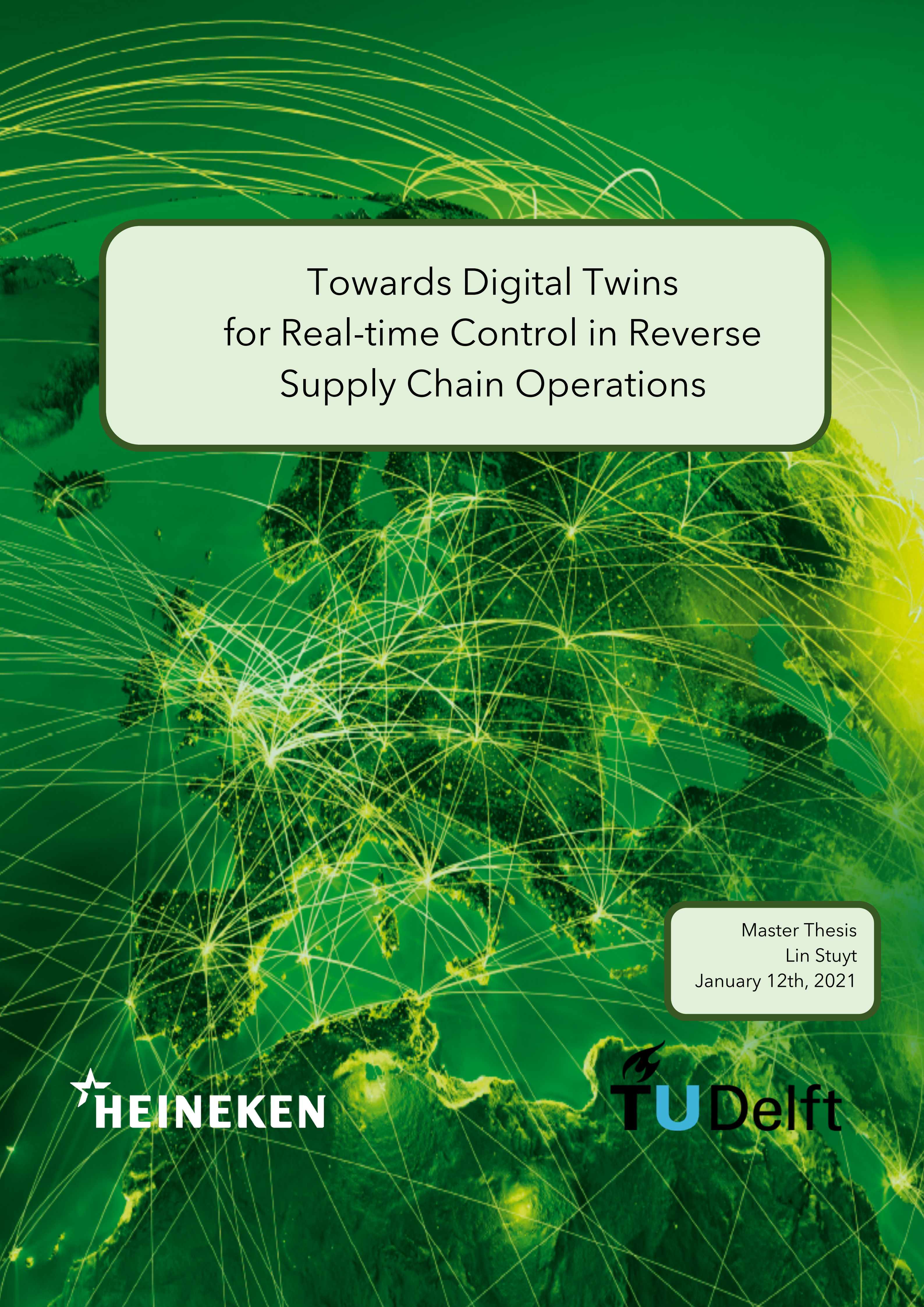

Towards Digital Twins for Real-time Control in Reverse Supply Chain Operations

Master Thesis
Lin Stuyt
January 12th, 2021

Towards Digital Twins for Real-time Control in Reverse Supply Chain Operations

A case study at Heineken Netherlands Supply and Heineken Germany

By

L. Stuyt

Master Thesis

in partial fulfilment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Department Maritime and Transport Technology of Faculty Mechanical, Maritime and Materials Engineering of
Delft University of Technology
to be defended publicly on Tuesday January 12, 2021 at 10:00 AM

Student number:	4227700	
MSc track:	Multi-Machine Engineering	
Report number:	2021.1MME.8426	
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Date:	January 12, 2021	

Delft University of Technology

GRADUATION ASSIGNMENT
COURSECODE ME54035
REPORT NUMBER 2020.MME.8426

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HEINEKEN NETHERLANDS SUPPLY AND HEINEKEN GERMANY

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January 2, 2021

Preface

Dear reader,

In front of you, you find my thesis to obtain the degree of Master of Science at the Delft University of Technology. This thesis is the last project of a masters degree program for Mechanical Engineering with a specialization in Transport Engineering and Logistics. It is the result of eight months of hard work in collaboration with Heineken Netherlands Supply.

First, I would like to thank my graduation committee of the University. I would like to thank my daily supervisor, Wouter Beelaerts van Blokland, for your input and guidance during these months. In these extraordinary times, you were always willing to find time for me, and pointed me in the right direction where needed. You helped me to put the 'blue jacket' on instead of the 'green one' and with your beautiful metaphorical sayings about the topic, you were able to keep me inspired. Also, thank you to my chair of the thesis committee, Rudy Negenborn, for your supervision over the research and your challenging questions during our meetings.

Secondly, special thanks to Terry Noorlander-de Gouw, for providing me the opportunity to do my research at Heineken and fully trust me being the project manager. This made the project for me personally very engaging. Due to COVID-19, the initial project had to be adapted. But thanks to your support, I was able to convince stakeholders of the importance of the project objectives. And therefore, proud to see that the project plan will actually be implemented at Heineken. This thesis can be considered a continuation of that project, and hopefully the insights and results will be beneficial for Heineken in the future.

Finally, I would like to thank my family and friends for their endless support. Your interest in this project has kept me motivated throughout this journey. My parents, Kees en Lut, for providing all the opportunities needed and my sister Tes for reflecting on this thesis in a broader context. Last, very special thanks to my boyfriend Jacob for your enormous support during the past years, specifically during this master thesis. I am very grateful for everything that I have learned at the University in Delft.

Lin Stuyt
Amsterdam, December 2020

Acronyms

3PL Third Party Logistics. 18, 42, 69, 78

AI Artificial Intelligence. 16

CAPEX Capital Expenditures. 19, 28, 34, 47, 48, 71, 72, 80
CE Circular Economy. 17, 18
CLSC Closed Loop Supply Chain. 11, 17–20, 23–28, 33, 38, 39, 42, 44, 47, 88
COGS Cost Of Goods Sold. 48
CPPS Cyber Physical Production System. 29, 31–33, 51
CPS Cyber Physical System. 11, 29, 32, 52
CPSS Cyber Physical Supply System. 51
CS&L Customer Service and Logistics. 44

DC Distribution Center. 18, 38, 43–45, 61, 68, 69, 72
DoH Days on Inventory Hand. 19

E2E End-to-End. 47

FIFO First-In-First-Out. 63
FL Forward Logistics. 17, 23, 24, 27, 38, 41, 68
FP Finished Product. 18, 38–43, 47, 48, 56, 68

H&B Hartog&Bikker BV. 18, 39–41, 43, 44, 46
HGER Heineken Germany. 11, 13, 15, 17–20, 36, 38–42, 44, 46–48, 54
HNC Heineken Netherlands Commerce. 15
HNL Heineken Nederland. 15
HNS Heineken Netherlands Supply. 11, 13, 15, 17–20, 36–39, 41, 42, 44, 46–48, 54

