Improving Operations and Layout Design in Retail Cross-Docking Warehouses

Luís Miguel Teixeira Fernandes

Master Thesis

Tutor at FEUP: Prof. Gonçalo Figueira

Tutor at the Company: Eng. José Soares

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Master's in Industrial Engineering and Management

2018-07-02

All animals are equal, but some animals are more equal than others.

George Orwell

Improving Operations and Layout Design in Retail Cross-Docking Warehouses

Abstract

The increasing competitiveness in the world of retail is leading companies to find ways to both improve service levels and reduce costs. Cross-docking has emerged as a solution for both issues. On one hand, a cross-dock based synchronised supply chain ensures products are delivered to customers on time. On the other, cross-dock based supply chains minimise inventory holding costs and transportation costs.

In that regard, the current thesis is framed in the context of developing and applying a methodology to improve operations through layout design. This thesis provides the literature with a methodology to solve layout design problems at cross-docking warehouses, while simultaneously displaying its application on a real-world case. The scope of application is on the cross-docking warehouse which distributes meat products to one of the biggest food retailers in the country. The operation at the cross-docking warehouse is handicapped by lack of capacity to supply growing demands. Those demands include new stores opening and increasing volumes ordered by pre-existing stores, powered by 5% forecasted demand growth a year.

The solution is bi-sectioned. The first stage develops an in-depth analysis of the flows within the warehouse to identifiy potential bottlenecks. Within this stage, data is analysed to understand demand seasonality, product mix distribution, buffer needs, demand per store or staging requirements. Finally, a step-by-step analysis of the current layout is displayed to serve as a benchmark. The second stage regards designing the solution, which emcompasses mitigating bottleneck impact prior to designing the new layout. Then, the new layout is designed considering all improvements made to the bottlenecks. Simultaneously, a new crate assignment policy is studied to potentially reduce the number of pallets dispatched by the warehouse, while delivering the same amount of product.

The solution designed increases the number of available stores by 30.5%. The sorting productivity is estimated to improve 55.5%. The introduction of the new crate assignment policy reduces the number of pallets dispatched by the cross-dock by 7.2%. The early results of implementation show the number of pallets has reduced 15% every single day while the productivity has improved 19%. The sensitivity analysis indicates the need for 28 pickers/shift for a peak day scenario.

Resumo

A competitividade crescente no mundo do retalho está a levar as empresas a procurar soluções que melhorem os níveis de serviço e reduzam custos. O *cross-docking* emergiu como uma solução para ambos os problemas. Por um lado, uma cadeia de abastecimento sincronizada baseada em *cross-docking* tenta garantir que os produtos são entregues ao cliente a tempo. Por outro lado, cadeias de abastecimento baseadas em *cross-docking* minimizam custos de inventário e custos de transporte.

Nesse sentido, a presente tese está enquadrada no contexto de desenvolver e aplicar uma metodologia que melhore as operações através de desenho de *layout*. Esta tese fornece à literatura uma metodologia que permite solucionar problemas de desenho de *layout* em armazéns de *cross-docking*. Simultaneamente, exibe a aplicação da dita metodologia num caso do mundo real. O âmbito de aplicação é o armazém de *cross-docking* de distribuição de carnes de um dos maiores retalhistas do país. A operação no armazém encontra-se com capacidade insuficiente para servir a crescente procura. A crescente procura implica aumento do número de lojas servidas, bem como uma crescente procura das lojas pré-existentes – a previsão de crescimento anual de procura cifra-se em 5%.

A solução é bi-seccionada. A primeira fase desenvolve uma análise profunda aos fluxos no armazém para identificar potencias estrangulamentos. Dentro desta fase, os dados são analisados para se compreender a sazonalidade da procura, a distribuição da gama de produtos, a necessidade de *buffers*, procura por loja ou necessidades de *staging*. Por fim, uma análise detalhada do *layout* atual é levada a cabo no sentido de se estabelecer um *benchmark*. A segunda fase relaciona-se com o desenho da solução, que abrange a mitigação do impacto dos estrangulamentos, previamente ao desenho do novo *layout*. Em seguida, é desenhado o novo *layout*, sendo consideradas todas as melhorias que visam reduzir o impacto dos estrangulamentos. Simultaneamente é estudada uma nova política de atribuição de caixas que poderá, potencialmente, reduzir o número de paletes expedidas pelo armazém, mantendo a quantidade de produto expedida constante.

A solução desenhada aumenta o número de lojas disponíveis em 30,5%. É estimado que a produtividade de *sorting* aumente 55,5%. É ainda estimado que a nova política de atribuição caixas reduza o número de paletes expedidas em 7,2%. Após implementação, esta política está a levar a uma redução diária de 15% no número de paletes expedidas, enquanto que a produtividade já melhorou 19%. A análise de sensibilidade desenvolvida aponta para a necessidade de existirem 28 operadores de *sorting* por turno, num dia de pico da procura. A produtividade melhorou 19% na fase inicial de implementação.

Acknowledgements

To Professor Gonçalo Figueira for the constant availability showed. Your critical thinking gave me the academic guidance I needed, for which I can say you are one of the main drivers of success of my thesis. To my tutor at the company, José Soares, I am grateful for the constant challenges and confidence displayed. Your acknowledgement of my work's quality is very important to me. I also want to thank Sérgio Marques for the permanent mentorship to execute my tasks. The knowledge you passed me is not only useful for my future professional endeavours but also for the conclusion of this thesis.

To the company that received me in such an important stage of my academic path, I hope the work I developed matched the expectations you had in me.

To the Faculty of Engineering of the University of Porto and all professors with which I crossed paths, thank you for helping me become an engineer. Your demands, knowledge and patience are greatly appreciated by me.

To all my friends, every single one of them, I want to thank you for being right beside me when I needed the most. A special thanks to João Soares for all the patience you displayed throughout 5 years of study and post-exam stress. Without you, everything would have been harder and much less enjoyable. And to Bruno, wherever you may be.

To my family, my parents, brother, sister and grandparents, everything I have accomplished happened because of you. Without your education, knowledge, support, kind words and, above all, patience, this thesis would not have been accomplished.

Finally, to Rita, for entering my life when I needed the most. You have endured through distance and unimaginable challenges. Despite all that, you have made everything easier to me, with patience, love and friendship. I hope this is just the beginning of a bigger journey we will go through together.

Index

Acronyms

3PL: Third Party Logistics

ADT: Internal Production for Stock

CDO: Cross-Docking Operator

CML: Cross-Dock-Managed Load

CV: Coefficient of Variation

DC: Distribution Centre

EP: External Production

FIFO: First in First Out

IP: Internal Production

JIT: Just in Time

JML: Joint-Managed Load

KPI: Key Performance Indicator

LTL: Less Than Truckload

P&P: Pick & Pack

SD: Standard Deviation

SKU: Stock Keeping Unit

SML: Supplier-Managed Load

WIP: Work in Progress

WMS: Warehouse Management System

Index of Figures

Index of Tables

1 Introduction

The ever-changing world of retail demands that responsive logistics flow all throughout supply chains, otherwise, customer service levels may be compromised. The companies that can better deliver customer needs timely and in the right place achieve a competitive advantage. In that sense, cross-docking is currently an emergent supply chain strategy. It aims at being an alternative to incumbent strategies such as warehousing, direct shipments or milk runs. Companies like Dell, Wal-Mart and Toyota owe their success to the implementation of this operational change (Hammer 2004). Cross-docking aims at ensuring the service levels required to be competitive while, at the same time, reducing supply chain costs. However, for being such a new strategy, scientific studies are required to aid on the design of cross-docking solutions in the industry. This thesis emerges because of that need, where it develops and applies a methodology to solve a cross-docking layout problem in a food retailer, particularly on its meat processing centre. Growing demand expectations together with an operation handicapped by inefficiencies has conducted the company to solve this problem through a layout redesign. Next, an in-depth look into the project framing, the problem at the company, the methodology and goals of the project is displayed.

1.1 Project Framing and Motivation

Cross-docking has emerged as a new supply chain strategy in recent years which aims to minimise delivery lead times and transportation costs while maintaining customer service levels. This strategy was implemented by Wal-Mart and is said to be one of its main drivers of success. It is widely used in multiple industries, with a big focus on retail (Ertek 2005). The concept of cross-docking differs from traditional warehouses in the sense that inventory is minimised, through the reduction of storage (Zhengping *et al.* 2008), whilst in warehouses, inventory is kept as a buffer to protect customer service levels from unsynchronized supply chains. Cross-docking requires a high level of synchronization between warehouse, suppliers and customers, through tightly controlled flows of materials and information (Zhengping *et al.* 2008). Once the upstream and downstream factors are accounted for and controlled, it is crucial to look for operational factors within the cross-docking warehouse that may hamper its capability to supply, if not managed correctly. One of the factors that stand out is the layout of the cross-docking (Van Belle *et al.* 2012; M. Apte and Viswanathan 2010), among others such as the shape of the cross-dock (J. Bartholdi III and Gue 2004), and the system and process constraints (M. Apte and Viswanathan 2010). The case study to be presented displays a real case of designing a layout on a hybrid cross-docking warehouse. It combines a retail cross-docking environment, in accordance to Napolitano (2000) classification, which is fed by external suppliers and an internal production facility while maintaining some storage capacity on its floor.

The overall capacity of a cross-dock is determined primarily by a combination of the capability of the personnel, the systems and the cross-dock design. Limitations in any of these three factors will reduce the efficiency of the cross-dock (Vogt and Pienaar 2010). Knowing this, the project is utilised as a proxy to implement methodologies proposed by the literature on cross-docking layout design (Vogt 2004). General approaches to designing cross-docking layouts are scarce in the literature (N.Sheikholeslam and Emamian 2016; Van Belle *et al.* 2012; Vis and Roodbergen 2008) being therefore relevant to provide further knowledge. Layout design is described as a strategic decision by Van Belle *et al.* (2012) making the establishment of standardized methods an important step forward to be taken. Yet, some literature already provides knowledge into this issue, detailing step-by-step approaches on real-world problems. Those steps include understanding the current state of the system, which clarifies why a redesign may be required. That understanding facilitates the definition of the future state, considering all the set constraints and requirements.

Methodologies suggested by the literature on how to design cross-docking layouts are combined to formulate the methodology followed in this thesis. Such methodologies include the Theory of Constraints (Goldratt 2005), a methodology developed by Vogt (2004) on how to design a cross-docking warehouse and a methodology assembled by Baker and Canessa (2009) on warehouse layout design. The use of the Theory of Constraints is suggested by Vogt and Pienaar (2010) and aims to identify and eliminate the current operational bottlenecks. Vogt (2004) details the steps and methods used to design a cross-docking layout. As mentioned by Baker and Canessa (2009), there is not a comprehensive systematic method for designing warehouses, let alone for cross-docking. Thus, for the lack of further insight on the subject, the method followed by Vogt (2004) is the starting point at which this case study looks to provide further knowledge. Baker and Canessa (2009) focus on traditional warehouse design though some of its characteristics are also applicable to cross-docking, namely the scenario creation and testing, where multiple hypothesis are run to understand the applicability of the achieved solutions.

1.2 Project Context and Company Description

The task of designing the layout of the cross-docking warehouse was presented by XY, which is the meat production facility of the food retailer X and the meat producer Y. This facility is a joint venture between X and Y which supplies the entirety of X’s stores with meat products on their scope of sale. Company Y provides the facility with its meat production expertise while X ensures a correct flow of materials and information, from XY’s suppliers to X’s stores.

Recently, several problems emerged which affected the operation at the cross-docking warehouse of the facility. In the past summer, the demand peaked resulting in an unresponsive warehouse to customer orders – service levels were compromised. Furthermore, there was a recent implementation of a new Warehouse Management System (WMS) which caused deep ripple effects, further complicating operational efficiency. The solution encountered was to partly outsource the operation to a 3PL, while the operation adapted to the new WMS and fine tunings to it were performed.

In the future, however, the goal is to internalise the entire operation without compromising the downstream supply chain. That must be accomplished knowing that the company expects to open 20 new stores per year. Now, it serves 252 stores which is already 20 more stores than were served last year by the time the operation started being unresponsive. Besides, the current layout does not hold space for 252 stores – it was designed to hold 246 stores - meaning it is working over capacity on that end. Simultaneously, the company expects 5% growths a year in global sales of meat, in line with the recent growth rate of the company as seen in Table 1. To further complicate matters, there are several bottlenecks hindering the operation, such as a slow reception process or an inefficient sorting process - the sorting productivities displayed at XY are low for X’s standards.

Table 1 - X’s growth rate since 2014

Year	Growth Rate
2014	1%
2015	1%
2016	6%
2017	5%

The outsourced operation has meanwhile been reinserted into XY’s cross-dock, yet, the operation has once again displayed inability to respond efficiently to demand even in low demand months. This presents further proof that changes must be undertaken.

The solution found is to conduct a thorough analysis of the current layout, product and demand flows, and its core processes to understand its capabilities to supply, while meeting some pre-requisites demanded by the company. The main one is to have a layout that can accommodate 290 stores, which means having a layout that will be responsive to the projected demand until the end of 2019. Since the current layout does not hold sufficient space for that number of stores, a new layout must be developed to support such demands. Additionally, the layout and operational processes would have to be sufficiently efficient that peak days could be overcome without significant consequences for stores and transportation costs.

One concept that cripples the operation and fosters this need to change is the strong seasonality within the week and within the year. The peak-to-average ratio, concept introduced by Vogt (2004) which compares the maximum demand value with the average demand, is 1.8. Friday’s seasonal index is 1.5, which means Fridays are on average 1.5 times more demanding than the average of the remaining days. These differences must be accounted for and the layout needs to be dimensioned according to the peaks, otherwise the issues present shall remain.

1.3 Project Objectives

The initial goal of this project is to identify the current problem and understand the issues that congest the operation. The insufficient layout capacity, the inefficiencies in productivity, the seasonality, the need for storage space or the size of crates utilised to hold the products are identified as problems. Once the problems are identified, the goal is to find solutions that tackle them in an efficient, yet effective way. To this, the following goals must be achieved, both in operations improvement and layout design (however, the improvement of operations is the ultimate goal behind the new layout design):

- Improving Operations:
  - Increase the overall sorting/picking productivity sufficiently to output the necessary volumes on time;
  - Anticipate and widen the shipping window;
  - Reduce the number of pallets dispatched by the cross-docking warehouse;
  - Create new process standards which output more efficiency.
- Designing a layout that:
  - accommodates at least 290 stores;
  - responds to demand on peak days;
  - has sufficient buffer space for the different product flows;

These objectives try to combine the restrictions imposed by the company while trying to cut wastes on transportation, space utilisation and labour. These are obtained through a series of operational improvements and a new layout introduction. To develop the cross-docking warehouse layout, a methodology will be utilised which is essential to set the parameters needed for the layout to work: productivity level, number of doors, staging capacity, store capacity and buffer capacity per flow. The application of the methodology detailed in Section 1.4 is aimed at providing the literature with further knowledge on a subject which is yet to be deeply explored by researchers (N.Sheikholeslam and Emamian 2016; Van Belle *et al.* 2012; Vis and Roodbergen 2008).

1.4 Methodology

The general methodology followed in this project is as follows:

- State the goals of the project;
- Understand the current situation;
- Establish the road map to achieve the goals and update them as challenges and opportunities emerge;
- Design the solution based on a combination of the methodologies proposed by Vogt (2004) and Baker and Canessa (2009).

The initial stage of the project took place to set the project deadline as well as the hard constraint on the number of stores to be supplied. Also, outsourcing the operation once again was set to be done only as last resort.

Secondly, the need to understand the current situation emerged. The goal was to understand the main challenges, through workshops and visits to the facility. This stage was thorough and included talking to operators who had a better grasp of the behaviour of the cross-dock, including the shortcomings of the WMS and the effects of seasonality. Plus, they added valuable insights on dimensioning the buffers needed for the different product flows, as one of the WMS's shortcomings is the data gathering.

Thirdly, the road map to the solution was discussed and built. Throughout the workshops, it was possible to observe the poor occupation ratio of crates with trays of product. The goals of the project were updated to include this opportunity. Once the goals and a general understanding of the current situation are accomplished, tasks and its due dates are set. This includes formulating the entire methodology of designing the layout and pinpointing the operational bottlenecks.

The methodology followed to set the new layout and improve operations is a combination of frameworks developed on the literature. It uses Vogt (2004)'s framework (Figure 8) when changing the fresh cross-docking layout of food retailer SPAR, while adding a sensitivity analysis to test scenarios (Baker and Canessa 2009; M. Apte and Viswanathan 2010). The combination of these methodologies, while following concepts introduced by Vogt and Pienaar (2010) on layout design, was used as a literature frame of reference, and is detailed in Section 2. By combining these methodologies, the solution was designed in the following way (Figure 1): The current state aims at providing the necessary data to construct a fact-driven solution. Based on the data gathered on processes, demand, product flows and system, the solution is developed, which combines the new layout with system and process improvements. Within this stage, a sensitivity analysis is performed to validate the solution prior to the physical implementation (M. Apte and Viswanathan 2010). Each of these stages will be thoroughly explained in Sections 3 and 4 and applied to the real-world case at XY's cross-docking warehouse.

This methodology was applied after the initial workshops and visits to the facility. This stage was more intensive in using spreadsheets and AutoCAD to analyse the data and draw potential layout scenarios. Measurements also took place frequently to ensure that the original blueprints were correct. The sensitivity analysis performed used software Microsoft Excel.

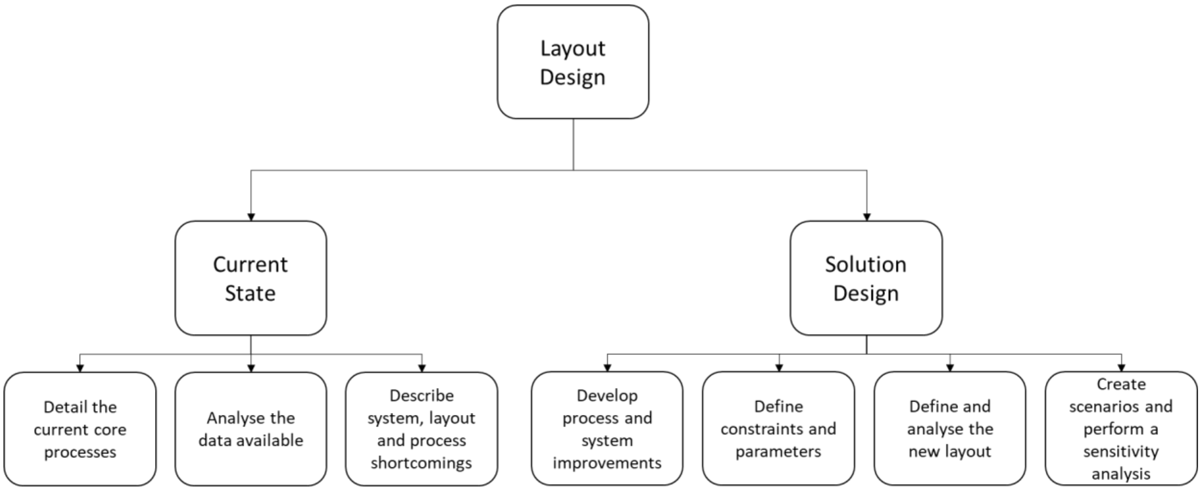

Figure 1: Methodology followed in this thesis, resulting from frameworks developed by Baker and Canessa (2009) and Vogt (2004)

This study had some inherent constraints which limited the work to be developed. The biggest of which was the sense of urgency showed by the company to implement the solution. Ideally, as Baker and Canessa (2009) suggest, simulation should be used to test the different layout hypothesis. This simulation can either be simulated animation or spreadsheet what-if analysis (M. Apte and Viswanathan 2010) and should be used to compare different feasible layouts. Albeit having performed what-if analysis, that was done assuming a layout as definitive. It was not performed to compare multiple feasible layouts. The potential gain of comparing multiple feasible layouts through simulation regards the ability to proceed with decision making on a more informed basis.

At the same time, the data made available was very limited, due to the recent implementation of the new WMS. Larger historic records and more detailed data (on the different product flows, productivity, demand by store, drop size, service levels) would have been important.

1.5 Thesis Structure

The thesis is spread through six chapters along which the context, the problem, the methodology and expected results are explained in more detail.

Chapter 2 presents the theoretical framing of all concepts and methods introduced in Chapter 1 that are relevant for the development of the solution to be proposed. This includes a framing of the concept of cross-docking, its main applications and advantages, before moving forward to displaying good practices on how to draw cross-docking layouts.

Chapter 3 presents the current state of the operation. This is the first stage of the proposed methodology where the core processes are described. Then, an analysis of the data available is performed to aid in establishing the requirements of the future layout. Finally, an analysis of the current layout is also performed, which will be helpful to benchmark the new solution.

Chapter 4 lays out the implementation of the layout. First, the process improvements suggested to overcome identified bottlenecks hampering the efficiency efforts are displayed. Then, the constraints and parameters of the layout are set. Next the proposed layout is deeply analysed. Lastly, scenarios are proposed to test the layout’s material limits.

Chapter 5 draws conclusions on the project besides suggestions being made for future improvements and implementations.

2 Theoretical Framing

Many distribution strategies are currently used to ensure a firm's logistical activities, four of which stand out: direct shipment, milk runs, warehousing and cross-docking (Buijs *et al.* 2014). Direct shipment sends the load directly from origin to destination. Milk runs group shipments into routes visiting multiple origins and destinations. Warehouses enable the consolidation of shipments to customers by assembling full truckloads of products stored in the warehouse.

2.1 Cross-docking Warehouses

2.1.1 What is Cross-docking

Cross-docking has emerged as a more efficient alternative to incumbent solutions and, according to Kinnear (1997), is defined as "receiving product from a supplier or manufacturer for several end destinations and consolidating this product with other supplier". The focus of this definition is transportation costs which proves the idea that cross-docking is a good way to save on transportation, when compared to the other alternatives. Further definitions state that cross-docking is "the process of moving merchandise from the receiving dock to shipping without placing it first into storage" (Van Belle *et al.* 2012). Boysen *et al.* (2007) also present a definition stating that cross-docking is "receiving product from a supplier or manufacturer for several end destinations and consolidating this product with other suppliers' product for common final delivery destinations". Yet, many types of cross-docking exist which do not fully fit in these generic definitions. The case study at hand, for instance, has a storage area in its floor, meaning it is a hybrid concept between cross-docking and typical warehouses. Furthermore, it has a sorting area, where there is depalletization, and products are rearranged into new multi-product pallets, which are headed to a specific store, before shipping – retail cross-docking (Napolitano 2000). This cross-docking flow can be seen in Figure 2.

Storage is mentioned in the previous definitions as being mostly non-existent in cross-docking environments. However, many cases exist where there is storage on cross-docks and the literature also accounts for that, mentioning that storage can be present for a period no bigger than 24 hours (Van Belle *et al.* 2012). Sorting may exist in between receiving and shipping, though that will depend mostly on the type of cross-docking implemented.

