answer the following sub questions:

- What are the design goals for the new FC and which design criteria follow from this?
- What are the design requirements that follow from the current FC and the growth perspective?
- Which system solutions can be defined for the system functions?
- Which design alternatives can be composed for the new FC?

4.1 Design goals and design criteria

The goal of the design is to establish a FC that can handle 20K orders per day while meeting the operational and service requirements and minimizing the total fulfilment costs per year. The final designs will be assessed on the basis of the following criteria:

- All-in productivity
- Surface area
- FTE
- CapEx
- OpEx
- Fulfilment costs per year

To reduce the amount of system functions for the different design alternatives, the system solutions for the storage systems will be assessed before the alternatives are composed. This is done because of the fact that the system solutions for picking are dependent on the storage system of the products.
The storage systems will be assessed on the following criteria:

- Storage capacity/m^2
- In-/output rate (throughput capacity of a singe aisle within the storage system)
- Flexibility (possibility to handle last minute order changes)

4.2 Requirements and constraints

According to Rushton (2016), the design requirements should include:

- Required capacities, both storage and throughput
- Service level to be achieved
- Specified facilities such as packaging, quality or other

Relevant constraints can include (Rushton, 2016):

- Time, e.g. facility to be up and running by a specified date
- Financial, e.g. limit on capital expenditure or on cost per unit of throughput
- Technical, e.g. to be compatible with existing company technology, to enable flexible throughput to meet high seasonal variations, or technology level to present ‘leading-edge’ company image

Based on Rushton’s research, the requirements are divided into capacity, design and process requirements. The constraints are split into time and financial constraints.

Capacity requirements:

1. The FC should be able to handle 20000 and 80000 articles per day (on a peak day)
2. The FC should be able to receive and store articles on pallets
3. All-in productivity should be 155 items per hour

Design requirements:

1. The FC should have an ambient buffer zone
2. The FC should be able to grow over time

Process requirements:

1. The FC should be able to handle a range of 3500 ambient SKUs
2. The FC should facilitate late evening cut-off for next day afternoon and evening
3. The FC should be able to receive inbound articles all day
4. The FC should be able to replenish articles all day
5. The FC should have the capability of adding fresh articles the same day of delivery
6. The FC should have the capability preparing orders the day before delivery

Time Constraints:

1. Order cut-off 22:00
2. First outbound truck at 10:00
3. Last outbound truck at 20:00
4. Evenly spread outflow over time
5. Inbound all day

Financial Constraints:

1. The direct labour costs when handling 20000 orders should be a maximum of 0,11 cents per item

4.3 System functions

The system functions are the functions in the system on which can be varied on. Based on the literature review and the analysis of FC0 the system functions are:

1. Receiving
2. Replenishing
3. Product storage
4. Picking FMs
5. Picking MMs
6. Picking SMs
7. Order storage
8. Consolidating
9. Storing
10. Transportation products
11. Transportation orders

All the above listed system functions can be performed in a manual, mechanized or automated way. If the system function is automated no person is required to complete the process. In contrary, if the system function is mechanized, a person is needed.

4.4 Possible system solutions

Below, possible system solutions (in the Morphological chart referred as means) are discussed based on the degree of mechanization. In Appendix 7, specified information on the different system solutions can be found.

4.4.1 Solutions for receiving

Manual receiving/splitting: In FC0 manual splitting of HEs is performed. The splitting is performed to increase the efficiency of the replenishment process. Manual splitting effort could be decreased when suppliers deliver the FC on RCs which are sorted per aisles. Besides the manual splitting of HEs, it is also possible to manually receive pallets for direct pallet pick.

Decanting: Decanting is required when the products are stored in an AS/RS system using totes. The CEs are taken out of the packaging and put into a tote. This is done at decanting stations. At the decanting station, a screen presents the type and number of articles to put in the tote. Dependent on lead time, sales volume and SKU characteristics, multiple SKUs can put into a tote. Decanting effort could be decreased when suppliers deliver the products in totes at the FC.

Mechanized splitting (with the help of a sorter): The sorting (splitting) of HEs can also be done with the help of a sorter (Figure 18). A sorter is a conveyor belt system with for example trays, which can sort by pushing products from the conveyor belt into exits. The sorter is supplied with products through induction points. More information on the sorter can be found in Appendix 7 (Figure 60 and Figure 61).

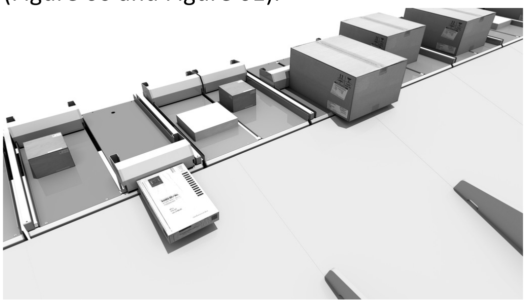

Figure 18: Push tray sorter (Distrisort, 2016)

4.4.2 Solutions for replenishment

Manual: Manual replenishment is explained in depth in the analysis phase. The internal transport of the goods is performed on RCs and the replenishers manually fill the storage cupboards with CEs. Therefore, the HEs have to be unpacked, leading to a decrease in productivity.

Semi-mechanized: Semi-mechanized replenishment can be done with the help of conveyor belts. In Figure 19 a conceptual visualization of the mechanized replenishment of HEs into the aisles is presented. To minimize space usage, the conveyor belts can be installed in such a way that it is still possible to use the space beneath them. Spiral conveyors can be used to descent the HEs into the aisles.

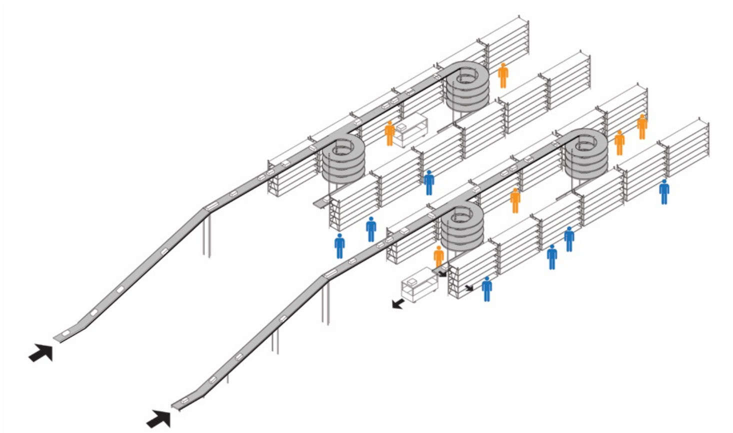

Figure 19: Mechanized replenishment with spiral conveyors (Author, 2016)

Mechanized: Mechanized replenishment is required when products are stored in an AS/RS. In this case, decanting has to be performed to put the products into the product storage totes. The replenishment from the decanting station into the AS/RS is performed with conveyor belts. Depending on the kind of AS/RS the vertical and horizontal transport within the AS/RS is performed with the help of cranes, lifts or shuttles. Different type of AS/RSs are explained below.

4.4.3 Solutions for product storage

Manual racking: In FC0 products are stored with the help of racking. It is also possible to store the products on pallets. When products are stored on pallets, the HEs have to be unpacked by the picker. This decreases pick productivity.

Mechanized Autostore: The Autostore system is an AS/RS on which Autostore 'robots' drive on top of the system. At receiving, products are placed into standardized totes that get conveyed to the induction points of the AutoStore system. Robotic mobile vehicles move on an XY axis atop a 17' high storage buffer consisting of vertical stacks of totes Robots automatically retrieve totes from the vertical stacks for presentation at picking work stations (Swisslog, 2016). Each robot has two sets of wheels that enable it to move along perpendicular axes. This makes it possible for all robots to reach any position, and any bin on the grid independently. This virtually eliminates the possibility of single-point system failure providing near 100 percent system availability. An operator can pick the required SKUs and quantity from the tote. Thereafter the tote with residual inventory is returned back to the top of the cube to be stored in a vertical stack. The system holds approximately 30 minutes of live picking tasks in its queue at any one time, and continuously optimizes the delivery of bins to pick stations. Any order can be redirected to any one of the pick stations at will as the need arises (McMahon, 2015). In Figure 20 the grid of the Autostore system and an Autostore robot is depicted. A main disadvantage of the Autostore system is the many movements that are required to pick a tote from above. This decreases the flexibility of the system if there are last minute order changes. Main advantages are the high dense grid and the fairly high I/O-rate.

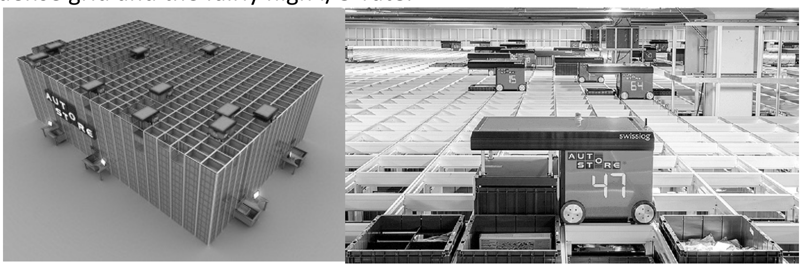

Figure 20: Autostore system (Swisslog, 2016)

Mechanized Miniload: A Miniload AS/RS is often used for small parts order picking (Chun Park, Foley, White, & Frazelle, 2003). Main characteristics of a Miniload system is the presence of one or more cranes to store and retrieve storage containers, numerous modular storage containers for housing the articles, and load stands at the end of each aisle to facilitate order picking. The crane moves the storage containers with horizontal, vertical of diagonal movements from the rack to a conveyor belt which brings the crate to the order picker. Because of the multiple narrow aisles and big number of container storage per square meter, the Miniload is very compact. The throughput from the system is among others, dependent on the speed of the cranes. A Miniload is often used for slow or medium movers. In combination with a picking station, the Miniload has a typical order picking rate of 150 -175 articles per hour. Throughput capacity of Miniload AS/RS is limited to the machine's vertical and horizontal speed, therefore only a limited number of cycles (70 – 150) available per aisle. In the figure below, a Miniload system is shown.

Figure 21: A Miniload system with a single crane and with multiple cranes (Schaefer, 2016)

Mechanized shuttle: The shuttle is a well known type of AS/RS in the grocery fulfilment. Two separate transport devices carry out vertical and horizontal movements. A lift, like an elevator, at one or both sides of the unit, moves up and down to the designated storage levels within the system. Some lifts are designed to raise and lower more than one load at a time. Then, to move products horizontally—meaning to and from the lift and in and out of the storage aisle—each level is equipped with one or more load handling devices: shuttles. Rogers (2012) writes that shuttles can multiply throughput rates. "Because there can be a number of shuttles operating in a single aisle, and these shuttles are moving simultaneously, the throughput per aisle can be five to 10 times greater than a typical mini-load AS/RS. A shuttle system can carry a storage container up to 50 kilograms (this is much lower than the 450 kilograms a Miniload can carry). However, compared to the Miniload the shuttle has extreme low energy consumption at full speed (Rogers, 2012). In Figure 22 a system overview and a detailed picture of a shuttle system is depicted. More information on all AS/RSs can be found in Appendix 7 (Table 33).

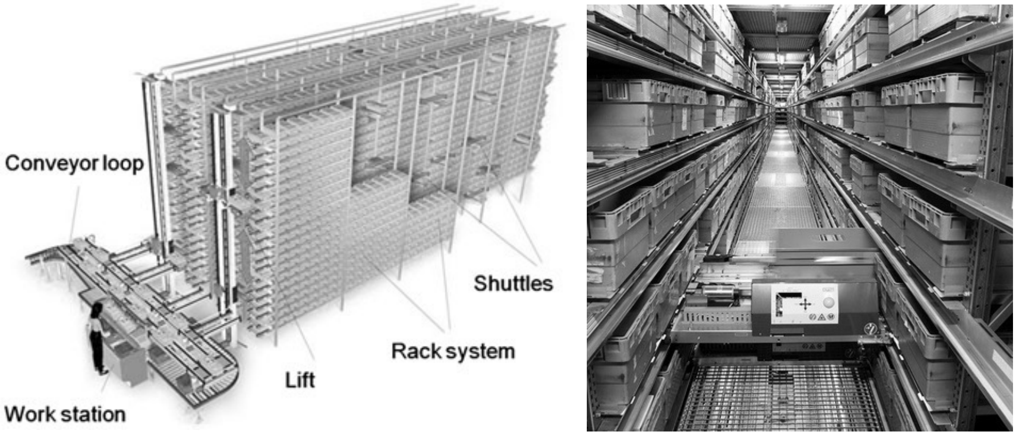

Figure 22: A shuttle system with multiple shuttles and lifts (Knapp, 2016)

4.4.4 Solutions for FM, MM and SM pick

Manual: Like explained in the exploration phase, manual picking can be performed on the basis of different strategies. Manual picking is currently done in batches and sorted while picked. Other pick strategies (manual and mechanized) are presented in Appendix 7 (Table 34). Manual pick productivity is highly dependent on the length of the pick circuit. Currently the PC is also prepared manually. It is possible to mechanize the PC preparation in combination with manual picking. This will increase pick productivity.

Mechanized: With mechanized picking, picking with the help of a zone picking station (Figure 24) or a GTP station (Figure 23) is meant. A zone picking station is a station which uses conveyor belts to transport order and product totes into a zone in which the picker moves to pick different items. When a GTP station is used, the picker stays in the same place. Therefore, higher pick rates can be achieved at a GTP station than in a zone. In Figure 25, it can be seen that separate conveyor belts transport the product and order totes. It is also possible to transport the totes to the station with the help of a robot. However, in practice this is only seen at Amazone (Figure 27).

Figure 23: GTP station (Wehkamp, 2016)

Figure 24: Zone pick station (Ocado, 2010)

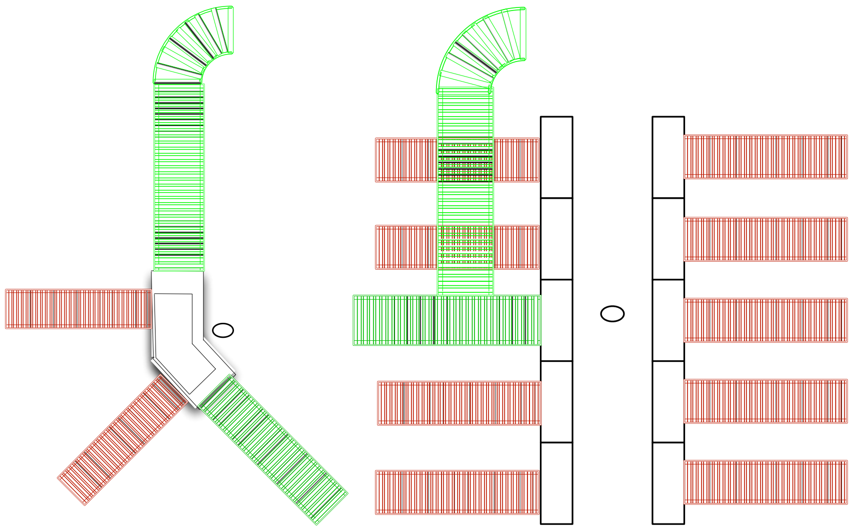

Figure 25: Conveyor belt overview GTP (left) and zone station (right), Author (2016)

Robotised: Robotised picking is currently at a very early stage. The differentiation in size, weight and fragility of the products make it very hard to use robotics to pick a single item and to put it in a tote. One of the robotised picking solutions is a robot picking arm from DelftRobotics which is still under development. This robot uses cameras and deep learning techniques to identify products and to treat every product unique (Deurzen, 2016). A robotised picking arm is depicted Appendix 7 (Figure 62).

4.4.5 Solutions for order storage

Manual: Currently order storage is done on DPFs in the outbound area. The DPFs are used to transport and store the orders.

Mechanized: Mechanized order storage is possible with the same AS/RSs as explained in Paragraph 4.4.3. A Miniload, Autostore and Shuttle system can therefore also be used as order storage system. There have to be underpinned that the grid of the Autostore system can only be filled with the designated (large and heavy) Autostore totes. When there is chosen to realize this system, these totes will have also have to be used to transport the order to the customer.

4.4.6 Solutions for consolidation methods

Consolidating is the procedure of last minute adding of items in the tote. This can be performed for items which where not available during the normal pick process or fresh items which have to be added to the order 'just-on-time' (JIT). To offer a higher service level, the design will have to include a solution to consolidate orders.

Manual: Manual consolidation can be performed during storing into the DPF.

Mechanized: Mechanized consolidating can be performed with GTP stations. This has to be performed in combination with an AS/RS. Order totes could be retrieved from the AS/RS. Items can be decanted in totes and redirected to the GTP stations.

4.4.7 Solutions equipment (un)loading

Manual: Order totes are transferred from the PC into a DPF. Storing is performed with the help of a RF-scanner.

Mechanized: The despatching could also be performed with the help of a despatch frame loader. The despatch frame loader retrieves the totes from a conveyor belt and mechanically loads the frame. In Figure 26 an automatic storer (frame loader) of Knapp is depicted. This mechanism can also be used load an unload PCs with order totes.

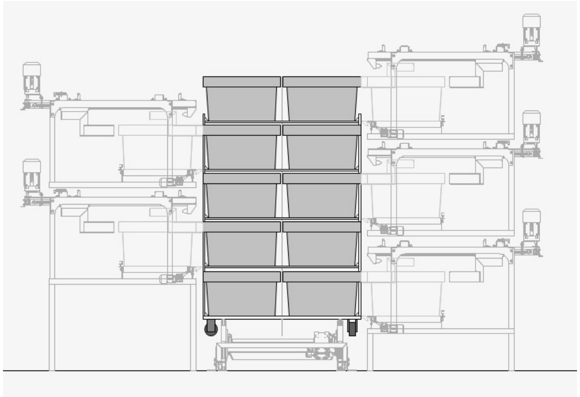

Figure 26: Automatic Storer (Knapp, 2016)

4.4.7 Solutions for the transport of products and orders

Manual: In FC0 products are transported in RCs. Within the pick circuit the orders are transported on a PC and after storing orders are transported in a DPF.

Mechanized: Mechanized transport can be done with conveyor belts and lifts. Order and product totes can be transported on the conveyor belts. It is also possible to transport HEs with conveyor belts to increase replenishment productivity within a manual pick circuit. As explained in the exploration phase, vertical transport is more difficult to realize than horizontal transport (Wehkamp,2016).

Robotised: Robots can be used to transport products and orders. In practice, Amazone uses KIVA robots to transport product cupboards to bring the product to the picker (Figure 27). The picker picks the product at a pick station. KIVA robots use RFID navigation to orientate. The robot can carry up to 450 kg and has a velocity of 1,3 m/s (Amazone, 2015).

Figure 27: KIVA robots (Amazone, 2015)

The discussed solutions for the system means are schematised shown in the Morphological chart in Figure 28. The figure is based on a Morphological chart. A Morphological chart analysis is one of the formal design tools enabling collaborative product development (Huang & Mak, 1999). Due to the nature of this project, this is the most suitable methodology to use in order to create effective design alternatives. Within the Morphological chart the system functions are written on the X-axis. The solutions for the system functions (means) are listed below the system functions. Combinations of different system means are made to generate alternatives.

Means	System functions										
	Receiving	Replenishment	Product storage	Picking FM	Picking MM	Picking SM	Order storage	Consolidating	Storing	Tranportation products	Transportation orders
	Manual splitting	Manual	Racking	Manual	Manual	Manual	DPF	Manual	Manual	Manual	Manual
	Manual decanting	Semi-mechanised	Autostore	Zone station	Zone station	Zone station	Autostore	GTP station	Mechanise	Conveyor belt	Conveyor belt
	Mechanised	Mechanised	Miniload	GTP station	GTP station	GTP station	Miniload			KIVA	
			Shuttle				Shuttle				

Figure 28: Morphological chart (Author, 2016)

4.5 Alternatives

In this paragraph the design alternatives are generated. However, in this phase of the research it is not clear if the alternatives will meet up with the design criteria. This will be tested in the assessment phase. If the designs do not meet the criteria, they will be adjusted after the assessment and assessed again. To generate alternatives, suitable storage and picking combinations should be chosen. Possible combinations are displayed in Figure 29. The grey striped outlined systems are AS/RSs. Like already explained in the previous paragraph, storage systems will be assessed based on I/O-rate, storage capacity per square meter and flexibility (picking changes due to last minute order change.) In Table 9, the main specifications are presented per AS/RS. I/O-rate is measured per aisle, storage capacity is measured for the average height per system and flexibility is assessed qualitatively. It can be concluded that the I/O-rate of a Miniload system is too slow (70 – 150 cycles per hour) and the flexibility of an Autostore system is also not sufficient enough to fulfill the capacity requirements of the FC. Therefore, the Autostore and Miniload will not be included in the alternatives.

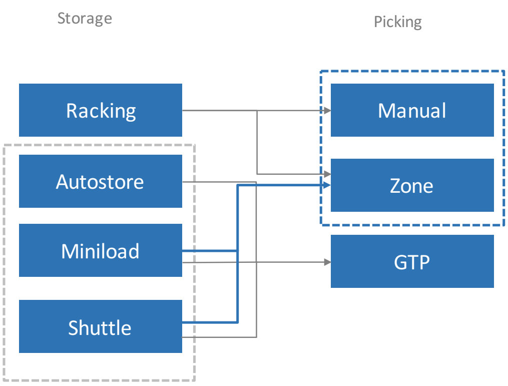

Figure 29: Possible combinations of storage and picking systems (Author, 2016)

Table 9: Summary main specifications AS/RS

	In-/output rate	Storage capacity	Flexibility
Autostore	~300-400 [totes/hr]	~20 [totes/m^2]	-
Miniload	~70-150 [totes/hr]	~50 [totes/m^2]	+
Shuttle system	~400-550 [totes/hr]	~20 [totes/m^2]	++

In Figure 29 combinations of different possible solutions are made to generate four different alternatives. Alternative 1 is based on FC0. Alternative 2 is semi-mechanized (manual picking with mechanized surrounding processes), alternative 3 is highly mechanized with three different pick strategies and alternative 4 is fully mechanized with one pick strategy and the use of KIVA robots for the transport of the products.

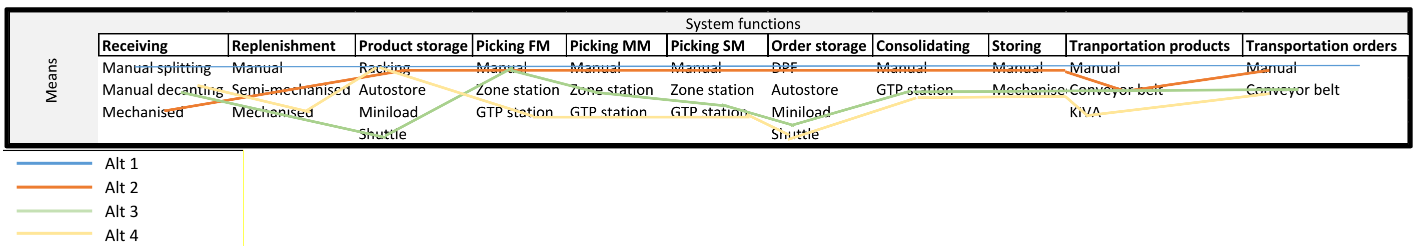

Figure 30: Alternatives generated from Morphological chart (Author, 2016)

Combinations of system functions are made in consultation with supply chain experts from Picnic. The combinations of certain systems functions are obligatory because of the dependency on each other. First the alternatives will be explained in more detail. Subsequently, the possible advantages and disadvantages and the possible effects on the criteria will be discussed. An overview of the alternatives with corresponding system solutions can be found in Appendix 8 (Figure 63). Conceptual layouts of the alternatives including process steps are depicted in Appendix 9.

4.5.1 Alternative 1: fully manual

Alternative 1 is an alternative in which the processes are performed fully manual. Manual splitting will still be in place and the replenishment and picking will also be performed manual. Order storage will be executed on DPFs, consolidating and storing will be performed by hand and the transportation of products and orders will be performed manually with the help of RCs and DPFs. To enable the fulfilment of the large scale of orders, the pallet circuit will include picking from pallets. FMs will also have two places in the circuit to decrease the chance of queuing for a product (Appendix 9, Figure 64).

4.5.2 Alternative 2: semi-mechanized

Alternative 2 is based on the knowledge that the picking in the current FC0 is relatively efficient at the moment. Therefore, in this alternative picking remains manual within a pick circuit which also facilitates pallet pick. However, surrounding activities like splitting and pick cart preparation are mechanized. The replenishment of products is facilitated with conveyor belt transport from the sorter into the different aisles. To insure that the conveyor belts will not block the replenishment aisles, the conveyor belts will be installed above walking height. Spiral conveyors will be used to descend the products. A conceptual drawing of a replenishment conveyor belt and spiral conveyor is shown in Figure 19. To facilitate last moment addition of fresh products, consolidation will be performed with GTP stations. Orders totes can be stored in an AS/RS, when these totes need to be consolidated with fresh products, the totes will be transported to a GTP station. At the GTP station, the fresh products will be added to the tote (Appendix 9, Figure 65).

4.5.3 Alternative 3: highly mechanized, product transport with conveyor belts

Alternative 3 is a highly mechanized alternative. Within the ambient picking circuit, three different pick strategies will be installed to optimize picking rates. These pick strategies are installed in separate areas within the FC. FMs will be directly picked from pallets. This will be performed with the help of a PC and a sort-while-pick strategy. MMs will be picked with a zone pick strategy. SMs will be picked at a GTP station. The pick strategies are dependent on the sales volume of the SKU. To pick items in a zone or at a GTP station, HEs will have to be decanted from pallets into totes. The product totes are stored in an AS/RS. The AS/RS will also be used for the storage of orders. The order storage is useful when orders have to be pre-picked or consolidated. The consolidation with fresh goods will be done at GTP stations. The transport of the product and order totes is done with the help of conveyor belts (Appendix 9, Figure 66).

4.5.4 Alternative 4: fully mechanized, product transport with KIVAs

Alternative 4 is fully mechanized. This alternative contains the same pick strategy for SMs, MMs and FMs. GTP stations will be used to pick all products. KIVA robots are installed to transport the products in cupboards to the GTP station. Conveyor belts will transport the order to the GTP station. The cupboards will be filled at decanting stations. Consolidation will also be performed at GTP stations (Appendix 9, Figure 67).

4.6 Possible advantages and disadvantages of alternatives

In this chapter possible advantages and disadvantages and expected effects of the different alternatives on the criteria are defined. This will give better insights in the outcomes of the model in the assessment.

4.6.1 Advantages and disadvantages of alternative 1

Alternative 1 enhances fully manual processes. In the assessment a re-design of the pick circuit has to be taken into account to facilitate manual order picking for 20K orders. Main advantages of a fully manual FC are low CapEx. Besides this, the processes are very flexible and therefore easy to change and to scale. Main disadvantage is the productivity. Especially the pick productivity, which will decrease when the pick circuit increases. It could also occur that the required high number of pickers, will cause queuing in the pick-circuit. The high number of required FTE, together with large surface area requirements to ensure flow, will generated high OpEx. Expected is that this alternative will not meet the productivity (155 items per hour) and the OpEx (0,11 cents per item) requirements.