INCOSE International Council on Systems Engineering. 20

IoT Internet of Things. 16, 29, 31

IT Information Technology. 29, 32

JIT Just-In-Time. 76, 80

KPI Key Performance Indicator. 19, 27, 28, 34, 47, 48, 72

LCDB Logistic Center Den Bosch. 18, 38–45, 47, 48, 56, 61, 68, 69, 71–73, 76

MPC Model Predictive Control. 26, 27, 54, 60, 62, 64, 65, 67, 72, 73, 76, 80, 88

NASA National Aeronautics and Space Administration. 29

OOS Out of Stock. 19, 25, 28, 34, 37, 47, 48, 53, 72, 73, 80

OPCO Operating Company. 15

OPEX Operational Expenditures. 19, 28, 34, 47, 48, 72, 73, 80

PLM Product Life-cycle Management. 29

RFID Radio Frequency Identification. 19, 23, 25, 26, 34, 52–54, 56, 60, 63–65, 70, 72, 83, 87, 88

RL Reverse Logistics. 11, 17, 23, 24, 26–28, 38, 41, 47

RoRo Roll-on Roll-off. 43

RPM Returnable Packaging Materials. 11, 13, 17–19, 23–26, 28, 33, 34, 37–39, 42, 47, 48, 53, 60, 68, 76, 78

SE Systems Engineering. 20, 21, 67

SKU Stock Keeping Units. 13, 38, 39, 47, 48, 72, 73

WIP Work In Progress. 63

Abstract

The Heineken Company, known as Heineken, is a global and family-owned brewing company of Dutch heritage. With more than 300 different high quality beers and ciders and 167 breweries around the world, consumers are enjoying their products in more than 190 countries. Heineken Netherlands Supply (HNS) is a regional Operating Company (OPCO) and with three breweries in the Netherlands, HNS supplies Heineken products to their customers, including Heineken Germany (HGER). The supply chain between HNS and HGER is used as a case study for this thesis.

This supply chain is a Closed-Loop Supply Chain (CLSC) in which Returnable Packaging Materials (RPM) such as crates, are circulating through the supply chain. Heineken, including HNS and HGER, aspires to continuously eliminate inefficiencies and charge future growth through strategic investments and initiatives.

Nowadays, production volumes for the German market are growing increasingly and supply chains are under pressure since they are required to be faster, more flexible, more efficient and consumers have high expectations regarding product availability. Hence, strategic decisions regarding supply chains have become more important and featuring reliable data to measure Key Performance Indicators is essential. Therefore, Heineken is planning on introducing Radio Frequency Identification (RFID) gateways to measure actual crate cycle times, since they are currently based on assumptions.

Scope The HKR Cluster crate will be the first RPM Stock-Keeping-Unit (SKU) which is going to be tracked through the supply chain, since the largest beer volume of the total volume for the German market (33%) are kept in this SKU. The initial idea is to install the RFID gateways and at 3 main locations:

- Brewery in Den Bosch (Netherlands)
- LCDB: Logistic center in Den Bosch (Netherlands)
- Warehouse in Werne (Germany)

For the purpose of this master thesis a scope and system boundaries have to be defined. Figure 1 presents the CLSC between HNS and HGER. The scope is limited to the three main locations in the Reverse Logistics (RL) flow of the CLSC. Since the HKR Cluster crate is considered to be the first RPM SKU to be tracked, this research will focus on this type of RPM.

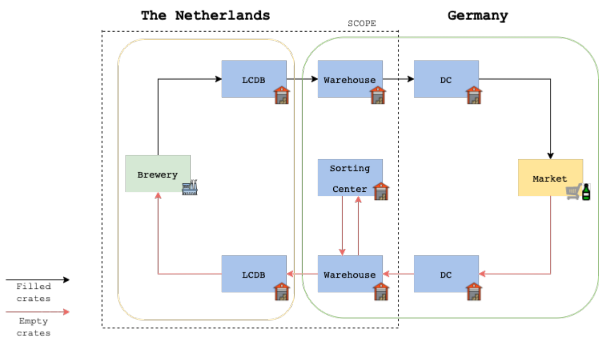

Figure 1: Closed loop supply chain between HNS and HGER.

Objective and Method From the initiative to implement RFID gateways, it can be concluded that there is not enough RPM visibility and information transparency in the supply chain, which results in lack of integral RPM flow control. Improvement in this area can make the supply chain intelligent and more efficient. In literature, digital twins are found to be explored as a means of improving performance of physical entities. A digital twin is a virtual representation of a real entity and the concept has gained much interest over the years. The world of supply chain and logistics is lagging behind when it comes to adapting digital possibilities to current conditions. Therefore, the objective of this master thesis is to enable supply chain control of RPM flows using data provided by the RFID gateways, from a Digital Twin design perspective. The research is driven by the ambition and visions for digital transformation in supply chains.

To obtain the research objective the following main research question is defined: *How can real-time control in the reversed supply chain be enabled, with use of RFID data?*. To answer the main research question multiple sub research questions are defined and are used as guidance through the thesis. A current state analysis will help to understand how the supply chain currently operates and performs. Based on this analysis a Digital Supply Chain Twin (D-SC-T) framework for the current supply chain is proposed. Then, a mathematical model for control is proposed and simulations are done in MATLAB. The impact of control will be assessed and evaluated by comparison of financial Key Performance Indicators (KPI's) in the current state (no control) with the future state financial KPI's (control).

Current state analysis Before systems are modelled or designed, a current system states analysis is performed to determine how the current supply chain operates. The analysis confirms the earlier found inefficiencies in the current state. The cycle times are based on assumptions and approximate to be 25 weeks, which is considered to be high. This is because the average time spent at the locations is high due to large inventories. There are large safety stocks to avoid out of stock situations, while there is limited storage capacity. It is very common that at the inventory locations, LCDB and warehouse, the storage space is at full capacity and an external storage location has to be rented. Furthermore, the planning for production at the brewery is made a relatively long time in advance and therefore lacks flexibility. It can be concluded that there is little RPM visibility throughout the supply chain and data availability for planning departments. Change in demand, weather and events can cause inaccurate forecasting. In conclusion, there is no centralized control of inventory levels in the current supply chain.

Heineken's reversed supply chain, driven by returnable packaging, is defined to be a push-based supply chain. Crates are pushed through the channel from the location where it is returned by the customer up to the brewery. Every supply chain agent has its own priorities and inventory management preferences. This can lead to unnecessary inventory costs.

Design Digital twins are found to be explored by means of improving performance of physical entities by using models combined with various data to interpret and to predict the behavior of a real system. Therefore, digital twins have the potential to increase the intelligence of a specific environment. This leads to the motivation of digital twins of supply chains. First steps towards D-SC-T creation are done by proposing a framework according to its functions and requirements.

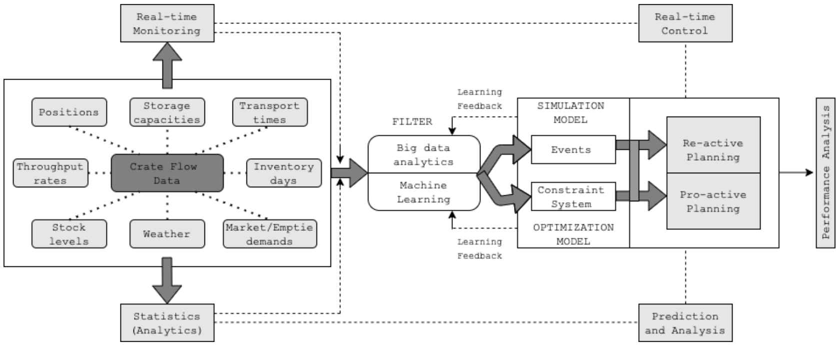

Figure 2: Digital supply chain twin for managing and controlling crate flows.