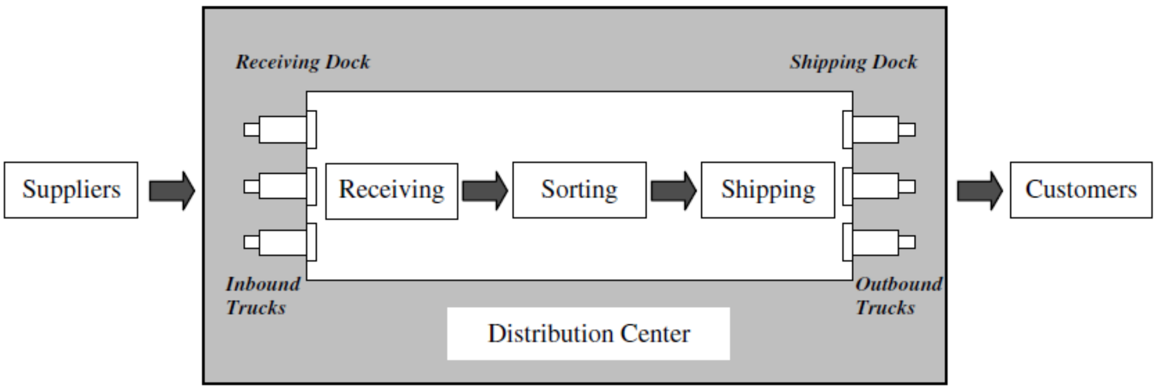

Figure 2 - Typical flow in a cross-docking system (Yu and Egbelu 2008)

Cross-docking emerged as a new strategy in logistics which nowadays companies use in a myriad of industries (Van Belle *et al.* 2012), one of them being retail companies, such as Wal-Mart, whose success is attributed to its successful implementation of cross-docking (Ertek 2005). With the increased competition in most industries, mostly retail and groceries (Ertek 2005), this supply chain strategy can accomplish significant reductions in total costs and lead times. Looking at Figure 2, it can be observed that cross-dock facilities serve as transfer points where there is a synchronization between inbound (suppliers) and outbound (customers), with the goal of reducing storage in between, as much as possible (Zhengping *et al.* 2008). Thus, this distribution strategy requires good planning, dynamic scheduling and coordination (Zhengping *et al.* 2008). These warehouses embedded in a network behave as transfer nodes, instead of storage nodes.

The introduction of JIT (Napolitano 2000) ends up introducing the concept of cross-docking, which shifts the supply chain management approach from controlling inventories at traditional warehouses, to a more focused approach in ensuring that the right products are passed through the cross-dock at the right time, whilst maintaining service levels (M. Apte and Viswanathan 2010) and reducing costs. This JIT approach is negated by Vogt and Pienaar (2010) as it is mentioned that JIT approach is more appropriate with balanced operations, which cross-docks rarely are. Instead, it is proposed that the Theory of Constraints (Goldratt 2005) is utilized which aims at identifying and correcting operational bottlenecks. Figure 3 details the different approaches to supply chain management depending on whether the company follows a synchronized or a traditional approach, outlining the fact that a synchronized strategy reduces inventory buffers, therefore demanding a more synchronized flow of materials and information.

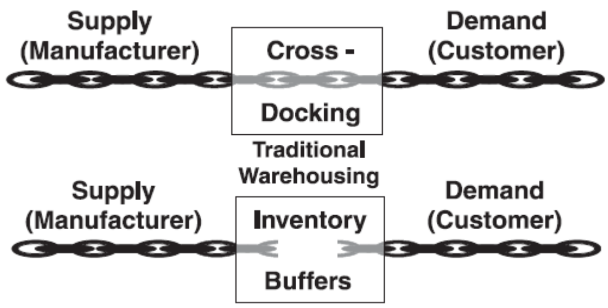

Figure 3 - Synchronized supply chain model vs
Traditional supply chain model (Kulwiec 2004)

The definitions presented for cross-docking are ideal, but other cases may exist in real context. The case study here does not reflect a reality with no storage, nor does it send products directly from inbound docks to outbound docks. As Figure 2 depicts, many times there is a sorting phase in between, where products are rearranged to new, multi-SKU pallets, according to their destination. Then, a staging phase takes place to ensure a correct loading while the product waits for the outbound truck. All of these stages bring additional complexity to the operation as both sorting (or picking) and staging require either big capital investments in automation or investment in human resources (Vogt and Pienaar 2010). The biggest challenge is to find an efficient way to connect all nodes of this operation (receiving, sorting and shipping) while being effective, knowing that there are many constraints and requirements imposed. Those constraints, or bottlenecks, are, according to Vogt and Pienaar (2010), the sorting phase. The sorting phase is the one that needs to ensure that product delivered from an inbound truck reaches the outbound truck on time. If this intermediate phase is not sufficiently efficient, the scheduling of trucks needs to be rearranged accordingly, which may hamper the benefits of the cross-docking.

2.1.2 Hybrid Cross-Docking

M. Apte and Viswanathan (2010) mention that most of the times, cross-docking warehouses do not operate as pure cross-docking environments. Instead, they provide a hybrid warehousing strategy, as seen in Figure 4, where some items flow through a typical cross-docking environment and others are also placed in warehousing to have higher safety stocks to protect against lost sales, or to ensure higher service levels. Incoming materials are here coupled with storage that was previously inside the warehouse. Plus, if the warehouse is coupled with a manufacturing facility, the production output can be redirected to the pallets that will be forwarded downstream, through coupling with those inbound (Kulwiec 2004). In other circumstances, material from incoming trucks may also stay in storage for a certain period, instead of being immediately dispatched. Both these cases happen in the facility of XY, where there is a production facility feeding the cross-docking and, in some occasions, stock originated from supplier deliveries remains on the floor of the warehouse for more than 24 hours. The reasons for this are that orders are placed 48 hours before delivery, meaning the needs may change until the actual delivery. Besides, in case of more sporadic suppliers, it may compensate to order more quantity at a time. Table 2 details the key differences between the two approaches of cross-docking - traditional and hybrid cross-docking.

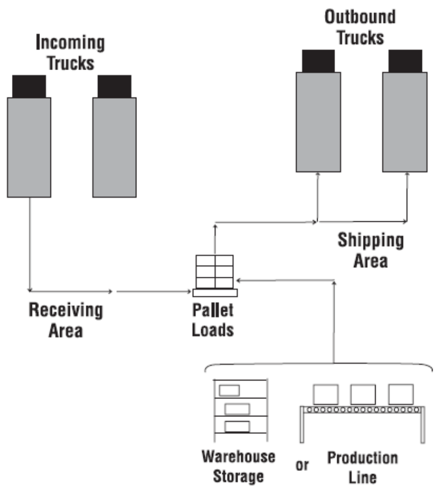

Figure 4 - Hybrid cross-docking warehousing strategy (Kulwiec 2004)

Table 2 - Key differences between a hybrid cross-docking warehouse and a traditional cross-docking warehouse (M. Apte and Viswanathan 2010)

Hybrid Cross-Docking Warehouse	Cross-Docking Warehouse
Items are put away to storage or order picking areas and can reside in the warehouse for more than a day.	Items typically flow in and out through the warehouse in a single day without being put away to storage or order picking areas.
Items enter the inventory records in the warehouse system.	Items do not need to enter the inventory records of the warehouse.
Relabelling and packaging activity may be carried out in the warehouse	May function without any relabelling or repackaging-

2.1.3 Requirements of Cross-Docking

For cross-docking to work properly, the items that flow through should be demanded and pulled out for stores (M. Apte and Viswanathan 2010). It is critical that demand levels are not unbalanced and not very variable, otherwise the operation may be compromised. In XY, the seasonality within the week and the year is notorious and is one of the reasons why the operation at study is so demanding. When looking at Figure 5, it is concluded that products with stable and constant demand rates are the ones ideal for cross-docking. Based on this, meat, which is more demanded in weekends and in the summer, at least in this specific case, could be a potential candidate for traditional warehouses. Yet, for perishable products, this kind of strategy is ideal (Witt 1998) since these products cannot be stored at home by consumers nor can they be stored at a warehouse because of short expiration dates (M. Apte and Viswanathan 2010), meaning cross-docking is actually the ideal strategy. These products require lot control for quality reasons, which further complicates the operation. A first in first out (FIFO) approach is used to smooth this problem (Knill 1997), despite not solving it entirely. Besides analysing the demand rate and variability, Richardson (1999) states that the product's delivery time should be taken into consideration when including it into a cross-dock based supply chain.

Unit stock-out costs \ *Product demand rate*	Stable and constant	Unstable or fluctuating
High	Cross-docking can be implemented with proper systems and planning tools	Traditional distribution preferred
Low	Cross-docking preferred	Cross-docking can be implemented with proper systems and planning tools

Figure 5 - Guidelines for the use of cross-docking (M. Apte and Viswanathan 2010)

In case products follow a steady rate of demand, planning of transportation, safety stocks at the store and at the warehouse can all benefit (M. Apte and Viswanathan 2010), reinforcing the importance of implementing a levelling strategy in XY. If the operation can be levelled in warehouses such as these ones, demand peaks will be less frequent, decreasing the bullwhip effect (Waller *et al.* 2006) on the supply chain. The importance of levelling is stated by Liker (2004), as it smooths the volume and mix of products, meaning little variation from day to day, which outputs a low inventory supply chain with high responsiveness.

2.1.4 Advantages and Disadvantages of Cross-docking

Cross-docking is aligned with the principles of achieving a lean supply chain, through the fast and frequent delivery of smaller and more visible inventories (Cook *et al.* 2005), as it minimizes time wasted, equipment and labour, thus optimizing the distribution process (Panousopoulou *et al.* 2012). Reeves (2007) mentions the use of small batches and JIT deliveries as being the main drivers of lean manufacturing. Applying those concepts to supply chains will result in a lean supply chain as well. The implementation of this lean supply chain through cross-docking strategies, instead of traditional warehouses, outputs the following advantages:

- Decrease in cost of the supply chain (Gümüş and Bookbinder 2004);
- Economies in transportation (Boysen *et al.* 2007);
- Decrease in the cycle time of order (M. Apte and Viswanathan 2010);
- Improved customer service (Van Belle *et al.* 2012);
- Reduction of storage space (Van Belle *et al.* 2012);
- Faster inventory turnover (Van Belle *et al.* 2012);
- Fewer overstocks (Van Belle *et al.* 2012).

When comparing cross-docking with point-to-point deliveries, Van Belle *et al.* (2012) mention an improved resource utilization (e.g. full truckloads) and a better match between shipment quantities and actual demand as the main advantages.

Notwithstanding, there are some disadvantages inherent to cross-docking:

- Need of costly technology for implementation (M. Apte and Viswanathan 2010);
- Waller *et al.* (2006) state that retailers with both traditional warehouses and cross-docking environments must deal with a gap that blocks economies of scale;
- The bigger the number of stores an organization has, the less the benefit of cross-docking (Waller *et al.* 2006). This disadvantage is explained by the fact that as the number of stores increases, the bigger the probability of increases in demand of these stores being offset by decreases in other stores. There are economies of scale in safety stock.

2.1.5 Types of Cross-docking

As seen, cross-docking can display many variations, from a more traditional and fast operation where products flow immediately from inbound trucks to outbound trucks, to a more hybrid approach with storage and sorting area in between. Napolitano (2000) proposes the following classification for the different types of cross-docking:

- Manufacturing cross-docking: receiving and consolidating inbound supplies to support JIT manufacturing. An example is a plant that may lease a nearby warehouse to consolidate parts. This way there is no need to keep stock of those parts;
- Distributor cross-docking: consolidating inbound products from different vendors into a multi-SKU pallet, which is delivered when the last product is received. Computer producers often use this strategy to deliver multiple sourced products in consolidated shipments to a costumer;
- Transportation cross-docking: consolidating shipments from different shippers in LTL and small package industries to gain economies of scale;
- Retail cross-docking: receiving product from multiple vendors and sorting them into outbound trucks for different stores;
- Opportunistic cross-docking: in any warehouse, transferring an item directly from the receiving dock to the shipping dock to meet a known demand.

In XY's case, besides being a hybrid cross-docking environment, where there is storage and there is a production facility feeding the cross-dock, a retail cross-docking strategy is applied as multiple SKUs are combined into a pallet which is destined for a store.

However, Napolitano (2000) also classifies cross-docking according to whether the product is allocated to a customer at the supplier facility, or only at the cross-docking facility. The former is known a Pre-allocation, while the latter is known as Post-allocation. Pre-allocation can be divided into consolidation at the supplier or at the cross-docking operator (CDO). In the second case, despite a product being pre-allocated to a client at the supplier, it is only moved to the customer's pallet at the CDO location. In the case study, the cross-docking is mostly post-allocated, as when they arrive at the cross-dock, they do not have a fixed destination yet. Pre-allocation also happens but just in specific SKUs.

Vogt (2004) also classifies types of cross-docking into Cross-Dock-Managed Load (CML), Joint-Managed Load (JML) and Supplier-Managed Load (SML), which differ from one another as follows:

- SML immediately transfers pallets from inbound to outbound trucks;
- JML requires sorting into new pallets and only then are the pallets moved to outbound trucks;
- CML requires labelling of pallets when received, sorting and only then are pallets moved to outbound trucks.

CML is an equivalent denomination given to Post-allocated consolidation, while SML and JML are Pre-allocated consolidation. SML is consolidated at the supplier while JML is consolidated at the CDO. CML is the type of cross-docking present at XY, while JML also happens in some specific cases. This classification by Vogt (2004) is similar to the one previously proposed by Napolitano (2000).

2.1.6 Cross-docking vs Warehouses

Cross-docking warehouses can act as alternatives to traditional warehouses (Simchi-Levi *et al.* 2003), which provide a solution with intermediate inventory points. The time the cargo spends on the warehouse composes the biggest difference between the two alternatives (Luo 2008).

In a traditional warehouse, the most common functions are receiving, storage, order picking and shipping (Van Belle *et al.* 2012), from which order picking and storage are the most costly. Order picking is labour intensive while storage implies inventory holding costs (Parvez *et al.* 2013). Cross-docking is an approach that can cut these two costs considerably. In most cases, these costs can still exist, though they will be largely reduced. This is why Vogt and Pienaar (2010) mention that warehouses are the least efficient of the two supply chain strategies.

Traditional warehouses are used as a supply chain approach because customers demand accuracy and speed, and without powerful forecasting capabilities, a company cannot maintain a good service level without a buffer (inventory) (Zhengping *et al.* 2008). Thus, companies looking to implement a cross-docking facility, which drops the cost of inventory, must find powerful tools to forecast demand, while simultaneously maintaining communication with partners through information systems to ensure coordination at the material and information level (Ertek 2005).

2.2 Cross-docking Layout

Cross-docking emerged as a new supply chain strategy which aims at having a responsive, yet lean profile. This is achieved through a series of steps, mainly the need for a synchronized and balanced activity between all parties involved. At the same time, an efficient management of such facilities requires the implementation of efficient layout design (Richards 2011), in its most import areas: receiving, sorting, regrouping (staging) and shipping (Berg and Zijm 1999). This is the reason why Van Belle *et al.* (2012) classify layout design as a strategic decision, because otherwise the shift for a cross-docking operation would not be successfully accomplished.

The general idea displayed by researchers is that there are very few published papers about layout design of cross-docks, its dimension, the arrangement and its internal shape (N.Sheikholeslam and Emamian 2016; Van Belle *et al.* 2012; Vis and Roodbergen 2008). Most published literature focuses on traditional warehouses, where storage and order picking are the focus. New approaches to layout design in cross-docking environments are required in the literature (Horta *et al.* 2016).

Like in any facility, a cross-docking operation requires that many key questions are answered, such as the land size, the equipment, building specifications, flows, interior layout design, type and number of trucks it serves (Su and Liao 2014). According to Ladier and Alpan (2016), the layout is determined by external constraints, namely the land size and shape, influencing the internal and external shape of the layout, the number of doors and their position. Based on this, J. Bartholdi III and Gue (2004) studied the most efficient shape of a cross-docking warehouse, even though this could be highly dependent on external constraints. They seek to evaluate the different forms with the goal of minimizing the product traveling distance. The decision criteria are based on the number of gates, receiving to shipment rate and distribution of material flow. The conclusion is that *I* shaped layouts are the most manpower efficient in cross-docking environments with less than 150 doors. The case study displays a cross-dock with 17 doors and an *I*-shaped cross-dock, meaning it is conformant to what the literature supports.

Vis and Roodbergen (2011) state that the definition of a layout design should go through three separate stages:

- Determining the block layout which places the different areas within the layout (Aiello *et al.* 2002; Meller and Gau 1996);
- Determining the detailed layout of the internal areas;
- Determining the control policies for the cross-docking environment;

While J. Bartholdi III and Gue (2004) provide some insight about the first stage, Vis and Roodbergen (2011) detail the connection between the second and third stages and how those can be improved. The conclusion is that a top-down approach should be followed while having an integrated view into the following stages and how they interact with each other. The case study focuses on the second stage while understanding the limitations and changes that need to be provided in terms of control policies.

Despite the very limited literature on the topic of cross-docking layout design, there is consensus that a good layout should minimize travel distances, without creating congestion, while being able to fulfil all pre-set requirements (Luo 2008). Vogt and Pienaar (2010) state that "the efficiency of the cross-dock with regard to the physical layout is determined by measuring the total travel distance with mass moved within the facility for all goods", which is the concept of centre of gravity. The objective function of a layout design is expressed in Equation (1), where the goal is to minimise the sum of the distance covered by each pallet – N stands for total pallets while i stands for each individual pallet. Makespan is also deeply mentioned in the literature as a Key Performance Indicator (KPI) of the success of the cross-docking (Arabani *et al.* 2012; Boysen 2010; Liao *et al.* 2012). In reality, Alpan *et al.* (2011) state that as important as makespan and travel distance may be, the most important KPI for managers is the number of hours worked. Travel distance often lacks data while makespan often depends on the scheduling of trucks which is often an uncontrollable variable.

$$Min \sum_{i}^{N} Distance\ Covered_{i} \quad (1)$$

As difficult as it may be to apply the concept of "distance with mass moved", since achieving a feasible layout considering the physical constraints of the warehouse is not simple, it is a good notion to have when locating the bigger demand stores, after the layout is setup. Vogt (2004) further details this concept by recommending that bigger demand stores should be as close to the docks as possible since it should minimise the travel distance with mass. Moreover, it is also detailed the concept of S-pick and U-pick, seen in Figure 6 , where S-pick is the one that minimises travel distance since not all stores are visited in every tour around the circuit. Therefore, the layout should be designed in such a way that allows for S-pick instead of U-pick.

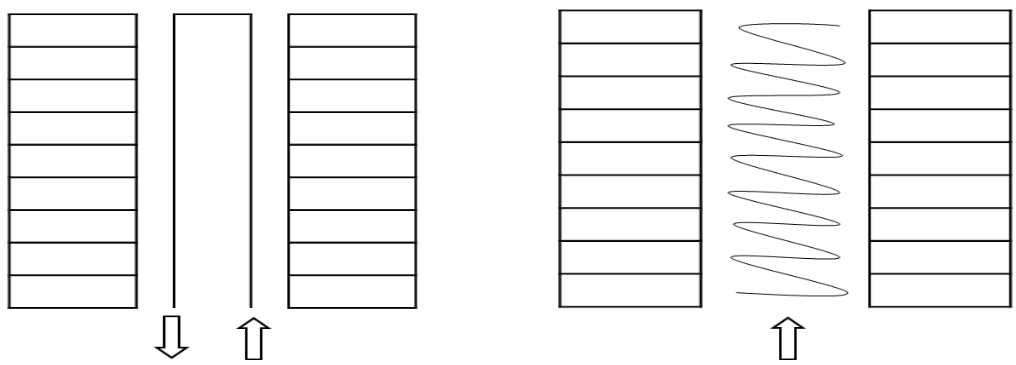

Figure 6 – U-pick (left) and S-pick (right) picking

The number of doors is determined based on the number of customers that should be served at the same time and which are not served with the same route (Vogt and Pienaar 2010). The number of routes that will be served at the same time is dependent on the timeframe the cross-dock is shipping and the cycle time of loading a truck.

Designing a generic layout for a cross-dock is not an easy task since facilities and conditions vary widely (Vogt and Pienaar 2010). What can be done, however, is to follow certain guidelines which favour the attainment of good solutions. For instance, depending on the volume of the operation, two different concepts of store allocation in the sorting area and its layout can be applied (Vogt and Pienaar 2010). These two concepts are known as Low volume and High-volume and can be seen in Figure 7. The Low volume layout assigns a floor space to a store with a certain depth to hold pallets throughout the day, depending on the demand of that store. At the end of day, those pallets are forwarded to the docks to be shipped. The High-volume layout also assigns a floor space to a store, however, that space does not hold sufficient space for the entire demand of the day. Instead, once a pallet is complete, the pallet is removed to the shipping dock correspondent to that store and is held in the staging line until it is loaded onto the truck. For that reason, the staging lines in the shipping area are longer in High-volume layout. Alternatively, the pallets may be sent straight to the truck, in case it is already parked at the dock, serving as an extension of the cross-dock area.

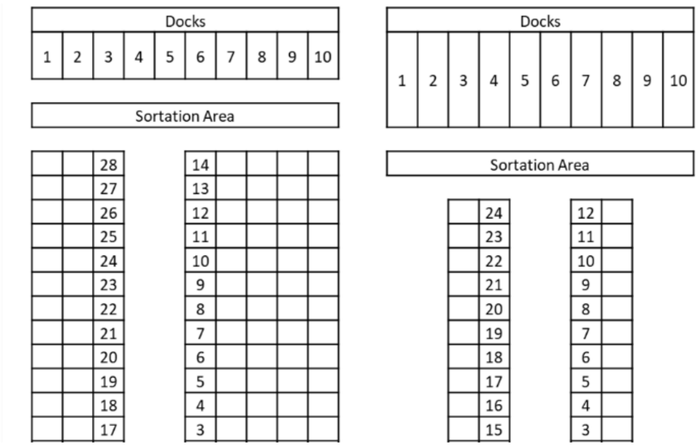

Figure 7 - Low volume (left) and High-volume (right) cross-docking layouts

2.3 Framework for Layout Design

In spite of being such a critical component to the success of a supply chain, systematic methods to design warehouse layouts are lacking (Baker and Canessa 2009). The same can be said of cross-docking, where only Vogt (2004) has provided the literature with a distinct method and practical application, on how to develop a cross-docking layout. The framework assembled by Baker and Canessa (2009) can be used, however, as a parallel method to aid in the design of the cross-docking layout, since many of the steps proposed are applicable to this case.

Vogt (2004) proposes the following methodology to assemble a new layout, depicted in Figure 8:

- Design Aims: in this stage the design criteria are set, such as the minimisation of crate and pallet movement, while having aisles that ensure a clear flow that does not compromise the remaining activities in the cross-dock;
- Design Requirements: the conditions imposed by the operation are here set, such as understanding the need to be responsive to demand with a certain service level and knowing that it needs to answer to the weekly and monthly peaks;

- Design Parameters: all parameters such as the working time, the inbound and outbound windows and the number of docks, are set in this stage. Simultaneously, the need for buffers, the need for levelling inbound and outbound trucks, delaying production from the facility, or increasing/decreasing the sorting window are here determined. All of this is done after an analysis of the current state of the warehouse;
- Process of Design: the data is analysed, including the store analysis, the aggregated demand, the demand cycles, the sorting productivity, the arrival of suppliers, the reception productivity, the buffer needs, the floor occupancy. All this data is helpful to dimension the new layout and its parameters;
- Process: all major processes are here understood and detailed, which can be helpful in identifying potential bottlenecks;
- Design layout: the iterative process of designing layouts that match the requirements and parameters set and eventually reaching one that fits all of them and is approved by the operations.

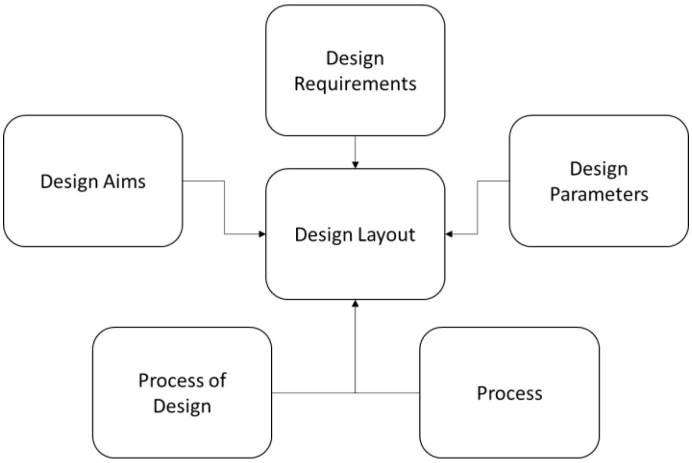

Figure 8 - Process for the design of a cross-dock layout (Vogt 2004)

The process for the design of a cross-dock was proposed in a real-world case in a fresh cross-docking warehouse, which outputted a new layout for the retailer SPAR. In the case study, a Low volume layout approach was applied (Vogt and Pienaar 2010), where store locations were given different depths according to its maximum demand. Simultaneously, an S-pick approach was utilised since it outputs the most effective layout for smaller facilities (Vogt 2004). All these methods and steps should be considered when designing the future layout of a cross-dock.