4.6.2 Advantages and disadvantages of alternative 2

Alternative 2 has surrounding processes mechanized. The possible disadvantages due to the manual picking circuit explained in alternative 1, will also apply for alternative 2. Expected is that all-in productivity will increase due to the mechanization of the splitting, the replenishment, the pick cart preparation and storing. The installation of the conveyor belts for replenishment and consolidation will decrease flexibility of the system compared to alternative 1 and increase the CapEx. The installation of an AS/RS to store order totes will enable operating with a pre-picking schedule and sequencing for the mechanized storing of totes. If the AS/RS is connected to GTP stations, these stations can be used for the consolidation of JIT products.

4.6.3 Advantages and disadvantages of alternative 3

Alternative 3 is highly mechanized and therefore the least flexible alternative. Alternative 3 requires multiple pick strategies for the ambient articles. This will increase the order tote travelling between the different pick strategies. The mechanization will lead to an increase of the pick productivity and therefore in a decrease of the required FTE. Due to the installation of the AS/RS, it is expected that the number of surface area will decrease. The increase of pick productivity will decrease the OpEx. A major possible disadvantage of the system is the large number of conveyor belts and the transportation of totes between the different pick strategies.

4.6.4 Advantages and disadvantages of alternative 4

Alternative 4 is a fully mechanized but contains less conveyor belts. For the transport of the products, KIVA robots are used. Expected is that to ensure high productivity, a considerable number of cupboards with products should queue in front of the GTP stations. Consequently, a major number of KIVA robots is required. It is possible that the productivity rates which are achieved when the GTP stations are connected to conveyor belts, will not be reached. Expected is that the large number of KIVAs will result in high CapEx. Besides this, the cupboards used to store the products, cannot be higher than picking reach. Therefore, the required surface area for product storage will be higher than when a shuttle system is installed.

4.6.5 Expected effects on criteria

The expected effects given in the table below, are based on a FC handling 20K orders and are compared to alternative 1 (in which all processes are handled manually.) A plus sign represents an increase of the criteria; a minus sign stands for a decrease of the criteria. For example: a minus sign corresponding ‘FTE’ for alternative 2 means that it is expected that FTE on site will decrease for alternative 2, compared to alternative 1.

Table 10: Expected effects on design criteria

Design criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
All-in productivity	0	+	++	+
Surface area	0	+	--	+
FTE	0	-	-	-
CAPEX	0	+	++	+++
OPEX	0	-	--	-
Costs per year	0	+	++	+++

4.7 Conclusions design

In the design phase, the following sub questions where answered:

Sub question 7: What are the design goals for the new FC and which design criteria follow from this?
The goal of the design is to establish a FC that can fulfil 20K orders per day while meeting the operational and service requirements and minimizing the total fulfilment costs per year. The criteria on which the design will be assessed on are: all-in productivity, surface area, FTE, CapEx, OpEx and fulfilment costs per year.

Sub question 8: What are the design requirements and constraints that follow from the current FC and the growth perspective?
Main requirements are regarding the capacity, the design and the processes within the FC. Constraints are related to financial issues and timeliness. Requirements regarding the processes in the FC and the order and range characteristics, follow from FC0. Requirements regarding the number of to handle items are a result of the growth perspective.

Sub question 9: Which system solutions can be defined for the system functions?
The possible system solutions for the system functions can often be divided into manual, semi-mechanized and mechanized solutions. There are constraints regarding the combination of different solutions. Not all solutions can be combined with each other. Therefore, a pre-assessment is performed from which can be concluded that the Miniload and Autostore system are not suitable as an AS/RS within the FC.

Sub question 10: Which design alternatives can be composed for the new FC?
The four design alternatives are differing on the degree of mechanisation due to the combination of different system solutions. The first alternative is based on FC0 and is fully manual. Within the second alternative the picking process remains manual but the surrounding processes are mechanized. The third alternative is highly mechanized and includes three different pick strategies. The picking of FMs remains manual, MMs are picked within zones and SMs are picked at a GTP station. The zone and GTP stations are connected to a shuttle system. The shuttle system is also used for the storage of order totes. Within this alternative, conveyor belts are used to transport products and orders. The fourth alternative is fully mechanized in which all products are picked from GTP stations. All products are stored on cupboards which can be transported by KIVA robots. Orders totes are transported on conveyor belts and stored in a shuttle system.

Assessment

‘Does it seem realistic?’ Hans Eijkman
Progress meeting, August 2016

5. Assessment

An assessment will be performed to calculate the effects on the criteria and define if the alternatives meet the design requirements. In the assessment answers will be found on the following sub questions:

- What are the methods to assess the design alternatives?
- What are the effects of the alternatives on the design criteria?
- Which alternative meets the requirements and the growth perspective of Picnic?

To assess the four different alternatives, a mathematical deterministic model is developed to quantify and stress the alternatives. Van der Vorst (2009) distinguishes analytical models where relationships between elements are expressed with the help of mathematical equations and simulation for real-world systems that are too complex to allow for analytical modelling. Due to the deterministic character of the data and the need for Activity based costing (explained in the exploration phase), the model is a deterministic analytical model. The model is made in Excel and includes the quantification of the main processes with the corresponding logic between the processes and variables. Developing a valid model is an iterative process where several versions of a model are developed prior to obtaining a valid model (Sargent, 2015).
To construct the model, this iterative approach has been run through several times. In the report the final state of the model is presented. In Figure 31, the iterative model development according to Sargent is depicted. The first stage, the analysis and 'modeling' of the problem entity is performed in the previous phases of the research. In the next paragraph, in the conceptualization, the conceptual model is constructed. The conceptual model is face validated by Picnic supply chain professionals and therefore not further discussed. In the specification paragraph, the computer programming (the formulas and logic used in Excel) is explained. The 'computerized model' is verified in Paragraph 5.4 and validated in Paragraph 5.5

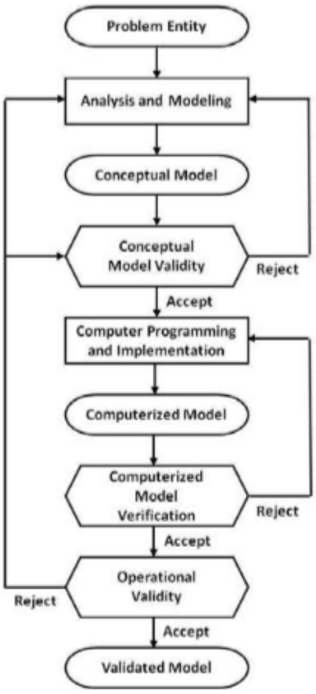

Figure 31: The model development iterative process (Sargent, 2015)

5.1 Conceptualization

In the conceptualization phase, the IDEF-0 diagrams from the exploration phase, are used to include the main systems functions in the model. The 11 system functions are integrated in the modules (Figure 32). These modules will be specified in the next paragraph. There are three main factors which are used as an input. These are the scenarios regarding the order profile, the number of orders and the work schedule.

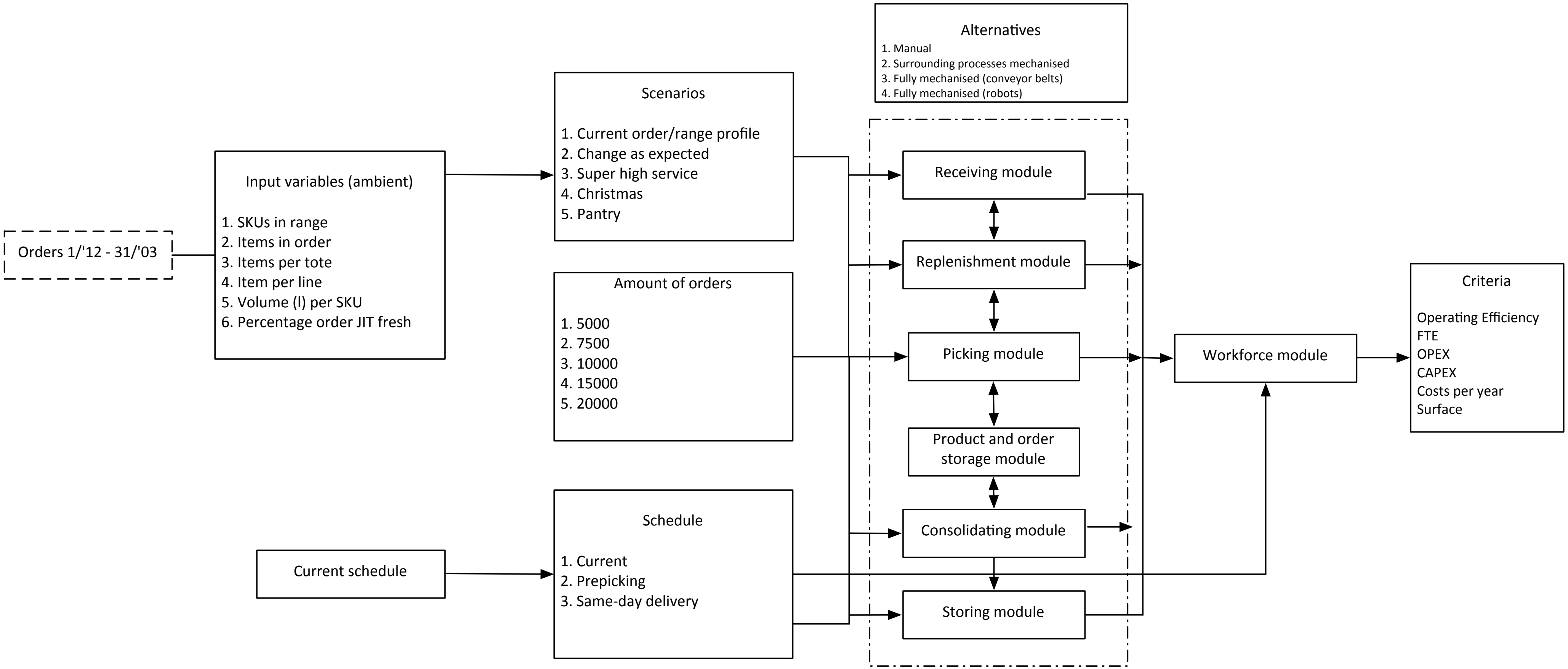

Figure 32: Set-up of the model (Author, 2016)

In the model, the different modules lead to productivity of different processes, which are used in the workforce module (Appendix 12, Table 48). This workforce module is used to calculate the required workforce in every alternative in combination with a certain order profile, number of orders and schedule. The workforce module is required to calculate the effect on the criteria. In Table 9, the formulas of how the criteria are calculated are presented. The model (and every alternative) is designed on the peak day. Meaning that on an average day there will be 21% less orders which have to be fulfilled. This is also called the busiest day method (Richards, 2014). Other methods are for example modelling on average day or typical day (Richards, 2014). Modelling on a peak day ensures that the design can handle the number of orders in the busiest day of the week.

Table 11: The design criteria

All-in productivity [items/hour]	Number of total handled items divided by the total hours of direct labour.	$\frac{Total\ amount\ of\ handeled\ items}{Total\ amount\ of\ hours\ direct\ labour}$	(1)
FTE on site [FTE]	The number of FTE on site. Sum of the minimum required number of people per process.	$\sum \frac{Amount\ of\ items\ to\ be\ handeled}{(Productivity * available\ hours)}$	(2)
Surface area FC	The sum of the required square meters per process	$\sum Surface\ per\ process$	(3)
CapEx [€]	The capital expenditure of the equipment.	$\sum Costs\ per\ equipment$	(4)
OpEx [€]	The operational expenditure based on the direct labour and rent (for one year).	$(Surface * rent) + (Hours\ direct\ labor * wage)$	(5)
Costs per year [€]	Total costs of depreciation of the CapEx and the OpEx per year	$\frac{CapEx}{Depreciation\ period\ (6\ years)} + OpEx$	(6)

5.2 Specification

In the specification phase the input and modules are specified in more detail. After an explanation regarding the input, the models will be explained on the basis of formulas.

5.2.1 The input

To get better insights in the behavior of the alternative on the criteria, the order profile (scenarios), number of orders and schedule can be adjusted in the model. In this paragraph the different scenarios and schedules will be discussed. The scenarios are based on five different variables regarding the order profile of the customers. These main variables are:

- Number of SKUs in ambient range
- Number of ambient items in order
- Number of items per tote
- Number of items per line
- Average volume per SKU (in liters)
- Percentage of orders to add JIT fresh

The variables form different scenarios. These scenarios are:

- Current order profile
- Change as expected (increase of SKUs, increase of number of items per order)
- Super high service (high number of SKUs, high percentage of JIT fresh)
- Christmas (high number of SKUs, high number of items per line, high percentage JIT fresh)
- Pantry order characteristics (low number of items per tote, high volume per SKU, low percentage JIT fresh)

In Appendix 10 the quantification and the combination of variables per scenario are presented (Table 39 and Table 40).
Beside the scenarios, there can be chosen from three different schedules. The schedules influence the number of hours that can be spent on every process (Appendix 11). The schedules are:

- Current schedule
- Pre-picking schedule
- Same day delivery schedule

In the pre-picking schedule, picking hours are added because orders are partially picked the day before. In the 'same day delivery schedule' more orders have to be picked on the of delivery, picking hours remain the same but expected is that the required FTE will increase drastically.
In the causal relationship diagram (CRD) below the causal relationships of the main variables in the model on the criteria are presented. The input variables have a striped outline. The output variables are fully outlined. The degree of mechanization is shown with a dotted outline. The degree of mechanization is the decision variable per module. All variables used in the Excel model are given in Table 44, Table 45, Table 46 and Table 47 in Appendix 12.

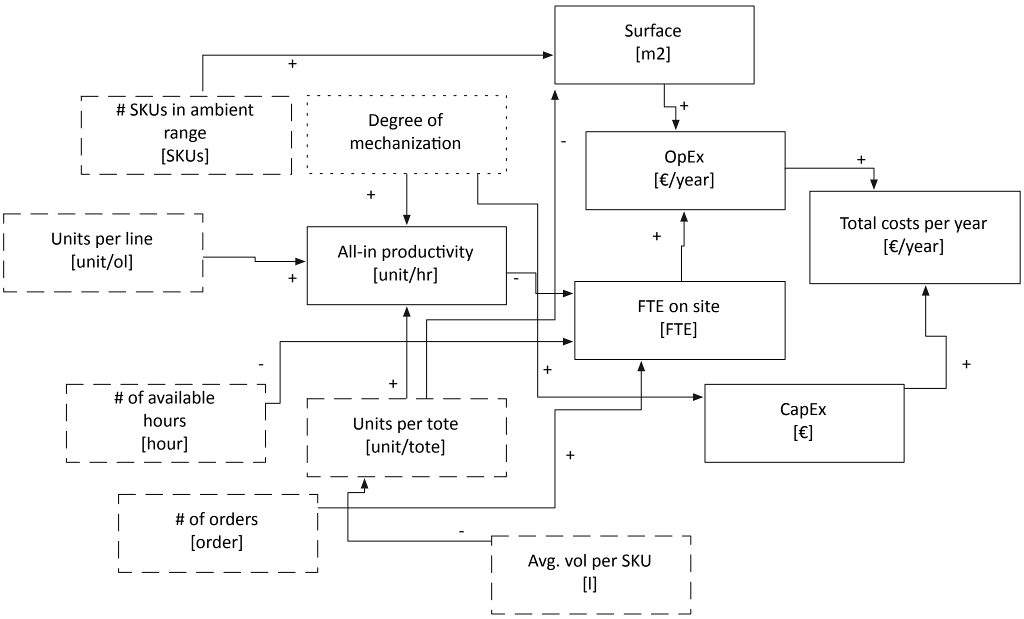

Figure 33: CRD of main variables in model

5.2.2 The modules

The model is built up from different modules to calculate the productivity per system function. The equipment that is installed for the processes is based on the system solutions, the corresponding productivities are calculated in the modules. The modules also influence each other. For example: the receiving productivity influences the required productivity when items are replenished. A module for a certain process (e.g. picking) can be built up differently per alternative. This is because in the mechanized alternatives other variables effect the productivity in comparison to the manual alternatives. Below the modules are specified. The explanations of the mathematical notations are given below the formulas. If the variable begins with '*Vi*' it is an input variable related to the amount of orders, the schedule scenarios or the order profile scenarios.

Receiving module

Alternative 1

The receiving module for alternative 1 is based on the current receiving process and productivity. Assumed is that HEs enter the FC on pallets. Because of the fact that productivity is already known, it requires only one step to calculate the required FTE (Formula 7).

$$A_{rc} = \frac{HE_i}{Pr_s} \div Vi_{hr} \tag{7}$$

A_{rc}	Number of receivers	[FTE]
HE_i	Number of HE inbound	[HE]
Pr_s	Productivity splitting	[HE/hr]
Vi_{hr}	Number of hours receiving	[hr]

Alternative 2

The receiving productivity of alternative 2 is based on a standard mechanized sorter. The number of HE to be sorted is defined in Formula 8. The number of standard sorters is calculated with Formula 9 and the number of induction points is calculated with Formula 10.

$$HE_i = \frac{(Vi_o \times Vi_{auo})}{A_{ch}} - HE_p \tag{8}$$

$$So = \frac{HE_i \div Pr_s}{Vi_{hr}} \tag{9}$$

$$Ip = \frac{Pr_s}{Pr_i} \tag{10}$$

HE_i	Number of HE inbound	[HE]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
A_{ch}	Number of CE per HE	[CE/HE]
HE_p	Number of HE in pallet circuit	[HE]
So	Number of sorters	[sorter]
Pr_s	Sorter productivity	[HE/hr]
Vi_{hr}	Number of hours receiving	[hr]
Ip	Number of induction points	[induction point]
Pr_i	Induction productivity	[HE/hr]

Alternative 3

Receiving in alternative 3 is performed differently per pick strategy. The zone and GTP strategy require decanting. The productivity of decanting is validated by supply chain professionals Wolters (2016) and Schoonderwoerd (2016). The number of decanting stations is calculated with Formula 11.

$$Ds_3 = \frac{(Vi_o \times Vi_{auo}) \times (\beta + \gamma)}{Pr_d} \div Vi_{hr} \tag{11}$$

Ds_3	Number of decanting stations alternative 3	[station]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
β	Percentage MM	[%]
γ	Percentage SM	[%]
Pr_d	Decanting productivity	[item/hr]
Vi_{hr}	Number of hours receiving	[hr]

Alternative 4

Receiving productivity of alternative 4 is fully dependent on decanting. All products are decanted and put into the cupboards that are transported by the KIVA robots. Formula 12 presents how the number of decant stations in alternative 4 is calculated.

$$Ds_4 = \frac{(Vi_o \times Vi_{auo})}{Pr_d} \div Vi_{hr} \tag{12}$$

Ds_4	Number of decanting stations alternative 4	[station]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
Pr_d	Decanting productivity	[item/hr]
Vi_{hr}	Number of hours receiving	[hr]

Replenishment module

Alternative 1

Productivity is assumed the be the same as in FC0. Number of FTE is calculated in the same way as Formula 7. But in stead of the receiving productivity, replenishment productivity is used.

Alternative 2

In alternative 2, productivity is calculated on the basis of the outflow of the spiral conveyors in the aisles, average walking distance of the replenishers, walking speed and filling speed. Assumed is that the outflow is evenly spread over the aisles. In reality this is not the case. Formula 13 shows how the inbound of HEs per aisle is calculated. Formula 14 results int the outflow per spiral conveyor.

$$Ai_{ib} = \frac{HE_i}{Vi_{hr}} \div Ai_2 \tag{13}$$

$$SC_{ob} = \frac{Ai_{ib}}{A_{sc}} \tag{14}$$

Ai_{ib}	HE aisle inbound	[HE/hr]
HE_i	Number of HE inbound	[HE]
Vi_{hr}	Number of hours receiving	[hr]
Ai_2	Number of two sided aisles	[aisle]
SC_{ob}	Spiral conveyor outflow	[HE/hr]
A_{sc}	Number of spiral conveyors per aisle	[SC/aisle]

To calculate the replenishment productivity, the outflow of the spiral conveyors is used (Formula 15). The required productivity is then calculated with Formulas 16, 17, 18 and 19. The number of replenishers per aisles is calculated with Formula 20. All formulas used in the replenishment module are presented in Appendix 12 (Table 51).

$$NPr = SC_{ob} \times A_{sc} \tag{15}$$

$$t_{tr} = t_{wr} + t_{ur} + t_{pr} + t_{sr} \tag{16}$$

$$t_{wr} = \frac{s_{wr}}{v_w} \tag{17}$$

$$s_{wr} = \frac{Ai_l}{A_{sc}} * s_{ws} \tag{18}$$

$$Pr_r = \frac{3600}{t_{tr}} \tag{19}$$

$$Rp_a = \frac{NPr}{Pr_r} \tag{20}$$

NPr_r	Required replenishment productivity per aisle	[HE/hr/aisle]
SC_{ob}	Spiral conveyor outflow	[HE/hr/sc]
A_{sc}	Number of spiral conveyors per aisle	[SC/aisle]
t_{tr}	Total time replenishment per HE	[s]
t_{wr}	Walking time replenishment	[s]
t_{ur}	Unpacking time replenishment	[s]
t_{pr}	Placing time replenishment	[s]
t_{sr}	Scanning time replenishment	[s]
s_{wr}	Average walking distance per HE	[s]
v_w	Average walking speed	[m/s]
Ai_l	Aisle length	[m]
s_{ws}	Share average walking distance	
Rp_a	Number of replenishers per aisle	[FTE/aisle]
Pr_r	Replenishment productivity replenisher	[HE/hr]

Alternative 3 and 4

Replenishment rates in alternative 3 are also dependent on the pick strategy. 'Manual' handling is required to replenish the pallets for FM pick. Replenishment of the AS/RS for the zone and GTP pick strategies is performed with the help of conveyor belts. The replenishment rates of the AS/RS are not taken into account in the model. The replenishment rates in alternative 4 are dependent on the decanting (Formula 12) and the timeliness of the products (transported by the KIVA) and the order totes. The model assumes that totes and KIVAs or on time at the AS/RS and in the Zone or GTP stations. Therefore, no calculations are made regarding the replenishment of the AS/RS, the zones and the GTP stations.

Picking module

Alternative 1 & 2

The pick productivity calculated in the picking module of alternative 1 & 2 is highly dependent on the length of the pick circuit. The length of the pick circuit is dependent on the number of SKUs and stock. The pick circuit formulas are presented in the product storage module below. In the outcomes of the model, it can be seen that there is a maximum mount of PCs within a pick circuit due to time and length constraints. The total time per pick round for alternative 1 and 2 is calculated with Formulas 21 and 22. This is used as an input for the time per item pick (Formula 23). The order line productivity (Formula 24) is calculated in the same way but in stead of using item quantities, order line quantities are used. All formulas used in this module are given in Appendix 12 (Table 50).

$$t_{pr1} = t_w + t_p + t_{pcp} \tag{21}$$

$$t_{pr2} = t_w + t_p \tag{22}$$

$$t_{ip} = t_{pr2} \div (T_{pc} \times Vi_{upt}) \tag{23}$$

$$I_{pp} = \frac{3600}{t_{ip}} \tag{24}$$

t_{pr1}	Total pick round time alternative 1	[s]
t_{pr2}	Total pick round time alternative 2	[s]
t_w	Walking time	[s]
t_p	Pick time	[s]
t_{pcp}	Pick cart preparation time	[s]
T_{pc}	Totes per pick cart	[tote/pc]
Vi_{upt}	Number of items per tote	[item/tote]
I_{pp}	Item pick productivity	[item/hr]
t_{ip}	Time per item pick	[s]

The flow in the circuit is calculated with the help of the departure rate (Formula 25). The maximum number of PCs in the circuit is calculated with Formula 26, 27 and 28. The required productivity is defined with Formula 29. This is an input to calculate the disparity between required and maximum achievable productivity (Formula 30).

$$Dr_{pc} = \frac{s_{min}}{v_w} \tag{25}$$

$$PC_{maxl} = \frac{L_{pcc}}{L_{pc}} \tag{26}$$

$$PC_{maxt} = \frac{t_{pr1}}{Dr_{pc}} \tag{27}$$

$$Pr_{mpmax} = \min(PC_{maxl}, PC_{maxt}) \times t_{ip} \tag{28}$$

$$\Sigma Pr_{pn} = \frac{(Vi_o \times Vi_{auo})}{Vi_{hp}} \tag{29}$$

$$\triangle Pr_p = Pr_{pmax} - Pr_{pn} \tag{30}$$

Dr_{pc}	Departure rate pick cart	[pc/s]
s_{min}	Minimum distance between pick carts	[m]
v_w	Average walking speed	[m/s]

PC_{maxl}	Maximum pick carts (length constraint)	[PC]
L_{pcc}	Length pick circuit	[m]
L_{pc}	Length pick cart	[m]
PC_{maxt}	Maximum pick carts (time constraint)	[PC]
Pr_{mpmax}	Maximum manual pick productivity	[item/hr]
Pr_{pn}	Required pick productivity	[item/hr]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
Vi_{hp}	Number of hours picking	[hr]
$\Delta\ Pr_p$	Difference between required and maximum pick productivity	[item/hr]

Alternative 3

Because of the different pick strategies, pick productivity for alternative 3 is calculated separately for SMs, MMs and FMs. The deviation of SMs, MMs and FMs could be varied on to find the optimal number of to handle items per pick strategy. The pick productivity within the FM area is highly dependent on the aisle length and the number of picks per pick round (this is calculated with the same formulas used in alternative 1 and 2, however within the pick circuit there are only pallets and no cupboards and dollies). Pick productivity within the MM (zone picking) area is dependent on the number of meters the pickers will have to walk and the capability of the order- and product totes being on time. In the model they are assumed to be on time. Formulas 31, 32 and 33 are used to calculate the pick productivity. With Formula 34, the number of zone stations is calculated. All formulas used in the picking module in alternative 3 are described in Appendix 12 (Table 52).

$$\sum t_{ipz} = t_{wp} + t_p + t_{pp} + t_{sp} + t_{cp} \tag{31}$$

$$t_{wp} = \frac{s_w}{v_w} \tag{32}$$

$$Pr_{zp} = \frac{3600}{t_{ipz}} \tag{33}$$

$$Z_p = \frac{(Vi_o \times Vi_{auo} \times \beta)}{Pr_{zp}} \div Vi_{hp} \tag{34}$$

$\sum t_{ipz}$	Total pick time per item in zone	[s/item]
t_{wp}	Walking time picking	[s/item]
s_w	Average walking distance	[s]
v_w	Average walking speed	[s]
t_p	Pick time per item	[s/item]
t_{pp}	Place time picking	[s/item]
t_{sp}	Scan time picking	[s/item]
t_{cp}	Click button time picking	[s/item]
Pr_{zp}	Zone pick productivity	[item/hr]
Z_p	Total number of zone pick stations	[station]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
Vi_{hp}	Number of hours picking	[hr]
β	Percentage MM (of total items)	[%]

The formulas used to calculate the productivity of the FM pick are similar to the formulas used to calculate the productivity of the MM pick. However, at the GTP stations no walking is required and therefore higher productivity can be achieved. Total time per item pick is calculated with Formula 35, the productivity with Formula 36 and the number of GTP stations with Formula 37.

$$t_{ipg} = t_p + t_{pp} + t_{sp} + t_{cp} \tag{35}$$

$$Pr_{gp} = \frac{3600}{t_{ipg}} \tag{36}$$

$$G2P_{p3} = \frac{(Vi_o \times Vi_{auo} \times \alpha)}{Pr_{gp}} \div Vi_{hp} \tag{37}$$

t_{ipg}	Pick time per item at GTP	[s]
t_p	Pick time per item	[s/item]

t_{pp}	Place time picking	[s/item]
t_{sp}	Scan time picking	[s/item]
t_{cp}	Click button time picking	[s/item]
Pr_{gp}	GTP pick productivity	[item/hr]
$G2P_{p3}$	Number of goods to person stations for alternative 3	[station]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
α	Percentage SM (of total items)	[%]
Vi_{hp}	Number of hours picking	[hr]

Alternative 4

The pick productivity for alternative 4 is dependent on the on-time presentations of the KIVAs and the order totes. In this module they are also assumed to be on time. However due to the lower maximum speed of KIVA (1,3 m/s) compared to the speed of a conveyor belt (2,5 m/s), it is excepted that lower pick productivity can be reached than in alternative 4.
The net volume of the KIVA cupboard is defined with Formula 38. The number of GTP stations and the required cupboards and KIVAs are calculated with Formulas 39, 40 and 41. All formulas used in this module are presented in Appendix 12 (Table 53).

$$V_{nKIVA} = \delta \times V_{KIVA} \tag{38}$$

$$G2P_{p4} = \frac{(Vi_o \times Vi_{auo})}{Pr_{gkp}} \div Vi_{hp} \tag{39}$$

$$Cp = \frac{(Vi_o \times Vi_{auo} \times Vi_{avs} \times \varepsilon)}{V_{nKIVA}} \tag{40}$$

$$\sum KIVA = (A_{ks} + A_{kq}) \times G2P_{p4} \tag{41}$$

V_{Kiva}	Gross volume KIVA cupboard	[l]
δ	Fill rate KIVA cupboard	[l]
$G2P_{p4}$	Number of GTP stations alternative 4	[station]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
Pr_{gkp}	GTP KIVA pick productivity	[item/hr]
Cp	Number of cupboards	[cupboard]
Vi_{hp}	Number of hours picking	[hr]
V_{nKiva}	Net volume KIVA cupboard	[l]
Vi_{avs}	Average volume per SKU	[l]
ε	Safety stock factor	
$Kiva$	Number of KIVAs	[KIVA]
A_{ks}	Number of Kivas for transport per station	[KIVA]
A_{kq}	Number of Kiva for queueing per station	[KIVA]

Storing module

Alternative 1

The storing productivity for alternative 1 is based on the current storing productivity in FC0. The number of FTE can be calculated with Formula 42.

$$A_{st} = \frac{A_{tt}}{Pr_{st}} \div Vi_{hs} \tag{42}$$

A_{st}	Number of storers	[FTE]
A_{tt}	Number of totes	[tote]
Pr_{st}	Storing productivity	[tote/hr]
Vi_{hs}	Number of hours storing	[hr]

Alternative 2, 3 & 4

The storing productivity for alternative 2, 3 & 4 is based on the productivity of the mechanized frame loader and the number of totes that need to be stored. The number of DPFs is calculated with Formula 43 and the number of frame loaders with Formula 44.

$$A_{dpf} = \frac{A_{tt}}{A_{tdpf}} \tag{43}$$

$$A_{fl} = \frac{A_{dpf}}{Pr_{fl}} \div Vi_{hs} \tag{44}$$

A_{dpf}	Number of DPFs	[DPF]
A_{tt}	Number of totes	[tote]
A_{tdpf}	Number of totes per DPF	[tote/dpf]
A_{fl}	Number of frame loaders (to store)	[frame loader]
Pr_{fl}	Productivity frame loader	[tote/hr]
Vi_{hs}	Number of hours storing	[hr]

Order storage module
Alternative 1
The order storage module for alternative 1 only contains the required number of DPFs for order storage (Formula 43).