The prediction function includes analysis of the behaviour of the supply chain before actual runtime. Planned crate flow processes are simulated prior to the actual transportation decisions in the supply chain system (pro-active planning). Consequently, supply chain parameters can be tested, while potential impacts on the supply chain performance can be evaluated. The monitoring function enables optimization when models are enriched with real-time data from physical sources, such as RFID. Therefore, the RFID gateways allow tracking and supervision of the current states of crate flow and inventory at the main locations. The RFID data, including live positional data from the crates, can be fed into the digital twin. If the current state measurements deviate from the preferred state, transportation decisions in the supply chain system can be calculated (re-active planning). Supply chain performance and behaviour diagnosis is usually enabled after an event and is done by data analysis.

Model Predictive Control (MPC) is a control strategy, by means of controlling a process based on some form of model. Literature shows that the digital twin and MPC have similarities in the way they capture and interpret the current state of the physical system and being able to use that current state to change the future state. Therefore, MPC seems a very suitable option for control of the inventory levels of the supply chain within the digital twin framework. A centralized MPC control model for the control of inventory levels and crate flows within Heineken's reversed supply chain is proposed.

The described MPC control model has the objective to optimize the supply chain performance by reducing Operating Expenditures (OPEX) and Capital Expenditures (CAPEX). The controller will accurately keep track of where crates are located in the supply chain and calculate the related OPEX and CAPEX, while meeting the requirements.

Results Simulation experiments are done to be able to quantify the impact of control on the supply chain in OPEX and CAPEX. In the experiments, the controller reacts to disturbances and unforeseen events, while optimizing inventory levels and meeting demand. This is demonstrated by 3 scenarios.

- **Scenario 1** Current supply chain with actual events
- **Scenario 2** Current supply chain with disturbance: peak in demand
- **Scenario 3** Supply chain with additional RFID gateway location with disturbance: capacity limitation

Simulation results	
Simulation	Financial KPI's (OPEX and CAPEX)
Scenario 1	
No control	€942.559
Control	€806.863
Scenario 2	
No control	€98.785
Control	€58.976
Scenario 3	
No control	€121.389
Control	€120.880

Table 1: Simulation results in OPEX and CAPEX.

Table 1 presents the simulation results for all scenarios and are presented including the results for the same scenarios with no control. When comparing the results of current supply chain with actual events, the most remarkable result is the difference in the location where inventory is allocated. In the base case scenario, the crate inventory levels are much higher at the LCDB, while with MPC control, the results show higher inventory levels at the warehouse. These more detailed results are shown in Chapter 6. In the second scenario the simulated event is an unforeseen high beer demand due to weather changes. The controller reacts to the occurring event and meets the demand at the brewery in time. In the third scenario the effect of having more supply chain information by including one additional RFID gateway location is determined. More detailed results and explanations on how the controller reacts to various events are provided in Chapter 6.

Conclusion, Discussion and Recommendations This thesis has created insights on what a digital supply chain is and what the effect of control can be on the supply chain performance. The controllability of the crate flows in Heineken's reversed supply chain driven by returnable packaging can be improved, using a centralized MPC control model within the proposed digital twin framework, combined with RFID data from the proposed gateways. These gateways measure crate positions and quantities per time. The controller uses this data to interpret and predict the supply chain behaviour. The RFID data of the current supply chain states are fed into the model. The controller interprets the states and calculates which actions lead to less CAPEX and OPEX, while meeting the modeling requirements. Due to the RFID measurements, data is visible and transparent for planning departments and other stakeholders and better coordination along supply chain agents can be made possible.

For this research MPC is the chosen control method for the control part within the digital twin. Therefore it only covers a small part of the wide variety of different control methods which could have been investigated and tested. Other control methods are still to be investigated.

This thesis offers a theoretical digital twin solution for the problems they have at Heineken's CLSC. But only a solution for the measure and control part has been brought forward. A digital twin also carries out big data analytics and machine learning possibilities. How these growing technologies fit into the digital twin concept could be interesting for further research.

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Part I

STATE OF THE PROBLEM

Chapter 1

Introduction

'The story of HEINEKEN really began on February 15, 1864, when Gerard Adriaan Heineken took over the Haystack brewery in Amsterdam. Gerard was only 22 years old and had little brewing experience. But with courage, self-confidence and entrepreneurial spirit he decided to start his own brewing company. First, he decided to brew only lager, even though the Dutch were much better at brewing ale, porter and brown. That decision, as we now know, paid off as the second Heineken brewery opened less than a decade later in Rotterdam.' - The Heineken Company

1.1 Research context: Heineken Netherlands Supply and Heineken Germany

The Heineken Company, known as Heineken, is a global and family-owned brewing company of Dutch heritage. With more than 300 different high quality beers and ciders, and 167 breweries around the world, consumers are enjoying their products in more than 190 countries. The company consolidates almost 250 million hectoliters of beer volume per year (Figure 1.1) and has a net revenue of €23.894 million annually [21]. Heineken is organized into five territories, which are Western Europe, Central and Eastern Europe, The Americas, Africa and the Middle East, and Asia Pacific. These are then segregated into multiple regional operating companies (OPCOs) [24].

Heineken Netherlands Supply (HNS) is one of them. Together with Heineken Netherlands Commerce (HNC), HNS forms part of Heineken Nederland (HNL). HNS is the producing operating company of HNL. With three breweries in the Netherlands, they produce beer and deliver Heineken products to their customers such as retailers, wholesalers and other OPCOs. One of these OPCOs is Heineken Germany (HGER). This research is conducted at HNS and the supply chain between HNS and HGER is used as case study for this thesis.

Heineken, including HNS and HGER, is one of the worlds largest beer brewing companies and aspires to continuously eliminate inefficiencies and charge future growth through strategic investments and initiatives. This is necessary to deliver a strong performance and to keep their international status. The beer market is increasingly competitive and supply chain continuity is an important objective. Therefore, the company has to ensure it performs as optimal and efficient as possible. Disruptions in the supply chain could lead to inability to deliver products to key customers, revenue loss and brand damage. Significant changes in the availability or price of raw

Figure 1.1: Global consolidated Heineken beer volume 2019 [21]

materials, commodities, energy and water may result in a shortage of those resources or increased costs [24].

As the world is being more digital, data will become more and more an asset for a company and technological developments are quickly following one other. Heineken will need to develop in this area to not lag behind and lose the battle [21]. Digital transformation is changing different industries and supply chains are rapidly evolving, being faster, more flexible, more accurate, and more efficient [42]. In addition, this transformation is changing the way logistics are being operated. Ignoring these changes could hinder Heineken in achieving its strategy and business objectives and may affect the company.

1.2 Research context: Digital Supply Chain

Digitalization has certainly changed how processes operate and is a key differentiator that will empower companies to remain being competitive. As everything becomes increasingly connected, using Internet of Things (IoT), data is collected from many intelligent devices. Digitalization assures creating flexibility, new efficiencies, optimized production quality, lower cost, and even shorter response time to market demands and indicates the potential of new business opportunities [54]. According to the Gartner report, "By 2023, at least 50% of large global companies will be using Artificial Intelligence (AI), advanced analytics and IoT in supply chain operations." [48].

Every industry gets hit by the growing technologies, such as IoT, big data and cloud computing. Also supply chains will be affected as it covers all integrated operations from customers to suppliers. Digitalization in supply chains are one of these fast changes in digital products and services along with the handling of supply chain processes. So, it can be said that the digital supply chain is an intelligent, value-added, advanced process that uses new approaches to create competitive value and network effects [9].

Supply chain digitalization is important since supply chain operations affect the rest of the business. Taking specifically intelligence into account, complete visibility and real-time tracking will be game changers [14]. Supply chain intelligence enables companies with real-time performance insights regarding demand and supply planning and prediction, production scheduling and inventory management and therefore, helps to get grip on the extending complexity of today's global supply chains by allowing continuous improvement. This is important for supply chain successes. Supply chain performance metrics allow executives to make smart strategic decisions [16].