Baker and Canessa (2009) assemble a methodology to design traditional warehouse layouts based on what the literature has developed through a review. These steps are applied to traditional warehouses, yet it is also stated that these can be somewhat applied to cross-docks. Nonetheless, that is not the focus of the paper. The steps of this framework are detailed next:

- Define system requirement: includes business strategy requirements and relevant constraints;
- Define and obtain data: this includes obtaining data such as product details, order profiles, goods arrival and dispatch patterns (Rushton *et al.* 2006);
- Analyse the data: this includes generating product mix per order, demand variability, inventory calculations, seasonality and daily distribution (Frazelle 2002);
- Establish unit loads to be used: it regards determining the size of the warehouse container. However, this is not relevant in a cross-docking environment;
- Determine operating procedures and methods: high level procedures and methods for each function of the warehouse. There is some bibliography on the theme, though it is

mostly focused on traditional warehouses. The concept regards creating standard ways to perform some core functions to the operation, such as receiving, sorting or shipping;

- Consider possible equipment types and characteristics: regards assessing which technology is needed to fulfil the pre-set requirements;
- Calculate equipment capacities and quantities: considering the warehouse flows and its productivity, this section can be assessed and easily applicable to cross-docking;
- Define services and ancillary operations: there is no particular methodology present in the literature that supports this decision-making, mainly because it does not have as much relevance as the remaining stages of the framework;
- Prepare possible layouts: this is an iterative process and which is performed by "experience and use of AutoCAD to draft layouts" (Baker and Canessa 2009). Mulcahy (1994) mentions that this stage should try to minimise space utilisation, and maximise access to products, efficient flows, safe working environment and expansion potential;
- Evaluate and assess: this step intends to validate the operational and technical feasibility of the proposed solutions when confronted with the initial requirements (Oxley 1994). Simulation is often used in this stage (Brito 1992);
- Identify the preferred layout: considering all the above methodology, a decision is taken. This can be done without any framework, however some quantitative (e.g. financial business case) and qualitative (e.g. SWOT analysis) methods can be used.

The differences between both methodologies are not considerable, as both focus on understanding the requirements, setting the parameters, obtaining and analysing the data and, eventually, setting up the possible layouts. The biggest difference is in the utilization of simulation methods by Baker and Canessa (2009), which Vogt (2004) does not. These methods can be various and are used with the purpose of providing understanding of the behaviour of complex systems and allow testing of new designs (M. Apte and Viswanathan 2010; Van Belle *et al.* 2012; Panousopoulou *et al.* 2012).

To perform a simulation analysis, data, such as equipment layout and specifications, product flow rates, receiving and shipping schedules and the dimensions of the product, is required (M. Apte and Viswanathan 2010). Once that data is obtained, scenarios can be built to consider multiple situations that can affect the system. That is done to test the solution's flexibility and robustness, by understanding which its breaking points are. These tested scenarios may include alternative growth forecasts, changes in order profiles, abnormal peak demand requirements (Baker and Canessa 2009), which may output data on utilisation of labour, equipment and storage space, throughput rates and cycle time. To support in this task, animated simulation software can be utilized. However, spreadsheet what-if analysis is also commonly utilised (M. Apte and Viswanathan 2010; Baker and Canessa 2009).

2.4 Discrete Event Simulation

Discrete Event Simulation (DES) consists of modelling continuous real-world processes with discrete events, dividing each activity into discrete parts to simplify the analysis (Silva Pereira 2016). A basic DES model consists of a source, an operation and a sink. The source represents the arrival of temporary entities into the system. The operation has a queue, which aims to simulate the real-world operation. The sink represents the entities leaving the system after being processed. The entities arrive at the system with a certain rate, while the operation processes entities at a certain service rate. These two components are usually stochastic, leading to a stochastic model. Multiple replications are needed to output meaningful results (Grigoryev 2016).

One advantage of DES is the simplicity to create the model. Inputs, states and outputs are the only requirements, simplifying the need to understand the internal functioning of the operation.

The modeller should only focus on designing the DES according to actual observations (Belli *et al.* 2006).

DES allows to solve problems which could potentially be mathematically solved by queuing theory. However, the former is more flexible in the sense that it is able to model complex systems without mathematical sophistication, whereas the latter typically requires assuming important simplifications. In this specific case, there are some aspects which would be hard to deal with using queuing theory:

- Different product flows with variable arrival rates;
- Different product flows which start and stop arriving in different moments;
- Variable service rates – variable productivity and variable number of pickers.

Additionally, the purpose of DES relates with outputting the time at which the sorting activity ends. Queuing theory is mostly helpful in determining the queue sizes and waiting times. Albeit being important to grasp into queue sizes, waiting times lack importance in the context of the real-world problem studied, as the products that get into the warehouse do not necessarily follow FIFO within the day.

Monte Carlo simulation poses itself as a solution to simulate certain events. It allows to estimate parameters under various statistical distributions (Mooney 1997), including the normal distribution. From an initial sample, the distribution is simulated through the generation of multiple random samples (Mooney 1997). Thus, Monte Carlo simulation main usefulness is to generate multiple results to an event with a pre-set probability to see the behaviour in the long run. In the real-world case at study, this is useful to generate multiple productivity and demand pattern distributions.

3 Current State

Before designing potential scenarios of new layouts, it is crucial to fully understand the behaviour of the cross-docking warehouse, and that requires knowledge of its current state. That knowledge is three-fold: process analysis, data analysis and current layout analysis. The process analysis aims at understanding the paths the pallets follow from the moment they enter the warehouse until the moment they leave. These processes are mandatory steps the pallets need to go through, independently of the proposed layout solution. Thus, it is essential to look for bottlenecks on these processes which are hindering the operation, to understand what can be improved. The data analysis looks for the numbers that justify potential bottlenecks, besides providing insight into product flows, demand and space requirements which will then be used to determine the new layout parameters. The current layout analysis is intended to have a starting point to construct new layout scenarios and to serve as benchmark when a new, feasible, scenario is obtained. This stage corresponds to the stages of Process and Process of Design proposed by Vogt (2004). From Baker and Canessa (2009) framework, this chapter captures attaining and analysing the data. Baker and Canessa (2009) do not suggest any framing of the current processes as a starting point.

3.1 Process Analysis

The Process stage mentioned by Vogt (2004) is here set. The core processes are understood to provide general knowledge into the system. This stage borrows knowledge from Vogt and Pienaar (2010) which recommend the identification of bottlenecks (Goldratt 2005) as the starting point of implementing a layout design in a cross-dock. The standard times and productivity of each process at the cross-dock are depicted in Table 3. Annex K depicts the different processes through pictures.

Table 3 - Standard time for each process and productivity per operation based on those standard times

Process	Standard Time (min)	Productivity (pallets/hour)
Reception	05:07	11.73
Pallet Build	02:00	30.00
Picking/Sorting	18:47	3.19
Pick & Pack	02:40	22.50
Loading	01:26	41.86

3.1.1 Reception

The process of receiving inbound products, which Yu and Egbelu (2008) mention as one of the main functions of a distribution centre (DC), is done at XY every day from 5 a.m. to 3 p.m. This process allows the physical and informational entrance of products coming from suppliers into the warehouse, which will then be sorted into store pallets. The product flow that goes through this process is known as External Production (EP).

Once these pallets are unloaded from the truck, they are placed in the neighbourhood of a reception workstation. The reception of the pallets, which are usually composed by 32 crates per pallet, depending on the supplier and on the product supplied, implies scanning all the crates into the system. Once the crates are scanned, a label is printed to identify the pallet. This new label contains the information of all the crates that belong to the pallet and is useful for the sorting phase. Once the pallets have a new label, meaning they are now on the inventory records of the WMS (Table 2), they are sent to a buffer zone within the sorting area. There, they wait to be picked up by a picker which will then proceed to sorting. Figure 9 displays the reception area of the current layout, including the gates and the staging lines – these staging lines serve as a buffer for reception and for shipping.

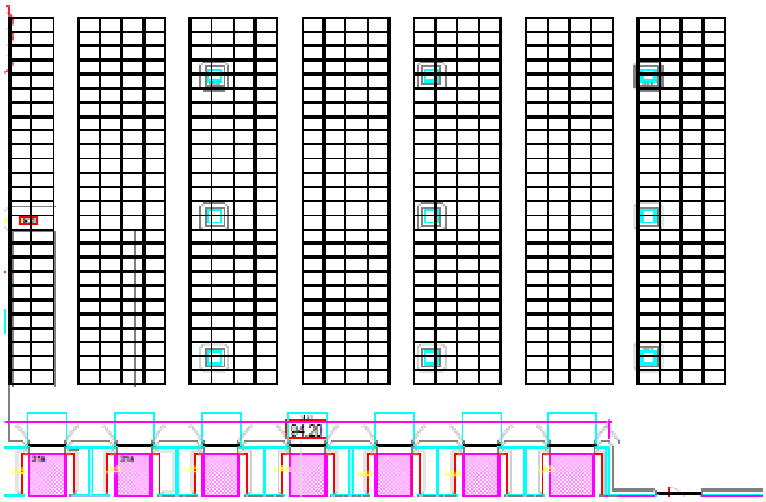

Figure 9 - Reception area of the layout

Despite reception being scheduled to last until 3 p.m., the reality differs. Many trucks are unloaded until 5 p.m. Still, since sorting is expected to end around 11 p.m., there should be sufficient time in between for the reception to complete its task on time for sorting to do the same. However, as seen in Figure 17 of Section 3.2.2, there is reception lasting until 11 p.m. which means sorting gets delayed, as does shipping. A solution to this bottleneck should be provided to the operation because otherwise, in peak days, reception may cause starving to the downstream bottleneck - sorting. In this case, the bottleneck could shift from sorting to reception. Section 3.2.1 and 3.2.2 analyse data regarding the demand and the product flows which will be helpful to better quantify the congestion on the reception. Section 4.1.1 proposes an alternative method to perform the reception, which should output a much faster and efficient reception, reducing the constraint on this process.

3.1.2 Pallet Build

Most cross-docking warehouses have a receiving, sorting and shipping area (Yu and Egbelu 2008), making up what is considered to a be a traditional cross-docking. The reality is that different paradigms exist in reality, such as cross-docks with storage space or with a production facility feeding the cross-dock, making up a hybrid cross-dock (Kulwiec 2004). XY profiles itself of such an example, where an inbound receiving area for EP is combined with production lines which provide the cross-dock with its Internal Production (IP). That can be seen in Figure 10, where the different flows, its locations and orientations are displayed.

Pallet build is the name given to the process of assembling single-SKU pallets with crates of products that are fed by the production lines. Adjacent to the cross-dock, there is a production facility, with multiple production lines, producing multiple SKUs, which dispatches its products in crates to the cross-dock. There, at the end of line, an operator oversees the pallet assembling. These pallets are composed by either 28 or 32 crates, depending on the SKU's production line. Once these pallets are produced, they are sent to a buffer within the sorting area and wait for sorting. On this buffer, the different product flows wait together (EP and IP) for the picker, however, since most of the products there are to be sorted on the current day, the order by which they are organised is not relevant - FIFO is not strictly followed.

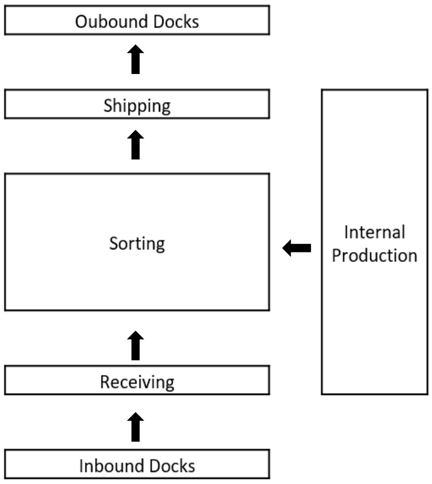

Figure 10 - Internal flow of the cross-docking warehouse of XY

The flow that goes through the pallet build is the IP which divides itself into 2 different categories: Order and Stock. The Order flow is the one that is produced and dispatched on the same day. The Stock flow, known as ADT, is composed of products that are produced on a certain day but remain in storage at the cross-dock for following days. The purpose of this is to ensure a levelled production output throughout the week and to protect service levels from weekly seasonal effects. Earlier in the week, ADT is produced to fulfil orders later in the week when demand is higher. If this buffer is not provided, the production facility may not be able to fulfil Friday's demand. Sections 3.2.1 and 3.2.2 provide further detail on these flows.

The IP takes place from 7 a.m. to 1 a.m. each day, except on Sundays and Saturdays, where production is shorter. From 7 a.m. to 10 p.m. the output is a mix of ADT and Order products, while from 10 p.m. to 1 a.m., the products are exclusively ADT.

3.1.3 Sorting/Picking

The next stage products flow through is the sorting/picking which is often identified as the bottleneck of a cross-dock (Vogt and Pienaar 2010). Sorting is often studied in the context of traditional warehouses instead of cross-docking; however, the complexity is very similar. In a traditional warehouse, the picker carries a store pallet and heads to product locations. On cross-docks, the inverse logic applies. The picker carries product pallets and drops crates on the store pallet. The importance of picking efficiency is reinforced by de Koster *et al.* (2007), stating that any underperformance in order picking can lead to unsatisfactory service and high operational costs for the warehouse and, subsequently, the supply chain. Thus, to have an efficient operation, "the picking needs to be robustly designed and optimally controlled" (de Koster *et al.* 2007). As order picking is the highest priority for productivity improvements (de Koster *et al.* 2007), the layout and the processes designed must create conditions that allow good sorting/picking productivities.

The sorting/picking at XY is located at the centre of the layout, as seen in Figure 10. Within the sorting area identified, there is a buffer where the pallets from the different product flows are placed, after reception and pallet build. From there, pickers grab the pallets and start their tour around the circuit. A representation of the layout within the sorting area can be seen in Figure 30 of Annex A – the buffer is placed in the centre of the circuit to minimise distances. On sorting, pickers can drop multiple crates in the same store pallet at the same time, if they belong to a single SKU. If the product pallet has multiple SKUs, the picker needs to make several tours around the circuit equal to the number of SKUs in the pallet, until the pallet in emptied.

Store pallets are only allowed to hold 32 crates, independently of their sizes. This constraint is done to provide ergonomic comfort to pickers and to stores, however, it is insensitive to the sizes of crates used and it is observed that many store pallets have considerably low sizes. Once the store pallet reaches 32 crates, the burden to close the pallet, send it to the back of the store location and grabbing a new pallet and its label falls on the picker. If the back of the store location in not freed, the picker must also take the pallet to the staging area, reducing its productive output. This problem is further detailed in Section 3.3, as the new solution must try to solve this issue.

Unlike the reception or the IP, the picking takes place 24 hours/day. At 11 p.m., the picking for the following day begins, by sorting ADT. At 7 a.m., the first shift begins to sort the other flows, EP and IP, and will only stop to do so at 11 p.m. Despite this schedule, sorting end time is often delayed due to a delayed reception.

3.1.4 Pick & Pack

Pick & Pack (P&P) is the name given to the process of retrieving a pallet from its store location and placing it on its staging location, while wrapping it with vitafilm. Each store location has space for 2 pallets. While the first one is getting filled, the one on the back is closed - means it is filled with 32 crates. Once there is a pallet closed on the back side, the process of P&P is triggered - the operator removes the store pallet, placing it into the staging area. In the meantime, the second position on the store location is emptied. The picker can now place the current store pallet there as soon as it reaches 32 crates. The pallet gets wrapped on the way from sorting to staging by the P&P operator. This process is depicted in Figure 11, where there are 4 sorting positions, 2 of which now have an empty back because the pallet previously there has now been moved to staging.

This process, if conducted correctly, should ensure that pickers focus solely on sorting, instead of having to move pallets themselves, impacting their productivity and the global system output. In fact, P&P operators are not sufficient to reach a productivity that matches the sorting output. Thus, there is an upward trend in the congestion of the system as the day advances. Section 4.3 studies whether the concept of P&P should be altered when designing the new layout. This is dependent on whether a Low volume or High-volume type layout is chosen.

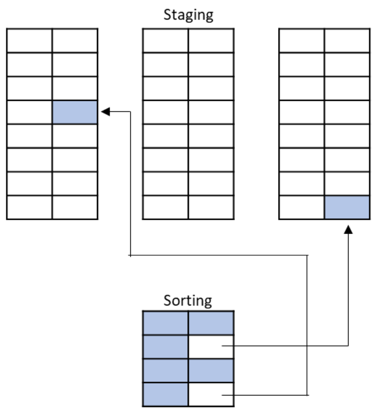

Figure 11 – Pick & Pack process

3.1.5 Shipping

The shipping area is one of the most important in a cross-dock according to the literature (Yu and Egbelu 2008), and in XY that same logic applies. The shipping takes place from 12 p.m. to 5 a.m., meaning that all the cargo must be staged nearby the loading docks by 12 p.m. The process of loading the trucks must be sufficiently effective not to delay the following trucks that load in the same dock.

The P&P process places the pallets in the staging area according to the transportation schedule. Each route, which is performed by a truck, is assigned to a dock and to certain positions on the staging lines at the beginning of the day. From that moment on, the pallets from the stores belonging to that route, are placed in the pre-set positions on the staging line. These positions are set in a way that places the store pallets in the inverse order to the route drop off sequence. This dynamic can be seen in Figure 12, where the last store to be loaded is the first stop on the route.

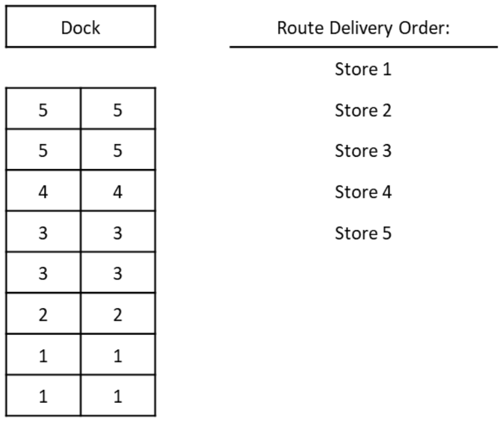

Figure 12 - Loading order according to the route drop off sequence

The biggest issue with shipping on the current layout is that the shipping window is very narrow, while the number of docks available is not high. Also, as Figure 9 shows, the staging lines are very close to one another to maximise the use of available space. This causes constraints when a truck delays its arrival, since the staging lines will remain occupied longer than initially expected, causing operational noise. Section 3.3 further details this issue.

3.2 Data Analysis

This section seeks to replicate Vogt (2004)'s guidelines on the analysis of data related to demand, seasonality and product flows. The Process of Design (Figure 8) reasoning is applied to the real-word case of XY's cross-docking warehouse. This method is corroborated by Baker and Canessa (2009).

The demand data covers only the first 10 months of 2017 which may pose limitations in terms of conclusions – ideally, the bigger the dataset and the more recent is information, the more robust will conclusions be. The data for the product flows, occupancy and productivity is relative to the past 4 months. Despite belonging to a smaller dataset, it is more representative of the current reality. Every assumption made when analysing the data will be timely mentioned and explained.

3.2.1 Demand

The operation faces big constraints because of its unstable demand. Despite stable demand being required to implement a cross-docking operation (M. Apte and Viswanathan 2010), the reality in this case differs since peaks are very common. The demand is variable from month-to-month, from weekday-to-weekday and from day-to-day, considering peaks seem to occur frequently. Figure 13 shows the monthly evolution of the average and the maximum values of daily demand, from January to October. November and December were withdrawn from this analysis since the operation was partly outsourced in this period, meaning the results would not be representative.

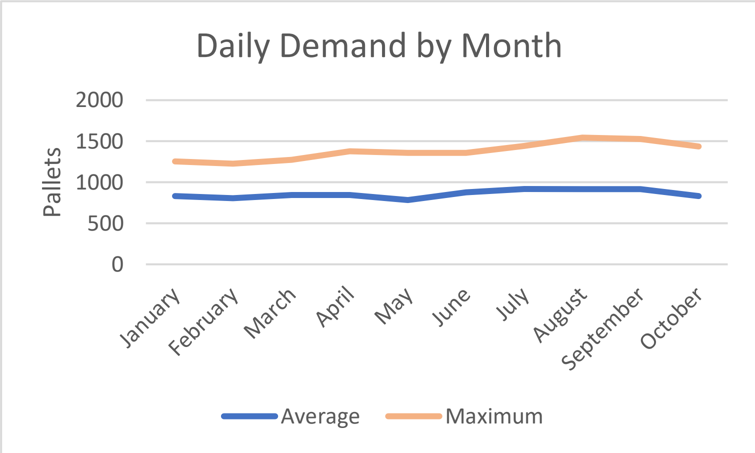

Figure 13 - Daily demand by month from January to October

The months of July, August and September display bigger demand rates, when compared to the rest of the year. This is translated into a peak-to-average ratio, concept introduced by Vogt (2004), of 1.8 - see Equation (2). This means that the maximum daily demand is 1.8 times bigger than the average demand of the cross-dock. However, the monthly variation is not very prominent. The coefficient of variation (CV), the ratio between standard deviation and mean, from month-to-month is only 5.62%. If the maximum values are used, it equals 7.89%. The average monthly seasonal indexes (3), which represent how much a month volume compares to the aggregate volume, are 1.07 for the months of July, August and September. One can therefore assume that monthly averages and maximums do not differ immensely among themselves, however the peaks that do occur are greatly impacting the general behaviour of the operation.

$$Peak\ to\ average\ ratio = \frac{Maximum\ Demand}{Average\ Demand} \tag{2}$$

$$Seasonal\ Index_i = \frac{Average\ Monthly\ Demand_i}{Global\ Average\ Demand} \tag{3}$$

Besides understanding that the summer months are the strongest in terms of demand, where the maximum number of pallets was 1544 when compared to an average of 856 pallets, it is important to understand whether there is intra-week variation. This intra-week analysis is useful to realise whether there is a clear pattern in peaks. In fact, analysing Figure 14 allows to conclude that Thursdays and Fridays experience demand peaks in relation to the other weekdays. That conclusion is supported by managers' perception.

While the peak-to-average ratio is the same, since the data set is the same as the one used to plot Figure 13, the CV for the average is now 27.83% as for the maximum is 24.01%. Fridays have a seasonal index of 1.5, while only Thursdays are over 1 besides Fridays. This clearly means that Fridays skew the average and that Fridays and Thursdays are the days to look at when dimensioning the new layout, assuming nothing is done to level demand.

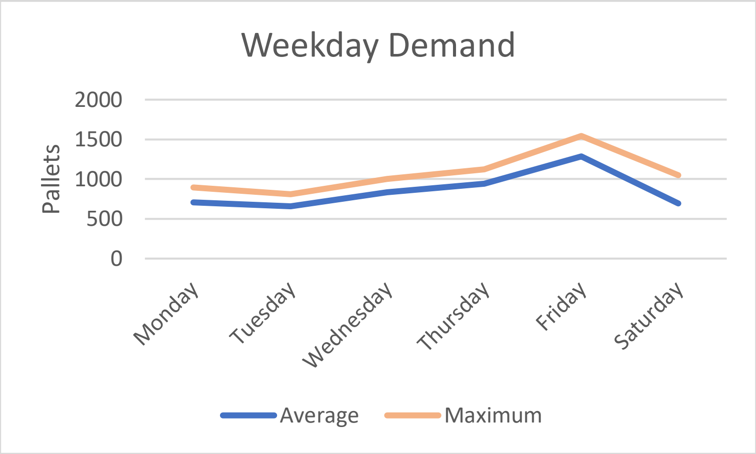

Figure 14 - Pallets demanded per weekday, considering data from January to October

The initial perception was that the biggest constraint in terms of demand were summer months. Now, the perception shifted to summer Fridays. In fact, the top 39 days in terms of demand of the year were Fridays, while the first seven were either in July, August or September.

The CV between months seemed to show a rather stable demand rate. However, when comparing weekdays' averages, the CV is 27.83%. A day-by-day analysis of the CV outputs a result of 28.32% (see Figure 31 of Annex B).