Alternative 2, 3 & 4
The order storage module for alternative 2, 3 & 4 calculates the required number of locations in the AS/RS for orders. This is done by calculating the in- and output flow of order totes during the day as a result of pre-picking and picking. The maximum number of order totes in the AS/RS defines the minimum required number of locations for order totes in the AS/RS. This is calculated with Formula 45. The amount of order tote locations required in the buffer over time is visualized in Figure 68 in Appendix 12.

$$\begin{aligned} L_o &= max_{t_0 \dots t_n} \{f(x_1), f(x_2), f(x_3)\} \\ f(x) &= B_{in} - B_{out} \\ t_n &= 48 \end{aligned} \tag{45}$$

L_o	Locations order totes	[location]
B_{in}	Number of totes going in buffer	[tote/0,5 hr]
B_{out}	Number of totes going out buffer	[tote/0,5 hr]

Product storage module
Alternative 1&2
Product and order storage capacity is based on the current capacities. However, due to alterations in the pick circuit when orders increase, storage capacity of products will also increase. The number of cupboards in which the orders are stored influence the length of the pick circuit. The length of the pick circuit is calculated by Formula 46. The length of the pallet circuit is based on the number of homogenous (non mixed) inbound pallets. More in depth formulas which are used to calculate the pick circuit can be found in Appendix 12 (Table 50).

$$L_{pcc} = L_{palcc} + L_{cupcc} + L_{dolcc} \tag{46}$$

L_{pcc}	Length pick circuit	[m]
L_{palcc}	Length pallet circuit	[m]
L_{cupcc}	Length cupboard circuit	[m]
L_{dolcc}	Length dolly circuit	[m]

Alternative 3
Product storage for alternative 3 is calculated based on the number of items and unique SKUs picked at the GTP and within the zone stations. The number of required locations for product totes in the AS/RS is dependent on the maximum possible items in a product tote. This is also dependent on the storage life time and the trash hold of the products (Wolters, 2016). In the model assumptions are made regarding storage lifetime (average number of days SKUs in AS/RS) and threshold per SKU. Formula 47 is used to define the number of locations for product totes. With Formula 48 the required total number of locations in the AS/RS is defined.

$$L_p = \frac{((Vi_o \times Vi_{auo}) \times (\alpha + \beta) \times Slt_{sku} \times \sigma)}{Vi_{ipt}} \tag{47}$$

$$\sum L_{AS/RS} = L_o + L_p \tag{48}$$

L_p	Locations product totes	[location]
Vi_o	Number of orders	[order]
Vi_{auo}	Number of items ambient order	[item/order]
α	Percentage SM (of total items)	[%]
β	Percentage MM (of total items)	[%]
L_p	Locations product totes	[location]
Vi_{ipt}	Item per product tote	[item]
Slt_{sku}	Storage life time factor SKU	
σ	Threshold AS/RS	[%]
$L_{AS/RS}$	Locations AS/RS	[location]
L_o	Locations order totes	[location]

Alternative 4
Product storage in alternative 4 is integrated in the picking module. Corresponding formulas can be found in Appendix 12 (Table 53).

Consolidation module
Alternative 1
For alternative 1 consolidation is only in place to merge the tote with items that where out of stock during the normal pick strategy. To calculate the FTE, Formula 7 is used but with the corresponding productivity and available hours for the consolidation process.

Alternative 2, 3 & 4
For alternative 2,3 & 4 consolidation is performed with GTP stations which are connected to an AS/RS. The number of stations is calculated based on the pick productivity at the GTP stations and the number of orders required to be consolidated. Important is to underpin that there is assumed that a tote receives one item for consolidation. The number of consolidation stations can be calculated with Formula 49.

$$G2P_{cs} = \frac{\left(A_{tt} \times Vi_{pojit}\right)}{Pr_{gp}} \div Vi_{hcjit} \tag{49}$$

$G2P_{cs}$	Number of GTP stations to consolidate	[station]
A_{tt}	Number total totes	[tote]
Vi_{pojit}	Percentage orders to add JIT fresh	[%]
Pr_{gp}	GTP pick productivity	[item/hr]
Vi_{hcjit}	Number of hours JIT consolidating	[hr]

5.3 Data collection
The data that is used in the model is based on the sales between the first of December and the end of March. From this data all the current values for the variables is calculated. Data is used to quantify equipment productivity is gathered from material handling suppliers like Knapp, Vanderlande and Districort. This data is imported from the initial values tab in the model. The initial values are presented in Appendix 13 (Table 54).

5.4 Verification
The usefulness of a model depends on the accuracy and reliability of the output. However, it has to be underpinned that a model is a limited abstraction of reality. Therefore the output always includes imprecisions (Beek, 2005). Its is highly important to make an estimation of the cause and effect of these imprecisions. To do this, a verification and validation analysis is performed.

Sargent (2005) describes verification as 'assuring that the computer programming and implementation of the conceptual model is correct'. The verification of the model is performed iteratively by continuously checking the different formulas and the outcomes of the different modules. If irregularities were detected, a backward step-by-step approach was used to detect the errors. Besides this, the model has been checked and discussed with supply chain professionals at Picnic.

Because of the difference of level of detail in the model, the uncertainty level differs per module. In some models it is assumed that there is a linear relationship between variables. However, in reality this is not always the case.
According to Sargent (2005), Extreme Condition Testing can be performed to check if the model structure and output is plausible for any extreme and unlikely combination of levels of factors in the system.

For the Extreme Condition Test, the model is run with an input of 50 orders. It has to be underpinned the the model does not generate a pick circuit for smaller than 5K orders. Therefor in alternative 1 and 2, the 50 orders are fulfilled with a pick circuit for 5K orders. The minimum equipment capacity of the model is, with some exceptions, 5K orders per day (e.g. 1 aisle of AS/RS). The outcomes of the test can be found in Table 12. It shows that alternative 1 can fulfil the 50 orders with the lowest costs. Alternative 2 will require the largest number of FTE. This is because of the presence of the different spiral conveyors in the pick circuit used for replenishment. Alternative 3 results in the largest CapEx. This is due to the high investments for the AS/RS aisles, the sorter, the conveyor belts and the spiral conveyors. On the other hand, alternative 3 results in relatively low costs compared to the other alternatives, this is because the required amount of KIVAs is much more flexible than the required amount of conveyor belts in alternative 3. It should be emphasized that IT systems such as the WMS and WCS are excluded from this research. In reality these systems will have a considerable influence on the total costs per year in alternative 4. The highest productivity when the Extreme Condition Test is performed is achieved by alternative 4. This can be explained due the fact that there is only one pick strategy maintained within this alternative and therefore only one decanting and GTP station with one FTE can fulfill the 50 orders.

Table 12: Extreme Condition Test: input 50 orders per day

Design criteria	Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4
All-in productivity	[item/hour]	49	17	99	130
Surface area	[m²]	6084	7059	2692	151
FTE	[FTE]	2	7	1	1
Direct labour costs	[€]	0,30	0,93	0,17	0,13
OPEX/year	[€]	512095	741310	231547	43312
Total costs/year	[€]	64K	4.5M	10.6M	3.6M

The outcomes of the Extreme Condition Test when running the model with an input of 50K orders are presented in Table 56 in Appendix 14. From the results in Table 56, it can be concluded that the model keeps scaling. However, it has to be emphasized that the maximum pick circuit in alternative 1 and 2 is for handling 20K orders.

5.5 Validation

Sargent (2005) describes validation as determining that the model-representation is ‘reasonable’ and the model’s output has sufficient accuracy for the intended purpose of the model. In the validation stage the model is compared to the actual system, it is checked if the model represents reality.

First of all, the correctness of the assumptions and theories underlying the conceptual model should be determined (Sargent, 2005). For this research, all assumptions made during modeling (Appendix 13, Table 55), were checked with one or more experts. Besides the check of the assumptions, the outcomes of the model should be compared with the current situation i.e., the productivity of FC0. This can be done by comparing the outcomes of alternative 1 (the fully manual alternative) with current productivities. For example: in the picking module of alternative 1 and 2 for a picking circuit for 5000 orders (including pallet pick), pick productivity is 156 lines per hour. This is when there is a replenishment rate of 4 times per day. This productivity (close to the current productivity) can be achieved because of the higher replenishment rate compared to the current situation. If replenishment was only one time per day, the aisle length would increase drastically and productivities would therefore decrease. Formula 46 can be used to calculate the length of the pick circuit (by adding the pallet, dolly and cupboard circuit). Within the model, the replenishment factor influences the cupboard circuit. (The dollies are only replenished once and the pallet circuit is replenished when needed.) The equation to calculate the length of the cupboard circuit is presented in Formula 50. With Formula 31 the time per item pick can be calculated. This formula is dependent on the walking time per pick round. Formula 51 shows the dependency of the walking time per pick round on the length of the pick circuit. These are natural effects, which would also occur in reality.

$$L_{cupcc} = \frac{\sum i_{ib_{<1pal}} \times \varepsilon}{\xi} \div \eta \tag{50}$$

L_{cupcc}	Length cupboard circuit	[m]
$i_{ib_{<1pal}}$	Inbound items smaller than 1 pallet	[item/day]
ε	Safety stock factor	
ξ	Replenishment frequency per day	
η	Product density	[item/m]

$$t_{wp} = \frac{L_{pr}}{v_w} \tag{51}$$

t_{wp}	Walking time picking	[s]
L_{pr}	Length pick round	[m]
v_w	Average walking speed	[m/s]

Some effects of mechanization on productivity are validated with the help of information from warehouses already mechanized. For example: the decanting rates at decanting stations and picking rates at pick stations where confirmed by (Buijsen, 2016) from Wehkamp, and the picking rates within zone stations were confirmed by Schoonderwoerd (2016) from Technische Unie.
An other way to validate the model is to compare the outcomes of the criteria with known productivities of other grocery FCs. The productivity of alternative 1 (fully manual) is close to the current productivity of the FC. Like expected, the productivity of alternative 2 with mechanized surrounding processes, is higher than alternative 1. Alternative 3 is comparable with an Ocado FC. However, Ocado has not disclosed witch processes were taken in account to calculate all-in productivity. All-in productivity of Ocado FCs differs between 120 and 200 items per hour.
Picnic supply chain professionals have confirmed that an all-in productivity of 153 items per hour is certainly achievable for a highly mechanized system with conveyor belts. It is harder to compare the outcomes of alternative 4 with FCs in practice. Amazone, who uses KIVA robots, doesn't share information on their productivity. However, because of the relatively low speed of the KIVA robots, it is assumed that picking rates will be around 300 items per hour. As expected, this leads to a lower all-in productivity compared to alternative 3, wherein productivities of 600 items per hour can be reached.

5.6 Results

As expected, the results per design criteria differ when the number of orders, the scheduling scenario and the scenario regarding tote and order characteristics is varied. Concerning design goals and requirements, Picnic has stated that the FC has to be able to handle 20K orders per day, with a minimum productivity of 155 items per hour and maximum direct labour costs of 0,11 cents per item. For this reason, results will be presented for a FC handling 20K orders. However, number of orders has a major effect on the design criteria. Therefore, these effects are presented. The effect of different scheduling scenarios on design alternatives is estimated consequently (Figure 42). The influence of different variables regarding the order profiles on output is presented in Paragraph 5.6.4. A sensitivity analysis is performed to define the effect of the assumptions made in the model on design criteria. Finally, a scenario analysis (combining the amount of orders, schedules and scenarios) is performed to get better insight in the effects of specific combinations of variables on the design criteria for alternative 3.

5.6.1 Results when handling 20K orders

When assessing the alternatives based on handling 20K orders per day, the order profile scenario is set on 'as expected' and the schedule is set on 'pre-picking'. This is because Picnic supply chain professionals have stated that this will be the most likely situation when handling 20K orders. Results are presented in Table 13.

Table 13: Effects on design criteria with 20K orders, change as expected scenario, pre-picking schedule

Design criteria	Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4
All-in productivity	[Item/hour]	54	81	153	132
FTE on site	[FTE]	641	327	198	245
Labour costs/item	[€/item]	0,28	0,20	0,11	0,13
Surface area	[m^2]	14.6K	18.1K	17.8K	21K
CapEx	[€]	4.2M	9.8M	30.6M	67.4M
OpEx	[€/year]	37.6M	25.2M	14.4M	16.4M
Costs per year	[€]	38.3M	27.3M	19.3M	27.8M

Table 13 shows that like expected, the manual alternative has the lowest all-in productivity. Alternative 3 results in the highest productivity. Therefore, highest costs are generated by alternative 1. Alternative 4 results in very high CapEx, however due to the low OpEx, the yearly costs are still lower than alternative 1. With alternative 3 the smallest workforce is needed. The nummer of FTE needed is nearly third of the number of FTE needed in the manual alternative.

For handling 20K orders, a pre-picking schedule and input variables changing alternative 3 is, as expected is most beneficial (Figure 34).

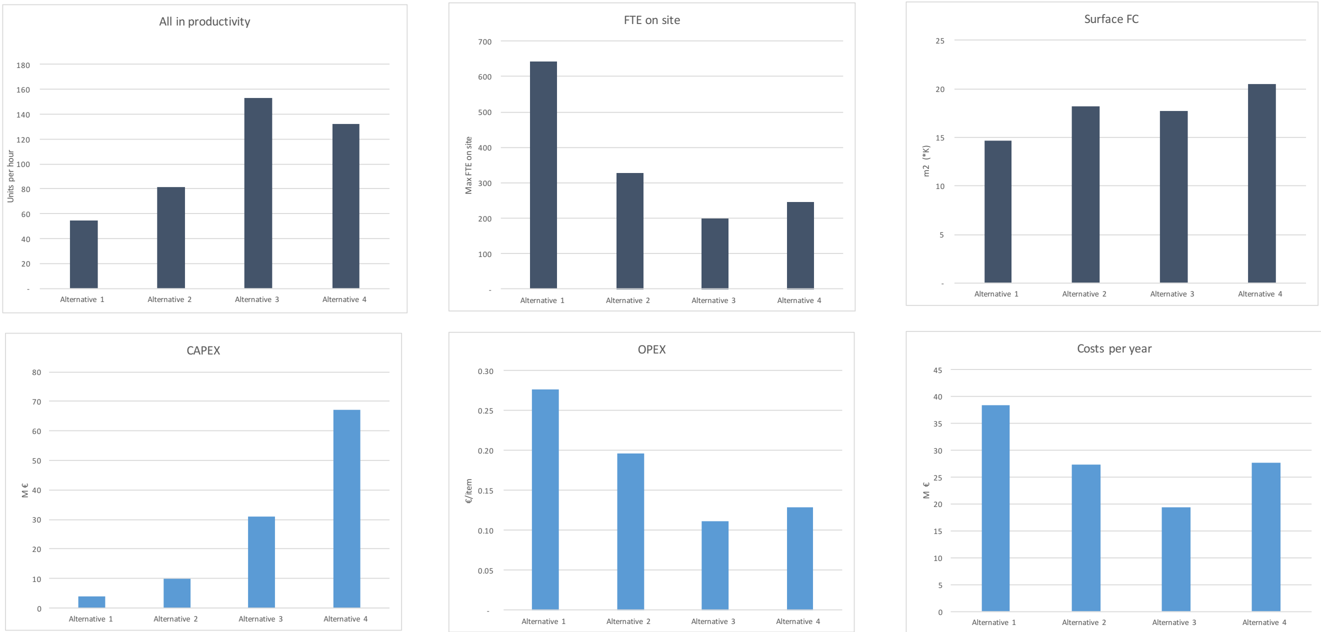

Figure 34: Graphic overview of results on criteria 20k orders

From this overview it can be concluded that only one design alternative (nearly) reaches the 155 items per hour productivity goal. It has to be emphasized that with 20K orders it is not possible to pick all orders with the pre-picking schedule, due to the time- and length constraints of the pick circuit. This can also be seen in Table 14. The maximum productivity of the pick circuit with 20k orders is 19.7K items per hour. This is much lower than the required productivity of 31.2K picks per hour. When handling 15K orders or less orders, required pick productivities can be reached.

Table 14: Required productivity versus achievable productivity

	20K	15K	10K	7.5K	5K
Max productivity [item/hr]	19.7K	27.9K	23.2K	19K	14.9K
Required productivity [item/hr]	31.2K	23.4K	15.6K	11.7K	7K
Difference [%]	-37%	19%	49%	69%	92%

5.6.2 Activity based costing

In Table 15, the outcomes of the ABC analysis are shown. Results show that picking is by far the generator of the highest costs. Alternative 1 and 2 nearly have the same picking costs per item (around the 20 cents). The total direct labour costs in alternative 1 are 1 cent higher than the current costs (38 cents). The picking costs for alternative 3 and 4 are a fourth of the costs of alternative 1 and 2. When costs are not displayed in the table, this means that there is no human labour is needed to fulfill this process. In Figure 35 the costs per process are visualised.

Table 15: Activity based costing

		Alternative 1	Alternative 2	Alternative 3	Alternative 4
Bagging costs per item	[€/item]	0,01	0,01	0,02	0,02
Receiving costs per item	[€/item]	0,01	0,00	0,01	0,02
Replenishment costs per item	[€/item]	0,03	0,01	-	-
Picking costs per item	[€/item]	0,19	0,21	0,05	0,06
Consolidation costs per item	[€/item]	0,01	0,00	0,00	0,00
Storing costs per item	[€/item]	0,02	-	-	-
Direct labour costs	[€/item]	0,39	0,32	0,11	0,13

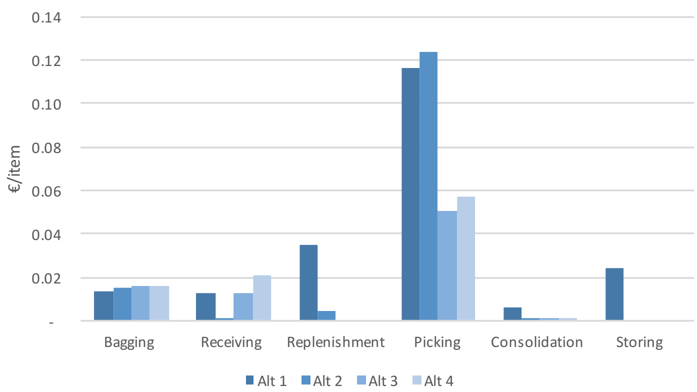

Figure 35: Costs per item per activity

5.6.3 Results with different number of orders

In this analysis, number of orders vary. As in the previous analysis, the order profile is set on 'as expected' and the schedule is set on 'pre-picking'. Results for all-in productivity and total costs per year are presented in Figure 36 and Figure 37. It can be concluded that the costs per year increase considerably when processes are fully manual (alternative 1). With an increasing number of orders, all-in productivity in alternative 1 and 2 decreases, but remains stable for the mechanized alternatives (alternative 3 and 4). This is because the mechanized alternatives are easier to scale. It has to be emphasized that all alternatives (especially alternative 2 and 3) have almost the same amount of total fulfillment costs per year when handling 5K orders.

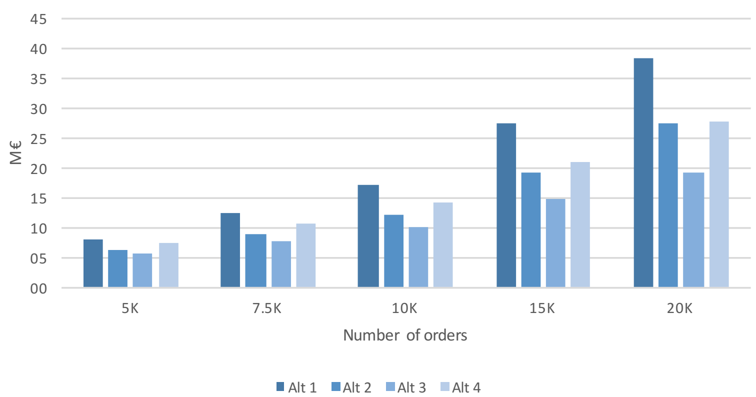

Figure 36: Total fulfilment costs per year with different number of orders

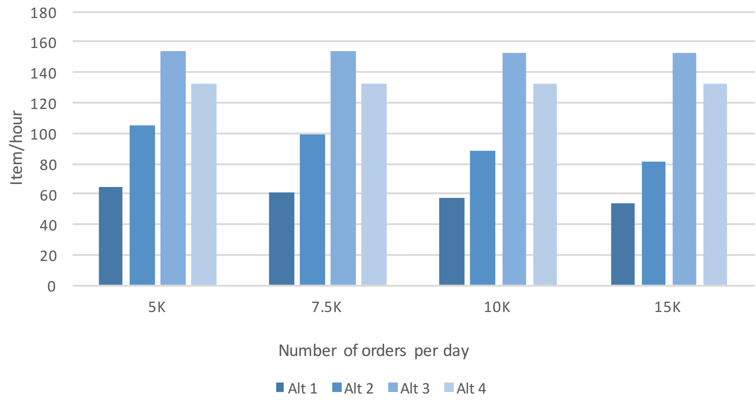

Figure 37: All-in productivity with different number of orders

5.6.4 Results with different single variables

In this paragraph qualitative and quantitative effects of different single input variables on design criteria are presented. Qualitative outcomes were used to estimate expected effects. Quantitative outcomes were compared with qualitative outcomes subsequently.

Expected effects

Variable 1. Increase of number of SKUs in range

Expected is that when the number of SKUs in the range increases, this will effect alternative 1 and 2 the most. This is because of the fact that due to the extra products in the range, the length of the pick circuit will have to increase and therefore pick productivity will decrease. Besides this, it is expected that these products will be categorized in the SM SKU group. This could have an effect on the required product storage capacity of the AS/RS in alternative 3. Alternative 4 will be effected less, because of the fact that this alternative knows one type of pick strategy only. In case of a high number of SKUs in the range, it is expected that more cupboards will be required to store the products. A higher number of SKUs in the range however, does not always have to lead to an increased number of items per order.

Variable 2. Increase of number of items per order

When the number of items per order increase, this could have an effect on the number of totes in the FC and therefore also on the productivity of different processes and the required storage capacity for orders. With increase of items per order, it is expected that there will be a more considerable effect on design criteria in the manual alternatives than in the mechanized alternatives.

Variable 3. Increase of number of items per tote

When the number of items per tote increases, this could be the result of a decrease of average volume per SKU. This could increase productivity and therefore decrease OpEx. It has to be emphasized that the input variables are not related causally with each other in this model. Therefore, an increase of the items per tote will not automatically result in a decrease of average volume (in liters) of the SKUs.

Variable 4. Increase of number of items per line

When the number of items per line increases, pick productivity can increase. This is based on the fact that less movements are required for picking the same number of items. Also, presentations of product totes at GTP stations probably are more effective.

Variable 5. Increase of volume (liters) of SKUs

When the volume of SKUs increases, the number of items in a tote will decrease. This will increase the number of ambient totes required for one customer. If the number of totes decreases, this can have an effect on the required order storage capacities in the AS/RS (in alternative 2, 3 and 4) and the number of pickers in alternative 2 and 3 (when a PC of 12 totes is used).

Variable 6. *Increase of percentage of orders with JIT products*

When the number of orders which have to be consolidated with JIT products (like bread) increases, the number of GTP stations in alternative 2, 3 and 4 will also increase. This will have a direct effect on required the surface area and the CapEx. For alternative 1 extra FTE will be required to consolidate the number of totes in the same time. This will have a direct effect on the OpEx.

Quantitative effects

The quantitative effects of the variables are calculated with an input of 20K orders and a pre-picking schedule. All other variables are set on 'current situation'. The variable varied on, is set on the highest input (Appendix 10, Table 39).

In Table 16 it can be seen that the increase of the SKUs has a major effect on the productivity for manual alternatives. The effect on the mechanized alternatives is minimal because of the fact that in the design, extra GTP stations or extra aisles in the AS/RS can be added easily. This results in a decrease of the CapEx. Surface area increases considerably for alternative 4 because the new SKUs are stored in extra cupboards with less density and height than in an AS/RS.