Even though emerging technologies are creating an enormous buzz right now, not much companies have deployed digital models in their supply chain. The world of supply chain and its logistics is lagging behind when it comes to digital maturity and most companies do have a long way to go [44]. This research is driven by the ambition and visions for digital transformation in supply chains.

1.3 Research Scope

1.3.1 Scope: German market

The Heineken brand is very demanding in Germany. To meet this demand and the expected demand growth with 24% until 2022, the produced beer volumes for the German market will increase, Heineken beer for the German market is produced by HNS, which has three breweries in the Netherlands. In Zoeterwoude, Den Bosch and Wijlre and only the brewery in Den Bosch produces for the German market. Since the supply chain between HNS and HGER is used to investigate in this research, the brewery refers to the one located in Den Bosch.

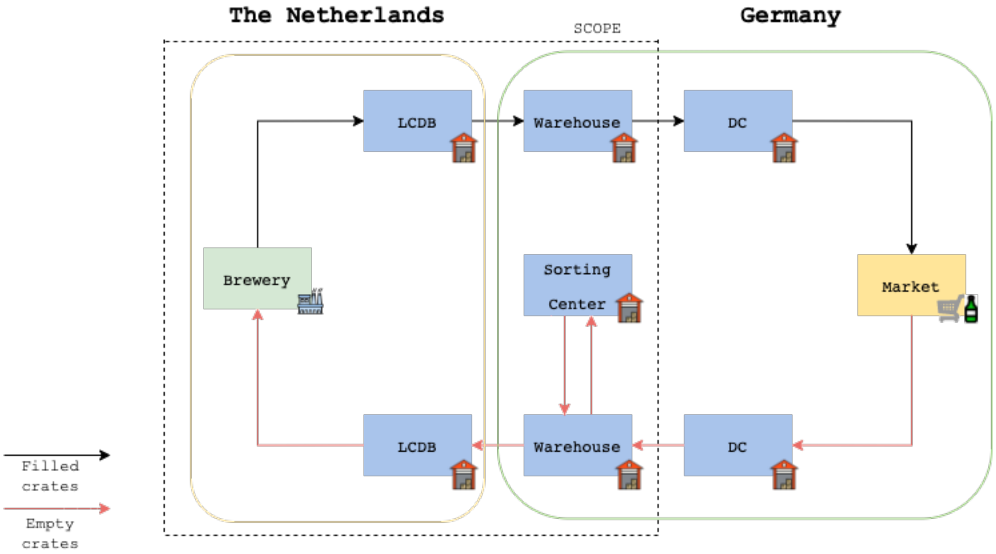


Figure 1.2: Closed loop supply chain between HNS and HGER.

The supply chain between HNS and HGER is a Closed Loop Supply Chain (CLSC), see Figure 1.2. A CLSC is the control and operations of a supply chain, which combines both forward logistics (FL) and reverse logistics (RL) [39]. RL collects and returns used of unused products [35]. As many companies have to be aware of their environmental footprints due to great globalization, increased competition, customer awareness and governmental legislation, they are facing an urgent need to embed the circular economy (CE) into their supply chain network by circulation of resources [41]. A form circulation of resources which Heineken utilizes is Returnable Packaging Materials (RPM). HNS produces 92% of the total German volume, whereof 96% is sold in RPM.

The CLSC between HNS and HGER consists of multiple stages, which are described in the following list.

- **Brewery:** The Brewery which produces for the German Market is the one in Den Bosch. Not only Heineken beer, but all other beer types for HGER are brewed here. After the beer is produced, it is gets packaged in kegs or crates and transported to the LCDB.
- **LCDB:** The Logistic Center Den Bosch (LCDB) is a distribution center located in Den Bosch, obviously. All finished products (FP) in RPM for HGER go to the LCDB. At this stage RPM is stored and is this is managed by Hartog&Bikker (H&B) which is a Third Party Logistics (3PL). Besides this, LCDB is the location where empty or used RPM of Heineken products enter before it will return to the Brewery to be filled again.
- **Warehouse:** The warehouse is located in Werne in Germany. All the RPM meant for HGER will consecutively enter, be stored and leave this location. Besides FPs, empty RPM will be processed via this location.
- **Sorting Center:** The sorting center is a 3PL located in Germany and managed by H.Leiter GmbH. The sorting center receives unsorted RPM in the form of crates and sorts them out. The sorting process guarantees that the bottles are in the corresponding crates, with the preferable quality. The latter refers to the dirt level of bottles and crates, such as when they have crown corks and straws.
- **DC:** Multiple Distribution Centers (DCs) are used in this CLSC to store RPM. From here FP can be sold directly to the consumer or can be transported to multiple retailers.
- **Market:** The market are the retailers, wholesalers and other customers of HGER. Usually these parties sell the Heineken products directly to the end consumer. In addition, they have the function of collecting empty RPM.

In the research scope, with regard to the physical stages in the CLSC, the Brewery in Den Bosch, the LCDB in Den Bosch, the warehouse in Werne in Germany and the Leiter Sorting Center will be considered. As there are over 30 DCs and the Market consists over 100 retailers and wholesalers, and there is limited time and data available, these stages will not be included in the scope of this research. Therefore, the DCs and the Market will be considered a black box.

1.3.2 Scope: HKR Heineken Cluster crates

As mentioned in the previous section (1.3.1), companies are facing an urgent need to embed the CE into their supply chain network by circulation of resources and Heineken makes use of RPM. HNS produces 92% of the total German volume, from which 96% is sold in RPM. RPM are Heineken products that are transported in returnable packaging such as glass bottles, crates and kegs. As there are more then 300 beers and ciders, all are differently packaged and due to limited time and data availability to conduct this research, the focus of this research will be on one type of RPM specifically: HKR Heineken Cluster Crate (Figure 1.3). This crate transports and protects glass, clustered bottles filled with Heineken beer.

Figure 1.3: The Heineken HKR Cluster crate.

1.4 Problem Definition

Nowadays, supply chains are under an intense pressure. They are required to be more dynamic, more international, more sustainable and while firms are always striving to save money, they still are asked to respond to innovation. The increasing consumer awareness of the impact of the environment makes companies strive for sustainable supply chains and both CLSC and RPM have become more important. Furthermore, supply chain digitalization by integration of innovative advanced technologies have received much attention due to its ability to increase performance and create optimization by its potential benefits.

The case study at Heineken shows a great example of a complex, international, CLSC driven by RPM in a competitive environment where very little digitalization is integrated. Due to the increasing production volumes for the German market (section 1.3.1) and the pressure on supply chains being faster, more flexible, more efficient and consumers having high expectations regarding product availability [10], the shared supply chain performance of HNS and HGER has the potential to improve. Additionally, at HNS RPM cycle times measurements are an important Key Performance Indicator (KPI), but crate cycle times are currently based on assumptions. Therefore, the company is planning on introducing RFID (Radio Frequency Identification) gateways to measure actual crate cycle times.

Besides cycle times, Days on Inventory Hand (DoH) are unreliable too and Out of Stock (OOS) frequently occur. There is not enough RPM visibility and information transparency in the supply chain. In conclusion, there is a lack of integral RPM flow control in the current supply chain.

Improvement in this area can make supply chains more intelligent, which provides Heineken with real-time performance insights regarding RPM planning and inventory management. This could directly affect the company's operational cost (OPEX) and investment cost (CAPEX).

1.5 Research Relevance and Objective

From the previous section it can be concluded that performance improvement of the HNS and HGER supply chain is necessary. Therefore, this thesis aims to investigate these improvement possibilities by exploring potential benefits of first steps towards digitisation of supply chains. One high-potential and state-of-the-art concept in particular came forward: the Digital Twin.