3.2.2 Product Flows

A traditional cross-docking environment serves the purpose of consolidating inbound cargo into outbound trucks, with multiple destinations. Generally, the cross-dock serves as a transfer node and not a storage node (Zhengping *et al.* 2008) and every product that flows has originated somewhere else. In this facility, this is only partly true, as there is IP which is fed by the production facility. To fully understand the needs of the operation, understanding how these flows interact and behave throughout the year, the week and the day is crucial. As processes are not balanced, buffers need to be created. The flows' analytical study aids in determining their ideal capacity.

External Production (EP)

The demand is obtained through the sum of the EP and IP (see Table 15 of Annex C) so, the same analysis done in Section 3.2.1 is performed here. Figure 15 presents the distribution per month of EP's demand, while Figure 16 depicts the EP's weekday distribution. The distribution along the graphs is like the one seen in Figure 13 and Figure 14. However, the seasonal index, peak-to-average ratio and CV differ. The month-by-month analysis returns a CV of 6.38% for the average and 11.58% for maximum values. The peak-to-average ratio is 2.15, powered by a maximum value of 976 pallets from EP in a single day. The seasonal index is similar at 1.10, for July.

The intra-week analysis returned a peak-to-average ratio of 2.16 while the CV is 33.50% for averages and 31.79% for maximums. The seasonal index on Fridays is 1.63. When comparing aggregated demand and EP's seasonal indexes, it is understood that EP represents a bigger slice of Friday's demand, meaning the reception is even more crowded. The variation among weekdays is also relevant, confirming managers' perception once again. This is further proof that Fridays are the most relevant weekday to base the layout design and simulation on.

A day-by-day analysis of variation returned a CV of 34.24%. Figure 32 of Annex B provides the graphical distribution of the EP's daily demand, where one can observe the variation within the daily distribution.

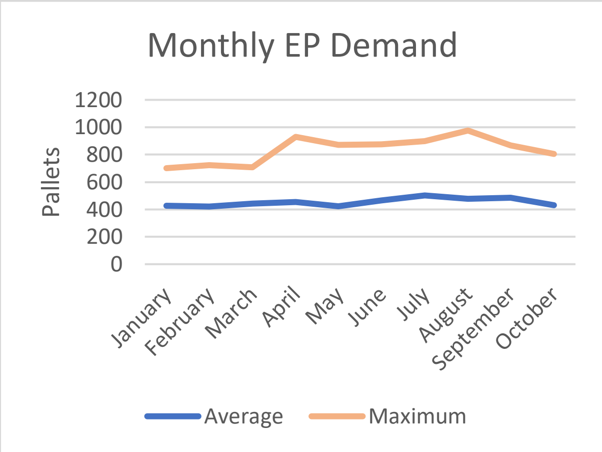

Figure 15 - EP pallets received per day of each month

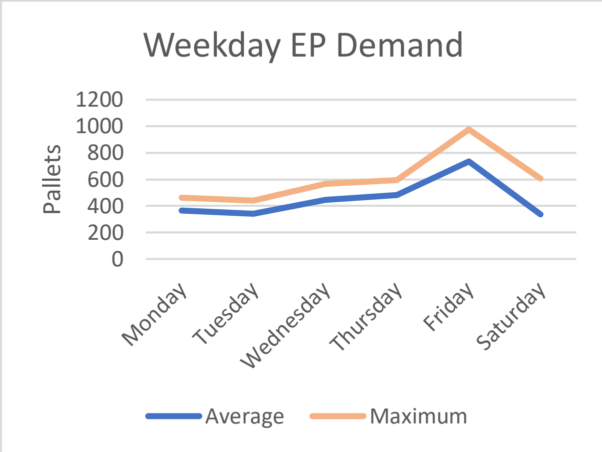

Figure 16 - EP pallets received per weekday

Despite being important to understand how the flows behave in a macro perspective, it is also crucial to know how the data behaves within a day. For that, an hour-by-hour analysis is required. Figure 17 displays that graphical distribution. The analysis provides further insight into the delay the reception is causing to the downstream processes like sorting. Despite physically receiving most pallets until 5 p.m., there are pallets that are only inputted into the system at 11 p.m. The data provided in Table 16 and Figure 34 of Annex D helps in realising this delay is particularly true on Fridays. On other days, the occurrence is less representative which poses less of a threat for sorting. The hourly reception's CV is 24.54% for the maximum values. Some of this variation is explained by the meal times where the operation partly stops. The distribution followed by the maximum values is used to perform the sensitivity analysis in Section 4.4. The maximum values are used because the purpose is to understand if the changes introduced can overcome peak days. The analysis also includes the forecasted growth rate of demand.

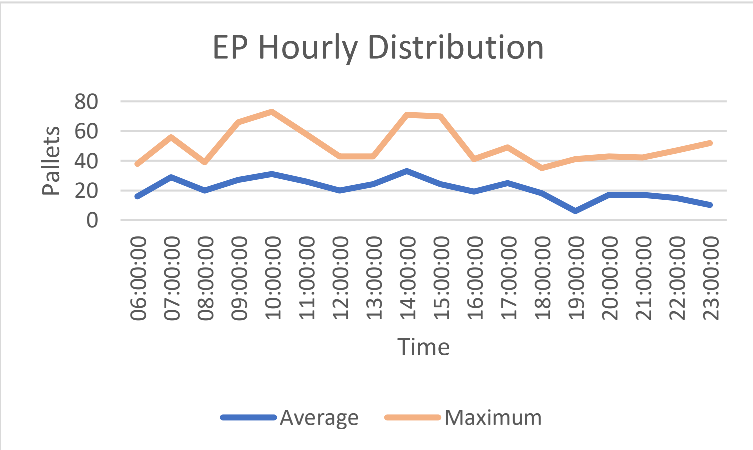

Figure 17 - EP real reception time distribution

Internal Production (IP)

IP follows the same pattern as aggregated demand and EP. Peaks are seen in August and September, mostly on Fridays - with a seasonal index of 1.37. That is depicted in Figure 18 and Figure 19. The month-by-month analysis outputs a peak-to-average ratio of 1.82. The CV is 5.56% and 10.37% for average and maximum distributions, respectively. The maximum IP in a day was 731 pallets. The CV for the day-by-day analysis of demand IP pallets outputs 24.76%. These results allow to conclude that IP demand is slightly less variable than EP. This is helpful in concluding that the process of reception needs to be prepared to absorb the variation inherent to EP's demand.

The intra-week analysis, Figure 19, outputs a CV of 21.91% and 19.50% for average and maximum distributions, respectively. The intra-week variation is less sharp for IP than for EP.

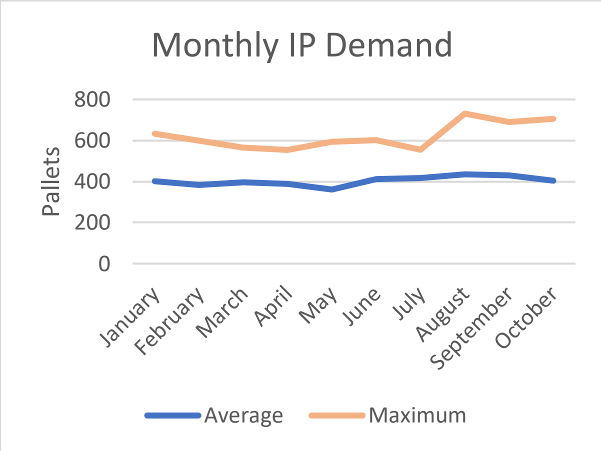

Figure 18 - Pallets produced per day of each month

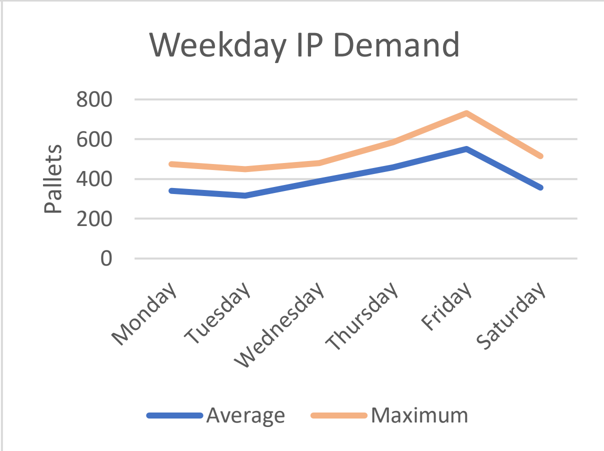

Figure 19 - Pallets produced per weekday

Like in EP, an intra-day analysis is required. This is useful to understand sorting inflow peaks. The CV for IP is 29.92% and 21.92% for average and maximum, respectively. This once again proves IP is slightly more stable than EP. Analysing Figure 20, it is perceived that the biggest contributing factor for the variation is the meal time. This means that the remaining flow is approximately constant, which provides some comfort to sorting. That happens in IP and not EP since the first flow originates in a balanced production facility with virtually null lead time to the cross-dock. EP, on the other hand, is dependent on suppliers' will to deliver at a given time.

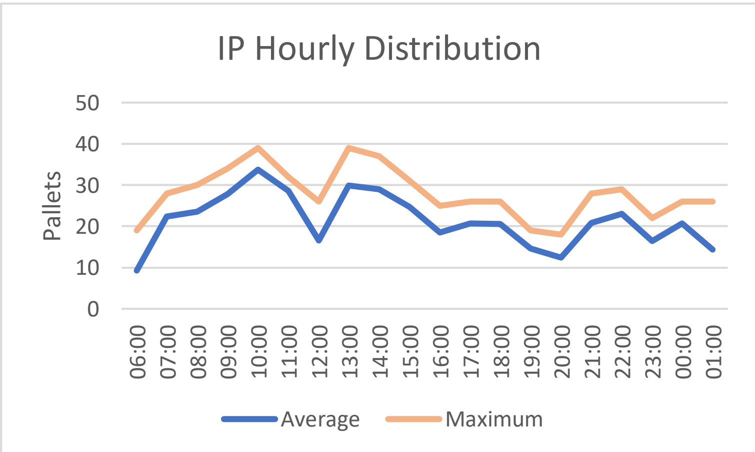

Figure 20 - IP hourly distribution, in pallets

In Section 4.4, this IP hour-by-hour distribution is utilized to aid in establishing scenarios. The maximum value distribution is the most important to test the new layout dynamics since that corresponds to demand's worst-case scenario.

ADT - Internal Production for Stock

Despite the ADT flow belonging to the IP flow, it requires a focused analysis. Since the ADT flow requires storage space, a study of such requirement is essential to design the new layout. Based on data extracted in the first three months of the year, the percentage of Order and ADT production per weekday can be seen in Table 4. Simultaneously, if that is compared to the demand of IP per weekday, it is understood that the amount of ADT stored in the cross-dock grows as the week passes. That is seen in Table 4 where, after considering the production and demand per weekday and the percentages of Order and ADT, the column "ADT Left" displays the number of ADT pallets that are, on average left at the end of each weekday. This analysis however useful, slightly differs from the perception passed by managers at the operation. The general understanding is that peaks are achieved on Thursday nights, while the previous days are building up stock. Moreover, they required the need to have storage space for 600 pallets which, according to them, has happened on peak days. The reason why that number was not achieved by the data is that there are no records of ADT in the WMS, or at least that data is not currently extracted. The results obtained were through a combination of historical records of demand (2017) with recent data on production (2018) explaining why the results may be lagging from reality.

Table 4 - Percentage of Order and ADT production per weekday, as well as the number of pallets of ADT left for storage at the end of each day

Day	% Order	% ADT	ADT Left
Monday	65%	35%	181
Tuesday	65%	35%	331
Wednesday	47%	53%	370
Thursday	50%	50%	310
Friday	76%	24%	132
Saturday	79%	21%	85
Sunday	34%	66%	134

Demand per Store

One of the requirements to correctly design a layout is to understand the demand per store (Vogt and Pienaar 2010), mostly if a Low volume layout is designed where store locations have sufficient depth to hold stores' daily demand. Table 17 of Annex E details the number of stores per number of demanded pallets according to the 95-percentile of each store's demand. This is useful to dimension the depths of store locations on the new layout. The criteria used to estimate the demand per store is the 95-percentile instead of the maximum value since the maximum value for aggregate demand does not necessarily correspond to the maximum value of demand for each individual store. In fact, the maximum demand was 1544 pallets in 2017, while the sum of each store's 95-percentile demand is 1667 pallets. This means that the 95-percentile criteria already account for a safety factor when dimensioning the depths.

3.2.3 Productivity Analysis

As de Koster *et al.* (2007) mention, any underperformance in the sorting productivity can impact service levels and operational costs, making productivity improvements the top priority in warehouses. In this case, the same reasoning applies, whether it is to reduce costs or to ensure the operation can be sustained in the same facility for 2 extra years, without any relevant investments.

In Figure 21, the week-by-week analysis shows that the productivity in the first 14 weeks of the year has been declining. This is further evidence that the layout is reaching its efficiency limit, as seen in the problems identified in Section 3.3. Figure 22 displays the productivity per weekday. While the global average is 105 pallets/hour, the average productivity on Fridays stands out as 115 pallets/hour. This is probably due to the increased workload and pressure to finish on time. However, the base used to estimate the new productivity because of improvements introduced is the global average – 105 pallets/hour. This assumption is used for the sake of circumspection.

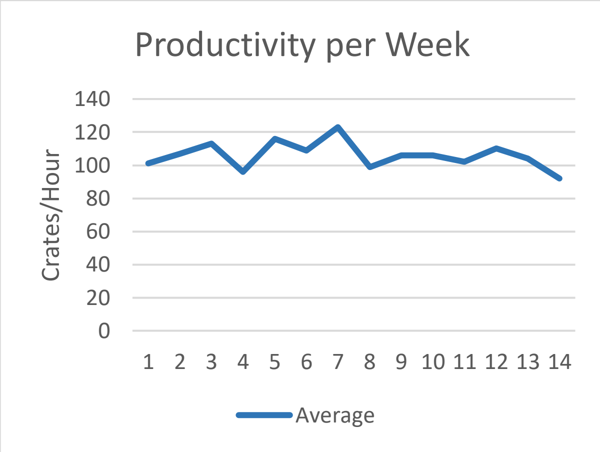

Figure 21 - Average productivity per week, based on the first 14 weeks of the year

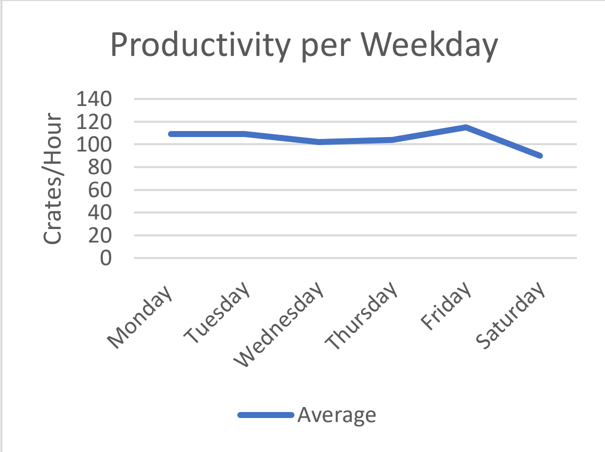

Figure 22 - Average productivity per weekday

Figure 23 provides the hour-by-hour distribution analysis where it is seen that productivity reduces over meal time and is trending downwards throughout the day. This distribution is used in Section 4.4 as the basis to simulate the sorting activity in the sensitivity analysis. Figure 35 of Annex F provides the same information but only for Fridays. The same trend as in Figure 23 is there visualised, meaning that there are no significant differences in terms of productivity patterns from Fridays to the remaining days.

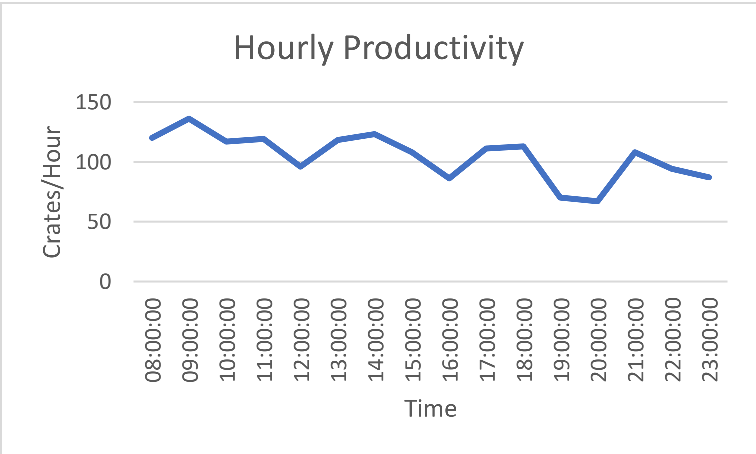

Figure 23 – Average hourly productivity

3.2.4 Floor Occupancy

The product flow distribution throughout the day is essential. However, the data available also allows to see the real buffer occupation through the pallets allocated to each WMS bin at a certain moment. That is seen in Figure 24 for the occupation of the IP buffer, which accounts for Order and ADT flows, based on the first 4 months of the year. The maximum value reached is 514 pallets – it occurred on a Thursday. Considering there is a ratio between the maximum of the year and the maximum of the first 4 months of 1,15, the buffer should have 600 pallets of space for ADT – confirming manager's perception. Considering EP, Figure 25 provides the buffer occupation throughout the day. A maximum value of 346 pallets is displayed – it occurred on a Friday. Considering a ratio between the maximum of the year and the maximum of the first 4 months of 1,05, the expected maximum occupation of the buffer is 360 pallets. All this information is useful for Section 4.2 when defining the needs of each buffer on the new layout.

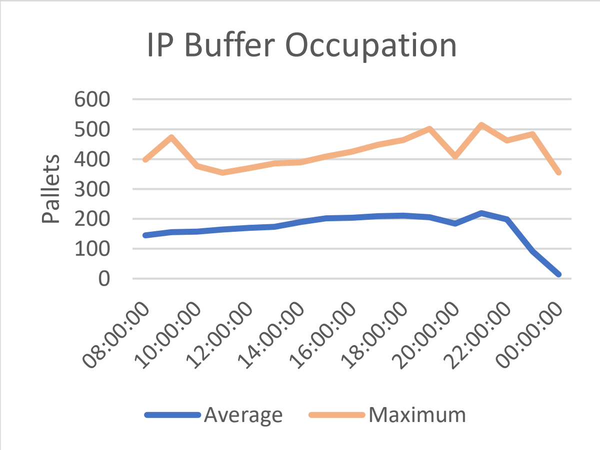

Figure 24 - IP buffer occupation throughout the day

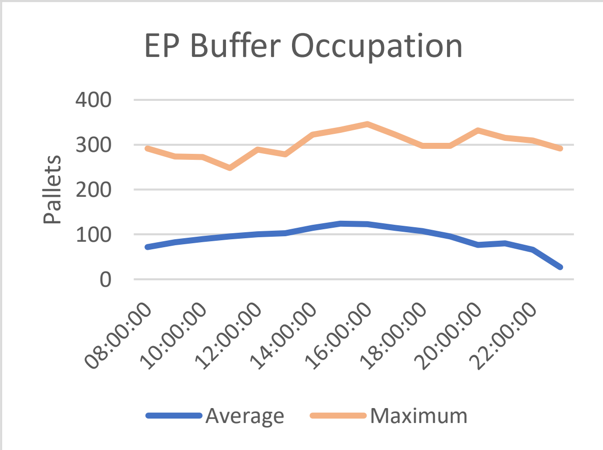

Figure 25 - EP buffer occupation throughout the day

3.2.5 Transports

Another key element for the functioning of the cross-docking warehouse is truck scheduling. Many articles focus on the scheduling of outbound trucks (Lim *et al.* 2006; Boysen 2010; Vis and Roodbergen 2008). However, that is not the focus of the project at hand. Nonetheless, increasing the shipping window through more efficient sorting and smoothing of pallets shipped per hour is needed and should help reduce the congestion on a troubled operation. Table 5 details the distribution of pallets shipped per hour based on one day's transport plan. This plan is created everyday according to the daily volumes, yet it does not differ much from day to day since delivery windows at the stores are not variable.

Table 5 - Pallets shipped per hour based on a Friday

Time of the day	Pallets
00:00:00	161
01:00:00	165
02:00:00	32
03:00:00	413
04:00:00	193
05:00:00	197

3.3 Current Layout Analysis

The current layout, which Figure 26 presents, is reaching its limit. It is currently serving 252 stores, while the goal is to extend it to 290. To better understand the current state, Table 6 provides further insight. When analysing the pallet capacity, the current layout holds physical capacity for 2349 pallets. Yet, its true capacity is smaller since the sorting area cannot serve the purpose of storage, reducing the real capacity to the sum of the buffer with the staging area's capacity (1845 pallets). A total of 388 pallets are reserved for ADT, IP and EP buffers. The remaining 1457 allocated to staging are not sufficient to support a peak day (at least 1544 pallets). Furthermore, in days with 600 pallets of ADT, the operation becomes unfeasible.

Applying the concept of centre of gravity (Vogt and Pienaar 2010), the distances covered by the pallets are displayed in Table 6. One pallet covers 413 meters for IP or 463 meters for EP, from the moment it enters the cross-dock to the moment it leaves.

Table 6 - Capacity description of the current layout

Characteristic	Capacity
# Pallets: Sorting	504
# Pallets: Staging	1457
# Pallets: Buffer	388
Total Pallets	**2349**
Meters Reception to Buffer	90
Meters Production to Buffer	40
Meters Sorting Circuit	323
Meters Sorting to Staging	50
Total Meters	**503**

Most of this travelling happens on the sorting circuit, which is 323 meters long. On this circuit, besides the inexistence of the S-pick concept, which largely reduces distances (Vogt 2004), despite not necessarily reducing congestion, there are some stages which the picker needs to walk even though there are no stores. This is a big waste of time for the picker, reducing its productivity without any upside. Figure 26 displays these wastes, as well as the start of the sorting circuit, the reception and shipping areas, the buffer and the sorting route.

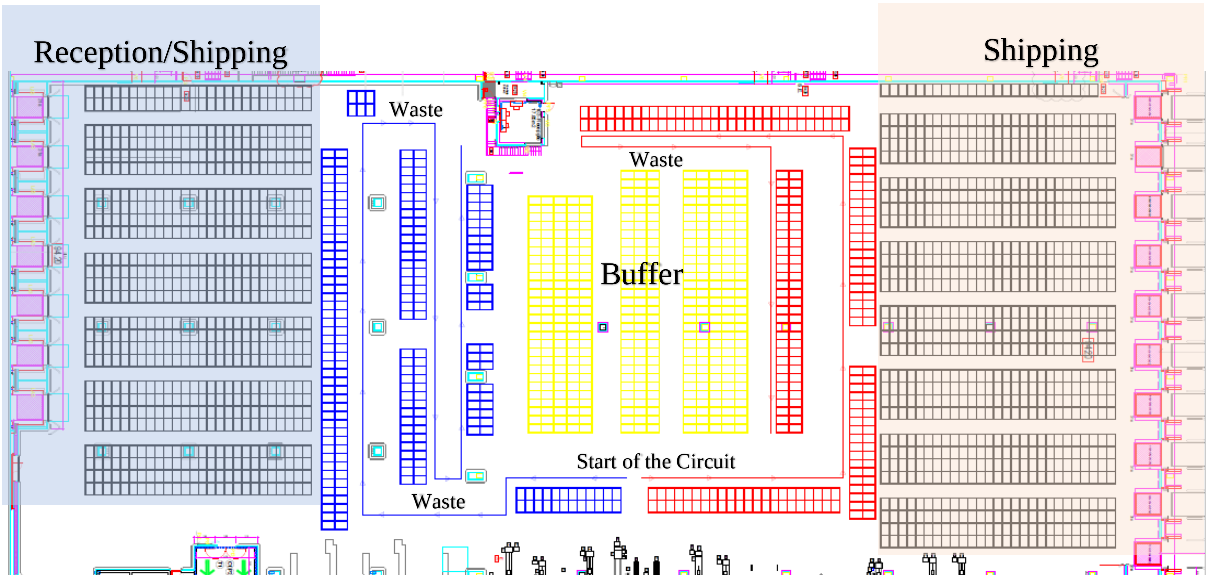

Figure 26 - XY's current layout, where staging for shipping, reception, buffers, end of lines and the sorting circuit are seen

Figure 36 of Annex G displays demand's heat map on the current layout. There is a hotspot for high demand stores at the beginning of the south circuit, causing congestion. That expected congestion is confirmed by observation, where recurrently pickers were blocking one another.