Table 16: Variable 1. Effect of increase of number of SKUs in range (with 81% from 3317 to 6000 SKUs)

Design criteria	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
All-in productivity	-27,0%	-37,5%	0,0%	0,0%
Surface area	38,1%	30,7%	3,0%	21,6%
FTE	24,6%	50,6%	0,0%	0,0%
Direct labour costs per item	36,9%	60,0%	0,0%	0,0%
OpEx/year	37,0%	58,4%	0,3%	1,9%
CapEx	1,5%	3,1%	6,4%	1,1%
Total costs/year	36,2%	54,7%	2,0%	1,6%

In Table 17, it can be seen that the increase of the number of items per order has no effect on the productivity. This can be explained by the fact that this variable is used in the workforce module to calculate the total inbound and the required productivity. The productivity itself is not effected. Therefore, only extra FTE is required and the OpEx per year will increase. However, the total number of sold items will also increase. Like expected, the CapEx remains the same for the manual alternatives.

Table 17: Variable 2. Effect of increase of number of items per order (with 26% from 21,46 to 27)

Design criteria	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
All-in productivity	0,0%	0,0%	0,0%	0,0%
Surface area	3,5%	2,9%	8,5%	21,4%
FTE	27,9%	23,2%	25,1%	25,8%
Direct labour costs per item	0,0%	0,0%	0,0%	0,0%
OpEx/year	26,3%	26,8%	24,0%	25,4%
CapEx	0,0%	0,0%	10,8%	21,2%
Total costs/year	**25,7%**	**25,0%**	**20,3%**	**23,7%**

In Table 18, it can be seen that like expected, productivity increases when the number of items per tote increases. This has a higher impact for the manual alternatives than for alternative 3 and 4.

Table 18: Variable 3. Effect of increase of number of items per tote (from 15,5 to 18 items per tote)

Design criteria	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
All-in productivity	7,5%	6,6%	5,0%	2,5%
Surface area	-1,9%	-1,6%	-2,0%	-1,5%
FTE	-5,2%	-7,9%	-4,2%	-2,2%
Direct labour costs per item	-7,0%	-6,2%	-4,8%	-2,5%
OpEx/year	-6,8%	-6,0%	-4,5%	-2,4%
CapEx	0,0%	0,0%	-0,3%	-0,1%
Total costs/year	-6,7%	-5,6%	-3,3%	-1,5%

As expected, the increase of number of items per line, increases productivity for all alternatives (Table 19). Therefore, the total costs decrease. The most substantial effect can be seen on alternative 4.

Table 19: Variable 4. Effect of increase of number of items per line (from 1,27 to 2 items per line)

Design criteria	Alt 1	Alt 2	Alt 3	Alt 4
All-in productivity	2,6%	4,0%	3,1%	9,3%
Surface area	0,0%	0,0%	-0,3%	-1,5%
FTE	-1,7%	-3,2%	-2,3%	-6,0%
Direct labour costs per item	-2,6%	-3,9%	-3,0%	-8,5%
OpEx/year	-2,5%	-3,7%	-2,8%	-7,9%
CapEx	0,0%	0,0%	0,0%	-8,6%
Total costs/year	-2,4%	-3,4%	-2,0%	-8,2%

Table 20: Variable 5. Effect of increase of volume (liters) per SKU (from 1,41 to 2 liters)

Design criteria	Alt 1	Alt 2	Alt 3	Alt 4
All-in productivity	-2,4%	-3,9%	0,0%	0,0%
Surface area	5,6%	6,9%	5,0%	19,7%
FTE	1,6%	3,7%	0,0%	0,0%
Direct labour costs per item	2,5%	4,0%	0,0%	0,0%
OpEx/year	2,6%	4,2%	0,4%	1,7%
CapEx	0,2%	0,4%	10,7%	2,7%
Total costs/year	2,5%	3,9%	3,3%	2,1%

The increase of volume per SKU (Table 20) results in a major increase of CapEx in alternative 3, due to a higher number of storage locations required in the AS/RS. Because of the increase of the length of the pick circuit, all-in productivity in alternative 1 and 2 will decrease.

Table 21: Variable 6. Effect of increase of percentage of orders with JIT products (from 40 to 55%)

Design criteria	Alt 1	Alt 2	Alt 3	Alt 4
All-in productivity	-1,1%	-0,3%	-0,5%	-0,4%
Surface area	0,0%	0,1%	0,1%	0,1%
FTE	0,0%	3,5%	0,9%	0,7%
Direct labour costs per item	1,1%	0,3%	0,5%	0,4%
OpEx/year	1,0%	0,3%	0,5%	0,4%
CapEx	0,0%	0,0%	0,8%	0,4%
Total costs/year	1,0%	0,2%	0,6%	0,4%

In general, it can be concluded that the variable regarding consolidation has a reduced effect on the outcomes of design criteria. However, increasing the percentage of order totes which have to be consolidated (Table 21), has it's maximal effect on productivity for alternative 1. This is because, in alternative 1, consolidation is performed manually. Besides this, it has to be emphasized that for the model it's assumed that one item needs to be added only. In reality it is more likely that multiple items will have to be added to the tote. This will increase the effect of the variable on the criteria.

To visualize effects of the alteration of variables per alternative, radar graphs were made. Every colored line represents a variable. Criteria are presented on the end points of the web. The percentages are representing the difference with the 'current situation'.

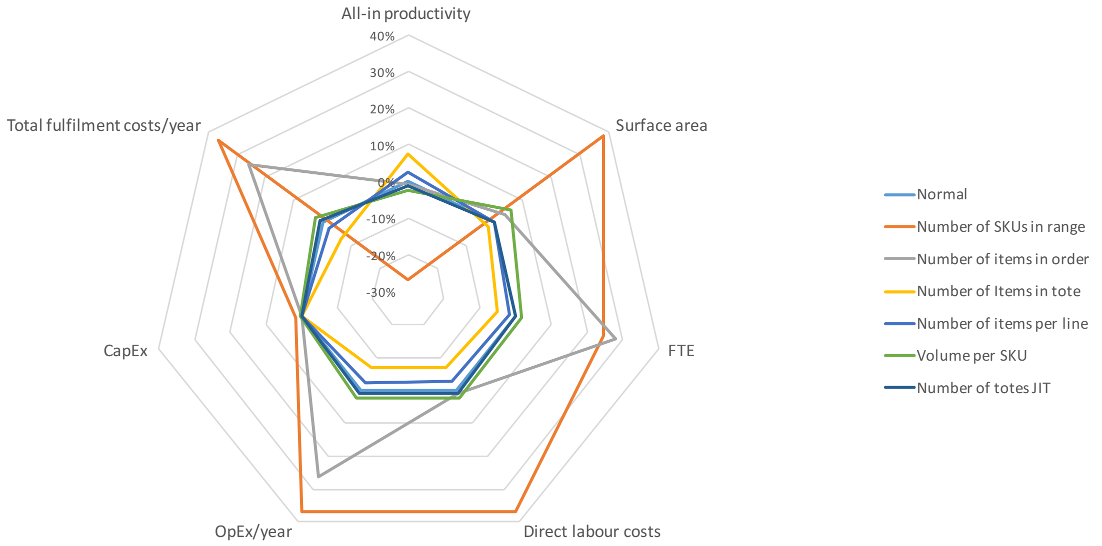

Figure 38: Effect alterations variables on alternative 1

In Figure 38 it can be seen that for alternative 1, increasing the number of SKUs in the range and the number of items per order have the biggest effect on the design criteria. Increasing the number of SKUs in the range, increases the total costs per year with more than 30%.

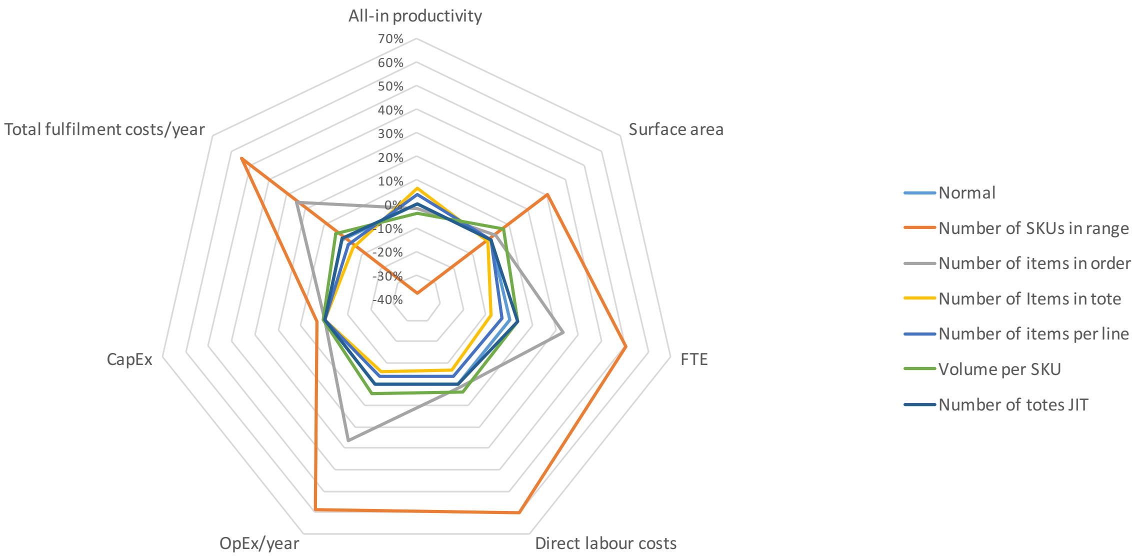

Figure 39: Effect alterations variables on alternative 2

Alternative 2 (Figure 39) reacts in the same pattern on the alterations of the variables as alternative 1, however, the number of required FTE and therefore also the OpEx per year is less effected.

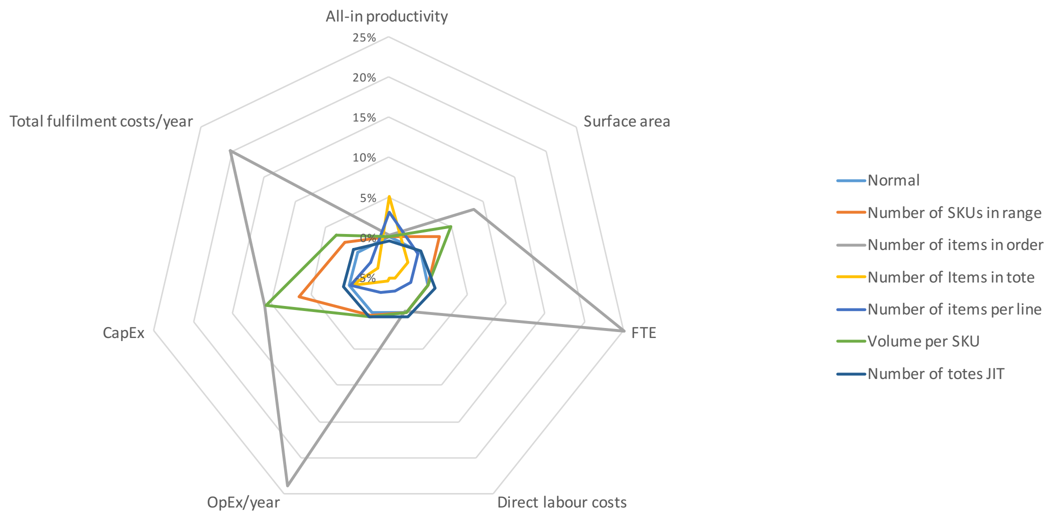

Figure 40: Effect alterations variables on alternative 3

In Figure 40 (alternative 3) it can be seen that the number of items per order has the highest effect on the criteria. By increasing the number of ambient items per order from 21 to 26, the total costs per year will increase with 20%. All-in productivity will remain the same.

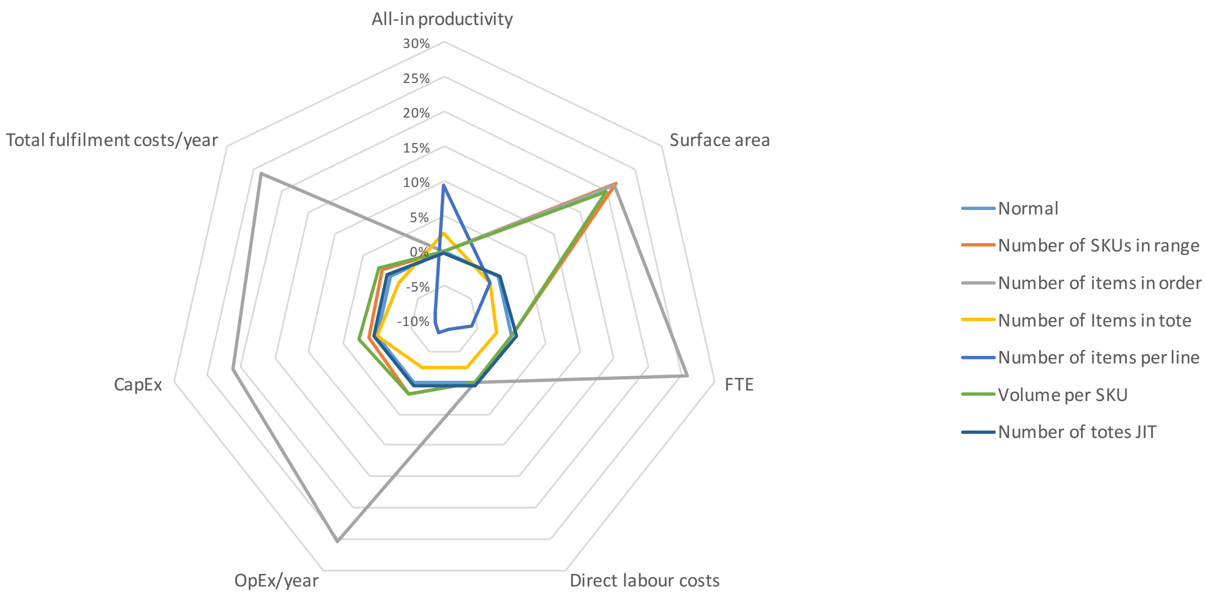

Figure 41: Effect alterations variables on alternative 4

The increase of the number of SKUs in the range also has the biggest effect on the criteria for alternative 4 (Figure 41). However, the CapEx and surface area is much more effected than for alternative 3

5.6.5 Results when varying on schedule scenarios

The model can be varied on the schedule scenarios. Different options are: the current schedule scenario (9 hours of picking), a pre-picking schedule scenario (16 hours of picking) or a same day delivery schedule scenario (12 hours of picking). From the schedules in Appendix 11, it could be concluded that the difference between pre-picking and same day delivery is only 4 hours of picking. However, there are more difficulties that come along with same day delivery. The fulfillment processes have to be flexible for order sequence changes and DPF planning. (E.g.: DPF sequencing and trip planning becomes a last minute procedure.) It requires alterations in the processes and extra buffer space in the DPFs (to insure that there is a storing location when an order arrives at the the last moment). Therefore, even with the only small higher number of required FTE for same day delivery (Figure 42) it is not clear if the alternatives can fulfill the orders when handling a same day delivery schedule.

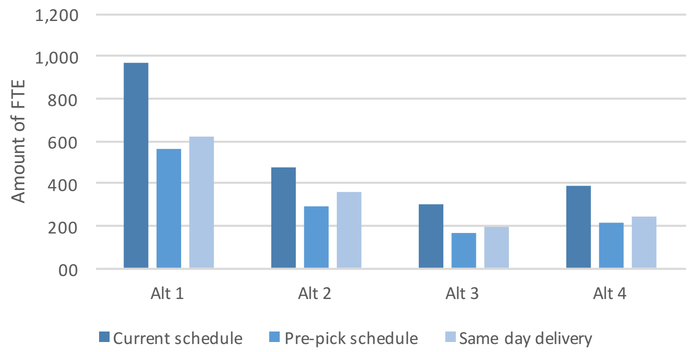

Figure 42: Number of FTE required per alternative, per schedule

5.7 Sensitivity analysis

According to Saltelli (2010) a 'Sensitivity analysis' aims to estimate how much model output values are effected by changes in model input values. He states that 'it's the investigation of the importance of imprecision or uncertainty in model inputs in a decision-making or modelling process'. For the sensitivity analysis, initial values are varied to understand the effects of these values on the design criteria.

Currently, Picnic is considering where to localize the new FC. This is a trade off between rental costs for housing per square meter, labor costs per hour and transport costs per kilometer from the FC to the hub. The latter is not in the scope of this research so is excluded from the calculations.

To get more insight into the impact of rental costs for housing and labour costs on the total costs per year, a sensitivity analysis was performed by varying these costs.

After this sensitivity analysis, a robustness analysis was performed to understand the impact of the used assumptions on the design criteria.

5.7.1 A FC close to a city

Having a FC close to a city can result in an increase of the rental costs for housing. However, it also means proximity to potential labour. On the other hand, if the FC is close to the city, wages could increase due to a higher demand for labour. The test is performed with the input scenario set 'as current' together with a pre-picking schedule. Results are presented and explained below.

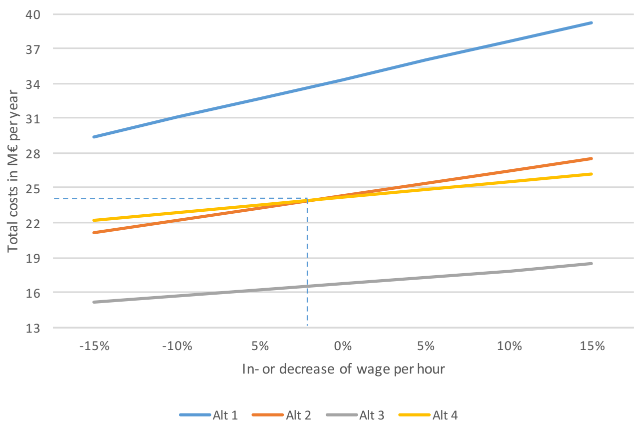

Figure 43: Effect of in- or decrease of wage costs on total costs per year per alternative

In Figure 43 it can be seen that an in- or decrease of the wage per hour has a linear effect on the total costs per year. In the model, the wages between alternatives differ because of the different required labour when fulfilling the orders manually or mechanized. However, it can be concluded that the effect for alternative 1 is the biggest, while the effect for alternative 4 is the smallest. This can be explained by the fact that for the operations of alternative 1, the highest number of people is required and for alternative 4 the lowest. Interesting is to see that alternative 2 becomes more attractive than alternative 4 when wage costs decrease with 5%.

Table 22: Effect on total costs per year when rent increases with 20%

	Alt 1	Alt 2	Alt 3	Alt 4
OpEx/year increase	0,2%	0,3%	0,4%	0,4%
Total costs/year increase	0,1%	0,3%	0,3%	0,3%

The increase of the rental housing costs has a very little effect on total costs per year. This is because costs related to rent have a low share in total costs.

Table 23: Effect on the total costs per year when rent and wage costs increase with 20%

	Alt 1	Alt 2	Alt 3	Alt 4
Total costs/year increase	19,6%	18,7%	14,4%	11,9%
Total costs/year [euro]	41.1M	28.9M	19.1M	27.1M

The increase of the costs related to the rent and wage has the lowest effect on alternative 4 because of the high share of CapEx within the total costs per year. It can be seen that if the wage and rental costs increase, alternative 4 becomes more attractive than alternative 2. However, overall, alternative 3 remains the most attractive alternative.

5.7.2 Robustness of the model

In this paragraph, the robustness of the model will be tested by varying on the assumptions which are made. The effect of the assumptions on the total costs per year will be calculated by performing the following alterations to the assumptions:

- Half the number of safety stock (alternative 1, 2, 3 and 4)
- Double the replenishment frequency (alternative 1 and 2)
- Double the product density (alternative 1 and 2)
- Double the walking distance within a zone (alternative 3)
- Double the walking speed (alternative 1, 2 and 3)
- Increase the fill rate of KIVA cupboards with 20% (alternative 4)
- Double the number of KIVAs required per pick station (alternative 4)
- Decrease the pick productivity with 30% because of the the order totes not being on time (alternative 3 and 4)

The results of the alterations on the total costs per year per alternative are presented in Figure 44. The four different colours stand for the four different alternatives. The assumptions varied on, are indicated on the edge of the radar graph. It can be seen that when the fill rate of the KIVA cupboards is halved, the yearly costs of alternative 4 increase with 60 percent. If order totes are not presented on time at the GTP station on zone station, assumed is that this will lead to a decrease of the pick productivity of 70%, resulting in an increase of 20% of total costs per year for alternative 3. Doubling the product density and the walking speed has the biggest effect on the total costs per year of alternative 2 (around the 20% decrease). Alternative 1 is effected less by this alteration. This can be explained by the fact that alternative 1 has higher total costs than alternative 2, therefore the gain is relatively small. The complete results are presented in Appendix 16.

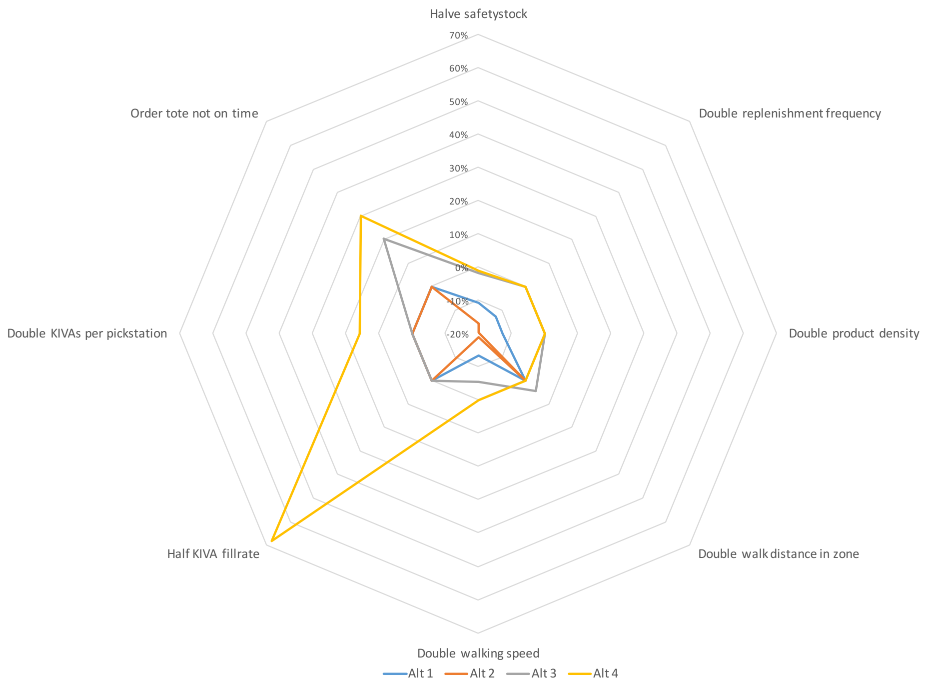

Figure 44: Effect of the alterations assumptions on total costs per year

5.8 Scenario analysis alternative 3

In paragraph 5.6.1 it was concluded that only alternative 3 meets the financial and productivity requirements. However, it is pivotal to know what the effect on the criteria of this alternative is in case of an aberrant order profile. Therefore, a scenario analysis is performed with the scenarios as described in Paragraph 5.2.1. The scenario analysis is performed when handling 20K orders on a pre-picking schedule. The outcomes of the scenario analysis are presented in Figure 45. The shape of the figure can be explained by the linear relationships between the variables of the model.

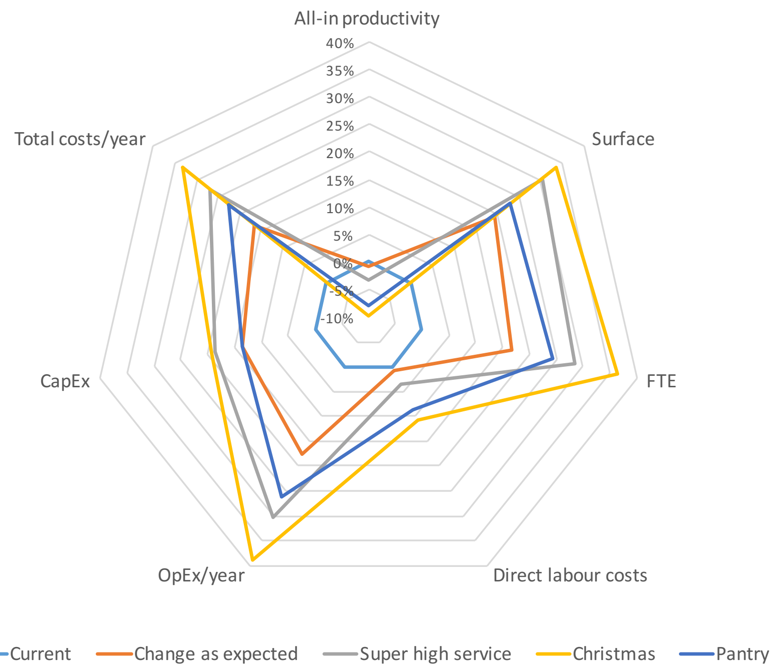

Figure 45: Effect of scenarios on criteria for alternative 3

The effect of the current order profile scenario on the design criteria is presented in blue. The effects of the other scenarios on the design criteria are visualized as a difference with the effect on the design criteria of the current order profile scenario.

The 'Christmas' order profile (yellow) has the biggest effect on productivity and total fulfilment costs per year. In this scenario, the highest number of people and the biggest surface area is required as well. Interesting is to see the effect on the variables of alternative 3 when the order profile is 'as expected' (orange). It also can be seen that the total costs for a FC handling 20K orders per year with this order profile, will be around 15% higher than with the current order profile. This is around €20M euro per year. Detailed figures can be found in Appendix 17.

5.9 Conclusions assessment

In the assessment phase the next sub questions were answered:

Sub question 11: What are the methods to assess the design alternatives?
To assess design alternatives, the effect on criteria is quantified with a deterministic model. The deterministic model consists of different modules which represent the system functions. The input of the model is based on the order profile, the number of orders and the working schedule. The different modules are used to calculate the productivity, the surface area, the required FTE the OpEx, the CapEx and the total fulfilment costs per year. A verification, validation and sensitivity analysis is performed to test the correctness and robustness of the model. These analyses show that assumptions made regarding product density and replenishment frequency have a major influence on the output of the manual alternatives. This also accounts for the assumption regarding cupboard fill rate for alternative 4.

Sub question 12: What are the effects of the alternatives and variables on the design criteria?
Alternative 3 results in the lowest total costs per year. However, when handling 5K orders, the semi-mechanized alternative becomes nearly as attractive as the highly mechanized alternative 3. Order growth, results in a higher increase of the total costs per year within manual alternatives compared to order growth within mechanized alternatives.
Increase of the ambient range has a major effect on all-in productivity of manual alternatives, but a minor effect on the mechanized solutions.
It should be emphasized that the outcomes of alternative 1 and 2 show that when manual picking is maintained while handling 20k orders, the conceivable pick productivity is 37% lower than the required pick productivity. The results of the sensitivity analysis indicated that rental costs of FC housing have such a low share in OpEx per year that this does not have to be taken into account when choosing a location
From the results of the scenario analysis it can be concluded that the 'Christmas' order profile has the biggest effect on the total fulfilment costs per year for alternative 3.

Sub question 13: Which alternative meets the requirements and the growth perspective of Picnic?
The only alternative which meets the productivity and financial requirements is alternative 3 (Table 13). However, the robustness analysis for this alternative showed that the assumption made regarding the timeliness of arrival of order totes has a major impact on the total costs per year. The total fulfilment costs when realizing alternative 3 are €19.3M per year.