As mentioned in the previous section, currently HNS and HGER plan to introduce RFID gateways to measure crate cycle times. The research objective is to enable supply chain performance improvement by control of RPM flows using data of the RFID gateway measurements from a Digital Twin design perspective.

In literature digital twins are found to be explored as a means of improving performance of physical entities by supporting advanced growing technologies. However, there are very few examples of validated benefits and very few papers showing substantial improvement. Significant effort is needed to even consider the digital twin concept as an appropriate solution [12].

This research contributes to the evaluation of the digital twin and associated processes and helps to determine in what cases it may operate. In addition, this research contributes to the continuous process of performance improvement by researching the possibilities of asset visibility and predictability of flow of goods in supply chains. Therefore, this thesis provides an investigation on how a digital twin can be used to predict the flow of goods in order to control a supply chain driven by returnable packaging and in order to advance its performance.

1.6 Research Questions

The problem definition (Section 1.4) and the research objective (Section 1.5) lead to the following main research question:

How can real-time control in the reverse supply chain be enabled, with use of RFID data?

To be able to answer this main research question, multiple sub questions are stated. The sub questions help understand the problem and to structurally answer the main research question. First, a literature review will be performed to investigate and summarize the existing literature on digital twins and CLSC driven by returnable packaging. Secondly, the processes at HNS and HGER's supply chain will be analyzed to establish its current performance. Then, a design of a digital twin that can control the supply chain will be introduced. Subsequently, this design will be modelled and tested by simulation. Finally, the impact of the design will be assessed and evaluated by comparing the current performance of the supply chain with the new performance. Once these sub questions are answered, an answer to the main research question can be defined.

1. *What are the characteristics of a supply chain driven by returnable packaging materials?*
2. *What are the key performance indicators of a supply chain driven by returnable packaging material materials?*
3. *What is a Digital Twin?*
4. *How does the supply chain driven by returnable packaging materials currently operate and perform?*
5. *How can the RFID gateways contribute to supply chain control?*
6. *How can a Digital Twin be modelled for controlling returnable packaging material flows in a supply chain?*
7. *What is the impact of material flow control in a supply chain driven by returnable packaging materials?*

1.7 Research Structure and Methodology

This research is divided in seven main parts, structured using the SIMILAR process approach. These seven main parts are then divided in chapters. The SIMILAR approach is a Systems Engineering (SE) method and can be seen as an iterative process road map. The SE perspective is based on systems thinking, which indicates a way of thinking that not only notices an entire system, but includes how parts within such a system interrelate. SE thinking can help to understand, define and work with real-world systems by sensing and modeling. The International Council on Systems Engineering (INCOSE) defines SE as a trans disciplinary and integrative approach to enable the successful realization and use of engineered systems by systems principles, concepts and methods [47].

The SIMILAR process approach is an abbreviation for the following process steps [4]:

- **S**tate of the Problem
- **I**nvestigate Alternatives
- **M**odel the System
- **I**ntegrate

- **L**aunch the System
- **A**ssess Performance
- **R**e-Evaluate

First, the SE problem has to be stated. Therefore, the research context has to be defined and after having a clear problem definition the research objective and questions can be described. The second step, includes a literature study which is performed. This study is to determine what has already been done with regard to the subject and what possible alternative solutions can be. In the third part includes first steps towards system modeling and to be able to perform this, an analysis of the current system state is done and a design method is selected. Integration refers to designing the future states and bringing system elements together so they work as a whole. The fifth part includes launching the system and refers to running the system and producing outputs [5]. This is done by a simulation model of the system. In a next stage, the system performance results of the designed states are assessed by verification and comparison with the current system performance. Finally, the research will be discussed and evaluated. The research overview is given by Figure 1.4.

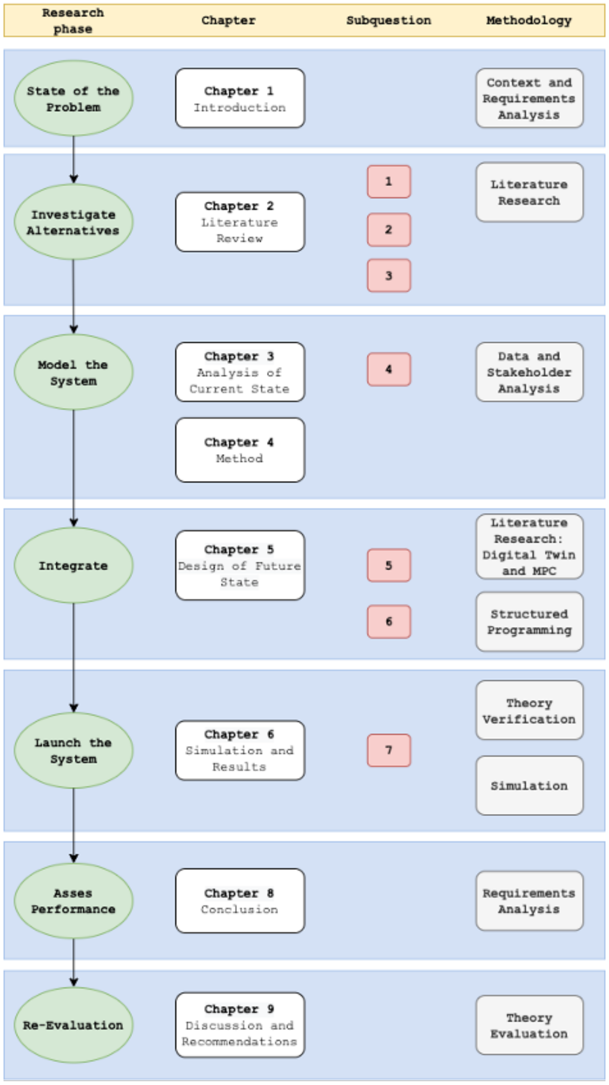


Figure 1.4: Research Overview

Part II

INVESTIGATE ALTERNATIVES

Chapter 2

Literature Review

In this chapter the existing relevant scientific literature will be reviewed. This is necessary to describe how this research is related to prior research, the originality and relevance of the research problem. It will also identify inconsistencies and research gaps in current literature [46]. In this thesis a literature review is provided on the digital twin and the digitalization of the supply chain, the returnable packaging supply chain, RFID technology and supply chain performance indicators.

By the end of this chapter the following sub questions will be answered:

1. What are the characteristics of a supply chain driven by returnable packaging materials?

2. What are the key performance indicators of a supply chain driven by returnable packaging materials?

3. What is a Digital Twin?

2.1 Supply Chain driven by Returnable Packaging

This section will describe how a supply chain driven by returnable packaging operates and what its characteristics are. A supply chain driven by returnable packaging (RPM) is generally a CLSC, as the RPM return to the beginning of the supply chain, which refers to a closed-loop. Existing literature studies show that a supply chain with RPM utilizes two streams: the classical forward logistics (FL) and reverse logistics (RL) .

2.1.1 Closed-Loop Supply Chains

Nowadays, numerous companies strive towards a circular economy and sustainable operations. Therefore, CLSC has gained much attention in literature and environmental benefits are highlighted. CLSC has the ability to reduce asset input, waste emissions and unnecessary energy losses through design, maintenance, repair, reuse, re-manufacturing, refurbishing and recycling [19] [60]. The aim of a CLSC method is not for minimizing costs, but to create more revenue for manufacturers [19].

As mentioned, the CLSC uses both the FL and RL streams. The forward supply chain is defined as all activities that include meeting customer requirements by suppliers, manufacturers, transporters, warehouses and retailers. While, RL normally begins with the collection of products used by the end customers. Later, these used products will be reintegrated into the supply chain [31]. RL has multiple key processes, shown in Figure 2.1. The used items are collected after use and have to be inspected before sorting can take place. After that, the materials can be returned to the supply chain through repair, reuse, re-manufacturing and recycling or they can be disposed [18].