Another issue present is related with the lack of focus the picker has on sorting. Many times, P&P operators are not outputting as much as sorting, meaning pickers must perform P&P's tasks - P&P is blocking sorting, behaving as a bottleneck (Goldratt 2005). P&P has a standard time of 02:40 minutes which translates into the time the picker wastes in non-value adding activities every time he entails on P&P tasks. Multiple sorting tours were observed and in all of them, pickers were performing P&P. If this waste was cut, the picking productivity could increase by 14%, based on the standard times of each process detailed in Table 3. The lack of data to quantify the percentage of sorting tours that require P&P by pickers does not allow to support the conclusions drawn by observation. The consequence is that the 14% estimation is an upper bound on productivity improvements.

The lack of batch picking, which is the ability to pick multi-SKU pallets on a single tour, profiles as a shortcoming of the WMS. This is not a limitation of the layout; however, the WMS should be updated to support this possibility. The advantages of this implementation are expounded in Section 4.1.2. Other issue is related to the criteria used to set if a store pallet is closed (full). Pallets are closed once they are filled with 32 crates, independently of the size of the crates it contains. Since many suppliers deliver with smaller crates than IP, many pallets will have lower sizes than they could have if a different rule was established to determine when a pallet is closed. This would allow better space management in the cross-dock and at the trucks. Section 4.1.5 and 4.1.6 describe the solutions found to minimise this inefficiency.

On staging, constraints happen on peak days. To start, the reception overlaps with shipping staging, as displayed on the left side of Figure 26. This means that throughout the day, pallets closed from sorting are assigned to a staging location that may be filled with a pallet being received. This creates the need of finding temporary positions for the finished pallets, which means rework, hence loss of productivity. Also, since aisles between each set of four rows of staging lines are very narrow, room to manoeuvre the electric pallet truck is very small. So, the docks (and staging lines) are assigned to trucks according to their shipping schedule such that the bottom right staging lines correspond to the first truck. The adjacent staging lines and dock correspond to the next scheduled truck, and so on. This should ensure there is always a clear path to grab every pallet to the truck. If delays do occur, the operation must improvise. That includes picking pallets from its 1,2 meters side instead of the 0,8 meters side, which implies rework before placing the pallet on the truck. The functioning, characteristics and issues with the current layout are here expounded. In Section 4, the new layout developed will try to mitigate as many of those issues as possible, with the goal of efficiency as the main priority.

4 Solution Design

This chapter presents the second stage of the proposed methodology to study layout designs on cross-docking operations. In Chapter 3, the first part of that methodology was presented and applied, through the description and data analysis of the current state of the warehouse. In the case of building an entire cross-docking warehouse from scratch, the data analysis should be done based on demand forecasts, expected sorting productivities and truck scheduling. Alternatively, if there was previously a similar operation, that should serve as a proxy to construct the new one. The process mapping and analysis should still be done, however not to correct something that was previously being performed inefficiently, but to design new, efficient processes. In this case study, the process mapping is done to contextualise and to design new, more efficient processes.

In this second stage of the methodology, a step-by-step approach is presented to solve the whole problem. Firstly, improving the current processes should output efficiency gains, through bottleneck impact minimisation. Secondly, it is crucial to understand the parameters and constraints that must be kept, to reach a feasible layout proposal. Only if there are no layouts that answer the constraints, will they need to be relaxed. Then, layout scenarios should be proposed. Finally, a sensitivity analysis is undertaken where different variables are tested to see how the proposed scenarios behave.

4.1 Process Improvements

In this section, based on the issues identified, the applied solutions are expounded. These solutions have been applied or are in development over the course of the project. All the proposed solutions are introduced as a direct result of the project.

4.1.1 Reception by Pallet

The process of receiving a pallet can take up to 5 minutes, as seen in Section 3.1. Knowing 33 pallets are unloaded from a truck, reception should take 165 minutes. Thus, reception should end, at most, 165 minutes after the last truck arrives. However, with all wastes, errors and consequent delays, the reception can last until 11 p.m. in peak days. Much of the errors that do occur regard the inability to scan all crate labels. It was observed that in most pallets, not all crates were scanned on the first try. That is the reason why the reception process took so long.

To ensure the goal of finishing sorting by 10 p.m., reception needs to end much earlier. So, a new reception process is implemented, where instead of scanning every crate of the pallet, only the pallet label from the supplier is scanned. This avoids potential scanning mistakes that often occur, reducing the number of scans from 32 to 1. This has been tested and reduces reception time to one minute/pallet – 80% reduction on process time, anticipating the end of reception. The upside is that previously the pallets were physically at the cross-dock but unavailable for sorting – causing congestion. Now, the pallets are at the cross-dock at the same time as before but they are now available for sorting, avoiding sorting from experiencing starving (Goldratt 2005).

4.1.2 Batch Picking

In traditional warehouses, order batching means setting a group of orders into a single set in such a way that it can be retrieved by a single picking tour (de Koster *et al.* 2007; Scholz *et al.* 2017). In cross-docking, the proposed concept of batch picking means that a multi-SKU pallet originating on the supplier can be emptied on a single tour around the circuit. The pallet label is scanned by the picker, and from that moment the WMS provides the drop spots and quantities for every SKU. This solves the current issue of the WMS only allowing one SKU to be picked by tour. Petersen and Aase (2004) state that batch picking is the most impactful measure to improve sorting productivity. Basing on the analysis of the first 3 months of the year, 16.4% of every received pallet from EP had multiple SKUs. On average, each of those pallets had 2.64 SKUs, which means that if batch picking is applied, 14% of total tours around the circuit can be removed. The percentage decrease of tours made by pickers can be calculated using Equation (4). Table 7 presents the data regarding multi-SKU pallets.

$$Tours\ Saved = \left((Average\ Number\ of\ SKUs - 1) * \%MultiSKU\right) * \%EP \qquad (4)$$

Table 7 - Multi-SKU pallets data

% Multi-SKU Pallets	Average Number of SKUs	Tours Saved
16.4%	2.64	14%

The batch will also be applied to the pallet build in IP. Currently, once the SKU changes on the production line, the open pallet is closed, even if it only has one crate on it. This results in poorly occupied pallets. With the capability to batch pick, that will change, meaning that only full pallets will be built, since multi-SKUs can now be picked. The impact of this change is not easily measurable since it is dependent on whether the last pallet of a SKU ends up full or just half full. However, since there are around 50 SKUs produced per day, there can be up to 50 pallets poorly occupied on the end of day. On a best-case scenario, 50 pallets and consequently 50 tours can be saved.

4.1.3 Pick by Ranges

One issue visualised on the operation is its congestion. Since high demand stores are located side by side, pickers are constantly crowding those areas (see Figure 36 of Annex G). If two pickers grab a pallet each, of the same product at approximately the same time, the system will tell both to stop at the same stores, dividing the demand by both pallets. This generates added congestion without any upside. To solve this problem, a solution is proposed: if multiple pickers are grabbing pallets from the same SKU, the system should send the first one to the first store with demand. The last store on this picker circuit should be the one where the SKU pallet is emptied after fulfilling all the previous stores' demand. The second picker should start sorting at the next store with demand after the last store with demand from the previous picker. This concept looks to avoid that multiple pickers stop at the same store with the same SKU, reducing congestion, which is mentioned by Luo (2008) as one of the main characteristics of a good layout. The name given to this process is Pick by Ranges and one example of its utilisation can be seen in Table 8. There, for a certain SKU, five pickers grab five pallets and the circuits are assigned in such a way that they do not go to stores previously supplied by any of the other pickers.

Table 8 - Example of the functioning of the Pick by Ranges Process

Picker	Start	End
1	Store 1	Store 11
2	Store 13	Store 27
3	Store 34	Store 58
4	Store 60	Store 93
5	Store 97	Store 157

Naturally, congestion will still exist due to multiple SKUs having pallets being picked at the same time. Moreover, multi-SKU pallets will also be harder to manage. Withal, this clearly mitigates one of the biggest problems observed and mentioned by managers. The gain in terms of productivity is hard to estimate, however. A simulation model with inputs such as the cycle time of dropping a crate, average drop size per store and per product, as well as the walking speed of pickers could allow to estimate this result.

4.1.4 Dispatch Full Pallets – Opportunistic Cross-Docking

The ability to dispatch full pallets of demand from reception directly to shipping staging should be made possible by the WMS, skipping sorting in its entirety. This concept, known as opportunistic cross-docking, has been introduced in the literature by Napolitano (2000) and Buijs *et al.* (2014). Despite the inexistence of intelligible data to support this, managers mentioned that on peak days, 50 pallets of high-rotation SKUs from EP could go through this process, since on these days, big stores take at least one pallet of those SKUs. The real impact on productivity is hard to estimate accurately. Firstly, there is no historical data on the number of pallets that qualify for opportunistic cross-docking. Then, if these pallets were carried to sorting, the productivity would also increase considerably. Despite all this, 50 pallets in a day with 1544 pallets of demand represents 3.2% less sorting tours. That means 1600 crates in a day, which is equivalent to two pickers/day at the current productivity.

4.1.5 Full Pallet Trigger by Height

As of today, pallets are closed at 32 crates, independently of their sizes. Often, this creates poorly occupied pallets because suppliers already deliver in smaller crates than IP does. Thus, pallets will be closed based on the actual height achieved by the pallet stowage. By coupling the smaller crates fed by EP with the renewed crate assignment policy for IP (see Section 4.1.6), where most SKUs will start using 17.4 cm high crates instead of 22.4 cm high crates, the expected number of total pallets is expected to drop by 7.2%. This improvement can also be applied to productivity, as the pallets that leave IP can now increase its number of crates per pallet, which translates in less tours around the sorting circuit, improving the global productivity of the system. Table 9 further details the impact of reducing the size of the crates utilised in IP on the number of tours performed. The conclusion is that, based on a sample of sales of 2017, the total decrease in tours could be as high as 22% for IP, which translates to 10.3% global sorting productivity gains – see Equation (7). Equation (5) and (6) represent the calculation of the remaining values of Table 9.

$$Expected\ Crates\ per\ Pallet = \sum_{i=1}^{3} Product\ Share_i * New\ Crates\ per\ Pallet_i \quad (5)$$

$$Previous\ Crates\ per\ Pallet = \sum_{i=1}^{3} Product\ Share_i * Old\ Crates\ per\ Pallet_i \quad (6)$$

$$Tours\ Saved = \frac{Expected\ Crates\ per\ Pallet - Old\ Crates\ per\ Pallet}{Old\ Crates\ per\ Pallet} * \%IP \quad (7)$$

Table 9 - Growth of crates per pallet in for the different IP product flows

	Reformed	Sliced	Counter
Product Share	33.0%	27.0%	40.0%
New Crates per Pallet	36	40	36
Expected Crates Per Pallet		37	
Old Crates per Pallet	32	32	28
Previous Crates per Pallet		30	
Tours Saved		10.3%	

4.1.6 Crate Assignment Policy

The layout design is one of the ways followed in the project to improve operations at XY's facility. However, many other approaches were followed to design the solution, most of which had a direct implication on the behaviour of the layout – processes and WMS related components. Knowing this, one observation in this fresh cross-docking facility is that most crates used were equal, mostly those originating in IP – the crate used is 22.8 cm high (crate LL6424). In fact, not only were they equal in size, but they also lacked satisfactory utilisation rates, since most of them were partially empty, affecting both the cross-dock and the transportation efficiency.

An analysis is performed to understand if a new standard could be introduced in crates utilised by IP. That analysis started by understanding, SKU by SKU, the number of trays per crate and the size of each crate. With that data, the height of the trays within the crate is calculated. The results identified that out of 216 SKUs, only two SKUs would not fit in a 17.4 cm high crate (crate LL6416). For those SKUs, the number of trays per crate was reduced since the benefits outweighed the cons. Therefore, the crate LL6424 was removed from the IP crate feeding chain, being replaced by crate LL6416.

The impacts of changing the standard were studied and are detailed in Table 10. Based on a sample from 2017's production, the introduction of the smaller crate (LL6416) reduces the number of IP crates by 15,4%. Considering IP represents 47% of total pallets, the expected reduction of store pallets shipped through the cross-dock is 7.2%.

Table 10 - Impact on pallets dispatched by the cross-dock with the introduction of the new crate standard

Crates per Pallet - LL6424	32
Demanded Pallets - LL6424	160177
Crates per Pallet - LL6416	40
Demanded Pallets - LL6416	135457
IP Pallet Reduction	24720
% IP Reduction	15.4%
% Aggregated Reduction	7.2%

The potential benefit on the number of store pallets is only obtained with the introduction of "Full Pallet Trigger by Height". Now, pallets with 32 LL6424 crates built a pallet with 182,4 cm of height. If 40 LL6416 crates are piled up, the pallet is 174 cm high. So, the same pallet can take eight extra crates while still being smaller than previous pallets.

Two potential further benefits arise because of this change. One is explained in Section 4.1.5 and Table 9 and regards the impact of higher pallets leaving production on sorting productivity. The other impact is related to the blending of IP with EP flows. Without "Full Pallet Trigger by Height", the small crates sent by suppliers had no impact on the reduction of pallets in the cross-dock. Now, since what matters is the height, both IP and EP flows' standards will contribute to improve operations. That is mostly true since the observation performed allowed to conclude that most suppliers already delivered their products in smaller crates than XY's IP. So, the 7.2% impact on store pallets may very well be higher. This is particularly useful for space and transport utilisation. Space because depths, staging and buffer sizes can be re-dimensioned in the future. Transports because a truck may now deliver to more stores than previously.

4.2 Definition of Constraints and Parameters

This stage regards setting the Design Aims, Design Requirements and Design Parameters as done by Vogt (2004). Defining system requirements is proposed by Baker and Canessa (2009).

The hard constraints are demands the new layout must meet to justify the investment and trouble of changing the entire cross-docking dynamics.

$$Number\ of\ Stores \geq 290 \tag{8}$$

$$Pallets \geq 1787 \tag{9}$$

$$Number\ of\ Shipping\ Docks \geq 13 \tag{10}$$

The shipping window must start at 10 p.m. and end by 5 a.m. of the following day.

Equation (9) originates from applying a 5% growth to the number of pallets dispatched by the cross-docking warehouse in the next 3 years, as forecasted by the company.

Further parameters are set, which serve as guidelines for setting the new layout:

- ADT buffer equal to 600 pallets (Section 3.2.4);
- EP buffer equal to 360 pallets (Figure 25);
- Order IP buffer sufficient to hold 1-hour production – approximately 42 pallets (Figure 20);
- Shorter sorting circuit than on the current layout;
- Layout that holds space for empty pallets, empty crates and problem-solving workstations.

4.3 Layout Design

This corresponds to the stage proposed by Vogt (2004) where the layout is detailed, namely the design, the capacity and its functioning. Baker and Canessa (2009) also support this stage which encompasses the design, the assessment and the choice of the layout.

4.3.1 Layout Design and Capacity

The current concept of the layout at XY is a High-volume layout, according to Vogt and Pienaar (2010) classification, meaning store pallets are sent to staging immediately after sorting. Knowing the parameters and constraints set, multiple iterations are performed to design a layout as similar as possible to the previous. This is so to avoid too many operational changes. Those iterations were performed using AutoCad software using the following top-down methodology:

- Design a layout with 290 store locations;
- Design a layout with sufficient staging and buffer locations in accordance to the parameters;
- Design a layout that matches the remaining parameters and constraints.

In the specific case at XY, after 27 iterations on High-volume layouts, no feasible layouts that would fulfil all hard constraints and parameters were accomplished. A shift is made to design Low volume layouts, where the store pallets would remain in the sorting area all throughout the day (Vogt and Pienaar 2010). Here, the slot for each store may have different capacity/depth, according to each store's historical 95-percentile of demand.

After 13 iterations on Low volume layouts, a feasible layout is achieved. This layout meets the hard constraints and the parameters set in Section 4.2, in accordance to managers' requirements. The most crucial is related to the number of store locations available: 321. Table 11 assembles the capacity description of the new layout. The new layout besides meeting the constraints, has capacity for 1557 pallets in the sorting area without using any adjacent buffers. The staging itself has room for 1217 pallets which is sufficient since the pallets can be held at the sorting locations if needed, without crowding staging. Buffers are sized at 1217 pallets and are spread around different areas of the layout to maximise the use of docks and the ability to start the sorting circuit from multiple entry points. The buffers overlap with the staging area since the store pallets remain at the sorting locations for most of the day, freeing the staging for auxiliary purposes. This way, the staging/buffer areas are not required by the two flows (SKU pallets and store pallets) simultaneously, maximising space utilisation. All of this can be seen in Figure 27, where the new XY's layout is depicted.

The total meters a pallet covers in sorting is 277, which represents a 14% decrease when comparing with the current layout. That reduction arises from the application of the S-pick concept (Vogt 2004). S-pick is the sorting method where consecutive stores on the sorting sequence are on opposite sides of the same aisle. This is beneficial, when compared with U-pick, because not all stores are visited in the same tour, minimising cross-aisle movements.

Table 11 - Capacity description of the new layout

Characteristic	Capacity
#Pallets: Sorting	1557
#Pallets: Staging	1217
#Pallets: Buffer	1217
Total Pallets	**2774**
Meters Reception to Buffer	20
Meters Production to Buffer	20
Meters ADT to Buffer	60
Meters Sorting Circuit	277
Meters Sorting to Staging	50
Total Meters	**427**

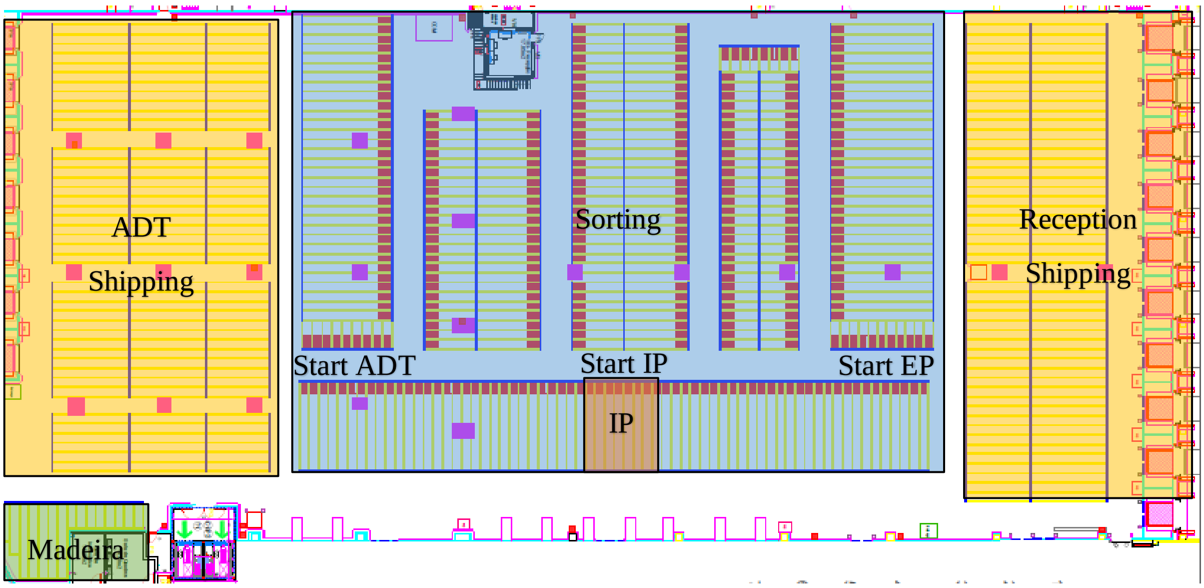

Figure 27 – New XY's cross-docking warehouse layout

4.3.2 New Layout Dynamics

This section details the new functioning of the layout, in each of the most important processes of the cross-docking warehouse.

Reception – External Production

Reception, from 5 a.m. to 5 p.m., happens from the right side (Figure 27), in accordance to the new process standards. Pallets are placed on the staging lines as work in progress (WIP) for sorting. Pickers grab the pallets and start the sorting from the closest location on the circuit, named as "Start EP" on Figure 27. Having multiple entry points for the sorting circuit reduces congestion and the walking distance from the buffers. This buffer has space to 539 pallets if need be. However, the need should diminish because of the new reception process introduced. The number of operators performing reception should remain unaltered. Productivity should improve resulting in an earlier end to reception.

Internal Production

The IP buffer is placed in front of the production lines, from where sorting will start. Once again, a different starting point to sorting should decentralise the congestion. This buffer has available space for 42 pallets which is equivalent to one-hour production (Figure 20). This flow starts at 7 a.m. and should finish before 9 p.m. to allow sorting to end by 10 p.m. The proximity from the production lines to the buffer is a big advantage, while not compromising the distance from the buffer to sorting. That distance is null as the sorting can start from the buffer itself.

ADT

ADT is the storage component of this hybrid cross-docking warehouse (Kulwiec 2004). It builds up throughout the week on the left side of the layout, Figure 27, from where it will be picked, starting from "Start ADT". Despite being further away from production lines than Order IP, it is close to sorting, meaning pickers do not waste too much time grabbing pallets from the buffer. The sorting of this flow begins at 5 a.m. and should finish before 10 p.m.

Sorting

The sorting circuit will follow a S-pick dynamic (Vogt and Pienaar 2010) explaining the 14% decrease in the length of the circuit, despite the number of available stores increasing from 252 to 321. Figure 28 displays the new proposed sorting layout where store locations have different depths, and on the upper side of the layout, S-pick is performed.

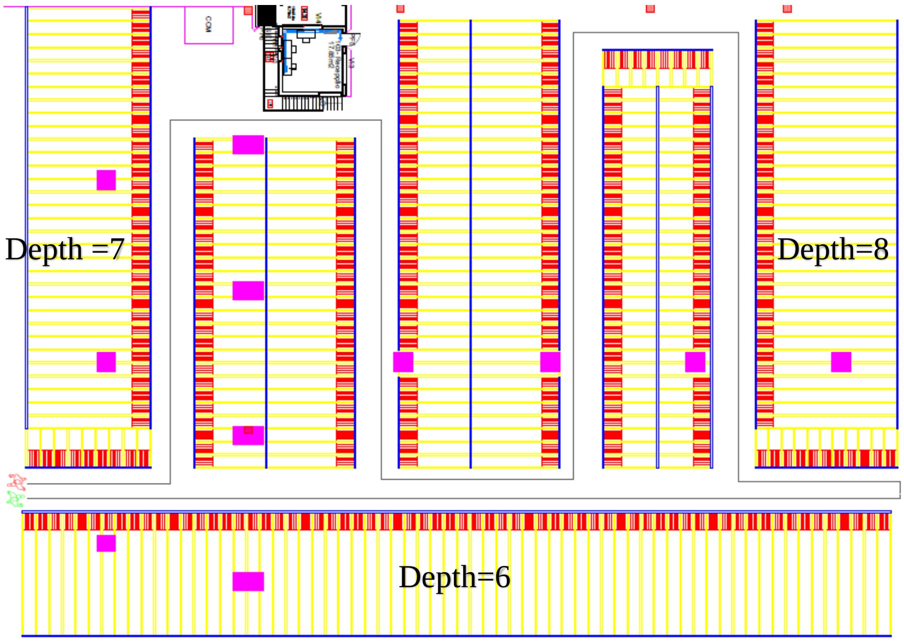

Figure 28 - New layout's sorting circuit

The sorting can begin in three different points of the circuit with the goal of maximising the dispersion of pickers. Simultaneously, since the main aisle is transversal to the remaining four aisles, if pickers finish their pallet in one of those aisles, they do not have to complete the remaining circuit with an empty pallet – the circuit has multiple exit points. They can just leave the circuit and grab a new pallet in any of the buffers, whichever is closest. These multiple exit points are also useful for pick by ranges, since pickers can go directly to where they want through shortcuts, skipping an entire section (two aisles) of the circuit.