Table 11: Effects on design criteria with 20K orders, change as expected scenario, pre-picking schedule

Design criteria	Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4
All-in productivity	[Item/hour]	54	81	153	132
FTE on site	[FTE]	641	327	198	245
Labour costs/item	[€/item]	0,28	0,20	0,11	0,13
Surface area	[m^2]	14.6K	18.1K	17.8K	21K
CapEx	[€]	4.2M	9.8M	30.6M	67.4M
OpEx	[€/year]	37.6M	25.2M	14.4M	16.4M
Costs per year	[€]	38.3M	27.3M	19.3M	27.8M

Advice

‘Tell me about the impact, not the effort.’ Frederik Nieuwenhuys
Fulfilment meeting Picnic, April 2016

6. Conclusions

In this final phase conclusions will be drawn, recommendations will be given and research methodology will be discussed.

6.1 The main research question

What are the logistic design characteristics of a (semi-) mechanized fulfilment centre of a fast growing pure play online grocery handling 20000 orders per day, taking into account operational and capital expenditure?

The fulfilment of groceries comes along with different challenges. These challenges are due to the high number of items and order lines per order, the different temperature zones, the different sizes and weights of the products and the fragility constraints of the items. The design of a FC is highly dependent on the order profile and range characteristics consisting of the number of SKUs in the range, number of items per order, items per tote, number of items per line, the sales volume per SKU and the size per SKU. The design of an online grocer FC can vary on the following 11 system functions: receiving, replenishing, product storage, picking of FMs, picking of MMs, picking of SMs, order storage, consolidating, storing, transportation of products within the FC and the transportation of orders within the FC. These system functions can be executed manually or mechanized. By mechanizing the processes OpEx can decrease with 60%, however CapEx will then be 6.5 times larger. To fulfil the ambient share of 20K orders for 0,11 cents per item with an all-in productivity of 154 items per hour, the highly mechanized alternative with three different pick strategies should be realized. With this alternative, 200 FTE will be required and the surface area of the ambient zone will be around 18K square meters. FMs will be picked manually, MMs within zone picking stations and SMs with the help of GTP stations. The SMs and MMs will be stored in a shuttle automatic storage and retrieval system. This system will also be used to store order totes to facilitate pre-picking and just-in-time consolidation with fresh goods. The total costs of this highly mechanized alternative will be around €20M per year.

6.2 Conclusions exploration

In the exploration answers where found for the following sub questions:

Sub question 1: What is known about the design of manual and mechanized processes in online grocer FCs?
FCs are designed based on the order, assortment and SKU characteristics. Picking is the main activity and during the design of the FC different manual or mechanized pick strategies can be taken into account. The processes within a FC, which are often mechanized, are picking (bringing the product to the picker) and the storage of product or orders. The performance of the mechanized processes is dependent on the combination of the systems. In grocer FCs it can be seen that the mechanization of the storage and picking is organized differently for products in different temperature groups (ambient and chilled) and sales volume groups. Frozen pick processes are not mechanized due to temperature challenges. Storage functions are mechanized with AS/RSs and picking is often mechanized with the help of zone-picking and GTP stations.

Sub question 2: What is known about the effect of mechanization on the productivity, service level, operational expenditure and capital expenditure? Mechanization can increase pick productivity up to 600 picks per hour, resulting in a decrease of the required FTE and direct labour costs. Ocado has a highly mechanized grocer FC with an all-in productivity of 155 items per hour and variable costs of 0,11 cents per item. There are no quantified known effects of mechanization on service level. However, it decreases flexibility and on the short term it can have a negative effect because of start-up procedures. On the long term it can increase service level because of the decrease in picking mistakes and the increase in flow. The CapEx put into FCs are often not published. However, through data from material handling suppliers it is possible to retrieve the costs for different equipment.

Sub question 3: Which methodologies can be used to analyse, design and model a FC?
To analyze the assortment characteristics and the costs of a FC, the ABC product analysis and Activity based costing analysis can be used. For the design of a warehouse Koster, Le- Duc & Roodbergen (2006) have defined several decisions that should be taken on a strategic, operational and tactical level. Besides these decisions, there are multiple frameworks in literature. The method used in this research is inspired on the framework of Baker & Canessa (2009). FC modelling can be performed with the help of simulation or analytical models. Due to the deterministic character of the data and the need for ABC, the model constructed in the assessment, will be a deterministic analytical model.

6.3 Conclusions analysis

In the analysis phase the following sub questions were answered:

Sub question 4: What is the design of FCO?
FC0 is designed to fulfil the orders fully manual within three temperature zones. The FC has a surface area of 3250 square meters from which the major part is used for the ambient zone. Different unit loads are used to fulfil the order (e.g. PCs, totes and

DPFs). Picking is 40% of the workload and is carried out in batches and sorted while picked. The assisting technology which is used during picking is the RF-scanner. The main processes within the FC are receiving, replenishing, picking, consolidating and storing. 73% of the SKUs are within the ambient temperature zone. From all articles, 81 SKUs represent 20% of the volume. Within ambient, 37 SKUs represent 20% of the volume. Differences in the pick strategy for SMs, MMs and FMs are not taken into account. Fragility of products is taken into account by strategically slotting the products.

Sub question 5: What is the effect of the design of FC0 on operational- and capital expenditure?
The current all-in productivity is 65 items per hour (excluding surrounding activities: 98 items per hour). 68% of the time is spent on main processes. The current direct labour costs are 38 cents per item. The aim of Picnic Supermarkets is to nearly half these direct labour costs for FC0. The current depreciation costs (CapEx) per item is 3 cents and the current on time delivery rate is 97%. From the productivity analysis it can be seen that pick productivity is reasonably good. The productivity of splitting HEs and storing ambient orders is relatively low.

Sub question 6: Which design variables have to be taken into account for the design of the new FC?
The main design variables which have to be taken into account are the input variables related to the order, range and tote characteristics. These variables are: the number of SKUs within the ambient range, the number of ambient items in one order, the number of items per tote, the number of items per line, the average volume per SKU (in litres) and the percentage of orders which has to be consolidated.

6.4 Conclusions design

In the design phase, the following sub questions where answered:

Sub question 7: What are the design goals for the new FC and which design criteria follow from this?
The goal of the design is to establish a FC that can fulfil 20K orders per day while meeting the operational and service requirements and minimizing the total fulfilment costs per year. The criteria on which the design will be assessed on are: all-in productivity, surface area, FTE, CapEx, OpEx and fulfilment costs per year.

Sub question 8: What are the design requirements and constraints that follow from the current FC and the growth perspective?
Main requirements are regarding the capacity, the design and the processes within the FC. Constraints are related to financial issues and timeliness. Requirements regarding the processes in the FC and the order and range characteristics, follow from FC0. Requirements regarding the number of to handle items are a result of the growth perspective.

Sub question 9: Which system solutions can be defined for the system functions?
The possible system solutions for the system functions can often be divided into manual, semi-mechanized and mechanized solutions. There are constraints regarding the combination of different solutions. Not all solutions can be combined with each other. Therefore, a pre-assessment is performed from which can be concluded that the Miniload and Autostore system are not suitable as an AS/RS within the FC.

Sub question 10: Which design alternatives can be composed for the new FC?
The four design alternatives are differing on the degree of mechanisation due to the combination of different system solutions. The first alternative is based on FC0 and is fully manual. Within the second alternative the picking process remains manual but the surrounding processes are mechanized. The third alternative is highly mechanized and includes three different pick strategies. The picking of FMs remains manual, MMs are picked within zones and SMs are picked at a GTP station. The zone and GTP stations are connected to a shuttle system. The shuttle system is also used for the storage of order totes. Within this alternative, conveyor belts are used to transport products and orders. The fourth alternative is fully mechanized in which all products are picked from GTP stations. All products are stored on cupboards which can be transported by KIVA robots. Orders totes are transported on conveyor belts and stored in a shuttle system.

6.5 Conclusions assessment

The assessment consisted of the development of a model, testing the model and analyzing outcomes of the model.

Sub question 11: What are the methods to assess the design alternatives?
To assess design alternatives, the effect on criteria is quantified with a deterministic model. The deterministic model consists of different modules which represent the system functions. The input of the model is based on the order profile, the number of orders and the working schedule. The different modules are used to calculate the productivity, the surface area, the required FTE the OpEx, the CapEx and the total fulfilment costs per year. A verification, validation and sensitivity analysis is performed to test the correctness and robustness of the model. These analyses show that assumptions made regarding product density and

replenishment frequency have a major influence on the output of the manual alternatives. This also accounts for the assumption regarding cupboard fill rate for alternative 4.

Sub question 12: What are the effects of the alternatives and variables on the design criteria?
Alternative 3 results in the lowest total costs per year. However, when handling 5K orders, the semi-mechanized alternative becomes nearly as attractive as the highly mechanized alternative 3. Order growth, results in a higher increase of the total costs per year within manual alternatives compared to order growth within mechanized alternatives.
Increase of the ambient range has a major effect on all-in productivity of manual alternatives, but a minor effect on the mechanized solutions.
It should be emphasized that the outcomes of alternative 1 and 2 show that when manual picking is maintained while handling 20k orders, the conceivable pick productivity is 37% lower than the required pick productivity. The results of the sensitivity analysis indicated that rental costs of FC housing have such a low share in OpEx per year that this does not have to be taken into account when choosing a location
From the results of the scenario analysis it can be concluded that the 'Christmas' order profile has the biggest effect on the total fulfilment costs per year for alternative 3.

Sub question 13: Which alternative meets the requirements and the growth perspective of Picnic?
The only alternative which meets the productivity and financial requirements is alternative 3. However, the robustness analysis for this alternative showed that the assumption made regarding the timeliness of arrival of order totes has a major impact on the total costs per year. The total fulfilment costs when realizing alternative 3 are €19.3M per year.

7. Recommendations

Based on the results of the assessment it can be advised that to facilitate foreseen growth, Picnic should mechanize fulfilment processes. The assessment also showed that the highest all-in productivity and the lowest fulfilment costs can be reached when, together with an automatic storage and retrieval system and conveyor belts for internal transport, different pick strategies for fast moving, mid moving and slow moving items are realized. This is because picking of least sold products with a high productivity, results in maximal operating efficiency.
However, because of a considerable investment of €30M and the maximum capacity of FC0 approaching rapidly, it is recommended to first realize a semi-mechanized FC (FC1), in which picking activities remain fully manual but surrounding activities are mechanized. This, because analysis showed that up to 5K orders, the total costs per year of alternative 2 (semi-mechanized) where close to the total costs per year for the highly mechanized alternative.
Analysis also indicates that the increase of the SKU range, will result in higher total costs per year. If possible, Picnic should therefore wait with increasing the SKU range until the highly mechanized FC is realized. The increase of the number of items in a tote has a considerable positive effect on the total costs per year. Picnic should aim for this to minimize the total fulfillment costs per year. To increase receiving productivity, Picnic could also look into possibilities of collaborating with suppliers to directly receive inbound of products in CEs and not in HEs. Observation of the current processes in FC0 suggest that with the increase of FC capacity, the upstream food supply chain is not ready for e-commerce and direct single piece order fulfilment.

7.1.1 Transition

Expected is, that FC0 will be running at full capacity in December 2016. To facilitate the foreseen growth while keeping the operation running, it is recommended to realize a new FC on a new location. Due to the minimum time (4 months) it is recommended to duplicate the current FC and realize enough floor space in FC1 to install the mechanized surrounding processes as fast as possible and if required during operation. FC0 will have an operating efficiency of around 70 items per hour and FC1 an operating efficiency of 110 items per hour.
Based on the growth forecast and the outcomes of the model, it can be concluded that the maximum capacity of FC0 combined with maximum efficient capacity of FC1 will be reached around July 2017. This is due to the large increase of total costs per year if the semi-mechanized alternative handles more than 5K orders per day as an effect on the decrease of all-in productivity.
Prior to reaching the maximum efficient capacity, the highly mechanized FC with three different pick strategies should be realized (FC2). Before realization of FC2, the assumption made regarding on-time performance of order totes should be investigated thoroughly. In consideration of depreciation costs, FC1, should remain operational for at least six years. After realization of FC2 however, FC0 can be shut down because of relatively high operational costs. In Figure 46 the proposed transition plan is depicted.

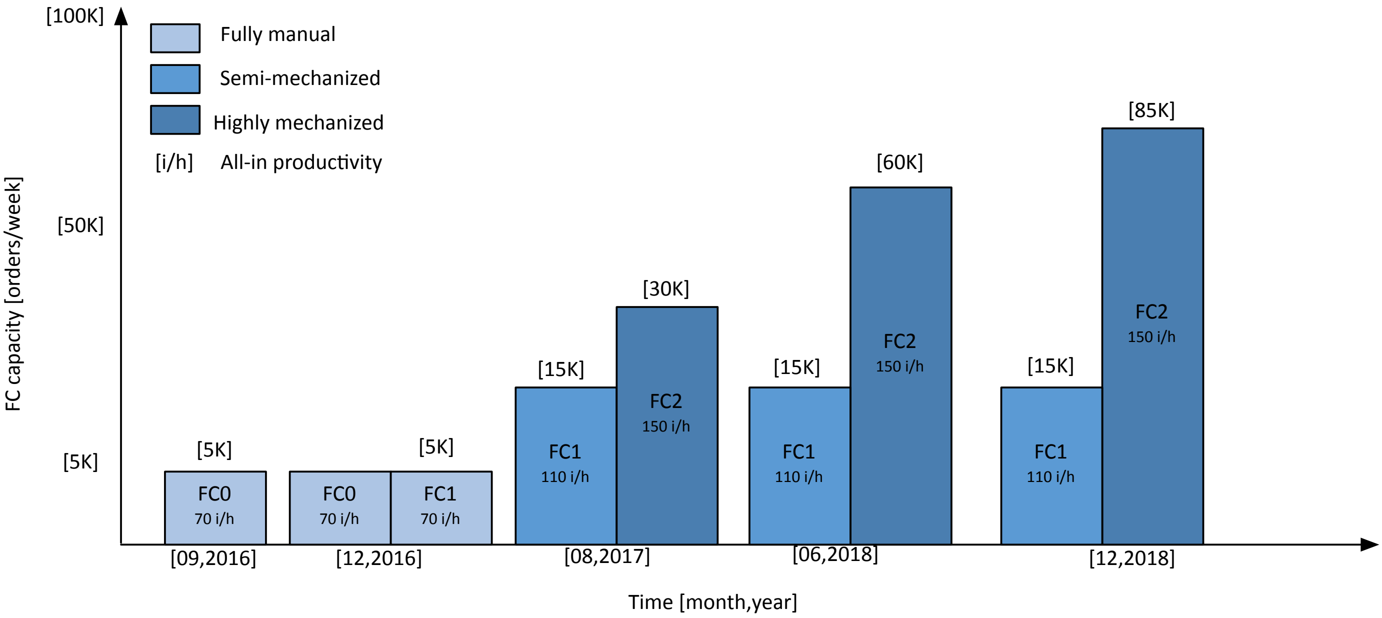

Figure 46: Transition plan (Author, 2016)

7.1.2 Further research

At first, Picnic should perform further research into the effect on the all-in productivity when the chilled and frozen temperature zones are also taken into account. Before the mechanization of the surrounding processes within FC1, assumptions regarding the productivity characteristics of the sorter, the dispatch frame loader and the replenishment of HEs with the help of conveyor belts should be stressed.

For the highly mechanized alternative, further research should be performed into the assumption of the totes being on time while travelling between the different pick strategies. It should be emphasized that the assessment indicated that alternative 4 (using robots for transport) comes along with very high CapEx, however, the robots increase flexibility because of the fact that there is no need anymore for conveyor belts. On the other hand, the low storage capacity of the KIVA cupboards requires a very high surface area. Picnic could also look into possibilities of combining the flexibility of the robots and the storage capacity (for products) of an AS/RS.

7.2 Recommendations for scientific research

This research gave insights in the productivity of processes within the ambient temperature zone. However, it is expected, that the processes within the remaining temperature zones will have an effect on all-in productivity. It is important to further analyze these effects. The robustness analysis also showed that there were multiple assumptions that have a major effect on the outcome of the total costs per year. These assumptions should be validated by testing and stressing them in more depth with simulation models or in practice. Important assumptions to deep dive into are the required number of KIVAs and cupboards for alternative 4 and the on-time performance of the order totes for alternative 3.

The calculations regarding the length of the pick circuit were all based on average product density. Although there is extensive scientific literature on manual pick circuits, a simulation study could be performed on the effect of scaling the number of orders on the length and design of manual pick circuits within online grocer FCs.

At last, the model used to assess the alternatives is deterministic and therefore linear. The input variables are based on averages. Simulation studies should be performed to get more realistic insights in the productivity of processes when multiple temperature zones are taken into account and bottlenecks within the FC.

7.3 Evaluation

The research is evaluated on the basis of the used research methodology and a personal reflection.

7.3.1 Research methodology

Because of the fact that there is no scientific literature on the mechanization of online grocer FCs, the chosen research methodology was explorative and performed in the five phases: an exploration, an analysis, a design, an assessment and an advice phase. The analysis was performed on the basis of an ABC product analysis and Activity based costing analysis. These tools were very helpful to get insights in the characteristics of the FC but had limits because of the deterministic characters. The assortment was continuously changing during the research however; the ABC product analysis only gives insights into the assortment at one moment in time. This also account for the Activity based costing analysis. Productivity of processes and required FTE were continuously changing, therefore, the ABC cold only be used on the basis of averages. The execution of the design step was performed on the basis of a Morphological chart to diverge the different design options and oversee all possible combinations of system solutions. However, fur further research it is recommended to diverge the design options with more in-depth quantified reasoning. The alternatives were assessed on the basis of a deterministic model. The model was constructed with the help of the iterative design approach of Sargent (2015). The verification and validation resulted in multiple adjustments of the model. Major restrictions of the deterministic model where the overall use of averages and the linear relationships between all variables. Nevertheless, the model gave useful insights into the design characteristics.

7.3.2 Personal reflection

This graduation project was a great experience. At times it felt like a bumpy road but it was definitely the most instructive part of my master study, on both a personal and an educational level. I was determined I wanted to perform my research at a company. However, I never expected that executing it at Picnic, one of the fastest growing start-ups in the Netherlands, brought so many extra dimensions to my master thesis.

At first it was heavy going searching for my research scope. Making the first few months quite chaotic. When the scope became clearer I could finely deep-dive into the subject which triggered my enthusiasm even more about the subject.

On the hind sight, I could have spent more time on the design and assessment phase and less on the analysis phase of FC0. At a certain moment it became clear that the order and range profile and the system solutions were more important for FC1 than processes and performances in FC0.

Also, it took quite some time before I figured out how to quantify the different alternatives. However, by brainstorming with fellow students, looking into methods material handling suppliers use and useful reflection meetings with Professor Lodewijks, Mr. Beelaerts van Blokland and Mr. van Duin, I constructed an assessment model. The process of the design of the model thought me a lot of new skills on how to use Excel and how to build a model with so many variables. The analysis process of the results thought me how to 'de-bug' such a model. At first I was largely analyzing the results with the help tables. When I found a way how to visualize the effects of the alternatives and variables on the design criteria (with the help of radar graphs) the effects became much clearer.

If I look back, I could have involved Picnic earlier with the design of the assessment model. As now they could only give me feedback when I already had the base. But nevertheless the feedback then was very useful.

Concluding; I am very pleased with the research. I can definitely say that I'm a (beginning) expert on the mechanization of retail warehouses. A great part of the knowledge I gathered was because Frederik and Wybe-Jan involved me with their first plans into exploring the options for a new FC and the fact that they allowed me to chair different interviews and meetings. And while Picnic was busy growing and I didn't know how to proceed any more, Hans always took the time to sit back, have a brainstorm and put everything in perspective. Professor Lodewijks, Mr. Beelaerts van Blokland, Mr. van Duin, Frederik, Wybe-Jan and Hans thank you for your time and the challenging experience.

The biggest lesson I learned and the advice I want to give to other master students when choosing a graduation subject and company: go for the unknown.

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Appendices

‘A little less conversation, a little more action please.’ Elvis Presley

Appendix 1: Online grocer FCs in practice

Ocado

Ocado is the largest dedicated online supermarket in Europe, handling over 200K orders per week (Ocado, 2016). Currently Ocado has 2 FCs in Great Britain and they will open a fully self designed and highly mechanized FC in Andover coming year. The FC in Andover will add 65K orders per week (Ocado, 2016) to the fulfilment capacity. The overall FC productivity of the 2 FCs is 155 items per hour and they are fulfilling the orders for 0,11 cents per item (Ocado, 2016). Ocado has 47K unique SKUs in its range. 40% of the range are fresh and chilled products.

Slow moving ambient articles are picked with the help GTP stations at which a pick productivity is reached of 600 items per hour. Fast moving articles in ambient and all chilled articles in a zone picking area where a productivity of 300 items per hour can be reached. Frozen articles are order picked in batches and are sorted while picked. The picking is done with the help of an RF-scanner. With the manual picking of frozen articles a productivity of 135 items per hour is reached. An AS/RS system is used for the storage of totes in the ambient and chilled area and the storage of products totes for the zone area and the GTP stations. Conveyors are used through the whole warehouse to transport the orders to different areas.

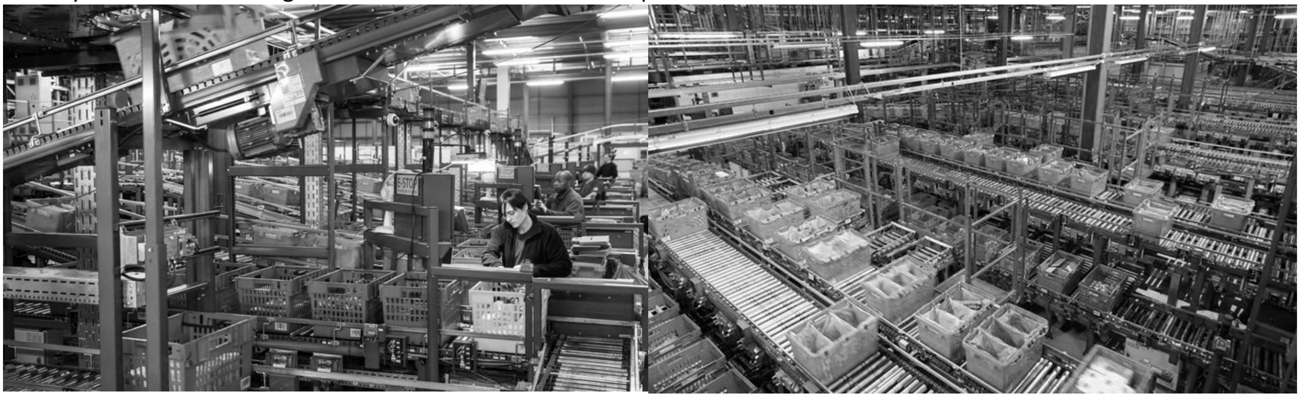

Figure 47: Mechanization at Ocado, the usage of conveyor belts (Ocado, 2010)

TuDespensa

TuDespensa is an online grocer in Spain serving around 350 customers per day Knapp (2016). TuDespensa has 7000 SKUs in their assortment. According to Knapp (2016), TuDespensa has an AS/RS shuttle for slow and medium movers with 5 GTPs for ambient and chilled products. Knapp (2016) states that the shuttle can handle 67,000 articles in 15 hours, meaning that the shuttle can facilitate a pick productivity of 890 articles per hour (with 5 pick stations). Pallet picking is done for large and heavy products but not for all FMs. The productivity reached when manual picking from pallets, is 100 items per hour. Totes are weighed at the GTPs to minimize picking errors. An AS/RS is used for product and order totes. With the help of GTP stations, TuDespensa adds fresh articles delivered in the morning, last minute to the order.

Figure 48: A shuttle system and a pick station at TuDespensa (Knapp, 2016)

Tesco

Tesco, has installed multiple pick strategies within their FCs. It is notable that they also make use of a Miniload AS/RS for their storage of product and order totes. According to Nieuwenhuis (2016) in one of the FCs, Tesco makes use of complex zone system in which articles with multiple sales categories are picked.

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Figure 49: The Tesco FC (Mclarengroup, 2013)

Peapod

Peapod was one of the first online supermarkets, started in 1989 and is currently owned by Ahold. It operates in selected cities around the United States by partnering with local supermarkets. Peapod operates with three types of FCs.

- Wareroom (ambient picked with RF-scanner in batches and chilled and frozen in store)
- XL shop centre (stand alone warehouse, pick with RF- scanner in batches)
- Semi-automated warehouse (zone picking in seven temperature zones)

The type of warehouse is dependent on which capacity the warehouses should handle. The FCs often evolve while capacity grows. At first a Wareroom is installed, thereafter the wareroom is rebuilt into an XL Shop Centre and at last the XL Shop Centre is rebuilt into a Semi-Automated Warehouse.

Figure 50: Peapod warehouses (Peapod, 2016)

Albert

Albert is the online grocery delivery service from Albert Heijn, active in the Netherlands and also owned by Ahold. The FC of Albert is not mechanized. Albert has three FCs for different temperature zones and article groups. They are supplied by the regional DCs of Albert Heijn with roll containers which can directly be used to replenish the shelves. This is because the Regional DCs of Albert Heijn fill the roll containers in such a way that no sorting and splitting is required before replenishing the shelves in the FC of Albert. Albert has an all-in productivity of 130 items per hour per FC. Average number of articles within an order of Albert is 70. Albert handles around 1500 – 2000 orders per day per shift (two shifts per day). Albert has around 25K unique SKUs in it’s range and has to handle a cross-dock stream to merge the totes from the different temperature zones to one order.