According to Rogers et al. [50] RL is "an efficient and cost-effective process from the moment of consumption to planning, implementation, and control of raw materials, inventory, finished products, and related process information to regain the value or properly dispose the destination". In conclusion, if both FL and RL are utilized, with the intention to create value during the life cycle of a certain product, a CLSC is considered [28].

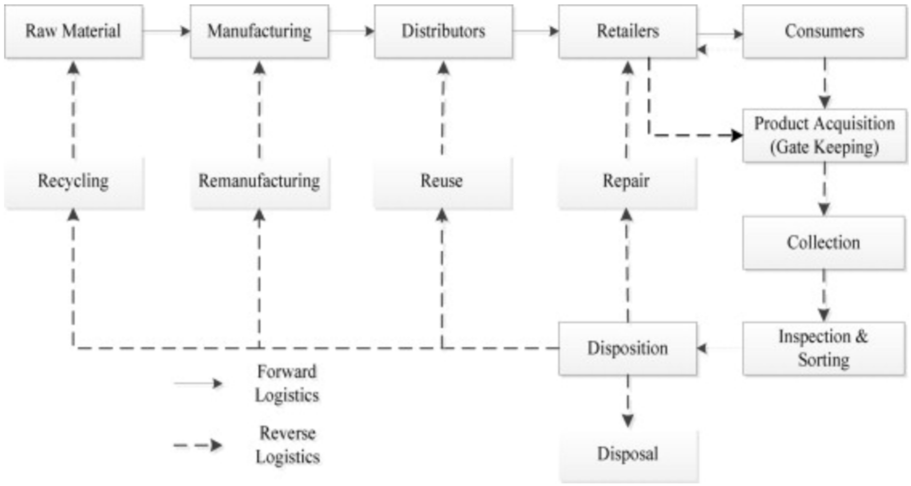


Figure 2.1: Basic flow of FL and RL activities [52]

2.1.2 Returnable Packaging in Closed-Loop Supply Chains

For terminology consistency, in this thesis the RPM term refers to primary packaging materials that are in direct contact with the consumed product [11]. The management of RPM in a CLSC addresses multiple issues. Therefore, R. Carrasco-Gallego et al. created a conceptual management model for CLSC, shown in Figure 2.2. The CLSC management model presented by this figure consists of three critical parameters, relating to three supply chain problems and their management issues.

The parameters in Figure 2.2 are successively cycle time, return rate and location. These critical parameters can be used to measure CLSC driven by RPM performances and are explained:

- **Cycle time:** Cycle time of RPM refers to the time that is needed starting from the production location to return to the same production location. At the latter, the RPM will be used again. In a CLSC, the RPM cycle time includes the transport times, storage times and usage times.
- **Return rate:** The return rate is defined as the amount of RPM that returns to the production location.
- **Location:** The location refers to the physcial inventory locations in the CLSC.

These parameters are linked to common CLSC problems such as fleet shrinkage, significant investments and limited visibility. Fleet shrinkage occurs when RPM is lost through the CLSC, consequently the return rate will be less than hundred percent. Secondly, RPM causes a significant investment. And thirdly, when there are great amount of RPM in the supply chain, the visibility is limited. Especially, when RPM is sold to the customer, no control can be performed.

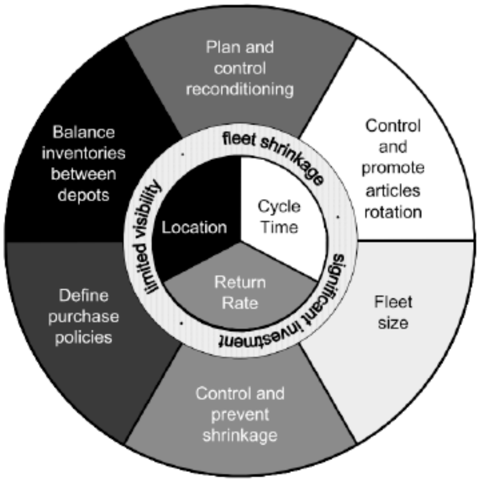


Figure 2.2: Closed Loop Supply Chain management model [11]

To be able to visualize and control assets or RPM throughout the supply chain, these units can be tracked. Due to available low-price tracking technologies, such as RFID, RPM visibility in the CLSC can be possible and beneficial.

Consequently, with greater visibility fleet sizes can be reduced. This is verified in literature in a performed research by Rosenau et al. In addition, multiple papers are found with regard to the benefits of asset visibility in the supply chain. For example, McKerrow and McFarlane et al. showed that asset visibility can increase RPM availability and that asset visibility can provide the feature of automatic handling [38].

2.2 Predictability in the Supply Chain

As mentioned, nowadays supply chains are under much pressure and fast response to changing conditions can be a great advantage for competitiveness within industry. Smart equipment items are deployed to supply information to the entire enterprise. For improvement of operational processes, resulting in better prediction, control, planning and scheduling decisions traceability and visibility of assets and RPM can be essential [34]. In literature multiple papers with regard to traceability and visibility of assets or RPM in operations are found and elaborated.

In many industries, the loss of RPM causes problems to firms. Investigation by Ilic et al. [29] led to results of 10% of yearly loss of RPM in the form of pallets. This can be caused by limited RPM return by customers. In literature a few papers argue strategies for companies in order to induce customers to return their RPM, such as deposits and penalties for late returns. For the latter, it may only be entirely effective if the position of a RPM unit is known in the supply chain [33].

Secondly, a problem with regard to RPM is that return flows are often uncertain and difficult to predict. RPM maintenance and purchase of new material is significant for companies and variations in return flow make it difficult. Kim et al. [58] points out that besides this, variety in return quantities and uncertain return times can lead to OOS situations which may lead to reputation damage of a firm and concludes that tracking the position of RPM in a supply chain is essential to increase return flows and optimize their predictability. Kelle et al. [32] examine the forecasting of RPM in the form of containers and develop a model for purchasing quantities of new units in a CLSC. Another paper by Kim et al. [58] researches a stochastic return of containers, where RFID technology is applied to enable the tracking of these containers in the supply chain.

Relating to tracking the position of RPM in a supply chain, RFID technology is addressed as a fitting solution to improve visibility and information on the return of asset, which leads to better return predictability and higher return rates. Consequently, RFID may support managing the RPM flow in a supply chain [33].

2.2.1 Radio Frequency Identification

RFID technology is for the first time applied in the Second World War. The technology refers to the wireless use of radio frequency waves in order to transfer data. RFID tags applied to RPM, allow users to identify and track the units automatically. RFID technology offers a cost effective solution and supports accurate inventory and shipping information. In comparison with other auto-ID technology, such as barcode, does RFID technology have the advantage that tags can be read without being in line of sight. Additionally, multiple tags can be scanned at the same time.

Figure 2.3: Electromagnetic spectrum with radio waves indicated [3]

RFID technology consists of different kind of tags. Active tags have their own transmitter and power source, usually a battery. They also have a larger reading range. While, passive tags uses power from the reader. This is because radio electromagnetic waves sent by the reader induce a current in the antenna of the tag.

In literature and industry, papers are found where RFID technology is used for tracking assets in parts of the supply chain or even in the entire the supply chain. Breen et al. [8], for example, presented the ability to reduce a fraction of carts taken off site by customers with use of RFID for large retailers. Roberti et al. [33] describe RFID-equipped containers for visibility and availability implemented by large companies, such as Marks&Spencer and Volkswagen. While, Hellström et al. [25] present a pilot case studies at IKEA and Arla Foods and demonstrated this by implementation of RFID systems. Both the companies are capable to reduce their RPM losses.

Kim et al. [58] used a CLSC from supplier to retailer and investigated how application of RFID technology can contribute to more information with regard to the RL and was able to make returns more predictable. Remarkably, even though RFID systems offer many advantages for controlling the flow of RPM in a supply chain, somehow companies are reluctant to adapt this technology into their systems [33].