Each store location will now store pallets from the beginning of the day until shipping. The shipping staging will be partially replaced by this feature in the layout design. Therefore, pickers will no longer have to carry pallets to staging (P&P) during their tours, minimising that waste. That cut on P&P operations can represent 14% gains in productivity, considering that, on average, a picker had to carry a pallet to staging per tour, as detailed in Section 3.3 observations.

The sorting lasts from 5 a.m. to 10 p.m. which is less 7 hours than today. The night shift will seize to exist; however, those operators will balance the needs in the remaining shifts. The reason why the sorting window reduces is to ensure that taking the pallets from store locations to staging does not compromise the safety of pickers, as that is performed with electric pallet trucks or low-level order picker machines. Despite this, the reduction of the sorting window is the only way found to reach a feasible layout.

Shipping

Shipping starts at 10 p.m. and finishes by 5 a.m. Store pallets are retrieved from store locations, after they have been wrapped, and put on the staging lines of one pre-specified load, in the inverse order to the route’s drop off sequence. Once every pallet is on the staging line assigned to a truck and the truck is parked, the loading starts. As soon as all assigned staging lines are freed, those can be filled again with the store pallets of the next truck assigned to that dock/staging lines combination. By the time the new truck parks, the staging lines are expected to have all pallets already there in the correct sequence.

The number of docks available in this layout is 17 docks. Despite this, in days of high ADT stock on the left side of the layout, Figure 27, less staging lines may be available for staging resulting in less availability for shipping docks. However, the days where ADT stock reaches its peak are Wednesday and Thursday (Table 4), which do not match the highest demand day – Friday (Figure 14). This way, on peak days (Friday), all 17 docks are available, meeting one of the hard constraints. This hard constraint is set knowing that 60 trucks must be loaded on a peak day, on a time span of 7 hours. From Table 3, the loading of a truck lasts one hour at most. This outputs nine docks needed, if shipping is levelled. Yet, from Table 5 is seen that outbound trucks distribution is unlevelled, requiring that at 2 a.m., 13 docks are available for loading. With the widening of the shipping window, however, this number should be reduced. The most levelled is the scheduling of outbound trucks, the smaller are operating times and bigger is the throughput of the cross-docking warehouse (Yu and Egbelu 2008). In the future, rearranging the truck scheduling policy should be done. For now, the widening of the shipping window minimises the congestion on this area.

To solve the tense operation of loading trucks as a result of thin aisles, staging lines now have 0,8 meters of width instead of the previous 1,2 meters. This further eliminates the need to have aisles in between staging lines, as shipping operators can grab the pallets from the end of the staging line. This change is possible since staging is only done immediatelly before shipping, making access to the lateral of staging lines unnecessary. That need existed to allow access to every staging location at all times, since store pallets were staged along the day. All of these applications minimise space utilisation, leaving more space available for other important activities.

The P&P concept is now divided into two separate actions, wrapping and transport to staging. The wrapping is done throughout the day while sorting is happening. The transport to staging only happens once sorting ends and the shipping window starts. Since this second stage now happens on the shipping window, unlike in the previous layout, the shipping team needs to be reinforced to ensure a constant flow of pallets to the staging areas, so that trucks do not get delayed.

Madeira

Madeira stores previously used staging lines to store pallets which are delivered on Tuesdays and Fridays. This caused additional constraints on a congested operation. In the new layout, as seen in Figure 27, Madeira stores have a dedicated space where pallets can be stored, with capacity for 60 pallets, which is sufficient for their demand. This solution provides comfort to a problem which was often overlooked by the operational design at the cross-dock. Madeira stores are not assigned a store location on the layout since they only receive twice a week and the products are not dispatched by store. Pallets of product are dispatched to the warehouse in Madeira, which is where store pallets get assembled.

Micro-Layout - Store Locations

One important aspect of the new layout is the assignment of stores to a certain location on the layout. Vogt (2004) states that bigger demand stores should be closer to the docks. With that in mind, the layout was designed to ensure that store locations with bigger depth, as Figure 28 depicts, were either closer to the docks (Depth=8 pallets; Depth=7 pallets) or with a clear path to the docks (Depth=6 pallets). Afterwards, the entirety of 252 stores were allocated to one or more locations on the layout according to Table 17 of Annex E, outputting Figure 37 of Annex H. These stores may stop having multiple store locations in the future if the store locations are required for new stores. In that case, the staging lines are utilised as a buffer for stores which go over capacity. Analysing the figure also allows to conclude that most stores' 95-percentile of demand matches the depth of the location they were assigned to. This means that buffers may be required in peak days. In fact, 16 stores, duly identified, have pre-assigned staging lines - right side of Figure 27- on peak days in case demand is expected to be over capacity, right from the start of the day. Those 16 stores - flow stores - are located on the right side of the sorting circuit to reduce travel distances.

Besides bigger stores being closer to the docks, stores which are shipped later were placed in the inner part of the layout, so that when staging is being filled, the layout is emptied outside-in. This is useful to allow machines to work with less obstacles.

4.3.3 Productivity Improvements Estimation

One of the goals of the project is to improve the sorting productivity sufficiently to output the necessary volumes on time. All operational improvements proposed and the new layout all aim at reaching a scenario where the cross-docking warehouse can supply all demand. With that goal, in this section, estimations of the productivity improvements are made for each of the introduced changes. Those estimations are assembled in Table 12, where it is concluded that productivity can increase by 55.5%. All the mentioned improvements in Table 12 are explained in previous sections. If those improvements are applied to a productivity that currently stands at 105 pallets/hour, the productivity may reach 163 pallets/hour. These estimations are upper bounds, mostly at early stages of implementation, as operators are expected to suffer from a learning curve with the new process, system and layout introduction.

Table 12 - Productivity improvements estimation

Improvement Introduced	Productivity Improvement (%)
EP Batch Picking	14.0%
Full Pallets – Opportunistic Cross-Docking	3.2%
New Crate Policy for IP	10.3%
New Layout	14.0%
New P&P Process	14.0%
Sum	55.5%

Further considerations can be made regarding the productivity improvements. The IP Batch process will allow that on production changeovers, the pallet build can use the same pallet even if SKUs differ. Despite existing around 50 changeovers a day, the effect of this on productivity is not easily quantifiable - 50 less tours are the upper bound on saved tours.

Furthermore, the new crate assignment policy, which reduces total pallets in the cross-dock by 7.2%, diminishes the need to open a new pallet in sorting in 7.2% of times. This process requires pushing the closed pallet to the back, getting an empty pallet and retrieving the store label from a distant location. This process improvement is also hard to quantify, yet it offers further efficiency.

The new layout design, with multiple entry and exit points, also allows further reductions on congestion, which coupled with Pick by Ranges should output even more picker dispersion on the sorting circuit. Plus, the multiple entry and exit points allow constant proximity to buffers meaning the walking distances from buffers to sorting are minimised. The maximisation of access to products is supported by Mulcahy (1994). Notwithstanding, the impacts on productivity are not quantifiable through existing data.

All these estimations provide the project with the expected results after implementation. Before moving forward to implementation. However, it is important to run a simulation that assesses the workforce needs for multiple scenarios, based on these estimations. The results of the sensitivity analysis performed in Section 4.4 validate the success of the layout design and operational improvements prior to implementation.

4.4 Sensitivity Analysis - DES

Baker and Canessa (2009) recommend the utilization of simulation to assess the feasibility of a layout. Several scenarios should be studied to test the limits of the layout in accordance to different variables' behaviour. Those scenarios may imply alternative growth forecasts, changes in order profiles or abnormal peak demand requirements. Data such as utilisation of labour, equipment and storage space, throughput rates and cycle time - makespan - is outputted (Baker and Canessa 2009).

With that in mind, a DES simulation is used to assess the feasibility of the proposed layout and operational dynamics. That choice is based on the three factors proposed by Faria (2015) on choosing the right simulation method:

- The purposes of the research project: establish a new layout and new operational dynamics at the cross-dock;
- The specific properties of the real-world problem: a wide range of variables, most of which behave in a stochastic manner, with complex interactions;
- The fitness between the method (in this case, DES) used to reach the desired outcome (first factor) and the specific problem properties (second factor).

Since the real-world case behaves as a stochastic queueing system, DES appears to be appropriate. However, some processes had to be simplified, such as the sorting process, since they would make the simulation too complex. In this way, the service rate - Equation (13) - is the only input needed to perform the operation section of the simulation. Monte Carlo is used to simulate individual events that follow a pre-determined statistical distribution. In this case, the hourly productivity is calculated using Monte Carlo simulation - see Section 4.4.1. Figure 29 displays the flowchart with the scheduling of events within the DES, including the result – calculating the ending time of the operation for given parameters.

Considering Alpan *et al.* (2011) input regarding the importance of the total number of hours worked, instead of the makespan or the travel distance, the simulation designed focuses on the number of pickers utilised and their productivity as the main drivers of success. The goal of the solution developed is that the number of pickers required to finish sorting before 10 p.m. is minimised. Of course, the number of pickers is calculated based on productivities which are already influenced by the travel distance KPI.

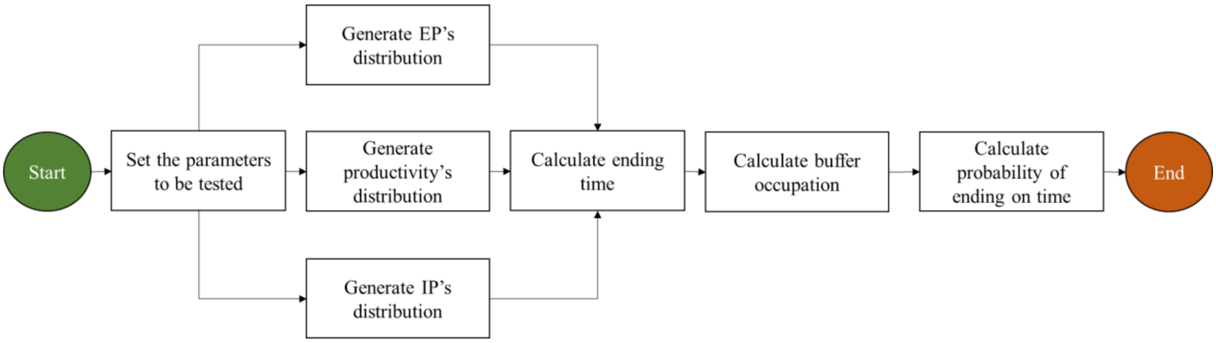

Figure 29 – Flowchart if the DES events

4.4.1 Variables

Productivity

The productivity tested in the simulation is based on the estimates performed in Section 4.3.3. Those estimates correspond to the expected aggregate productivity achieved by the operation under the new layout. So, to understand if those productivities suffice to meet demand until 10 p.m., the simulation needs to output positive results.

Starting from the estimates and historical records, the DES inserts a random component as well. Based on historical records, each hour has an average and a standard deviation (SD) of productivity. Thus, 1000 random values are generated - Monte Carlo simulation with normal distribution - for each hour, from where the new hourly average is extracted – this new hourly average is mentioned in Equation (12) as $Productivity\ Generated_i$. Then, for each new hourly average, the final productivity is calculated according to expressions (11) and (12). The index i represents the hourly period for which the productivity is being calculated. The $Productivity\ Ratio$ is constant in every iteration while $Productivity_i$ changes for every hour of every DES iteration as $Productivity\ Generated_i$ is recalculated in every iteration.

$$Productivity\ Ratio = \frac{Estimated\ Productivity}{Historical\ Aggregate\ Productivity} \qquad (11)$$

$$Productivity_i = Productivity\ Ratio * Productivity\ Generated_i \qquad (12)$$

Number of Pickers

For a given productivity, the number of pickers is the variable which determines the time at which the operation finishes. This is the variable that should aid managers dimensioning their team. This is the most relevant KPI according to Alpan *et al.* (2011).

The productivity/number of pickers combination determines the service rate of the operation in accordance to Equation (13). The resulting variable is measured in pallets per hour – that is obtained thought the multiplication of the equation by 32, which represents the average number of crates per pallet, at the current rate.

$$Service\ Rate_i = Productivity_i * Number\ of\ Pickers * 32 \tag{13}$$

External Production

EP is simulated using a random component to generate a new daily distribution in each iteration. This random component builds upon the maximum historical distribution for EP on Fridays detailed in Section 3.2.2. In this case, multiple scenarios of ending times are tested for EP, meaning the average (of the maximum values) per hour must change, from scenario to scenario. So, to ensure that the new generated distribution follows the same pattern as the historical distribution, the SD is calculated based upon the CV - 24.54% - of the historical maximum EP. The way the average and the SD of EP are calculated for each iteration are expressed in (14) and (15), respectively.

$$Average\ EP = \frac{Total\ Daily\ EP\ Demand}{Number\ of\ Hours\ of\ Reception} \tag{14}$$

$$SD = Average * Coefficient\ of\ Variation \tag{15}$$

The distribution calculated outputs the number of pallets that enter the system in period i, originated in EP. Unlike the productivity variable, the hourly average and SD are not used to determine the new distribution. Since the most extreme situation is to be tested, the maximum values are the ones used. The average and SD used to calculate the new distribution are withdrawn from the daily distribution of maximum values, instead of the hourly distribution. To insert the random component into the calculation of EP's distribution, the maximum distribution is assumed to behave normally.

Internal Production

IP is simulated under the same logic as EP. The calculated CV - 21.92% - is used to determine the SD, in accordance to equation (15), while the average is calculated according to expression (16). Then, the new distribution is calculated through the introduction of a random component.

$$Average\ Order\ IP = \frac{Total\ Daily\ IP\ Demand - ADT}{Number\ of\ Hours\ of\ IP} \tag{16}$$

The distribution calculated outputs the number of pallets that enter the system at hour i, originated in IP. The distribution used bases itself in the maximum values of each hour. The average and SD used are withdrawn from the daily distribution of maximum values, instead of the hourly average distribution. A normal distribution is assumed to insert the random component.

ADT

The ADT variable corresponds to the occupation on the buffer at the beginning of the day. The ADT is subtracted from the global IP to generate the IP which is produced on the present day (Order IP). The main impact of ADT is on the congestion of the buffers. The ratio at which it is sorted equals the ratio at which EP and Order IP are.

Buffer Occupation

This variable represents the inventory at the cross-dock at a given moment in time. The tracking of this variable is important to understand whether the system is not overcapacity for given parameters. The buffer occupation is calculated in an aggregated way, without differentiating Order IP, EP and ADT, since all buffers can receive products from every flow. Expression (17) displays the method to calculate the buffer occupation at hour i.

$$Buffer_i = Buffer_{i-1} + IP_i + EP_i + ADT_i - Service\ Rate_i \quad (17)$$

4.4.2 Parameters

Granularity

The DES performed has a time granularity of one hour. Every hour, the discrete event is simulated. The buffer occupation is transferred to the following i, ensuring the dynamism in the simulation - each discrete event influences the result of the simulation. For $i = 1$ the time is 5 a.m. while for $i = N$, the time is 12 p.m. The goal is that the operation finishes at $i = 18$ (10 p.m.).

Finishing Time

The finishing time is the variable which dictates whether the combination of productivity/number of pickers can produce all inputs on time. If the buffer occupation at 10 p.m. ($i = 18$) is zero, it means that the operation can finish on time, in accordance to manager's demands. The simulation outputs, for every iteration, the time at which it ends. Equation (18) gives the probability of sorting ending before 10 p.m.

$$Probability = \frac{Number\ of\ iterations\ finishing\ before\ 10\ p.m.}{Number\ of\ iterations} \quad (18)$$

Iterations

The DES used runs 1000 times. The final output of the DES is the time at which the operation ends and the maximum buffer occupation throughout the day. For given parameters, the probability of finishing not after 10 p.m. is calculated. That determines the applicability of the productivity/number of pickers combination in the real-world case.

Additional Parameters

The EP and IP proportions used in the simulation are the ones calculated in Table 15 of Annex C, which correspond to 2017 historical records.

The baseline for the growth rates is 5%, in accordance to X's forecasts. The scenarios will test the behaviour of the cross-dock in 2020 at a steady demand growth rate per year.

4.4.3 Results

The detailed assumptions made in each scenario tested are displayed in Annex I. This section presents the results and observations for each of the tested scenarios.

Table 13 expounds the main assumptions of scenarios 1 through 7, as well as the maximum occupation of the buffer, the expected end time and the probability of sorting ending before 10 p.m. These scenarios seek to output the ideal combination of productivity/number of pickers for given parameters. The anticipation of EP and IP window is also studied. Table 14 expounds the assumptions and results of the remaining scenarios tested (8 through 13). These scenarios are focused on understanding the impact of the remaining parameters such as the ADT, abnormal growth rates or low volume days. Each scenario expounded in Table 14 is tested for the optimistic and conservative productivity scenario. The number of pickers used are 25 and 28 pickers per shift for the optimistic and conservative scenarios, respectively.

The main assumptions used in the scenarios include:

- EP standard end time: 5 p.m;
- IP standard end time: 9 p.m;
- ADT = 400 pallets;
- EP and IP proportions remain constant;
- Demand growth rate stands at 5%.

Table 13 – Statistics for scenarios 1 to 7

Scenario	Main Assumption	Productivity	Maximum Buffer	End Time	End on time %
Scenario 1	24 pickers/shift	163 crates/hour	496	21:22:15	92.1%
Scenario 2	25 pickers/shift	163 crates/hour	425	21:05:43	99.4%
Scenario 3	25 pickers/shift	140 crates/hour	614	23:03:01	7.8%
Scenario 4	28 pickers/shift	140 crates/hour	450	21:22:22	92.0%
Scenario 5	EP and IP Anticipation	140 crates/hour	718	21:03:08	89.8%
Scenario 6	EP Anticipation	140 crates/hour	670	21:22:13	90.6%
Scenario 7	IP Anticipation	140 crates/hour	534	21:07:00	89.5%

Scenario 1 and 2 – Optimistic Productivity

In the most optimistic approach, these scenarios find the ideal number of pickers at the cross-docking warehouse. With 25 pickers/shift, the probability of sorting ending on time without delaying shipping is 99.4%. Simultaneously, the simulation outputs a maximum buffer occupation of 425 pallets (34.9% buffer occupation ratio – see Equation (19)). The average end time of sorting is at 21:05:43, meaning there is a time buffer to prepare shipping staging.

$$Buffer\ Occupation\ Ratio = \frac{Buffer\ Occupation}{Buffer\ Capacity} \tag{19}$$

Scenario 3 and 4 – Conservative Productivity

Under the same assumptions as scenarios 1 and 2, these scenarios estimate the impact of reducing the productivity to 140 crates/hour. To achieve satisfactory probabilities of ending sorting on time, 28 pickers/shift are required. Under that scenario, buffer occupation ratio reaches 36.9%. Together with a 92% probability of ending on time, 28 pickers/shift should be available under this productivity.

The assumptions used in scenarios 1, 2, 3 and 4 can be replicated to calculate the number of pickers for any other productivity scenario. In case productivity behaves worse than predicted, this simulation is the tool to be used on dimensioning the sorting team.

Scenario 5, 6 and 7 – Anticipation of Product Flows

These scenarios study the impact of anticipating the arrival of products from suppliers or increasing the production rate to have all products earlier at the cross-dock. Scenario 5 studies the impact of making both changes simultaneously. With the same combination of productivity/number of pickers as in the scenarios 3 and 4, the probability of ending on time remains unaltered. The biggest impact lies on the buffer occupation – 718 pallets (59% buffer occupation ratio). Scenarios 6 and 7 anticipate only one of the product flows. Their impact on the probability of ending on time is residual in comparison. The biggest impact observed relates with EP increasing the buffer occupation, while IP does not display a big impact on it. This is due to EP having higher volumes than IP, spread through a much smaller time window. By reducing the time window, the impact on buffers resulting from EP is bigger because the hourly arrival rate is also bigger.

Remaining Scenarios

Table 14 details the simulation results for Scenarios 8 to 13. Each scenario was run for two different productivities: the estimated productivity (163 crates/hour) and the conservative productivity (140 crates/hour).

Table 14 – Statistics for scenarios 8 to 13

		Productivity = 140			Productivity = 163		
Scenario	**Main Assumption**	**Maximum Buffer**	**End Time**	**End on time %**	**Maximum Buffer**	**End Time**	**End on time %**
Scenario 8	ADT=600	613	21:21:05	92.0%	625	21:04:58	99.9%
Scenario 9	ADT=200	432	21:24:53	88.6%	374	21:07:37	98.5%
Scenario 10	IP=60%; EP=40%	400	21:21:02	94.1%	400	21:05:52	99.7%
Scenario 11	Growth=10%	756	23:27:25	1.9%	698	22:47:29	14.8%
Scenario 12	Growth=2%	404	21:00:34	100.0%	411	21:00:00	100.0%
Scenario 13	Low Demand Day	434	21:29:37	86.5%	435	21:21:37	90.5%

Scenario 8 and 9 – ADT Sensitivity

These scenarios test the system's sensitivities to ADT, where high and low stocks are considered. However, as Table 14 displays, the impact on the probability of finishing on time is residual. Once there is no sequence to produce either flow, the expected end time is the same as the total demand remains unaltered. The biggest impact lies on buffer occupation, meaning ADT is only problematic in the perspective of having high buffer occupation.

Scenario 10 – Product Flows Proportions

Scenario 10 evaluates whether a shift on EP and IP proportion impacts the probability. This scenario is like scenarios 2 and 4. The comparative analysis allows to conclude that no relevant differences are found in the probability of ending on time or on buffer occupation. This happens because IP and EP flows are produced at the same service rate. Despite originating from different sources, their behaviour within the operation is undifferentiated. Thus, the proportion of product flows does not present any relevant impact on the sorting activity.

Scenario 11 and 12 – Alternative Growth Rates

If 10% demand growths were to happen, the operation would not supply demand on time most of the times in either of the productivity/number of pickers combinations. If instead, the demand only grows by 2%, both scenarios ensure a 100% on time operation. The conclusion is that, despite all the improvements introduced, the cross-docking warehouse is not prepared to support demand growths over the forecast. That assumption was one of the basis of designing the entire solution.

Scenario 13 – Low Demand Day

Scenario 13 provides insight into the system's behaviour on an average Friday, considering the expected growth. The results indicate that a three-picker reduction per shift, on either productivity scenario, is sufficient to output good probabilities of ending on time.

Observations

Multiple scenarios are tested to conclude about the feasibility of the proposed layout. In first place, if the estimated scenario of productivity improvements prevails, for the forecasted demand, the system requires 25 pickers/shift. This conclusion already accounts for meal time pauses. If, instead, the productivity does not reach the expected improvements, a scenario where the productivity reaches 140 crates/hour (33% increase) is tested and requires 28 pickers/shift. Thus, managers should make sure they have 28 pickers available for each shift. Additionally, as the literature suggests (Baker and Canessa 2009), other scenarios are tested – alternative growth forecasts, abnormal peak demands and changes in order profiles.

Simulation records on the utilisation of labour, equipment and storage space, throughput rates and cycle time should be kept (Baker and Canessa 2009). The simulation developed does provide an estimation of the necessary workers for sorting and the necessary storage space. The throughput rates correspond to the productivity on sorting. Cycle times are replaced by the expected end time of sorting. The cycle time of each pallet is not of extreme importance since sorting does not strictly follow a FIFO methodology. The equipment requirements are not on the scope of this simulation since sorting does not require valuable hardware. Thus, the simulation follows the principles suggested by the literature.

The simulation validates the layout and improvements introduced if 28 pickers are available for each shift. This conclusion assumes a conservative scenario when compared to estimates. ADT does not appear to influence the end time nor does the proportion of flows. Anticipating EP and IP flows creates unnecessary constraints on buffer availability. The forecasted growth rate is supplied by the conservative scenario. Extreme demand growth requires large additions to the sorting team. Otherwise, the simulation provides validation into the solution encountered.

5 Conclusion and Future Work

At XY's meat production facility, unresponsive logistics was handicapping the supply of products downstream the supply chain. Together with forecasted demand growths, the need to establish a solution which would solve the inefficiencies at XY's cross-docking warehouse arose.