Appendix 2: Layout FC0

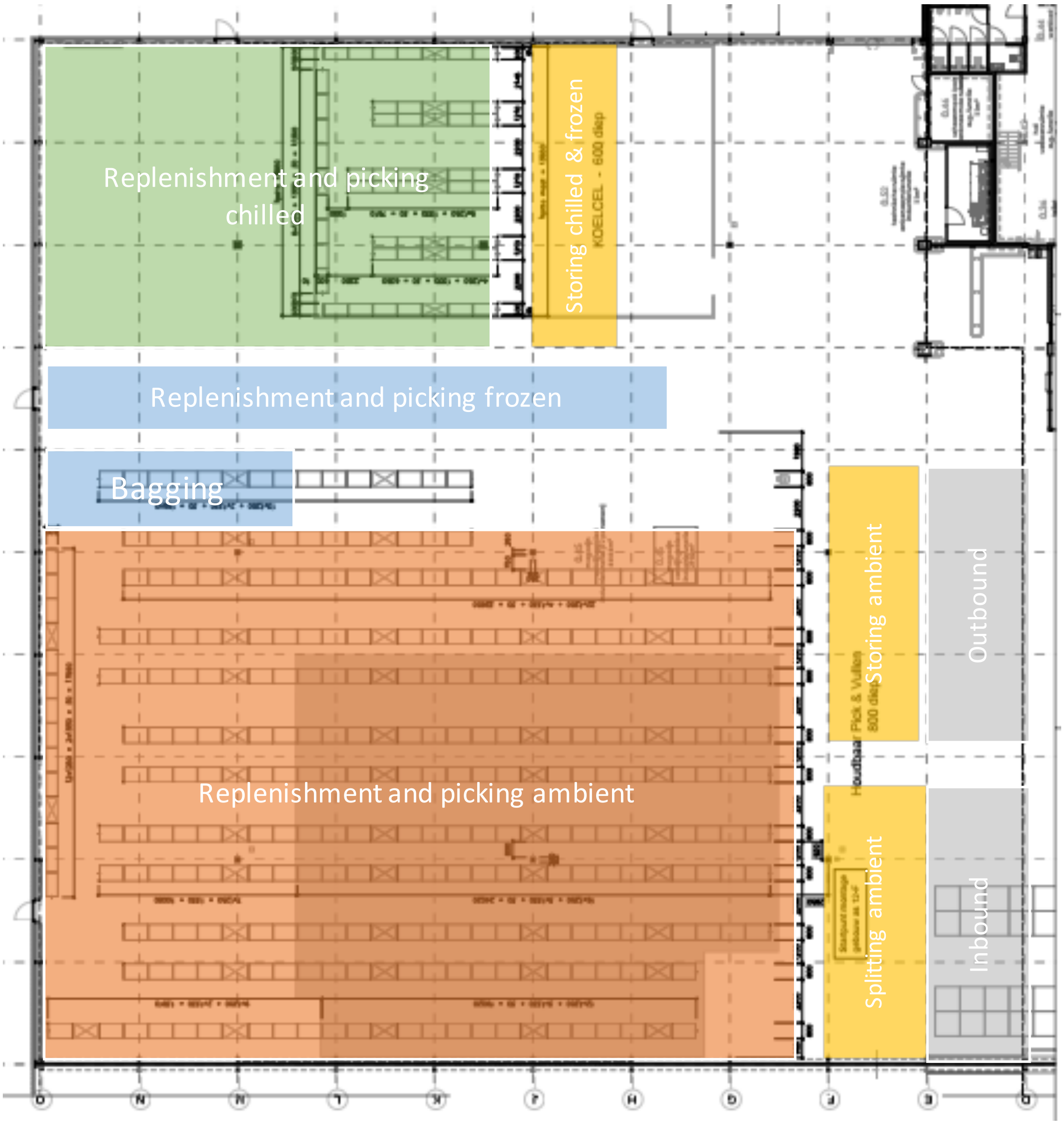

Figure 51: Layout FC0 (Author, 2016)

The FC of Picnic is 3250 square meters (excluding the second floor with offices). A layout of the facility is shown in Appendix 2 (Figure 51). The design of the picking areas is mainly dependent on the number and layout of the shelves.
The inbound area is used to store the RCs that come from the suppliers and the outbound area is used to store the PCs with the filled totes and the DPFs ready to ship to the hub. In the bagging areas, the totes are bagged. In these areas the bagged totes are also buffered when there all PCs are in use. Every day there is an inbound of articles. Some slow moving articles are delivered once per week. Then it can occur that there are more articles in the FC than can fit on the shelf. When this happens, the buffer zones are used. If required, the articles are moved from the buffer zones to the shelves. In the ambient zone, the buffers are divided per aisle. On the buffers there are now specific locations per article, this increases the chance of 'losing' the articles. The approximate number of square meters used for the different areas are presented in Table 24. It can be seen that ambient temperature zone needs the majority of the space, this is also because more than 2/3 of the unique SKUs are ambient.

Table 24: Square meters per temperature zone

Temp zone	Total	Picking	Storing	Buffer	Full PC buffer	Receiving	Empty PC buffer
Ambient	**1600**	1075	200	50	75	150	50
Chilled	**450**	275	100	25	25	25	25
Frozen	**175**	100	25	25	25	12.5	12.5

Several types of flow patterns regarding warehouse layout can be distinguished and used to maximize throughput (Mohsen & Hassan, 2002). Mohsen & Hassan mention the following patterns: U-shape, circular, straight line and serpentine. The layout of the FC is generally U-shaped. Meaning that the in- and outbound of the articles is at the same side of the warehouse but in different zones.

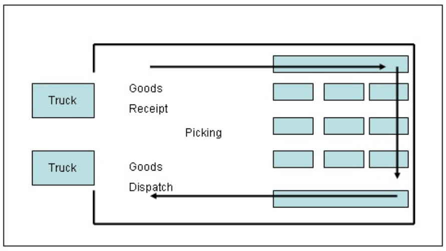

Figure 52: U-flow warehouse layout (Tunay, 2016)

According to de Koster, Le-Duc & Roodbergen (2007) the internal layout design engages the following questions:

- What is the length and number of aisles?
- How many storage blocks should be installed?
- Should there be cross aisles?
- Where is the location of the depot?

The ambient zone has five aisles of approximately 30 meters. The broader paths in between the shelves are the aisles for picking. The narrow aisles are used for the replenishment of the shelves. The layout is designed in such a way that heavy products are picked first and there is aimed to not combine foods with for example personal healthcare articles in the same bag. The aisles consist of 27 shelves (storage blocks) on each side. The shelves have planks on different heights, depending on the kind of products. The planks have one or multiple products divided by a separator. All products have their own pick location. The layout of the shelves (also called slotting) is based on a slotting model. The slotting model takes different variables into account to optimize the order preparation. The articles are located on a specific shelf based on, among others, weight, category and demand. The slotting model is also used to calculate the required space on the shelf needed for an article. This is done based on dimensions, demand and required safety stock. The picker walks all aisles and doesn't have the possibility of skipping a part of an aisle (there are no cross-aisles). Like already described above, the layout of the shelves is defined with the help of a slotting model. When an analysis is performed with the data from 1st of December until the 31st of March it can be seen that 32% of the products where picked in the F-aisle. The majority of the products picked in the F-aisle are fast movers (FM). FMs are products which represent the 20% highest volume sold products (Figure 53). The high number of picks within one aisle could lead to congestion.

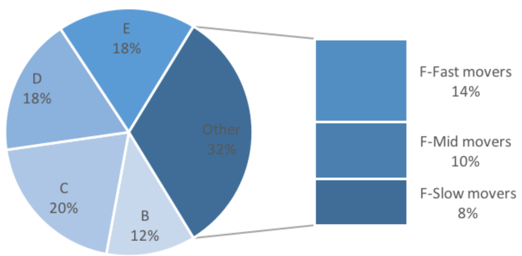

Figure 53: Deviation of picks per aisle (Author, 2016)

Appendix 3: Equipment

In Figure 54, a PC is shown which is used in the FC to pick the orders. The PC can transport 12 totes. Below a PC for ambient totes is depicted. Within the chilled zone a shorter PC is used because of the lack of space in the chilled cell.

Figure 54: Picking cart ambient zone

In Figure 55, DPFs are presented. The DPFs are used to transport the products from the FC to the Hub and in the E-Worker to the customer. A DPF always contains ambient totes or a mixture of frozen and chilled totes.

Figure 55: DPFs with ambient totes

In Table 25, the amount of transport equipment and unit loads in the FC is presented (April 2016). Because of the fact that Picnic is growing every week, the amount of transport equipment also keeps growing.

Table 25: Current amount of transport equipment and unit loads in FC0

Unit load	**Number in FC**	**Can store**
Totes ambient	1526	Avg. 12,2 articles
Totes chilled/frozen	1426	Avg. 13,8/2,1 articles
Picking carts	30 (A:14,C:14,F:2)	12 totes
DPFs (3 layers)	90	18 totes
DPFs (4 layers)	3	24 totes
Docks	6	1 truck
Truck for outbound	flexible	40 DPFs (double stacked)

Appendix 4: Range, order and tote analyses

In Table 26, the percentage of sold items versus the percentage of SKUs is presented. The data used, is from the sales of the 1st of December 2015 – 31st of March. It can be seen that 51% of the sold products within these period, are ambient products. Chilled '14-'16, represents the items in the ambient zone, which ideally have to be stored in '14-'16 degrees (fruit, vegetables etc.). In Table 27, the deviation of different sales categories over all sold items is depicted. From the results it can be concluded that 81 SKUs represent 20% of the volume. The average order characteristics with descriptive statics (of the order lines) are presented in Table 29. The fragility classification of the ambient products is presented in Table 30. Figure 56, Figure 57, Figure 58 and

Table 31 show the results of the tote analysis. Figure 56 shows the number of totes per order. Figure 57, the number of items per tote (within different tote categories). Figure 58 the tote fill rate and

.

Table 26: Range characteristics (1-12-2015 – 31-3-2016)

Row Labels	Number of items sold	Percentage of items sold	Number of SKUs	Percentage of SKUs
ambient	**664877**	**50,79%**	**3330**	**73,28%**
F	88257	6,74%	32	0,70%
M	206105	15,74%	255	5,61%
S	370515	28,30%	3043	66,97%
chilled	**508956**	**38,88%**	**900**	**19,81%**
F	103878	7,94%	16	0,35%
M	153675	11,74%	75	1,65%
S	251403	19,21%	809	17,80%
chilled 14-16	**86723**	**6,62%**	**41**	**0,90%**
F	63093	4,82%	9	0,20%
M	19469	1,49%	21	0,46%
S	4161	0,32%	11	0,24%
frozen	**48471**	**3,70%**	**273**	**6,01%**
F	9701	0,74%	10	0,22%
M	14858	1,14%	33	0,73%
S	23912	1,83%	230	5,06%
Total	**1309027**	**100,00%**	**4544**	**100,00%**

Table 27: Deviation articles over sales volumes

Type of article	Percentage of volume	Number of SKUs	Percentage of total range
Fast movers	20%	81 SKUs	2%
Mid movers	30%	390 SKUs	9%
Slow movers	50%	3702 SKUs	89%

Table 28: Average order characteristics (1-12-2015 – 31-3-2016)

Total number of orders 1-12-'15 - 31-3-'16	**39733**
Peak to average (orders)	1,2
Items per order	36,6
Items per order ambient	28,7
Items per order chilled	6,4

Items per order chilled 14-16	2,5
Articles per order frozen	1,2
Order lines per order	28,6
Items per order line	1,27
Order lines per order ambient	22,1
Order lines per order chilled	4,9
Order lines per order chilled 14 -16	2,2
Order lines per order frozen	1,1

Table 29: Descriptive statistics average order characteristics

	Articles per order	Order lines per order	Order lines per order A.	Order lines per order C.	Order lines per order C. 14-16	Order lines per order F.
Average	36,6	28,7	22,1	4,9	2,22	1,1
Std. Dev.	16,9	12,5	10,3	2,9	1,33	0,24
Min	2,0	1,0	1,0	1,0	1,0	1,0
Max	209	127	112	24	11	4

Table 30: Fragility classification of ambient products

Fragility classification	Percentage of sold products
1 Non-Fragile (Aisle B+C)	32%
2 Medium fragile (Aisle D)	18%
3 Fragile (Aisle E)	18%
4 Very Fragile (Aisle F)	32%

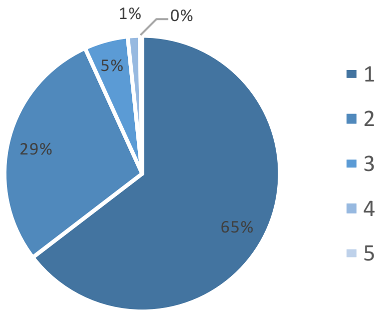

Figure 56: Tote analysis: number of totes per ambient order

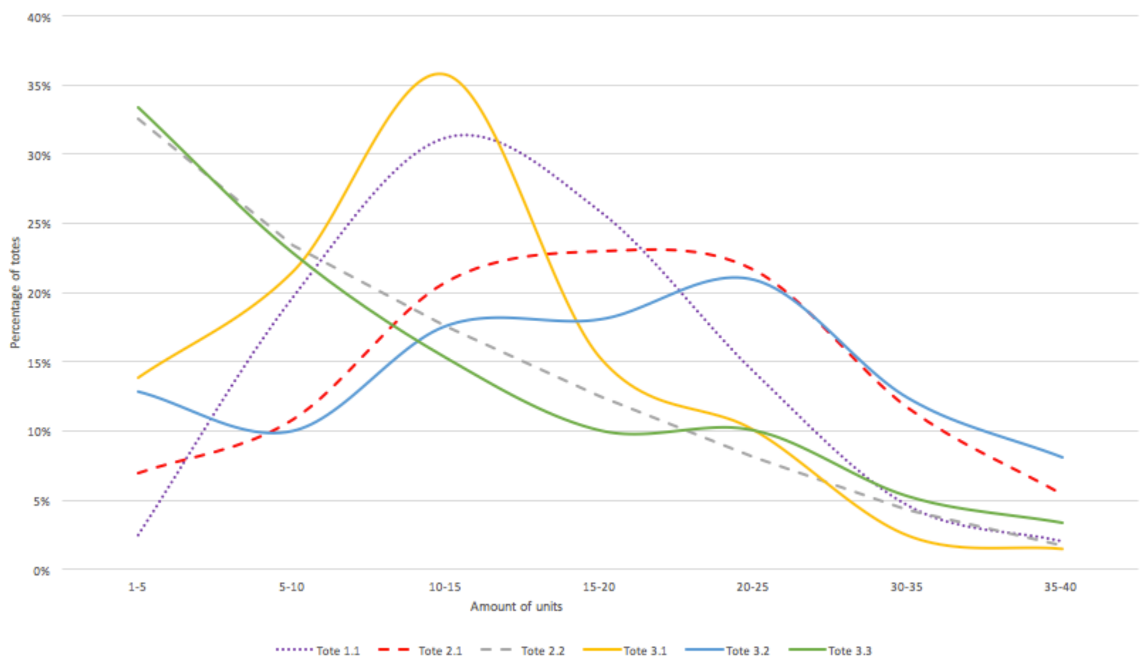

Figure 57: Tote analysis: number of items per tote (with different number of totes per order)

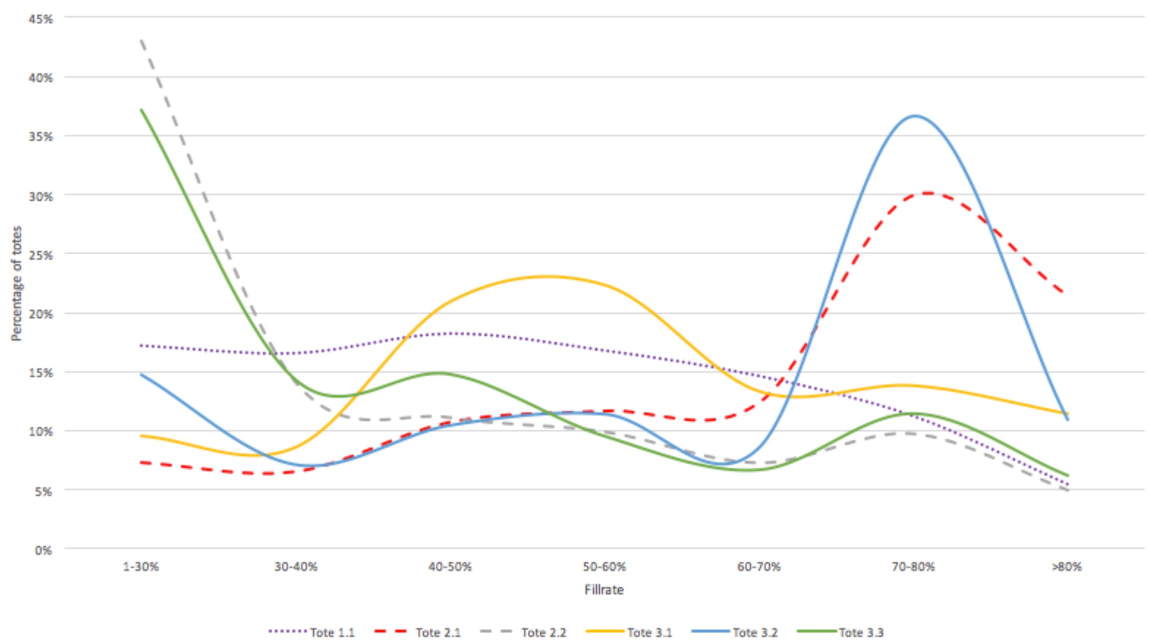

Figure 58: Tote analysis: fill rate per tote (with different number of totes per order)

Table 31: Tote analysis: number of items per volume and fragility category

			Non-frag	**Med-frag**	**High-frag**	**Total items**
Orders 1ambient tote	Tote 1	FM	3%	2%	17%	15,6
		MM	9%	9%	11%	
		SM	8%	22%	19%	
Orders with 2 ambient totes	Tote 1	FM	5%	2%	7%	17,8
		MM	14%	11%	7%	
		SM	12%	26%	16%	
	Tote 2	FM	1%	2%	25%	10,9
		MM	4%	7%	17%	
		SM	2%	17%	23%	

Orders with 3 ambient totes	Tote 1	FM	6%	2%	1%	12,91
		MM	26%	12%	2%	
		SM	21%	23%	7%	
	Tote 2	FM	2%	3%	11%	17,78
		MM	8%	11%	12%	
		SM	3%	27%	23%	
	Tote 3	FM	1%	1%	24%	11,38
		MM	5%	8%	19%	
		SM	2%	18%	23%	

Appendix 5: Productivity of processes

In Table 32, the productivity of different processes is presented. It can be seen that pick productivity is noticeably high when compared to the productivity of other processes.

All-in productivity [item/hr]	**64**
Pick productivity ambient [line/hr]	223
Pick productivity chilled [line/hr]	274
Pick productivity frozen [line/hr]	268
Split productivity ambient [HE/hr]	124
Fill productivity ambient [HE/hr]	44
Receive and fill productivity chilled [HE/hr]	91
Receive and fill productivity frozen [HE/hr]	51

Table 32: Current productivity of processes (April 2016)

Appendix 6: Value Stream Map

To give an overview of the decomposition of the productivity per process, the hours spent on each process and the total minutes spent on an order, a value stream map (VSM) is drawn. Value stream mapping is also defined as “The set of all the specific actions required to bring a specific product (whether a good, a service, or increasingly a combination of the two) through the three critical management tasks of any business: the problem-solving task running from concept through detailed design and engineering to production launch, the information management task running from order-taking through detailed scheduling to delivery, and the physical transformation task proceeding from raw materials to a finished production in the hands of the customer” (Womack & Jones, 1990). Value stream mapping is used to define the non-added value activities. In this research it is used to give an overview of the main processes and the hours spent on these main processes. Value stream mapping is often performed in four steps. From mapping the current state to achieving the future state. On the next page the current state of a day fulfiling 626 orders is mapped. The main disadvantage of the VSM is that it is deterministic. And that the current state varies depending on the order characteristics. The VSM shows the processes in the different temperature zones. Because of the fact that orders are prepared the same day and are shipped in waves, it is hard to define if the for example totes waiting to be stored is non-value added time. Therefore, one of the main conclusions made from the VSM is that 68% of the time is spent on main activities and the rest of the time on side activities. Besides this, it can be seen that currently there are sides activities (like consolidation) integrated in storing. And picking of WOI, integrated in the normal picking.

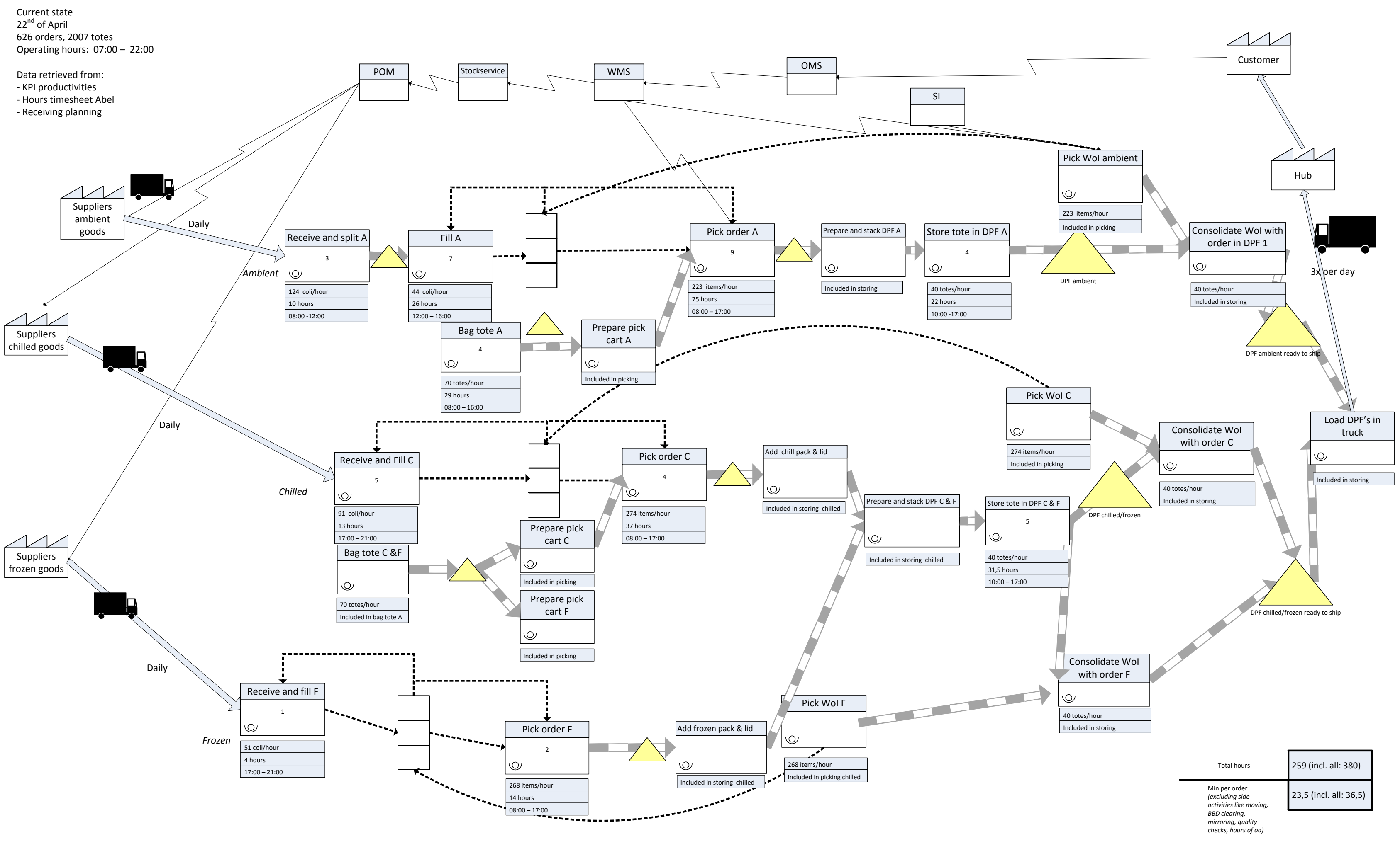

Figure 59: Value stream map FC0

Appendix 7: System solutions

Figure 60: Single push tray sorter (Distrisort, 2016)

Type sorter	Single Pusher	
Tray afmetingen	400x600	
Snelheid	1	m/s
Bruto capaciteit - 1 invoer gebied	7200	trays per uur
Effectiviteit	0,75	
Netto capaciteit	5400	trays per uur
Minimaal aantal uitgangen	54	orders per batch
Aantal pre-sort uitgangen	2	
Aantal speciale uitgangen (reject, no read, NI, etc.)	4	
aantal uitgangen aan de sorter	60	uitgangen
Totaal aantal batches	18,5	batches
Batch change time	3	minuten per batch

Invoeren in sorter		
Number of articles per FTE per hour	800	Articles per hour per FTE
Number of induction positions at sorter	6,8	Induction positions
Total induction time at sorter	30,6	Hours per day
Total number of FTE for induction	5,6	FTE

Figure 61: Specifications sorter (Distrisort, 2016)

Table 33: Main type of AS/RSs

Type of AS/RS	Main technique	General specifications	Advantages/disadvantages
Miniload system	Crane transports unit loads with horizontal, diagonal and vertical movements from rack to a conveyor.	• Throughput capacity: 70-150 totes per hour • Pick productivity in combination with pick station: 150-175 items per hour • ~20 locations/ m^2	+ Effective use of space + Relatively low costs - Low productivity - Sensitive for breakdown - Bins not suitable for all products
Shuttle system	Shuttles move the unit load horizontally inside the aisle. Lifts are used for vertical movements on the outside of the aisles.	• Throughput capacity: 400-550 totes per hour • In combination with pick station pick productivity: 400-500 picks per hour per station • Replenishment: 200 bins per hour • Costs: €1.3M for double rack system, 65mx8m, 10K locations, 2 pick stations and decanting conveyor • ~20 locations/ m^2	+ High productivity + Possible in chilled environment + Effective use of space + Replaceable shuttles - High investment - Bins not suitable for all products
Autostore system	Grid filled with unit-loads. Robots which can move horizontally and vertically rearrange the unit loads continuously and bring unit load to lift inserted in the grid.	• Throughput capacity: 300-400 totes/hour • In combination with pick station: 200-500 picks per hour per station • Robots: 25 moves per hour • €1,5M for 20K bins, 8 robots, 20mx20mx8m • €45.000 per robot • ~50 locations/ m^2	+ High productivity + Effective use of space + Replaceable robots - Bins not suitable for all products - Batteries last only 6 hours in chilled environment - No examples in practice with groceries - Last minute (high priority) picking of product not possible (e.g.: 5 movements required to grab the fourth tote in the grid).

Table 34: Different pick strategies

Order pick system		**Level of mechanization**
Picker-to-parts	Picker-to-parts systems are widely used in warehouses. Different strategies: - Discrete: all articles one order in single tour, can be in wave (time slots) - Batch: multiple orders in single tour, Pick-and-Sort (no sorting while picking) and Sort-while-Pick (direct sorting) Pick-and-Sort strategy increases pick productivity but requires downstream sorting.	**Low.** Assisting pick technologies can be: Voice-Pick, Pick-by-Light (P2L), RF-Pick, Pick-to-Graph.
Pick-to-box	Is also known as Pick-and-pass. Picking zones are connected with a conveyor which transports the picked articles. Is a sequential zone pick strategy. Pick to box can be done from all different unit loads (also from pallets).	**Medium**. Use of conveyors to transport the picked articles. Above assisting technologies can be used.
Pick-and-sort	Articles are picked simultaneously from all the zones, after orders are consolidated through a sorting system.	**Medium.** Conveyors are used to transport picked articles.
Parts-to-picker	A typical Parts-to-picker system consists of a AS/RS system with at the end a pick station. GTP stations can be used to pick articles per order or pick multiple articles in batches. Other possibility is the use of KIVA robots, moving cupboards which bring the part to the picker.	**High.** Picker does not have to move, only has to pick and place articles.
Automated picking	Often AS/RS systems with atomized retrieval. Can be done with: - Robotized picking (multi-fingered robot hands with sensing) - A frame - Dispensers	**High.** Picker is no longer required.