2.2.2 Model Predictive Control

Originally meant for control of chemical processes in the oil and gas industry, Model Predictive Control (MPC) is controlling a process based on a specific model. Key to MPC is that it consists of a dynamical model of a system, in which measured parameters in physical environments are used as input and compared to the parameters in a virtual model. The past input is used to predict future states of the process. And based on the parameter differences, the virtual model is able to make optimal choices and perform control [12].

MPC has the great advantages that it is able adapt to changes and prediction is automated and robust, and extensively used in various engineering fields. Jones et al. [12], points out numerous similarities between MPC and the digital twin, starting with data exchange between physical and virtual environments. A MPC delivers closed loop control through sensor-to-controller and controller-to-actuator connections along with physical-to-virtual and virtual-to-physical environment, shown in the digital twin characteristics. In addition, they both measure the current physical state and change the future physical state, whether this is for the purpose to optimize or react to problems [12]. By [37] it is declared that MPC is able to manage supply chains production and increase its performance.

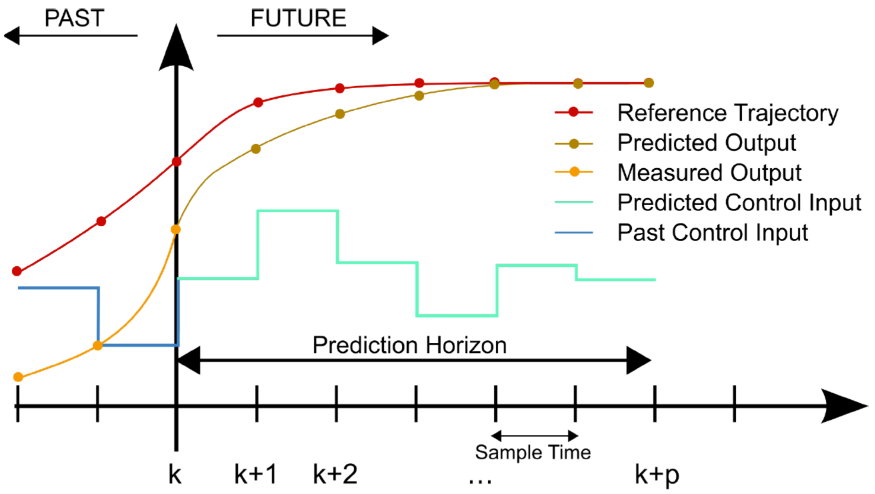


Figure 2.4: Running graph Model Predictive Control [2]

2.3 Supply Chain Performance

A supply chain is described as a process of multiple businesses that work together to obtain raw materials, manufacture these into products and in the end deliver these products to consumers. This description refers to the most traditional supply chain, with businesses such as suppliers, manufacturers, distributors and retailers. In the last years, due to changes such as globalization, e-businesses and mass customization, there has been more and more attention towards the performance, design and analysis of the supply chain as an entire system [6] [49]. Performance measurements of the supply chain are important for creating performance awareness within all layers of an organization. Performance measurements makes visible where supply chain improvement can be gained [1]. By measuring KPIs, a business can evaluate if goals are being achieved. Beamon et al. address three questions which affect performance indicators [49]:

- Which aspects should be measured?
- How to measure these aspects?
- How to use the measurements to analyze, improve and control the productive chain quality?

In literature, most performance analysis is done for FL. However, because of the increasing interest in extending the traditional supply chain to include RL, by recycling, re-manufacturing, re-use and repair, other KPI measurements become dominant. Since this research considers a CLSC, KPIs considering supply chain goals with regard to the RL will be evaluated and described in this thesis.

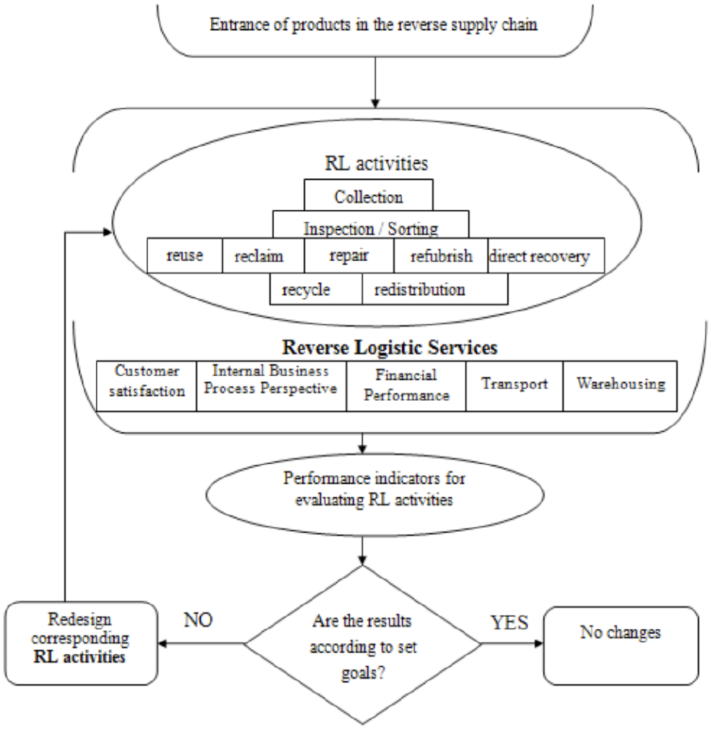


Figure 2.5: A general framework for evaluating the performance of RL [40]

A general framework is presented in Figure 2.5 in order to evaluate the performance of a supply chain including RL [40]. These RL activities include customer satisfaction, internal businesses, financial performance, transport and warehousing. Customer satisfaction is an important supply chain goal and can be linked to the KPI number of OOS situations, as these can lead to unsatisfied customers and brand damage. Additionally, satisfied customers are likely to be more loyal. From an internal business process perspective, if internal processes and services perform well, customers as well as stakeholder can profit from this. An interesting KPI with respect to this is the cycle time of RPM. As for the financial performance, reducing cost is almost for every business a goal. KPIs with regard to this can be CAPEX and OPEX. These consecutively refer to long term investments and day-to-day expenses a company suffers to keep a business operational. Transport is important, as it makes logistical processes possible. These processes can refer to various transport modes or routes between stages in the supply chain. KPIs related to transport can be, traveling distance, utilization of trucks and number of stages. Finally, warehousing is an essential part in supply chains. Design and lay-out of warehouses can have an impact on the performance of entire supply chains. Cost of storage and handling activities in warehouses can be KPIs in CLSC. Moreover, an important performance indicator to mention is the CO_2 -emission, due to the increasing awareness of the carbon footprints in processes and activities nowadays. CO_2 -emission with regard to supply chains could be the polluting emissions caused by transportation.

2.4 Digital Twin

The principles of the digital twin were generated from the National Aeronautics and Space Administration's (NASA) Apollo program. But the digital twin, as it is shaped today, can be assigned to Michael Grieves and his work with John Vickers of NASA. Grieves presented the concept in a lecture on product life-cycle management (PLM) at the University of Michigan in 2003 [12]. Initially, the digital twin is defined as an integrated multi-physics, multi-scale, probabilistic simulation of a system [53], see Figure **??**. Nowadays, in a world in which the information technology (IT) has exploded, the digital twin has greatly increased interest across both academia and industry and belongs to the top ten strategic technology trends by Gartner in 2019. Furthermore, it is praised for having a lot of potential of improving performance in design, optimization, process control, virtual testing and predictive maintenance disciplines [61]. But what is a digital twin?