The present thesis emerged to solve the existing problem at XY's cross-dock. The main goal was to simultaneously allow the cross-dock to supply the rising number of stores, while having an operation which would output all the necessary volumes on time – unlike what had been done in the past year. Simultaneously, the anticipation of the shipping window would provide company X with substantial financial gains on transportation. A layout design, which emcompassed process and system changes, in accordance to concepts introduced in the literature (Vogt 2004; Baker and Canessa 2009; Vogt and Pienaar 2010), was thouroughly developed to improve the operations at the cross-dock, while meeting the aforementioned objectives.

The proposed solution - layout design - was sectioned into the conceptualisation of the current state and the design of the new solution. The first section is focused on designing the paths products follow within the warehouse through observation and data analysis. Then, the solution is designed in accordance to what is observed in the first section. To support the developed layout, new processes are introduced which minimise the effects of inefficiencies. Finally, to aid in decision making, a sensitivity analysis is performed using DES, which is useful to validate the applicability of the proposed layout.

Currently, not all proposed improvements have been applied which limit the result presentation. Nonetheless, most of them are going through testing. The only change which is yet to be fully implemented or tested is the new layout. That is because the layout should wait for all auxiliary processes and system improvements to be tested and introduced. Notwithstanding, every proposed solution has been approved for implementation. DES is the tool used to assess the layout design results in the absence of a full layout implementation.

5.1 Main Conclusions

The development of the proposed methodology resulted in estimated sorting productivity improvements of 55.5%. That represents a leap from 105 crates/hour to 163 crates/hour. These improvements are the result of process improvements, reduction of the sorting circuit, WMS changes, waste elimination and the setting of a new crate assignment policy to IP. The main goal of changes lie on sorting productivity, as sorting is observed to be the main issue present and is often mentioned as the main bottleneck at warehouses (Vogt 2004).

The methodology followed, despite being adapted from the literature, structures the sequence of methods differently, placing a bigger emphasis on process improvements than Vogt (2004) and Baker and Canessa (2009) do. That is so to ensure that bottleneck impact is minimised (Goldratt 2005; Vogt and Pienaar 2010).

The first process improvement introduced is on the reception. With the purpose of reducing bottleneck impact (Goldratt 2005), a new standard to receive products from suppliers is introduced where the standard time per pallet reduces 80%. This should ensure that reception does not end at 11 p.m. like it does today. Instead, products are available for sorting much earlier.

Secondly, the concept of batch picking (Petersen and Aase 2004) is applied to minimise the number of tours around the sorting circuit. This concept applied to EP is estimated to improve sorting productivity by 14%.

The option to perform opportunistic cross-docking, where an item (pallet) is transferred directly from the receiving dock to the shipping dock to meet a known demand (Napolitano 2000), is created. This will happen when a customer (store) demands at least one pallet of product from the suppliers. By skipping sorting in its entirety, productivity improves by 3.2%.

To reduce congestion and ensure efficient flows (Mulcahy 1994; Luo 2008), a solution called Pick by Ranges is introduced. It ensures that two pickers with the same SKU do not serve the same store simultaneously. The upside in relation to productivity is hard to quantify; however, the reduction of congestion ought to manufacture productivity gains.

A new crate assignment policy allows to reduce the number of pallets dispatched at the cross-dock by, at least, 7.2%. This is useful to achieve better space utilisation, both in the cross-dock and on transportation. This implementation may also benefit productivity since the pallet build should now output less pallets. The estimated productivity improvement stemming from this changes are 10.3%. At the same time, the depths of store locations are more likely to suffice after the introduction of this change. The application of this change is only possible with the introduction of a new criteria to close store pallets. Instead of pallets being closed by the number of crates it contains, it is now closed by the height of the stowage it contains.

After performing an in-depth data analysis on demand, product flows, floor occupancy and productivity, the different parameters and hard constraints for the layout design were set (Baker and Canessa 2009; Vogt 2004). This stage is useful to guide the iterative process of designing new layouts, which is an extensive trial and error activity using AutoCAD software.

The new layout designed allows to go from 246 to 321 store locations available (30.5% increase) while simultaneously reducing the size of the sorting circuit by 14%. This is possible for 2 different reasons: the application of S-pick and a Low volume layout. S-pick allows to serve the same stores as U-pick with virtually half the distance covered (Vogt 2004). The main downside with S-pick lies on congestion fostering, which previous processes already aim to minimise. Then, the application of a Low volume layout, where store locations have sufficient depth to hold the pallets produced on the day, allows to have two store locations with a common backside. A High volume layout, like the previous layout, demands access to the front and to the back of the store location. Thus, the Low volume layout reduces the number of aisles required, allowing better space utilisation. Moreover, many other wastes which were idenfied in the previous layout are duly cut from the new one.

Mulcahy (1994) mentions access to products as one of the main characteristics of a good layout. With that in mind, the layout has three different entry points. In each of those entry points, there is a buffer with one of the three existing product flows – this reduces distances covered to retrieve product pallets. Simultaneously, congestion is reduced as pickers are divided by three different starting points of the layout.

Mulcahy (1994) also recommends that a layout should minimise space utilisation. With that purpose, staging and buffers utilise the same space, just at different timings. This is possible since EP and IP enter and leave the buffers before any staging occurs. The previous layout – High volume layout – did not allow this since staging was an ongoing activity all throughout the day, precluding the hypothesis of staging lines being utilised as buffers. This capability to utilise the same space twice further facilitates the attainment of good flows in the cross-dock. The elimination of aisles between staging lines also minimises also minimises space utilisation.

Vogt and Pienaar (2010) mention travel distance as the main KPI to evaluate the quality of a layout. As outlined, multiple entry and exit points, both of which are in the neighbourhood of buffers, minimise the distance covered to retrieve pallets to the sorting circuit. Furthermore, the micro-layout, which assigns stores to a location, is crucial. The layout is constructed ensuring that big depth locations, which are eventually assigned to stores with bigger demand, are close to the staging and buffer locations. This minimises the objective function expressed in Equation

(1). Pickers will therefore empty product pallets after short walking distances. Additionally, shipping operators who carry store pallets to staging will walk smaller distances since most pallets are close by staging.

The new layout has led to the attainment of further productivity improvements. Directly from the reduction of the sorting circuit, the productivity is expected to improve 14% - the overall walking distance can reduce up to 14%. The distances to buffers which also reduce are not accounted here since it is hard to measure how much the productivity could increase because of that. Nonetheless, the expectation is that it may have a positive impact. Plus, the new layout leads to a new P&P method - this new method minimises the time a picker wastes performing activities out of their scope of action. This can impact productivity by 14% as well. Furthermore, a different placement of empty pallets, store labels and problem-solving workstations reduce additional wastes in non-value adding activities.

The development of a DES was crucial to determine the feasibility of the new layout, through the establishment of multiple scenarios. The output variable is the time at which the sorting activity ends, which is bounded by the hard constraint of ending before 10 p.m. The output variable is dependent on a number of relevant input variables: product flows' in-day distribution, daily demand, ADT stocked, sorting productivity, start and end times of reception and IP, and the number of pickers KPI (Alpan *et al.* 2011). The combination of productivity/number of pickers correspond to the service rate of the DES's operation. The remaining inputs regard the arrival rate of entities into the system. Ultimately, for a constant productivity, the number of pickers determines the feasibility of the layout. Therefore, the simulation allows to conclude that 28 pickers/shift should be available at the cross-dock.

The DES allows to assess the system's sensitivity to other inputs. The ADT stock does not influence sorting end time. It does, however, compromise the buffer occupation - the more ADT stock is produced, the more occupied will buffers be at the beginning of the following day.

The scheduling of inbound trucks also leads to changes on buffer occupation. The earliest inbound trucks arrive at the cross-dock, the more congested will be the reception buffer. With that in mind, the recommendation is that inbound trucks schedule should not anticipate trucks. If anything, inbound trucks should be delayed.

The scenarios tested the peak day of last year and applied the forecasted demand growth. Thus, the simulation is testing for the worst-case scenario, even without considering the possibility of 7,2% pallet reduction from the new crate assignment policy. However, the sensitivity towards alternative demand growths showed that a 10% increase on demand yielded a 14,8% probability of ending on time, assuming the most optimistic productivity scenario. That leads to the conclusion that if demand growths surpass expectations, different solutions should be undertaken. If, on the other hand, demand grows only 2%, three pickers can be reduced per shift in either productivity scenario tested.

In case product flows' proportions change, there is virtually zero impact on sorting – sorting produces both flows at the same service rate.

All proposed objectives have been achieved – managers corroborate this assessment having authorised the implementation of every proposed solution. Nonetheless, some stages of the proposed solutions are yet to be implemented. The ones that have been implemented so far are reception, the new crate assignment policy, closing pallets by height, pick by ranges and batch picking. Reception has suffered some setbacks due to technological issues. On the plus side, the crate assignment policy has been applied and has consistently reduced pallets in the cross-dock by 15%, which largely surpass the 7.2% estimation. The impact of reducing pallets dispatched by the cross-docking at a 15% rate, should have relevant impacts on transportation costs. The impacts on sorting productivity are very promising as well, as after few days of implementation, productivity has already reached 125 crates/hour. It is expected that as the remaining processes are introduced and as pickers get acquainted with the new processes, productivities increase even further.

The achievement of the proposed objectives testifies into the applicability of the proposed solution to design a cross-docking warehouse layout whist improving operations. The methodology proposed by Vogt (2004) and the framework assembled by Baker and Canessa (2009) provided the thesis with the necessary framings to solve the real-world case of XY's cross-docking warehouse.

5.2 Future Work

The previously described actions are sufficient to achieve the objectives set. Despite that, further improvements may be introduced in the future to mitigate the effects of demand seasonality, to reduce congestion at the cross-dock or to improve the assignment policy of a store to a location. Plus, introducing productivity rewards should be studied to understand the impact on operators' productivity.

To reduce the congestion of the cross-dock, the DES showed that the more anticipated was the arrival of flows into the cross-dock, the higher was the congestion. In IP's case, delaying end of production is not feasible since it would compromise sorting's finishing time. However, if reception's implementation is a successful one, delaying the entrance of EP into the cross-dock may facilitate the operation at the buffers. A more dedicated simulation to the arrival of products from suppliers could be applied to understand the impact of this action at the cross-dock.

The layout is designed assuming the peak demands of Fridays. Even the sensitivity analysis performed investigates those days' behaviour. Thus, current Friday's demand is considered to design the entire solution. The solution designed tries to solve the problem on an operational level, without trying to solve the problem through changes in demand patterns. That approach, however, should be undertaken in the future to reduce Fridays 1.5 seasonal index. Currently, Fridays produce for Saturdays' and Sundays' store sales – Saturday's demand corresponds to 70% while Sunday's corresponds to 30% of Friday's demand. Saturdays produce for Mondays' store sales. If, for instance, Fridays now produce only for Saturday and Saturday produces for Sundays and Mondays, the daily output would become more levelled (Liker 2004), further reducing the impact of peaks at the cross-dock. Further studies on this levelling strategy should be performed as the operational and cost impacts can be significant. Notwithstanding, impacts on sales should be studied to safeguard the company's profitability.

Vis and Roodbergen (2011) propose the introduction of a dynamic layout methodology. A store location is assigned to a store, every day, at the beginning of the day. In a Low volume layout, where store locations have different depths, the occupation could be maximised in accordance to a store's expected demand. This is non-trivial to achieve as the info is often not available and it would require a complex algorithm to calculate the ideal assignment. Furthermore, operations managers are not very fond of this approach since pickers would not know where each store is located, compromising their knowledge of the layout. Albeit the cons, a study on this subject should be undertaken in the future.

Additionally, the lack of productivity reward to pickers according to their performance may be a driver of low productivity. With that in mind, future works at the cross-dock should regard the study of potential gains and losses because of such introduction. The remaining X's cross-docking warehouses should serve as benchmark.

References

Aiello, G., M. Enea and G. Galante. 2002. "An integrated approach to the facilities and material handling system design". *International Journal of Production Research* no. 40 (15):4007-4017. https://doi.org/10.1080/00207540210159572.

Alpan, Gülgün, Anne-Laure Ladier, Rim Larbi and Bernard Penz. 2011. "Heuristic solutions for transshipment problems in a multiple door cross docking warehouse". *Computers & Industrial Engineering* no. 61 (2):402-408. http://www.sciencedirect.com/science/article/pii/S0360835210002573.

Arabani, A. B., M. Zandieh and S. Ghomi. 2012. "A cross-docking scheduling problem with subpopulation multi-objective algorithms". *International of Advanced Manufacturing Technology* no. 58:741-761.

Baker, Peter and Marco Canessa. 2009. "Warehouse design: A structured approach". *European Journal of Operational Research* no. 193 (2):425-436. http://www.sciencedirect.com/science/article/pii/S0377221707011356.

Belli, F., C.J. Budnik and L. White. 2006. "Event-based modelling, analysis and testing of user interactions: approach and case study: Research Articles". *Software Testing, Verification & Reliability* no. 16 (1):3-32.

Berg, J. P. van den and W. H. M. Zijm. 1999. "Models for warehouse management: Classification and examples". *International Journal of Production Economics* no. 59 (1):519-528. http://www.sciencedirect.com/science/article/pii/S0925527398001145.

Boysen, Nils. 2010. "Truck scheduling at zero-inventory cross docking terminals". *Computers & Operations Research* no. 37 (1):32-41. http://www.sciencedirect.com/science/article/pii/S0305054809000811.

Boysen, Nils, Malte Fliedner and Armin Scholl. 2007. *Scheduling Inbound and Outbound Trucks at Cross Docking Terminals*. Vol. 32.

Brito, A.E.S.C. 1992. "Configuring simulation models using CAD techniques: A new approach to warehouse design". PhD, Cranfield Institute of Technology.

Buijs, Paul, Iris F. A. Vis and Héctor J. Carlo. 2014. "Synchronization in cross-docking networks: A research classification and framework". *European Journal of Operational Research* no. 239 (3):593-608. http://www.sciencedirect.com/science/article/pii/S0377221714002264.

Cook, R. L., B. Gibson and D. MacCurdy. 2005. *A lean approach to cross docking*. Vol. 9.

de Koster, René, Tho Le-Duc and Kees Jan Roodbergen. 2007. "Design and control of warehouse order picking: A literature review". *European Journal of Operational Research* no. 182 (2):481-501. http://www.sciencedirect.com/science/article/pii/S0377221706006473.

Ertek, Gurdal. 2005. "A Tutorial On Crossdocking". Paper presented at 3rd International Logistics & Supply Chain Congress, in Istambul, Turkey.

Faria, F.T. 2015. "Restructuring of Logistics Processes: Case Study of Order Picking at Terminal C2 of Grupo Luís Simões", Civil Engineering, Instituto Superior Técnico.

Frazelle, E.H. 2002. *World-Class Warehousing and Material Handling*. McGraw-Hill Education.

Goldratt, Eliyahu M. 2005. "The Goal: A Process of Ongoing Improvement". *Measuring Business Excellence* no. 9 (1):76-76. Accessed 2018/04/14. https://doi.org/10.1108/13683040510588882.

Grigoryev, I. 2016. *Anylogic 7 in 3 days*. 3 ed.: CreateSpace Independent Publishing Platform.

Gümüş, Mehmet and James Bookbinder. 2004. "Cross-Docking and Its Implication in Location-Distribution Systems". *Journal of Business Logistics* no. 25 (2):199-228.

Hammer, Michael. 2004. "Deep change. How operational innovation can transform your company". *Harvard business review* no. 82 (4):84-93, 141. http://europepmc.org/abstract/MED/15077369.

Horta, Miguel, Fábio Coelho and Susana Relvas. 2016. "Layout design modelling for a real world just-in-time warehouse". *Computers & Industrial Engineering* no. 101:1-9. http://www.sciencedirect.com/science/article/pii/S0360835216303175.

J. Bartholdi III, John and Kevin Gue. 2004. "The Best Shape for a Crossdock". *Transportation Science* no. 38 (2):235-244.

Kinnear, Ewen. 1997. *Is there any magic in cross-docking?* Vol. 2.

Knill, B. 1997. "Information pulls food distribution". *Material Handling Engineering* no. 4 (8).

Kulwiec, Ray. 2004. "Cross-Docking as a Supply Chain Strategy". *Target* no. 20 (3).

Ladier, Anne-Laure and Gülgün Alpan. 2016. "Cross-docking operations: Current research versus industry practice". *Omega* no. 62:145-162. http://www.sciencedirect.com/science/article/pii/S0305048315001991.

Liao, T. W., P. J. Egbelu and P. C. Chang. 2012. "Two hybrid differential evolution algorithms for optimal inbound and outbound truck sequencing in cross docking operations". *Applied Soft Computing* no. 12 (11):3683-3697. http://www.sciencedirect.com/science/article/pii/S1568494612002736.

Liker, Jeffrey K. 2004. *The Toyota way : 14 management principles from the world's greatest manufacturer*. New York : McGraw-Hil.

Lim, Andrew, Hong Ma and Zhaowei Miao. 2006. *Truck Dock Assignment Problem with Time Windows and Capacity Constraint in Transshipment Network Through Crossdocks*. Vol. 3982.

Luo, Gauhao. 2008. "An Integrated Model of Cross-Docking", University of Missouri-Columbia.

M. Apte, Uday and S. Viswanathan. 2010. "Effective Cross Docking for Improving Distribution Efficiencies". *International Journal of Logistics Research and Applications* no. 3 (3):291-302.

Meller, Russell D. and Kai-Yin Gau. 1996. "The facility layout problem: Recent and emerging trends and perspectives". *Journal of Manufacturing Systems* no. 15 (5):351-366. http://www.sciencedirect.com/science/article/pii/0278612596841987.

Mooney, Cristopher Z. 1997. *Monte Carlo Simulation*. Sage University Paper series on Quantitative Applications in the Social Sciences,. Newbury Park, CA: Sage.

Mulcahy, D.E. 1994. *Warehouse Distribution and Operations Handbook*. McGraw-Hill Education.

N.Sheikholeslam, M. and S. Emamian. 2016. "A Review and Classification of Cross-Docking Concept". *International Journal of Learning Management Systems* no. 4 (1):25-33.

Napolitano, Maida. 2000. *Making the move to cross-docking: a practical guide to planning, designing, and implementing a cross-dock operation*. Warehousing Education and Research Council (WERC).

Oxley, J. 1994. "Avoiding Inferior Design". *Storage Handling and Distribution* no. 38 (2):28-30.

Panousopoulou, Peggy, Eleni-Maria Papadopoulou and Vicky Manthou. 2012. "Cross – Docking A Successful Method in Warehouses: A Case Study of a 3PL Provider". Paper presented at 2nd International Conference on Supply Chains, in Katerini.

Parvez, Md, S. Sultana, A. A. Mamun, Pobitra Halder, A. S. M. Hoque and S. K. Dey. 2013. "A new approach of cross docking in supply chain of Bangladesh". *International Journal of scientific research and management* no. 1 (4):268-273.

Petersen, Charles G. and Gerald Aase. 2004. "A comparison of picking, storage, and routing policies in manual order picking". *International Journal of Production Economics* no. 92 (1):11-19. http://www.sciencedirect.com/science/article/pii/S0925527303002937.

Reeves, K. A. 2007. "Supply Chain Governance: A Case of Cross Dock Management in the Automotive Industry". *IEEE Transactions on Engineering Management* no. 54 (3):455-467.

Richards, G. 2011. *Warehouse Management: A Complete Guide to Improving Efficiency and Minimizing Costs in the Modern Warehouse*. Kogan Page.

Richardson, Helen L. 1999. "Cross Docking: Information Flow Saves Space". *Transportation & Distribution* no. 40 (11):51.

Rushton, A., J. Oxley, P. Croucher, Institute of Logistics and Transport. 2006. *The Handbook of Logistics and Distribution Management*. Third ed. London: Kogan Page.

Scholz, André, Daniel Schubert and Gerhard Wäscher. 2017. "Order picking with multiple pickers and due dates – Simultaneous solution of Order Batching, Batch Assignment and Sequencing, and Picker Routing Problems". *European Journal of Operational Research* no. 263 (2):461-478. http://www.sciencedirect.com/science/article/pii/S0377221717303855.

Silva Pereira, M. 2016. "Restructuring of Logistics Processes: Case Study of Cross-Docking Operations at Warehouse AZ1 of Grupo Luís Simões", Industrial Engineering and Management, Instituto Superior Técnico.

Simchi-Levi, D., P. Kaminsky and E. Simchi-Levi. 2003. *Designing and Managing the Supply Chain: Concepts, Strategies, and Case Studies*. McGraw-Hill/Irwin.

Su, Shong-Iee Ivan and Chien-Jung Liao. 2014. "The Planning for the Cross-docking Operations of a Large Supermarket Retail Supply Chain". Paper presented at Production and Operations Management Society 25th Annual Conference, in Atlanta, Georgia.

Van Belle, Jan, Paul Valckenaers and Dirk Cattrysse. 2012. "Cross-docking: State of the art". *Omega* no. 40 (6):827-846. http://www.sciencedirect.com/science/article/pii/S0305048312000060.

Vis, Iris F. A. and Kees Jan Roodbergen. 2008. "Positioning of goods in a cross-docking environment". *Computers & Industrial Engineering* no. 54 (3):677-689. http://www.sciencedirect.com/science/article/pii/S0360835207002185.

———. 2011. "Layout and control policies for cross docking operations". *Computers & Industrial Engineering* no. 61 (4):911-919. http://www.sciencedirect.com/science/article/pii/S0360835211001495.

Vogt, John. 2004. The design principles and success factors for the operation of cross-dock facilities in grocery and retail supply chains. PhD Dissertation. South Africa: Stellenbosch University.

Vogt, John and Wessel Pienaar. 2010. *Implementation of cross-docks*. Vol. 8.

Waller, Matthew A., C. Richard Cassady and John Ozment. 2006. "Impact of cross-docking on inventory in a decentralized retail supply chain". *Transportation Research Part E: Logistics and Transportation Review* no. 42 (5):359-382. http://www.sciencedirect.com/science/article/pii/S136655450500013X.

Witt, C. E. 1998. "Crossdocking: Concepts demand choice". *Material Handling Engineering* no. 53 (7):44-49.

Yu, Wooyeon and Pius J. Egbelu. 2008. "Scheduling of inbound and outbound trucks in cross docking systems with temporary storage". *European Journal of Operational Research* no. 184 (1):377-396. http://www.sciencedirect.com/science/article/pii/S0377221706011052.

Zhengping, Li, He Wei, Sim Cheng Hwee and Chen Chong Chuan. 2008. "A solution for cross-docking operations planning, scheduling and coordination". Paper presented at 2008 IEEE International Conference on Service Operations and Logistics, and Informatics. 12-15 Oct. 2008.