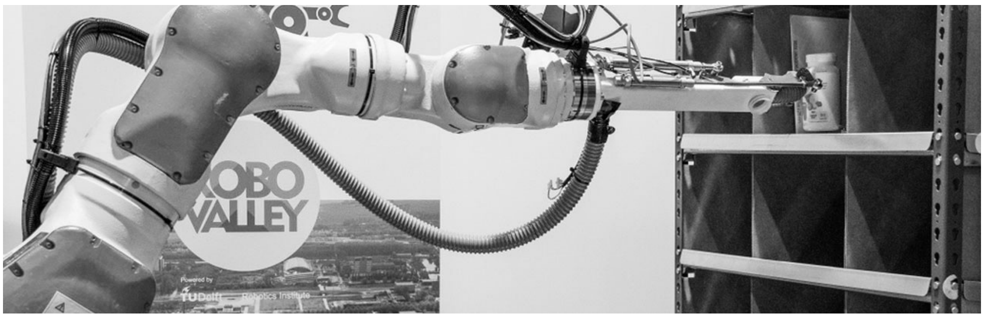

Figure 62: Robotized picking (Deurzen,2016)

Appendix 8: The system solutions per systems function per alternative

Process	Alternatives			
	Alternative 1 *Fully manual alternative, productivities of receiving (splitting), replenishment, consolidating and storing are based on current situation. Pick circuit differs for different amounts of orders.*	Alternative 2 *Picking is manual, surrounding processes are mechanised. Pickcarts are prepared with the help of a pickcart loade, transport of HEs for replenishment is done with conveyor belts and spiral conveyors. DPFs are loaded with a DPF loader. Pick circuit differs for different amounts of orders.*	Alternative 3 *Highly mechanised alternative, picking concepts are dfferent for FM/MM/SM, orders and products (for FM and MM) are stored in an AS/RS. Transportation is done with conveyor belts. Orders are also stored in AS/RS, mechanised frameloader is used to store DPFs.*	Alternative 4 *Transportation of goods is done with the help of KIVA robots. All products are stored in cupboards that can be transported with the help of KIVA robots. The cupboards are driven to a Goods to person station. Orders are brought to a goods to person station with the help of a conveyor belt. Orders are stored in an AS/RS.*
Bagging	Manual	Manual	Manual	Manual
Receiving	Manual splitting [HE]	Mechanised splitting (sorter) [HE]	Decanting [CE]	Decanting [CE]
Replenishment	Manual	Mechanised transport	Mechanised	Mechanised
Product storage	Aisle cupboards/ Pallet Buffer	Aisle cupboards/pallet Buffer	AS/RS	KIVA cupboards
Picking FM	Manual batch sort while pick	Manual batch pallet sort while pick	Manual batch pallet sort while pack	Goods to person station
Picking MM	Manual batch sort while pick	Manual batch sort while pick	Zone pick	Goods to person station
Picking SM	Manual batch sort while pick	Manual batch sort while pick	Goods to person	Goods to person station
Order storage	DPF	AS/RS	AS/RS	AS/RS
Consolidating	Manual	Goods to person station	Goods to person station	Goods to person station
Storing	Manual	Mechanised frameloader	Mechanised frameloader	Mechanised frameloader
Tranportation products	Manual	Mechanised (conveyor belt)	Mechanised (conveyor belt)	KIVA
Transportation orders	Manual	Manual	Mechanised (conveyor belt)	Mechanised (conveyor belt)

Figure 63: System means per alternative

Appendix 9: Conceptual layouts per alternative

Below, conceptual layouts for the alternatives are depicted. In orange the areas are presented where picking takes place. The numbers are different steps in the fulfilment process. Every color represents a different flow. Below the layouts, a legend is presented.

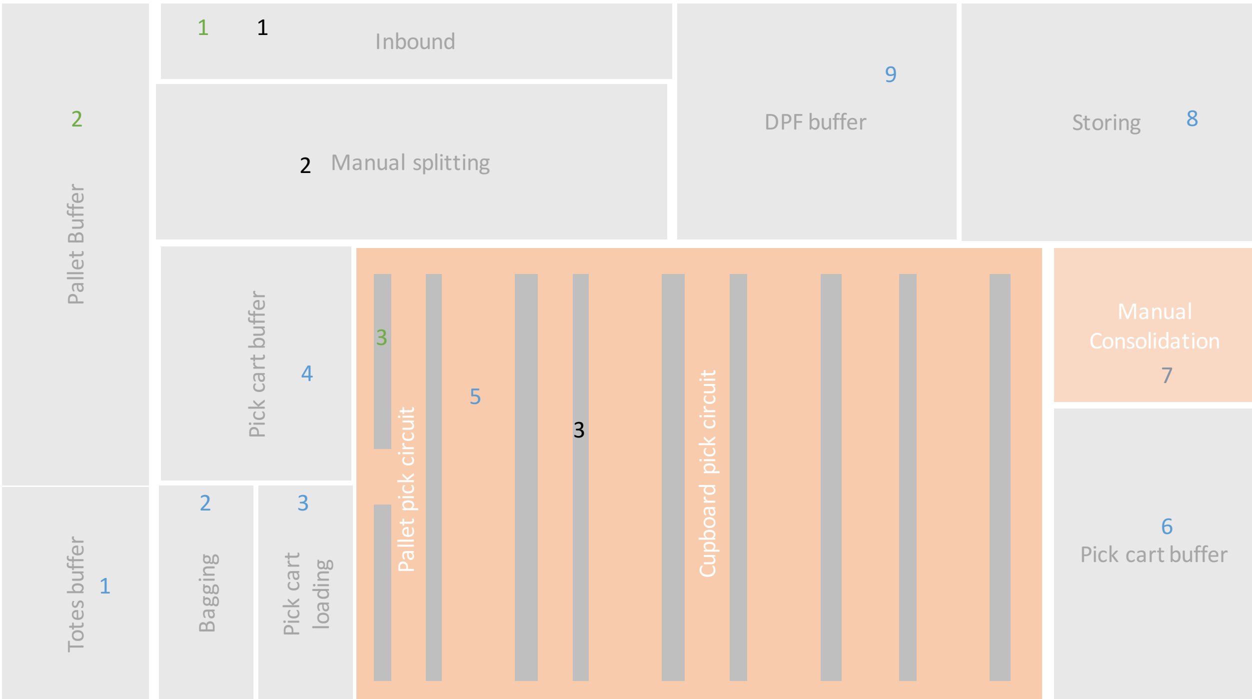

Figure 64: Conceptual layout alternative 1 (Author, 2016)

Table 35: Legend conceptual layout alternative 1

Colour	*Process*	*Start- and endpoint*
Green	Pallet replenishment	Inbound – pallet pick circuit
Black	HE replenishment	Inbound – cupboard pick circuit
Blue	Order tote flow	Totes buffer – DPF buffer

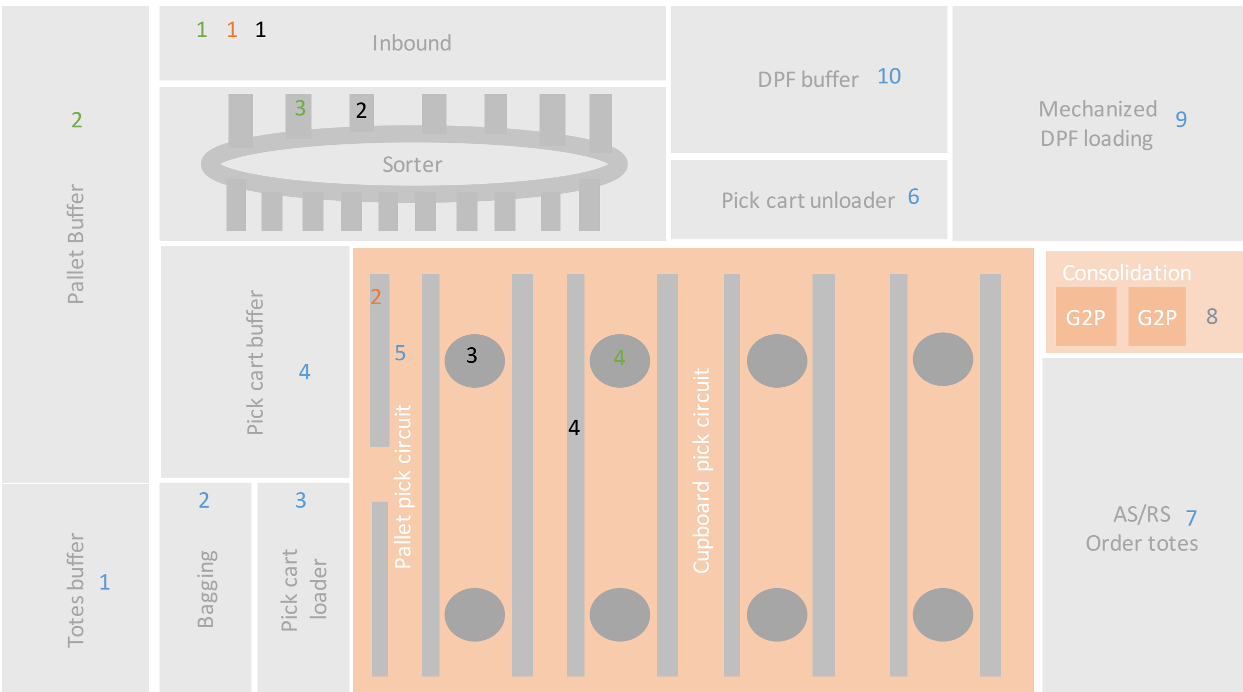

Figure 65: Conceptual layout alternative 2 (Author, 2016)

Table 36: Legend conceptual layout alternative 2

Colour	*Process*	*Start- and endpoint*
Green	HE replenishment via buffer	Inbound – cupboard pick circuit
Black	HE replenishment	Inbound – cupboard pick circuit
Orange	Pallet replenishment	Inbound – pallet pick circuit
Blue	Order tote flow	Totes buffer – DPF buffer

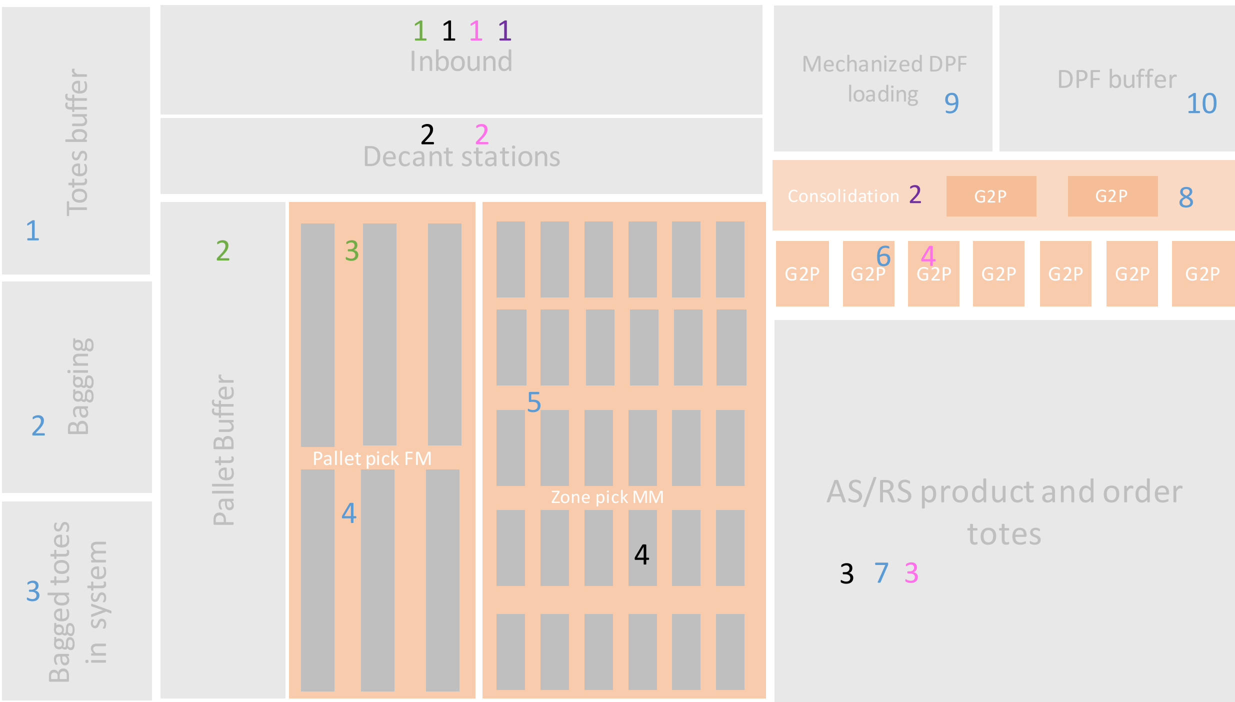

Figure 66: Conceptual layout alternative 3 (Author, 2016)

Table 37: Legend conceptual layout alternative 3

Colour	*Process*	*Start- and endpoint*
Green	Pallet replenishment FM	Inbound – pallet pick circuit
Black	CE replenishment MM	Inbound – zone pick station
Pink	CE replenishment SM	Inbound – GTP pick station
Blue	Order tote flow	Totes buffer – DPF buffer
Purple	JIT fresh replenishment	Inbound – GTP pick station

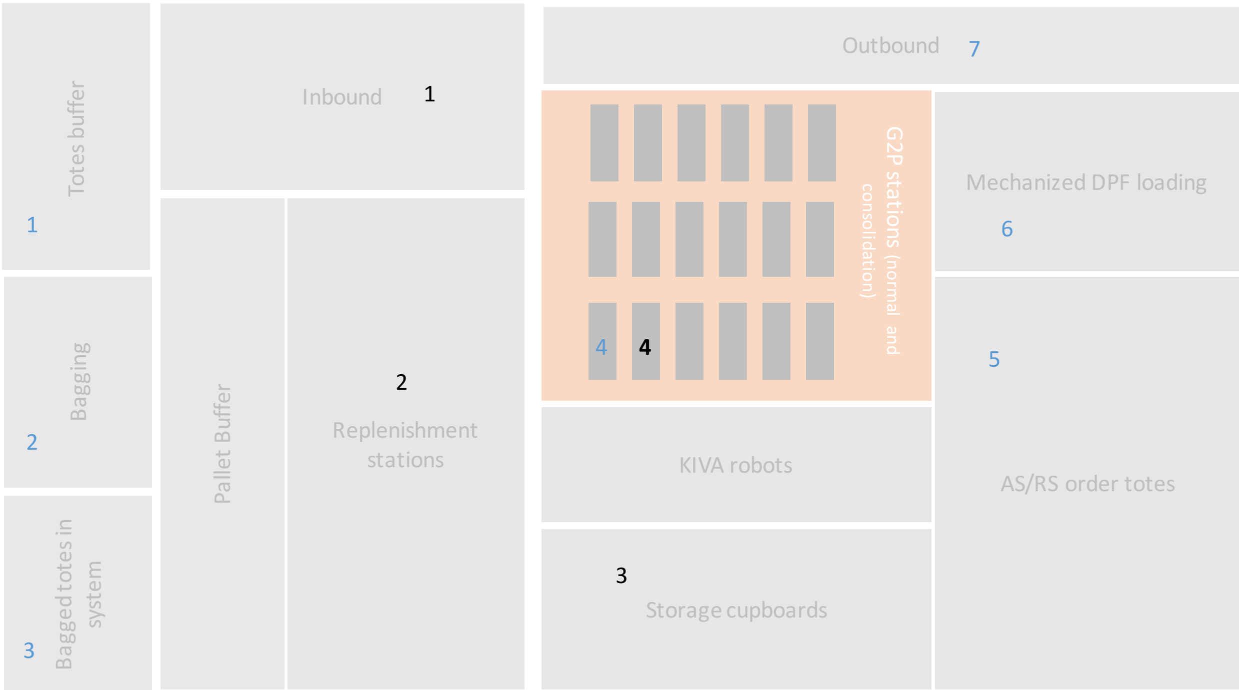

Figure 67: Conceptual layout alternative 4 (Author, 2016)

Table 38: Legend conceptual layout alternative 4

Colour	*Process*	*Start- and endpoint*
Blue	Order tote flow	Totes buffer – DPF buffer
Black	CE replenishment	Inbound – GTP pick station

Appendix 10: Variables used for the scenarios

Table 39: Quantification per variable

Var.	Variable	Name	Unit	Independent variables				
1	Vi_asr	Amount of SKUs ambient range	[SKU]	Modelinput				
				1	1	As current	0%	3317
				1	2	Low growth	26%	4500
				1	3	Expected growth	51%	5000
				1	4	High growth	81%	6000
2	Vi_auo	Amount of units ambient order	[unit]	Modelinput				
				2	1	As current	0%	21,46
				2	2	Low growth	3%	22
				2	3	Expected growth	16%	25
				2	4	High growth	26%	27
3	V_ipt	Units per tote	[unit]	Modelinput				
				3	1	As current	0	15,5
				3	2	Growth	3,23%	16,00
				3	3	Decline	-6,45%	14,50
				3	4	High decline	-9,68%	14,00
4	Vi_aul	Amount of units per line	[unit/line]	Modelinput				
				4	1	As current	0%	1,27
				3	2	Small decline	-2%	1,25
				4	3	Small growth	2%	1,29
				4	4	High growth	3%	1,31
5	Vi_avs	Average volume per SKU	[l]	Modelinput				
				5	1	As current	0%	1,41
				5	2	Low growth	3%	1,45
				5	3	Medium growth	4%	1,46
				5	4	High growth	6%	1,5
6	V_pojit	Percentage orders to add JIT fresh	[%]	Modelinput				
				6	1	As current	0	40%
				6	2	As expected	25%	50%
				6	3	Decline	-13%	35%
				6	4	High growth	38%	55%

Table 40: Variables per scenario

Scenario	Scenario name	Explanation	Vi_asr Amount of SKUs ambient range	Vi_auo Amount of units ambient order	Vi_aul Units per tote	Vi_avs Amount of units per line	Vi_asf Average volume per SKU	Vi_pmm Percentage orders to add JIT fresh
Model input 1	Current range/order profile	Variables will increase/decrease as	1	4	1	1	1	1
			3317	27	15,5	1,27	1,41	0,4
1	Current range/order profile	Variables will increase/decrease as expected	1	1	1	1	1	1
	△		0%	0%	0%	0%	0%	0,00%
2	Change as expected	Variables will increase/decrease as expected	3	3	2	3	3	2
	△		51%	16%	3%	2%	4%	25,00%
3	Super high service	Clients demand a high amount of extr SKUs in the range. Due to the high amount of SKUs, the amount of units i an order will also increase.	4	4	2	3	4	4
	△		81%	26%	3%	2%	6%	37,50%
4	Christmas	Large orders, large amount of units/line	4	4	3	3	3	4
	△		81%	26%	-6%	2%	4%	37,50%
5	Pantry order characteristics	Client will change their shopping behaviour to more pantry like items. High amount of units/line, large average volume per SKU	3	3	4	4	3	1
	△		3%	16%	-10%	3%	4%	0,00%

Appendix 11: Time schedules

Table 41: Current schedule

Current schedule																								
	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Receiving		1	1	1																				
Replenishment												1	1	1	1									
Bagging														1	1	1	1	1	1	1	1	1		
Picking														1	1	1	1	1	1	1	1	1		
Receiving JIT																								
Consolidating WoI																					1	1	1	1
Consolidating Jit												1	1	1										
Order despatching (in)														1	1	1	1	1	1	1	1	1	1	
Storing (out)															1	1	1	1	1	1	1	1	1	1

Working hours	
Receiving	3
Replenishment	4
Bagging	9
Picking	9
Receiving JIT	0
Consolidating WoI	4
Consolidating Jit	3
Order despatching (in)	10
Storing (out)	10

Table 42: Pre-picking delivery schedule

Pre-picking																								
	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Receiving											1	1									1	1	1	1
Replenishment										1	1	1	1	1	1	1	1	1						
Bagging												1	1	1	1	1	1	1	1	1	1	1	1	1
Picking	1	1	1	1								1	1	1	1	1	1	1	1	1	1	1	1	1
Receiving JIT											1													
Consolidating WoI												1	1	1										
Consolidating JiT												1	1	1	1	1	1	1						
Order despatching (in)	1	1	1	1	1							1	1	1	1	1	1	1	1	1	1	1	1	1
Storing (out)															1	1	1	1	1	1	1	1	1	1

Working hours	
Receiving	6
Replenishment	9
Bagging	13
Picking	17
Receiving JIT	1
Consolidating WoI	3
Consolidating JiT	7
Order despatching (in)	18
Storing (out)	10

Table 43: Same day delivery schedule

Same day delivery																								
	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Receiving											1	1	1								1	1	1	1
Replenishment											1	1												
Bagging												1	1	1	1	1	1	1	1	1	1	1	1	1
Picking	1	1	1	1	1	1						1	1	1	1	1	1	1	1	1	1	1	1	1
Receiving JIT											1													
Consolidating												1	1	1										
Consolidating JiT												1	1	1										
Order despatching (in)	1	1	1	1	1							1	1	1	1	1	1	1	1	1	1	1	1	1
Storing (out)															1	1	1	1	1	1	1	1	1	1

Working hours	
Receiving	7
Replenishment	2
Bagging	13
Picking	19
Receiving JIT	1
Consolidating WoI	3
Consolidating JiT	3
Order despatching (in)	18
Storing (out)	10

Appendix 12: Specification of the modules

Table 44: Variables picking and storage module alternative 1 and 2 in Excel model

	Variable	Unit		Variable	Unit	Variable	Unit
Cupboard circuit	Safety stock in cupboards		**Pickcart preperator**			Pick productivity per hour	[item/hr]
	# items per meter	[item/m]		Pickcarts	[PC]	Pick productivity per hour	[ol/hr]
	# items (excl pallet pick &(AGF+bread))	[item]		Productivity	[item/hr]	Departure rate	P[C/minute]
	# Replenishment			Required amount PC preparator	[prep]	Max pickcarts in circuit (length constr.)	[PC]
	# meters	[m]	**Productivities**			Max # pickcarts in circuit (time constr)	[PC]
	# meter when SKUs increase	[m]		Items per frame	[item/frame]	Max productivity	[item/hr]
Dolly circuit (bread)				Picks per frame	[ol/frame]	Pickcarts per aisle	[PC]
	# crates on dolly	[crate]		Amount of meters	[m]	Required productivity	[item/hr]
	# breads in crate	[bread]		# totes per pickcart	[tote/PC]	Difference	[%]
	# breads	[bread]		Scan per tote	[s]		
	# dollies	[dolly]		Set-up time per frame	[s]		
	Length aisle dollies	[m]		Set-up time per frame	[m]		
	Replenishment			Travel speed , incl start/stop	[m/s]		
	Length needed	[m]		Time per pick , incl scanning	[s]		
Flow in circuit				Pick penalty for multi-item picks	[s]		
	Length pickcart	[cm]		Penalty for WoI	[s]		
	Length pickcart	[m]		Chance WoI	[%]		
	Pick speed	[m/s]		Travel time walking	[s]		
	Min distance between pickcarts	[m]		Travel time walking	[m]		
	Total space needed pickcart	[m]		Picking time single o.l.	[s]		
	Max # pickcarts per aisle	[pickcart]		Picking time single o.l.	[m]		
	Pick cart can leave every	[s]		Picking time incl multip	[s]		
Ailse length				Picking time incl multip	[m]		
	Required # meters	[m]		Picking time incl multip & WoI	[s]		
	Total length pick circuit	[m]		Picking time incl multip & WoI	[m]		
	Aisles length	[m]		Total time per pick route	[m]		
	Number of one sided aisles	[aisle]		Total time per pick route (excl double pal)	[m]		
	Number of double sided aisles	[aisle]		Total time per pick route (excl double pal	[s]		
	Total length pick round	[m]		Total time per pick route	[s]		
M^2 needed				Time per item pick	[s]		
	Aisle width	[m]		Time per order line pick	[s]		
	Amount of one-sided aisles	[aisle]					
	Amount of squared meters picking circuit	[m^2]					

Table 45: Variables picking module alternative 3 in Excel model

Variable	Unit	Variable	Unit
Amount of SKUs per zone		**Mechanised picking productivity**	
Percentage SKUs	[%]	# Facings product totes	[product tote]
Percentage Lines	[%]	# Facings order totes	[order tote]
Percentage Units	[%]	Avg meters walking per pick	[m]
Percentage Volume (l)	[%]	Speed walking	[m/s]
Amount SKUs	[SKU]	Time product pick	[s]
Total lines	[line]	Time place product	[s]
Total items	[item]	Time scan	[s]
Lines per hour	[line/hr]	Time click button	[s]
Items per hour	[item/hr]	Total time per product	[s]
Volume per hour	[liter/hr]	Productivity	[item/hr]
Avg # items in tote	[item/tote]	**Design zone system**	
Avg # lines in tote	[line/tote]	# of stations needed	[station]
Totes per hour	[tote/hr]	Mirrored lines	[line]
Item per line	[item/line]	Stations per line	[station/line]
Volume per item	[l/item]	Sides per station (front and back)	[side/station]
Replenishment pallets	[pal/hr]	Levels per side	[level/side]
Picking Items per hour per picker	[item/hr/picker]	Product tote per level	[tote/level]
Lines per hour per picker	[line/hr/picker]	Product totes per station	[tote/station]
Number of stations	[station]	Product totes per line	[tote/line]
Manual picking productivity		Total product totes	[product tote]
Min length circuit	[m]	Product totes per SKU	[tote/SKU]
Min lenght circuit	[m]	# product totes per SKU/line	[tote/line]
Aisle length	[m]		
# aisles	[aisle]		
Picks per aisles	[item/aisle]		
Order lines per aisles	[line/aisle]		
# totes per pickcart	[tote/PC]		
# items per pickcart	[item/PC]		
# lines per pickcart	[line/PC]		
Scan per tote	[s]		
Set-up time per frame	[s]		
Set-up time per frame	[min]		
Travel speed incl start/stop	[m/s]		
Time per pick incl scanning	[s]		
Pick penalty for multi-item picks	[s]		
Penalty for WoI	[s]		
Chance WoI	[%]		
Travel time walking	[s]		
Travel time walking	[min]		
Picking time single o.l.	[s]		
Picking time single o.l.	[m]		
Picking time incl multip	[s]		
Picking time incl multip	[min]		
Picking time incl multip & WoI	[s]		
Picking time incl multip & WoI	[min]		
Total time per pick route	[min]		
Total time per pick route	[s]		
Time per item pick	[s]		
Time per order line pick	[s]		
Pick productivity per hour	[item/hr]		
Pick productivity per hour	[order line/hr]		

Table 46: Variables picking and storage module alternative 4 in Excel model

	Variable	Unit
Dimensions Cupboard		
	Length	[cm]
	Width	[cm]
	Height	[cm]
	Max carry load	[kg]
Storage capacities		
	Total volume	[l]
	Avg. # planks	[plank]
	Thickness planks	[cm]
	Extra pick space/plank	[cm]
	Fill rate	[%]
	Average volume SKU	[l]
	Nett volume	[l]
	Safetystock	
	Avg item in stock	[item]
	Avg vol article	[l]
	Vol. Items	[l]
	# Cupboards needed	[l]
Productivity		
	Pick productivity	[item/hr]
	Item	[item]
	Items/hour	[item/hr]
	# pick stations needed	[station]
Deviation SKUs		
	SKUs	[SKU]
	Lines	[line]
	Item	[item]
	Volume	[l]
	SKUs	[SKU]
	Lines per hour	[line/hr]
	Items per hour	[item/hr]
	Volume per hour	[liter/hr]
	Avg # items in tote	[item/tote]
	Avg # lines in tote	[line/tote]
	Hours	hr
	Item per line	[item/line]
	Volume per item	[l/item]
	# Cup for vol.	[cup]
	Extra KIVAs spread FM	[KIVA]
	Extra cupboards spread FM	[cup]
Kiva robots		
	Kivas for queue per station	[KIVA]
	Kivas for transport per station	[KIVA]
	Total Kivas	[KIVA]
Total cupboards		
	Total surface	[m2]
	Extra surface for movement robots	[m2]