Annex A: Sorting Circuit Representation

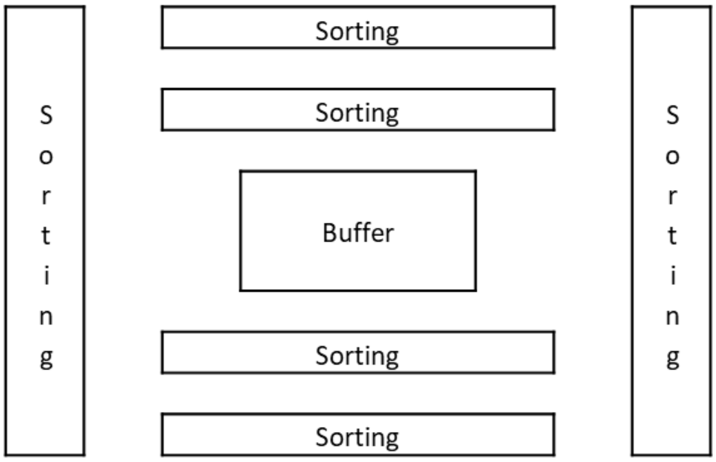

Figure 30 – Layout of the sorting circuit

Annex B: Demand by Day in 2017

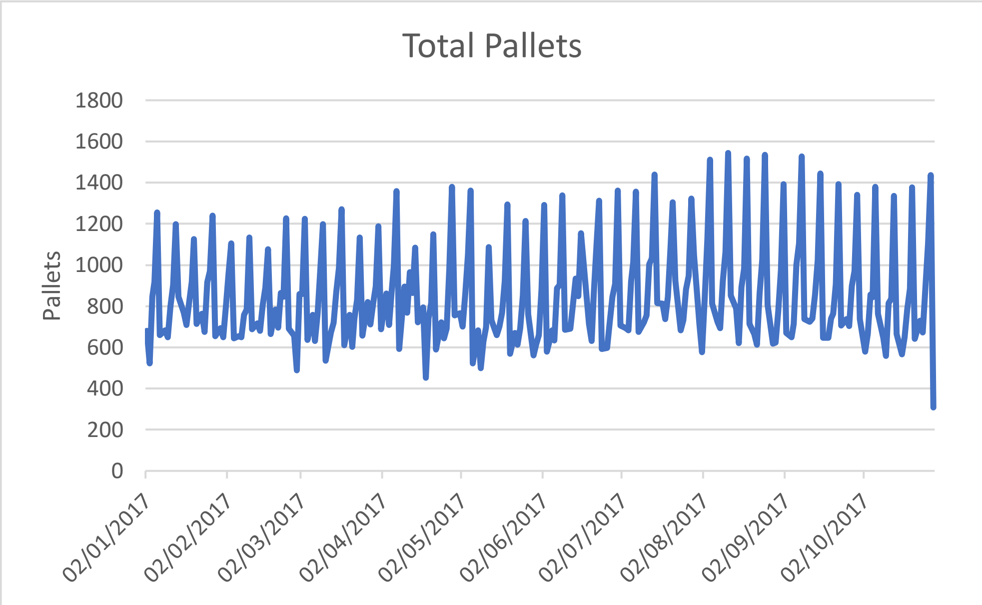

Figure 31 - Day-by-day demand of total pallets

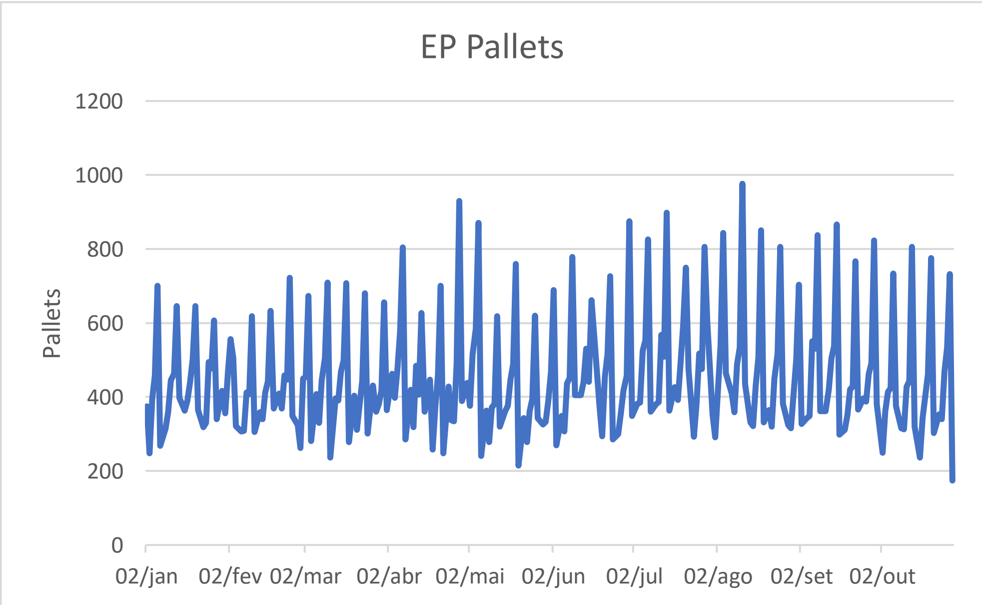

Figure 32 - Day-by day demand of EP’s pallets

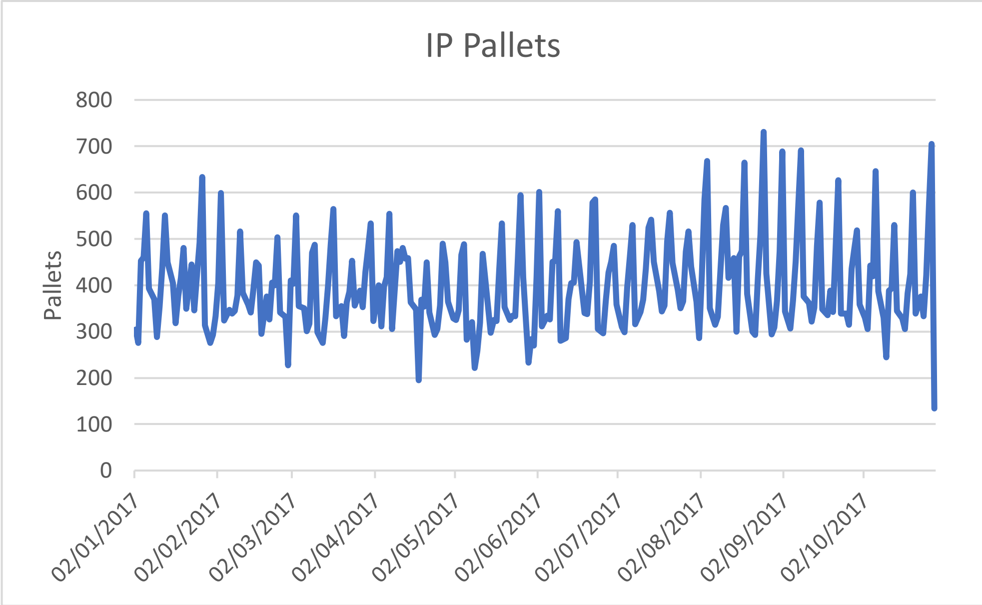

Figure 33 - Day-by-day demand of IP’s pallets

Annex C: IP and EP Proportion

Table 15 - IP and EP proportion of total demand throughout the analysed months

Month	IP%	EP%
January	48%	52%
February	48%	52%
March	47%	53%
April	46%	54%
May	46%	54%
June	47%	53%
July	45%	55%
August	48%	52%
September	47%	53%
October	48%	52%
Aggregated	47%	53%

Annex D: EP Hourly Distribution

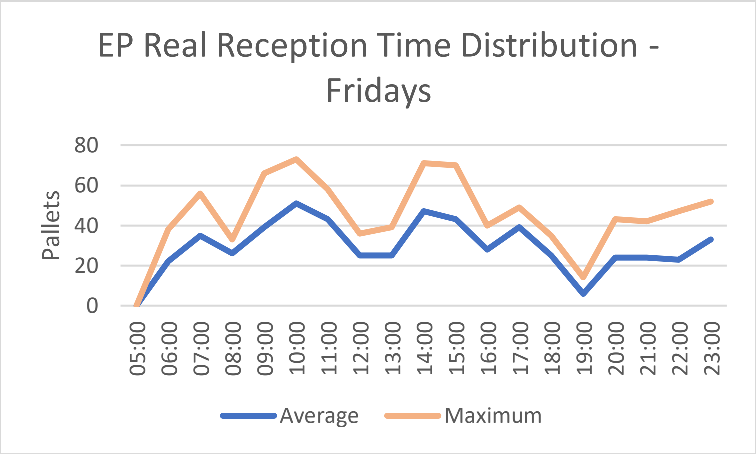

Figure 34 - EP real reception time distribution

Table 16 - Time of the last pallet received on the weekday in the first 3 months of the year

Weekday	Time of Last Reception
Monday	22:00
Tuesday	22:00
Wednesday	22:00
Thursday	22:00
Friday	23:00
Saturday	22:00

Annex E: Demand per Store

Table 17 - Number of stores with a certain number of pallets as demand

Pallets	Number of Stores	Pallets	Number of Stores	Pallets	Number of Stores
34	1	**18**	1	**9**	4
33	2	**17**	1	**8**	11
31	1	**16**	4	**7**	21
29	2	**15**	3	**6**	27
28	3	**14**	3	**5**	45
22	1	**13**	3	**4**	37
21	1	**12**	2	**3**	38
20	1	**11**	5	**2**	27
19	1	**10**	3	**1**	4

Annex F: Friday's Productivity

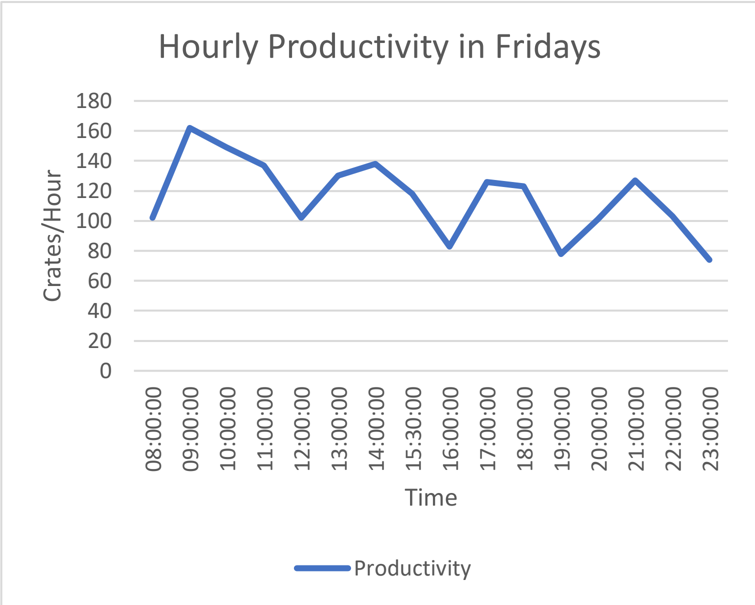

Figure 35 - Hourly Productivity on Fridays

Annex G: Current Layout's Heat Map

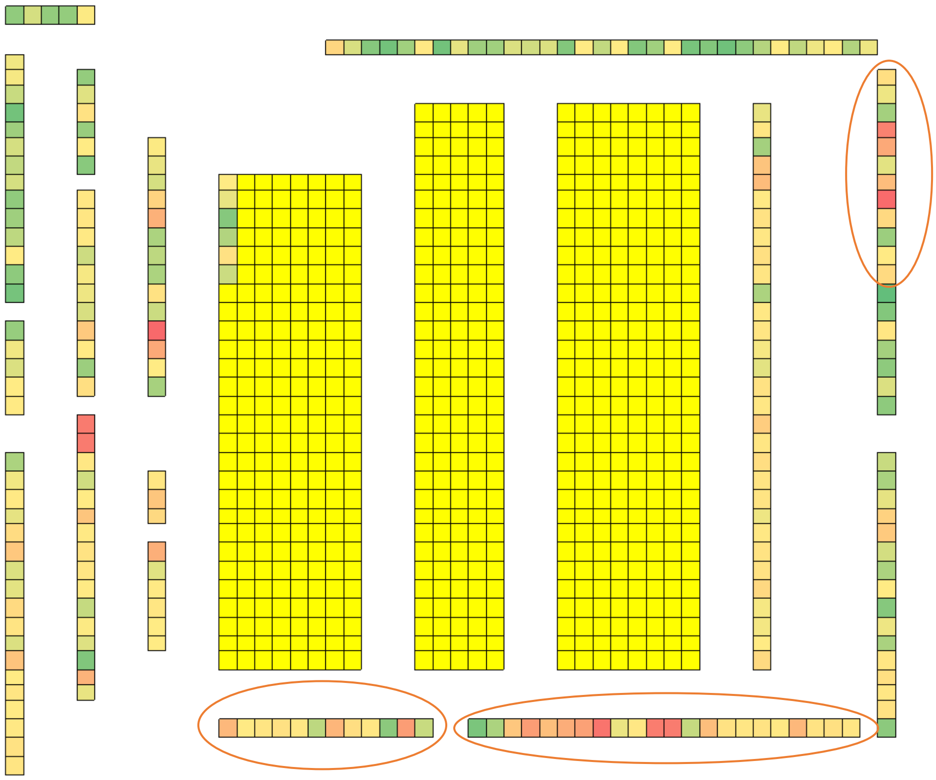

Figure 36 - XY's current layout demand heat map

Annex H: Micro Layout

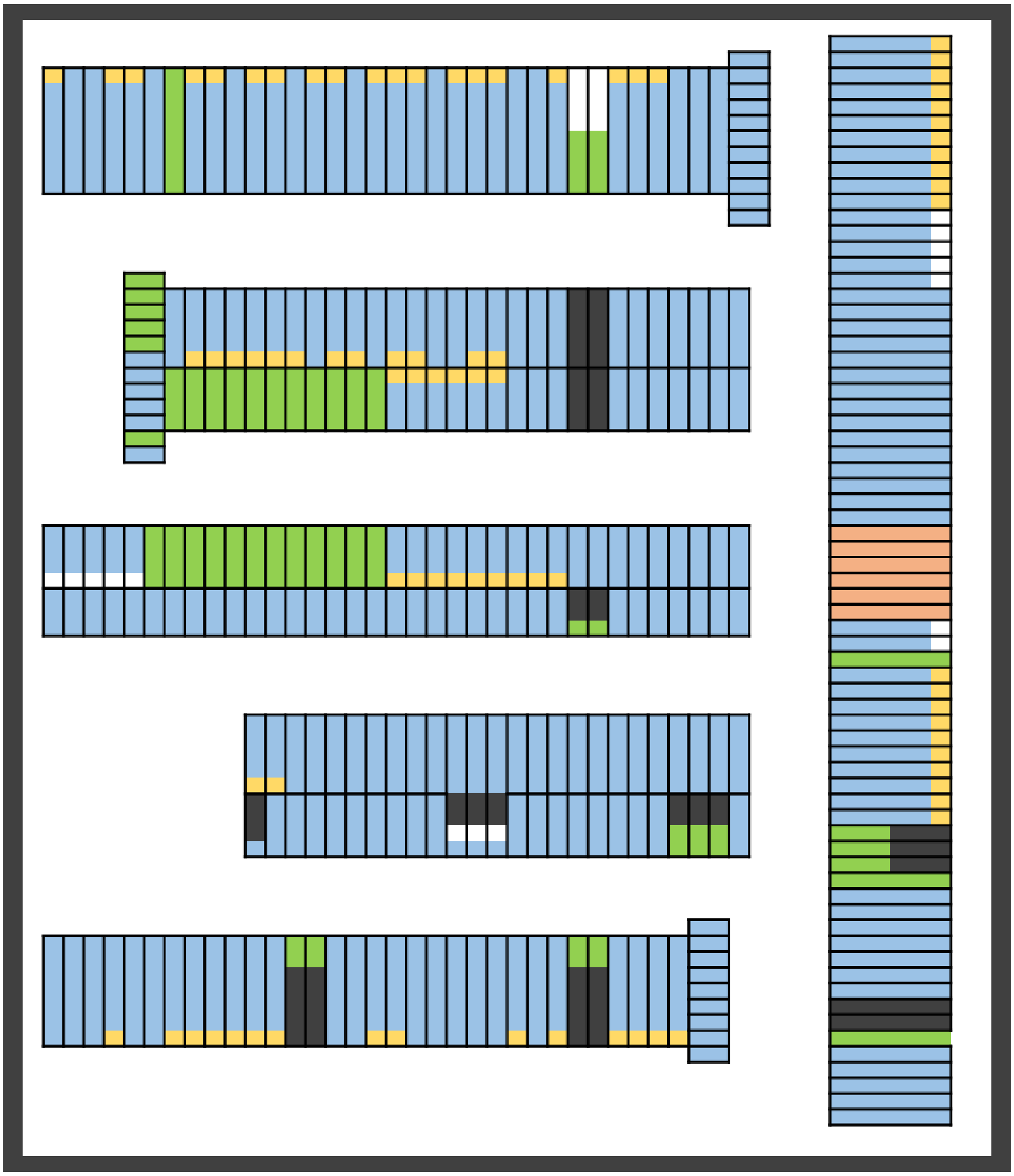

Figure 37 - XY's new micro layout

The blue locations represent the 95-percentile of store's demand. If the entire location is blue, then the 95-percentile of demand for that store equals the depth of the location. The red represents the IP buffer. The green locations represent free locations. The yellow squares represent stores that were given multiple store locations because its demand is bigger than any of the depths available.

Annex I: Sensitivity Analysis Scenarios

Scenario 1

$$Productivity = 163\ Crates/hour$$
$$Number\ of\ pickers = 24\ Pickers/shift$$
$$ADT = 400\ Pallets$$
$$Growth\ Rate = \ 5\%/year$$
$$Demand = 1787\ Pallets$$
$$05:00:00 \leq EP \leq 17:00:00$$
$$07:00:00 \leq IP \leq 21:00:00$$

Scenario 2

$$Productivity = 163\ Crates/hour$$
$$Number\ of\ pickers = 25\ Pickers/shift$$
$$ADT = 400\ Pallets$$
$$Growth\ Rate = \ 5\%/year$$
$$Demand = 1787\ Pallets$$
$$05:00:00 \leq EP \leq 17:00:00$$
$$07:00:00 \leq IP \leq 21:00:00$$

Scenario 3

$$Productivity = 140\ Crates/hour$$
$$Number\ of\ pickers = 25\ Pickers/shift$$
$$ADT = 400\ Pallets$$
$$Growth\ Rate = \ 5\%/year$$
$$Demand = 1787\ Pallets$$
$$05:00:00 \leq EP \leq 17:00:00$$
$$07:00:00 \leq IP \leq 21:00:00$$

Scenario 4

$$Productivity = 140\ Crates/hour$$
$$Number\ of\ pickers = 28\ Pickers/shift$$
$$ADT = 400\ Pallets$$
$$Growth\ Rate = \ 5\%/year$$
$$Demand = 1787\ Pallets$$
$$05:00:00 \leq EP \leq 17:00:00$$
$$07:00:00 \leq IP \leq 21:00:00$$

Scenario 5

$$Productivity = 140\ Crates/hour$$
$$Number\ of\ pickers = 28\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \leq EP \leq 15:00:00$$

$$07:00:00 \leq IP \leq 19:00:00$$

Scenario 6

$$Productivity = 140\ Crates/hour$$

$$Number\ of\ pickers = 28\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \leq EP \leq 15:00:00$$

$$07:00:00 \leq IP \leq 21:00:00$$

Scenario 7

$$Productivity = 140\ Crates/hour$$

$$Number\ of\ pickers = 28\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \leq EP \leq 17:00:00$$

$$07:00:00 \leq IP \leq 19:00:00$$

Scenario 8

$$Productivity = 140\ and\ 163\ Crates/hour$$

$$Number\ of\ pickers = 28\ and\ 25\ Pickers/shift$$

$$ADT = 600\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \leq EP \leq 17:00:00$$

$$07:00:00 \leq IP \leq 21:00:00$$

Scenario 9

$$Productivity = 140\ and\ 163\ Crates/hour$$

$$Number\ of\ pickers = 28\ and\ 25\ Pickers/shift$$

$$ADT = 200\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \leq EP \leq 17:00:00$$

$$07:00:00 \le IP \le 21:00:00$$

Scenario 10

$$Productivity = 140\ and\ 163\ Crates/hour$$

$$Number\ of\ pickers = 28\ and\ 25\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \le EP \le 17:00:00$$

$$07:00:00 \le IP \le 21:00:00$$

$$\text{IP} = 40\%\ \text{and EP} = 60\%$$

Scenario 11

$$Productivity = 140\ and\ 163\ Crates/hour$$

$$Number\ of\ pickers = 28\ and\ 25\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \le EP \le 17:00:00$$

$$07:00:00 \le IP \le 21:00:00$$

$$Annual\ Growth\ Rate = 10\%$$

$$Demand = 2055\ Pallets$$

Scenario 12

$$Productivity = 140\ and\ 163\ Crates/hour$$

$$Number\ of\ pickers = 28\ and\ 25\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1787\ Pallets$$

$$05:00:00 \le EP \le 17:00:00$$

$$07:00:00 \le IP \le 21:00:00$$

$$Annual\ Growth\ Rate = 2\%$$

$$Demand = 1639\ Pallets$$

Scenario 13

$$Productivity = 140\ and\ 163\ Crates/hour$$

$$Number\ of\ pickers = 23\ and\ 20\ Pickers/shift$$

$$ADT = 400\ Pallets$$

$$Growth\ Rate = \ 5\%/year$$

$$Demand = 1489\ Pallets$$

$$05:00:00 \leq EP \leq 17:00:00$$

$$07:00:00 \leq IP \leq 21:00:00$$

Annex J: Sensitivity Analysis Layout

Calculate   Update

Productivity	Number of Pickers	Growth Rate	Volume
140	28	5,0%	1787

External Production

Maximum	Proportion	Year	Start Time	05:00:00
947	53%	3	End Time	17:00:00

Internal Production

Maximum	Proportion	Year	ADT	Start Time	07:00:00
440	47%	3	400	End Time	21:00:00

Pallets Left	P(X=0)	P(Ending at 22)	Maximum Buffer	Ending Time
3	40%	94%	469	21:21:38

Figure 38 - DES interface to set parameters

Calculate

Productivity	Number of Pickers	Growth Rate
140	28	5%
Ending Time	Buffer at 22	
19:00:00	0	

	Time	ADT	IP	EP	Buffer - Start	Buffer - End	Pickers	Productivity	Crates Produced	Pallets Produced
1	05:00	400	0	82	400	359	28	140	3920	123
2	06:00	0	0	75	359	311	28	140	3920	123
3	07:00	0	34	80	311	302	28	140	3920	123
4	08:00	0	34	95	302	301	28	148	4144	130
5	09:00	0	26	132	301	301	28	180	5040	158
6	10:00	0	28	75	301	278	28	143	4004	126
7	11:00	0	35	96	278	271	28	157	4396	138
8	12:00	0	38	68	271	320	14	129	1806	57
9	13:00	0	39	55	320	347	14	153	2142	67
10	14:00	0	26	90	347	326	28	156	4368	137
11	15:00	0	26	0	326	231	28	138	3864	121
12	16:00	0	23	0	231	156	28	112	3136	98
13	17:00	0	40	0	156	68	28	146	4088	128
14	18:00	0	31	0	68	0	28	148	4144	130
15	19:00	0	0	0	0	0	14	92	1288	41
16	20:00	0	0	0	0	0	14	127	1778	56
17	21:00	0	0	0	0	0	28	144	4032	126
18	22:00	0	0	0	0	0	28	124	3472	109
19	23:00	0	0	0	0	0	28	124	3472	109
20	00:00	0	0	0	0	0	28	109	3052	96
			1628		400	359				

Figure 39 - DES calculation spreadsheet

Iteration	Pallets	Buffer Start	Buffer End	Buffer at 22	Time
1	1785	400	362	0	21:17:34
2	1954	431	431	69	22:37:38
3	1860	400	351	0	21:48:40
4	1865	400	368	0	21:47:37
5	1711	400	367	0	21:00:00
6	1829	400	369	0	21:36:40
7	1800	400	370	0	21:18:52
8	1840	400	397	0	21:41:28
9	1837	400	357	0	21:35:02
10	1822	400	359	0	21:32:12
11	1792	400	359	0	21:20:38
12	1790	400	389	0	21:11:20
994	1780	400	357	0	21:08:59
995	1767	400	362	0	21:07:12
996	1854	400	340	0	21:46:34
997	1817	400	381	0	21:30:14
998	1808	411	411	0	21:20:38
999	1737	400	379	0	21:00:00
1000	1742	400	342	0	21:00:00

Item	Average	Standard Deviation	Maximum
Pallets	1786	73,24605628	1992
Buffer Start	401	6,373395576	469
Buffer End	361	23,66374975	469
Buffer at 22	3	12,24757033	110
End Time	21:21:38	00:25:00	23:00:00

Frequency	912
Frequency %	91,2%

Calculate

Figure 40 - DES's results spreadsheet

Annex K: XY's Cross-Docking Warehouse

Figure 41 - Unloading process

Figure 42 - Reception process – scanning crate by crate

Figure 43 - Pallet transportation within the cross-docking warehouse

Figure 44 - Pallet build process

Figure 45 - Sorting process

Figure 46 - Pick & Pack process - wrapping

Figure 47 - Loading process