Table 47: Variables replenishment module alternative 2 in Excel model

	Variable	Unit
General		
	HE inbound	[HE/hr]
	Items inbound	[item/hr]
Sorting A2		
	Sorts/hour	[HE/hr]
	Hours	[hr]
	Sorters needed	[sorter]
	Exits	[exite]
	HE/hour induction	[HE/hr]
	Induction points needed	[induction point]
Replenishment A2		
	# aisles	
	Aisle length	[m]
	Diameter conveyor spiral	[m]
	Belth speed transport replenishment	[m/s]
	Belth speed conveyor spiral	[m/s]
	# conveyor spirals per aisle	[m]
	Total spiral conveyors	[SC]
	# chutes per conveyor	[chute]
	HE inbound/ aisle/ hour	[HE/aisle/hr]
	HE outbound/spiral/hour	[HE/SC/hr]
	Required productivity per aisle	[HE/aisle]
	Amount of replenishers per aisle	[replenisher]
Productivity repl.		
	Average walking distance per HE	[m]
	Travel speed, incl start/stop	[m/s]
	Time walking per HE	[s]
	Time unpacking per HE	[s]
	Time placing articles	[s]
	Time scanning	[s]
	Total time per HE	[s]
	Productvity replenisher	[HE/hr]
Decanting A3/A4		
	Item for decanting/hour	[item/hr]
	Item/hour	[item]
	Decanting stations needed	[station]
Single push tray sorter design	Tray width	[mm]
	Tray length	[mm]
	Tray length	[m]
	Sorts per hour	[HE/hr]
	Sorts per minute	[HE/m]
	Exits	[Exit]
	Sorts/hour/exit	[HE/hr/exit]
	Sorts/min/exit	[HE/m/exit]
	Total length	[m]
	Amount of trays on sorter	[tray]
	Average travel distance on sorter HE	[m]
	Belt speed	[m/min]
	Belt speed	[m/sec]

Table 48: Workforce module (when handling 20K orders)

Process	Variable	Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Bagging						
	Amount of bags per tote	[bag/tote]	3	3	3	3
	Amount of totes	[tote]	27690	27690	27690	27690
	Productivity	**[bag/tote/h/p]**	**210**	**210**	**210**	**210**
	Amount hours	[h]	13	13	13	13
	Amount people	[p]	30	30	30	30
	Total amount hours	[h]	396	396	396	396
Receiving						
	Amount HE	[HE]	44050	44050	25976	53650
	Amount CE	[CE]	429200	428000	254220	429200
	Productivity	**[HE-CE /h]**	**124**	**5000**	**800**	**800**
	Amount hours	[h]	6	6	6	6
	Amount people	[p]	59	6	53	89
	Total amount hours	[h]	355	38	318	537
Replenishment						
	Amount HE	[HE]	44050	44050	-	-
	Productivity	[HE/h/p]	44	378	-	-
	Amount hours	[h]	6	6	-	-
	Amount people	[p]	167	19	-	-
	Total amount hours	[h]	1001	116		
Replenishment pallets						
	Amount pallets	[pal]	529	529	*529*	-
	Productivity	[pal/h/p]	20	20	20	-
	Amount hours	[h]	6	6	6	-
	Amount people	[p]	4	4	4	-
	Total amount hours	[h]	26	26	26	
Picking FM						
	Amount CE	[CE]	429200	429200	164385	429200
	Amount lines	[l]	27690	27690	120692	27690
	Productivity	[CE/h/p]	129	129	219	300
	Amount hours	[h]	16	16	16	16
	Amount people	[p]	207	207	47	89
	Total amount hours	[h]	3315	3315	751	1431
Picking MM						
	Amount CE	[CE]	-	-	123266	-
	Amount lines	[l]	-	-	98908	-
	Productivity	[CE/h/p]	-	-	439	-
	Amount hours	[h]	-	-	16	-
	Amount people	[p]	-	-	18	-
	Total amount hours	[h]			281	
Picking SM						
	Amount CE	[CE]	-	-	130955	-
	Amount lines	[l]	-	-	108899	-
	Productivity	[CE/h/p]	-	-	600	-
	Amount hours	[h]	-	-	16	-
	Amount people	[p]	-	-	14	-
	Total amount hours	[h]			218	
Consolidating JIT + (WoI)						
	Percentage totes to consolidate	[%]	40,00%	40,00%	40,00%	40,00%
	Totes to consolidate	[totes]	11076	11076	11076	11076
	Productivity	[tote/h]	65	400	400	400
	Amount hours	[h]	7	7	7	7
	Amount people	[p]	24	4	4	4
	Total amount hours	[h]	170	28	28	28
Storing						
	Amount of totes	[tote]	27690	27690	27690	27690
	Amount of DPFs	[DPF]	1648	1648	1648	1648
	Productivity	[tote/h]	40	1008	1008	1008
	Amount of hours	[hour]	10	10	10	10
	Amount of people	[p]	69	-	-	-
	Total amount hours	[h]	692			

Table 49: Legend symbols

Term	symbol
Length	L
Total	∑
Time	t
Item	i
Order line	ol
Waiting on Inventory	WoI
Amount	#
Pallet	Pal
Pick cart	PC
Circuit	CC
Safety stock	SS
Replenishment	Repl
Frequency	Freq
Inbound	ib
Seconds	s
Alternative	alt
Minimum	min
Maximum	max
Productivity	prod
Hour	hr
Difference	∆
Outbound	ob
Average	avg
Midmovers	mm
Slowmovers	sm
Fastmovers	fm
Product tote	prodtt
Order tote	ordertt

Table 50: Formulas used in product storage and picking module alternative 1 and 2

Length pick circuit A1, A2			
	L pick CC	[m]	L pal CC [m] + L cupboard CC [m] + L dolly CC [m]
	L pal CC	[m]	SKUs ib 1<x<2 pal [SKU] + 2*(SKUs ib >2 pal) [SKU] * pal size [m]
	L cupboard CC	[m]	(∑i ib (<1 pal [item] * SS factor) / repl freq / i per m [i/m]
	L dolly CC	[m]	∑dollies [dolly] *L dolly [m]
	∑ dollies	[dolly]	∑ib bread [bread] / ∑crates on dolly [crate] / ∑breads in crate [bread]
	∑ aisles	[aisle]	L pick CC [m]/ L aisles [m] / number of sides aisle [m]
	L pick round	[m]	L pick CC [m] + ∑aisles [m] * L turn aisle [m]
Productivity A1, A2			
	i per frame	[i]	∑i in tote [i] * ∑Totes on PC [tote]
	ol per frame	[ol]	i per frame [i] / i per ol [i]
	Set up t frame	[s]	∑ totes on frame [tote] * t to prepare tote [sec]
	∑ t walking	[s]	L pick round [m] / walking speed [m/s]
	Pick t single i ol	[s]	i per frame [i]* t per pick [s]
	Pick t multiple i ol	[s]	I per frame [i]– picks per frame [picks] * pick penalty multiple i [s]
	Pick t WoI	[s]	Chance on WoI [%] * i per frame [item] * pick penalty WoI[s]
	∑ pick t	[s]	Pick t. single i ol [s]+ pick t multiple i ol [s] + pick t WoI [s]
	∑ t alt 1	[s]	∑t walking [s]+ ∑pick t [s] + set up t frame [s]
	∑ t al 2	[s]	∑t walking [s] + ∑pick t [s]
	t per i pick	[s]	∑t [s]/ i per frame [i]
	t per ol pick	[s]	∑t [s]/ ol per frame [ol]
	Pick prod	[i/hr]	3600 [s]/ t per i pick [s/i]
	Pick prod	[ol/hr]	3600 [s]/ t per ol [s/ol]
Flow in circuit A1, A2			
	m per PC	[m]	Min m between PCs/2 [m] + l PC [m]
	Max # PC per aisle	[PC]	Ailse L [m] / m per PC [m]
	Departure rate PC	[PC/s]	Min m between PCs [m] /walking speed [m]
	Max PCs in CC (L constraint)	[PC]	L pick CC [m] / m per PC
	Max PCs in CC (t constraint)	[PC]	∑t alt (1 or 2) [sec] / departure rate
	Max prod	[i/hr]	Min (max PCs in CC (L constraint), max PCs in CC (t constraint)) [i/hr] * t per i pick [s]
	Needed prod	[i/hr]	∑ib i [item] / hr [hr]
	∆ prod	[i/hr]	Needed prod - max prod
Pick cart preparator A2	PC to prepare	[PC]	3600 [s] / departure rate PC [PC/s]
	∑ PC preperator	[Pcprep]	PC to prepare [PC/s] / PC preparator productivity [PC/s]

Table 51: Formulas used in replenishment module alternative 2, 3, 4

Sorting A2			
	∑He ib	[HE]	(Amount orders * amount of units per order) / Ce per HE - amount of HE in pallet circuit
	∑ sorters	[sorter]	∑He ib / sort prod / hr
	∑ induction points	[induction point]	Sort prod/induction prod
Replenishment A2			
	Ib per aisle	[HE/aisle/hr]	∑He ib/∑aisles/hr
	ob per aisle	[HE/spiral/aisle]	Ib per aisle [HE]/ ∑spiral conveyor per aisle [spiral conveyor]
	repl prod per aisle	[HE/hr/aisle]	ob aisle * ∑spiral conveyor per aisle [spiral conveyor]
	∑ repl per aisle	[replenisher]	repl prod per aisle / prod repl
Productivity replenisher A2			
	Travel t per HE	[s]	Avg walking distance per HE [m]/ walking speed
	∑t per HE	[s]	Travel t per HE [s] + unpacking t per HE [s] + placement t per HE [s] + scanning t per HE [s]
	Prod repl	[HE/hr]	3600 [s]/ ∑t per HE
Decanting A3/A4			
	∑decant stations	[decant station]	∑i decanting/ decant prod
	∑i decanting	[i]	ib SM i + ib MM i

Table 52: Formulas used in picking module alternative 3

Mechanised picking MM A3			
	t per product mm	[s]	m walking per pick [m] /walking speed [m/s] + ∑(t product pick [s] + t place [s] + t scan [s] + t click button [s])
	pick prod mm	[i/hr]	3600 [s]/ t per product
Mechanised picking SM A3	t per product sm	[s]	∑(t product pick [s] + t place [s] + t scan [s] + t click button [s])
	pick prod sm	[i/hr]	3600 [s]/ t per product
Design MM system A3	∑zone stations	[station]	∑i mm [i] / pick prod mm [[i/hr]
	∑prodtt per station	[prodtt/station]	Sides per station [side] *levels per side [level] *prodtt per level [prodtt]
	∑stations per line	[station/line]	∑zone stations [station]/ mirrored lines [line]
	∑prodtt per line	[prodtt/line]	∑stations per line [station/line]*∑prodtt per station [prodtt/station]
	∑prodtt	[prodtt]	∑prodtt per line * mirrored lines [line]
Design SM system A3	∑G2P stations	[station]	∑i sm / pick prod sm

Table 53: Formulas used in storage and picking module alternative 4

Storage capacity A4			
	Nett volume cupboard	[l]	Total volume Kiva* fillrate
	Items in stock	[i]	Items * SS
	Volume articles	[l]	Items * avg vol articles
	Min cupboards needed	[cupboards]	Avg vol articles / nett volume
Picking A4			
	Amount pick stations needed	[station]	items mm_sm_fm/hour / productivity
	Amount kivas needed	[kiva]	kivas for queue station * # of stations + kivas transport station * # of stations
	Total cupboards	[cupboards]	Min cupboards + extra cupboards FM
	Extra cupboards FM		Vol l/h FM * hr / net volume cupboard

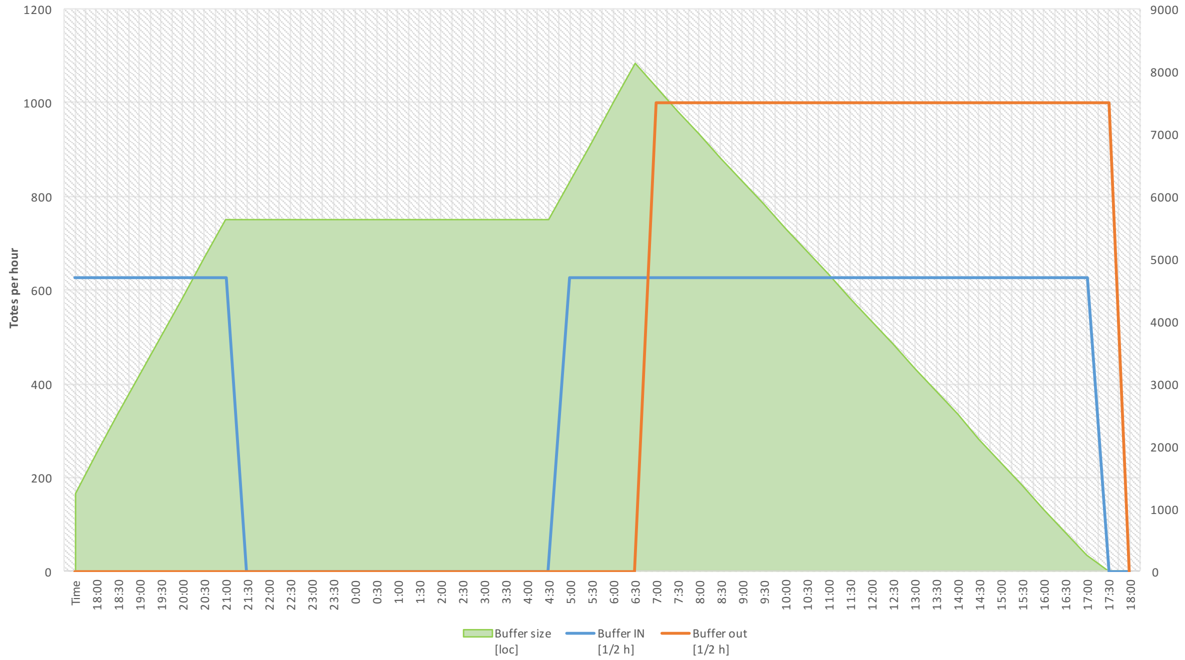

Figure 68: Required number of order tote locations in AS/RS

Appendix 13: Initial values and assumptions

Table 54: Initial values model

Variable	Name	Value	Unit
V_dlc	Direct labour costs per hour	15,00	[€/h/person]
V_dlcsm	Direct labour costs per hour (semi-mechanised)	16,00	[€/h/person]
V_dlcm	Direct labour costs per hour (mechanised)	17,00	[€/h/person]
V_ce	Amount of CE per HE	8,00	[CE]
V_rm	Rent per m²/year	70,00	[€/m2/year]
V_sdl	Salary direct labour	15,00	[€/h]
V_ab	Amount of bags in tote	3,00	[bags]
V_prodcb	Productivity current bagging	210,00	[bag/h]
V_prcr	Productivity current receiving	124,00	[HE/h/person]
V_prcrp	Productivity current replenishment	44,00	[HE/h]
V_prcp	Productivity current picking	232,00	[unit/h]
V_prcc	Productivtity current consolidating WoI	65,00	[unit/h]
V_prcs	Productivity current storing	40,00	[tote/h]
V_wpa	Width per (one-sided) aisle	3,00	[m]
V_lpc	Length pickcart	275,00	[cm]
V_tppc	Totes per pickcart	12,00	[totes]
V_abpt	Amount of bags per tote	3,00	[bags]
V_tpf	Average amount of totes per frame	16,80	[tote]
V_wep	Width EURO pallet + margin	100,00	[cm]
V_ lkc	Length Kiva cupboard	130,00	[cm]
V_wkc	With Kiva cupboard	90,00	[cm]
V_hkc	Height Kiva cupboard	250,00	[cm]
V_mcl	Max carry load Kiva	600,00	[kg]
V_tl	Tray width sorter	400,00	[mm]
V_ls	Tray length sorter	600,00	[mm]

Table 55: Assumptions model

Assumption	Tab	Name	Value	Unit	Explanation
A_sdd	Schedules	Same day delivery	4	[hour]	Same day delivery extra hours during night (higher salary)
A_ss	Pickcircuit	Safety stock	2,3	factor	Units in stock (for 2 days +30%)
A_rf2	Pickcircuit	Replenishment freq alt 1,2,4	4,00	frequency	(Replenishment SKUs <1 pallet)
A_bpp	Pickcircuit	Threshold buffer palletplaces	2,00	factor	
A_scpt	Pickcircuit	Scan per tote	10,00	[sec]	Scanning time when preparing pick cart
A_pwoi	Pickcircuit	Penalty waiting on inventory	90,00	[sec]	90 seconds extra when there is a WoI
A_mindbp	Pickcircuit	Min. Distance between pickers	10,00	[m]	
A_apm	Pickcircuit	Articles per m2	150,00	[units]	Estimated with current slotting and safetystock
A_al	Pickcircuit	Aisle length	33,75	[m]	Estimated with current ailse (in combi with input R. De Koster)
A_cpl	Pickcircuit	Amount of meters to take corner in pickcircuit	7,00	[m]	
A_tst	Productivity summary	Productivity totes storer in DPF Knapp	60,00	[frame/hr]	Mechanized DPF storer from Knapp
A_pfm	Pick A3	Percentage SKUs representing fast movers zone	0,05	[%]	5% SKUs with the highest value will be picked in FM zone (Alternative 3)
A_pmm	Pick A3	Percentage SKUs representing mid movers zone	0,2	[%]	20% SKUs with thereafter highest value will be picked in FM zone (Alternative 3)
A_psm	Pick A3	Percentage SKUs representing slow movers zone	0,75	[%]	75% SKUs with thereafter highest value will be picked in FM zone (Alternative 3)
A_avp	Pick A3	Average volume on pallet	576	[l]	
A_cwoi	Multiple	Chance WoI	0,99%	[%]	
A_mwz	PickA3	Meters walking per zone per line	3,2	[m]	WJ: fast movers are closer to the station in the zone
A_ts	Multiple	Travel speed picker incl pickcart	0,56	[m/s]	Including start and stop
A_tse	Pick A3	Travel speed picker excl pickcart	1,00	[m/s]	
A_tpp	Multiple	Time per pick (pallet and cupboard) , incl scanning [s]	11	[sec]	
A_pp	Multiple	Pick penalty for multi-item picks [s]	6	[sec]	
A_ rpp	Productivity summary	Replenishment productivitiy pallets	20	[pal/h]	
A_ptc	Productivity summary	Productivity tote consolidation (G2P)	300	[tote/h]	
A_frkc	Pick_storage A4	Fill rate Kiva cupboard	0,7	[%]	
A_ppK	Pick_storage A4	Pick productivity from a Kiva	300	[items/h]	
A_pkq	Pick_storage A4	Amount of Kiva's for queue at station	5	[kiva]	
A_ tk	Pick_storage A4	Amount of Kiva's for transport cupboards per station	5	[kiva]	
A_surpr	Output	Extra surrounding direct labour activities	0,38	[%]	
A_pdpf	Surface	Percentage DPFs in warehouse (when AS/RS is installed)	0,25	[%]	
A_ppc	Productivity summary	Pick circuit A1, A2	60	[cart/hour]	
A_acb1	CAPEX/Surface	Amount of conveyor belt alt 2	1000	[m]	
A_acb2	CAPEX/Surface	Amount of conveyor belt alt 3	6000	[m]	Wehkamp has 5400 m of conveyor belt (lower amount of GTPs)
A_acb3	CAPEX/Surface	Amount of conveyor belt alt 4	3000	[m]	
A_hpb	CAPEX/Surface	Height pallet buffer	5	[layers]	
A_slt	Shuttle_ZoneA3	Storage lifte time	2	[days]	
A_ths	Shuttle_ZoneA3	Threshold shuttle	0,2	[percentage]	
A_lc	CAPEX	Length cupboard aisle picking	1,24	[m]	
A_sp	Rec_Repl mod	Amount of spiral conveyors per aisle	2	[conveyors]	
A_pdc	Rec_Repl mod	Productivity decanting	800	[CE/hour]	
A_ps	Rec_Repl mod	Productivity sorter	5000	[HE/hour]	
A_is	Rec_Repl mod	Induction sorter	800,00	[CE/hour]	
A_bs	Rec_Repl mod	Belt speed transport replenishment	1,00	[m/s]	
A_bssc	Rec_Repl mod	Belt speed spiral conveyor	0,25	[m/s]	
A_phb	Pallet height buffer	Amount of stacked pallets buffer	5,00	[pallet]	
A_consp	Productivity summary	Consolidation produc	400,00	[tote/h]	
A_lpb	Surface	Length pallet buffer	40,00	[pallet]	
A_hpb	Surface	Height pallet buffer	4,00	[pallet]	
A_bcm	Productivity summary	(JIT) Bread consolidation alternative 1	80,00	[totes/h]	

Appendix 14: Extreme Condition Test

Table 56: Extreme Condition Test: input 50000 orders

Design criteria	Unit	Alternative 1	Alternative 2	Alternative 3	Alternative 4
All-in productivity	[item/hour]	50	77	161	130
Surface area	[m^2]	21565	18477	27748	41524
FTE	[FTE]	1514	691	410	533
Direct labour costs per item	[€]	0,30	0,21	0,11	0,13
OpEx/year	[€]	86855444	56752583	28344008	35625759
Total costs/year	[€]	9985761	13697870	59018768	135180752

Appendix 15: Robustness analysis

Table 57: Effect of alterations assumptions on total costs per year

	Alt 1	Alt 2	Alt 3	Alt 4
Halve safety stock	-11%	-17%	-2%	-1%
Double replenishment frequency	-13%	-20%	0%	0%
Double product density	-13%	-20%	0%	0%
Double walk distance in zone	0%	0%	4%	0%
Double walking speed	-13%	-19%	-5%	0%
Half KIVA fill rate	0%	0%	0%	68%
Double KIVAs per pick station	0%	0%	0%	16%

Table 58: Effect on criteria when safety stock is doubled

Design criteria	Alt 1	Alt 2
All-in productivity	12%	21%
Surface area	-24%	-30%
FTE	-7%	-16%
Direct labour costs per item	-11%	-17%
OPEX/year	-11%	-18%
CapEx	-1%	-2%
Total costs/year	-11%	-17%

Table 59: Effect on criteria when replenishment frequency is doubled

Design criteria	Alt 1	Alt 2
All-in productivity	14%	25%
Surface area	-28%	-35%
FTE	-8%	-19%
Direct labour costs per item	-12%	-20%
OPEX/year	-13%	-21%
CapEx	-1%	-2%
Total costs/year	-13%	-20%

Table 60: Effect on criteria when product density is doubled

Design criteria	Alt 1	Alt 2
All-in productivity	14%	25%
Surface area	-28%	-34%
FTE	-8%	-18%
Direct labour costs per item	-12%	-20%
OpEx/year	-13%	-21%
CapEx	-1%	-2%
Total costs/year	-13%	-20%

Table 61: Effect on criteria when number of walking meters in zone is doubled

Design criteria	Alt 3
All-in productivity	-5,15%
Surface area	1,78%
FTE	4,03%
Direct labour costs per item	5,43%
OpEx/year	5,11%
CapEx	2,45%
Total costs/year	4,37%

Table 62: Effect on criteria when walking speed is doubled

Design criteria	Alt 1	Alt 2	Alt 3
All-in productivity	16%	27%	8%
Surface area	0%	0%	-1%
FTE	-9%	-18%	-6%
Direct labour costs per item	-14%	-21%	-7%
OpEx/year	-14%	-20%	-7%
CapEx	0%	0%	-1%
Total costs/year	-13%	-19%	-5%

Table 63: Effect on criteria when KIVA cupboard fill rate is halved

Design criteria	Alt 4
All-in productivity	0%
Surface area	463%
FTE	0%
Direct labour costs per item	0%
OpEx/year	41%
CapEx	108%
Total costs/year	68%

Table 64: Effect on criteria when number of KIVAs per pick station is doubled

	Alt 4
All-in productivity	0%
Surface area	6%
FTE	0%
Direct labour costs per item	0%
OpEx/year	1%
CapEx	31%
Total costs/year	16%

Appendix 16: Scenario analysis alternative 3

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
All-in productivity	154	153	149	139	142
Surface area	15K	18K	19K	20K	18K
FTE	170	198	218	232	211
Direct labour costs/ item	0,11	0,11	0,11	0,12	0,12
OpEx/year	12M	14M	15M	16M	15M
CapEx	27 M	31M	33M	33M	31M
Total costs/year	16M	19 M	21M	22M	20M

Appendix 17: Interview R. de Koster (Erasmus University)

Function: Professor of Logistics and Operations
Date: 09/05/16
Location: FC0 Nijkerk

Conclusions:

- Graphic pick on pick cart more suitable in operations where CEs and HEs are both picked
- P2L on pick cart is double when product and tote also have to be scanned
- Visual graphics have to be improved on cupboard to make the height of plank more clear
- Voice picking will delay the operation (is more suitable for pallet pick)
- With P2L problems will occur when multiple pickers are picking in the same area
- de Koster has done studies into optimizing expected individual pick productivity of picker in combination with the to pick orders
- With zone picking a maximum of 800 bins per hour can be handled
- Not DPF buffering but queuing in aisles will become the first bottleneck
- More aisles will give you more freedom to allocate the products
- Shorter aisles (20 meters) will decrease the chance on congestion
- Mechanization is dependent on size, weight and fragility of the product
- Postpone automation (current concepts not proven to be successful)
- Picking concept not bad, supporting activities should be mechanized (replenishment, storing)
- Difficulty of the operation: large number of orders, large range of SKUs, large number of items in order
- Zone-pick with goods moving around is not possible because of large number of items per order
- The combination of a shuttle system with a picking system & zone pick within one temperature zone will result in too many movements between the different processes (also because of the fact that fragility will have to be taken into account).
- Believes in one pick strategy (zone-pick) per temperature zone. But max for zone pick is around 8K orders (with 16 hours pick)
- Enthusiastic about the alternative of partly preparing orders the day before, using a Miniload AS/RS as dispatch buffer and adding JIT items via GTP station

Appendix 18: Interview E. Buijssen (Wehkamp)

Function: Technical program manager (Arcadis)
Date: 11/05/2016
Location: Wehkamp DC Zwolle

Specifications DC:

- 35.000 m^2
- 468K totes, 50.000 items per day
- 2 order box sizes, 40 x 60 cm totes
- 300K SKUs
- 6 days operational for picking (not on Saturday no delivery on Sunday)
- 7^{th} day operational for inbound/return flow

Timeline realization DC:

- Spring 2013: start of business case
- Summer 2013: decision made to build a new central DC
- August 2013: contract with suppliers
- March 2014: start building
- May 2015 - September 2015: testing software and systems
- November 2015: opening
- Nov 2015 – February 2016: migration of stock from old to new DC

Conclusions:

- On peak days currently 75% of operational design capacity used
- On average day currently 50% of operational design capacity used
- Warehouse only fulfils order for same or next day delivery
- Fulfilment of parcels, other DC for two-man delivery (more voluminous) goods
- Decanting productivity 600 items per hour (lower than 800 due to sortation of different size of products)
- Pick productivity at GTP station 500 items per hour

Appendix 19: Interview R. Wolters (Knapp)

Function: Managing director Knapp Benelux
Date: 18/05/16
Location: FC0 Nijkerk

Conclusions:

- Multiple systems delivered to online grocers (TuDespensa, Ocado)
- On time presentations of order and product totes is possible
- Currently working on prototype of mechanized DPF loader
- Average pick productivity at GTP is 600 items per hour
- Average pick productivity within zone is 450 items per hour
- Average decanting productivity is 800 items per hour

Appendix 20: Interview B. Schoonderwoerd (Technische Unie)

Function: Director logistics at Technische Unie
Date: 20/7/2016
Location: Technische Unie, Alphen aan de Rijn

Conclusions:

- Warehouse makes use of zone pick system from Witron
- Mechanization is realized in phases (over the years)
- Zone pick system is connected to Miniload AS/RS
- Productivity is around the 200 lines per hour per picker
- Witron installation has decreased the required surface area
- Pick productivity has increased due to zone picking