The digital twin, together with Cyber Physical System (CPS) and IoT are all main concepts in Industry 4.0 and smart manufacturing. They both refer to a representation of an equipment item in cyber space [30]. Therefore, it is important to know the difference between the two and how they relate to each other, as they correlate to the digital twin concept. In general, CPS consists of physical components, transducers and IT systems combined. Transducers include sensors and actuators, while IT systems include network and computation systems. In some definitions the human operator is included in the CPS. Furthermore, it can be a closed-loop or an open-loop system, which means that a CPS can control the real system or sense the real-world parameters for analytical purposes.

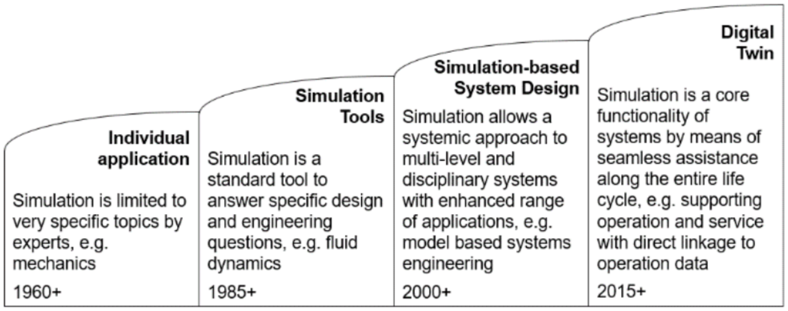


Figure 2.6: Development digital twin in simulation context.

In a large context, IoT includes all trackable data objects, as well as interactive and smart objects. The digital twin is generally a digital replica of a physical entity that contains its characteristics, parameters, conditions and behaviour trough models and data. It includes the data connections between the physical and digital entity [56]. In literature, the digital twin use is mostly considered for the operation of a Cyber Physical Production System (CPPS), which refers to a production environment which contains CPS. Digital twins have the potential to increase the intelligence of a CPPS by performance optimizations, analytical assessment and predictive diagnosis [15]. The potential of a digital twin is the rate of succession between simulation and the occurrence. Therefore, digital twins have three main functions [45]:

- Prediction: Analysis of the behaviour of the real system in advance of the actual runtime.
- Monitoring: Prediction of the real system state for the aim of monitoring and controlling the real system.
- Diagnosis: Analysis of unpredicted failures after real system operation.

Consequently, the objective of a digital twin is to facilitate decision-making processes and to enable decision automation through simulation of specific components and processes within the real system [45].

Digital Twin Characteristics		
No.	**Characteristic**	**Description**
1	Physical Entity	A ‘real-world’ artefact.
2	Virtual Entity	A computer generated representation of the physical artefact.
3	Physical Environment	The measurable ‘real-world’ environment in which the physical entity exists.
4	Virtual Environment	Any number of virtual ‘worlds’ or simulations that replicate the state of the physical environment and designed for specific use cases.
5	Fidelity	The number of parameters transferred between the physical and virtual entities, their accuracy, and their level of abstraction.
6	State	The current value of all parameters of either the physical or virtual entity/environment.
7	Parameters	The types of data, information, and processes transferred between entities.
8	Physical-to-Virtual Connection	The connection from the physical to the virtual environment.
9	Virtual-to-Physical Connection	The connection from the virtual to the physical environment.
10	Twinning Rate	The act of synchronisation between the two entities and the rate with which synchronisation occurs.
11	Physical Processes	The physical purposes and process within which the physical entity engages.
12	Virtual Processes	The computational techniques employed within the virtual-world.

Table 2.1: 12 Characteristics of the digital twin [12].

2.4.1 Characteristics

While, the digital twin has significantly increased in interest over the past years, with a growth of visions and potential benefits, so did the number of related publications, processes and concepts. Consequently, D. Jones et al. performed a literature review to gain a consistent view on what the digital twin is. As a result, the authors were able to define 12 digital twin characteristics: physical entity, virtual entity; physical environment, virtual environment, state, realisation, metrology, twinning, twinning rate, physical-to-virtual connection, virtual-to-physical connection, physical processes and virtual processes [12]. In this paragraph these defined characteristics by D. Jones et al. will be elaborated.

The first digital twin characteristic is a physical entity. All digital twins need an artefact in the ’real-world’ to ’twin’, such as vehicles, models, systems, or components of systems. A virtual entity is the second characteristic and which existence is in cyber-space with respect to its physical entity. Multiple virtual entities may be present in a digital twin, all with a certain purpose, such as scheduling, or monitoring. Third, a physical environment is required to be able to operate. This physical environment refers to a ’real-world’ space whereof specific environmental details are measured and transferred into the virtual twin to provide an accurate virtual environment for optimization, simulation and decision making. In order to be more specific, the physical environment includes all measurable parameters that have an effect on the system. The virtual environment is the twinned physical environment in the digital domain and can be achieved by sensors, that measurements the key parameters in the physical environment. The virtual environment also refers to the underlying technology, such as the database or cloud platform [12].

The fifth characteristic refers to the system parameters, which can be the types of data, information and processes that are transferred between the physical and virtual twins. The next digital twin characteristic is fidelity, which describes the number of parameters, their accuracy and level of abstraction. The state points out to the current values of the measured parameters of the physical and virtual twins. Real-time state estimation and prediction of past, current and future states are considered by the state of both physical and virtual twins. These states are connected by the characteristics physical-to-virtual and virtual-to-physical connections. The physical-to-virtual connection provides the update of the virtual parameters to reflect the values of the physical parameters. These connections can be made by IoT sensors, web-services and 5G.

The physical-to-virtual connection consists of two phases: 1. the metrology phase, in which the current state of the physical entity is measured and 2. the realisation phase, in which the state of the virtual entity is updated by the measured physical state. The virtual-to-physical connection is expressed as the information flow from the virtual to the physical entity. This is necessary in order to control the physical entity. Besides, the physical-to-virtual connection the virtual-to-physical connection also contains a metrology and realisation phase. However, in the latter the metrology phase refers to determine an optimal set of parameters within the virtual domain for the physical domain. In this realization phase the difference between the new optimal parameter values and the existing state is calculated and so the physical entity will be updated according to this difference [12].

The tenth characteristic is the twinning rate of the digital twin, which refers to synchronization of the physical and virtual states. Preferably, the physical and virtual states have the same parameter values. When this occurs, it can be stated that the entities are 'twinned'. Together with the physical-to-virtual connection the virtual-to-physical connection enables a continuous optimization cycle, where possible states can be predicted, monitored and analyzed. An important aspect of the digital twin is the collection and utilization of historical data, which means that the digital twin can learn from its past [12].

The last digital twin characteristics described, are physical and virtual processes. They introduce the activities that are conducted by the physical entity (within the physical environment) and the virtual entity (within the virtual environment). In general, these activities include simulation, modelling and optimization, monitoring, prediction and analysis of 'what-if' scenarios. Table 2.1 gives an overview of the digital twin characteristics with a short description and Figure 2.7 shows the twinning processes and the inter-relations of characteristics within the digital twin [12].

2.4.2 Level of Integration

As previously mentioned, the digital twin is able to increase the intelligence of a CPPS, or any other system, by facilitating decision-making processes through simulation of processes in a real, physical environment. For making this possible, models have to be fed with real-time or near real-time data referring to the current states to run simulation experiments [36]. Elements in the physical and virtual environments are connected through sensors, actuators and communication systems that provide the coupling of the operational data with the digital models. As the digital twin label has extremely increased in popularity. Therefore, it is important to distinguish different meanings with regard to the digital twin term. The extend to which these data flows are automated, makes three levels of integration and distinguish the digital twin differences [27].

- Digital Model: Data flows are regulated manually and state changes of the physical entity do not directly affect the virtual entity's state and the other way around. This is mostly for simulation purposes.
- Digital Shadow: Data flows are regulated automatically and state changes of the physical entity do not directly affect the virtual entity's state or the other way around.
- Digital Twin: Data flows are regulated automatically and state changes of both the physical and virtual entity affect one another. This is for controlling purposes.

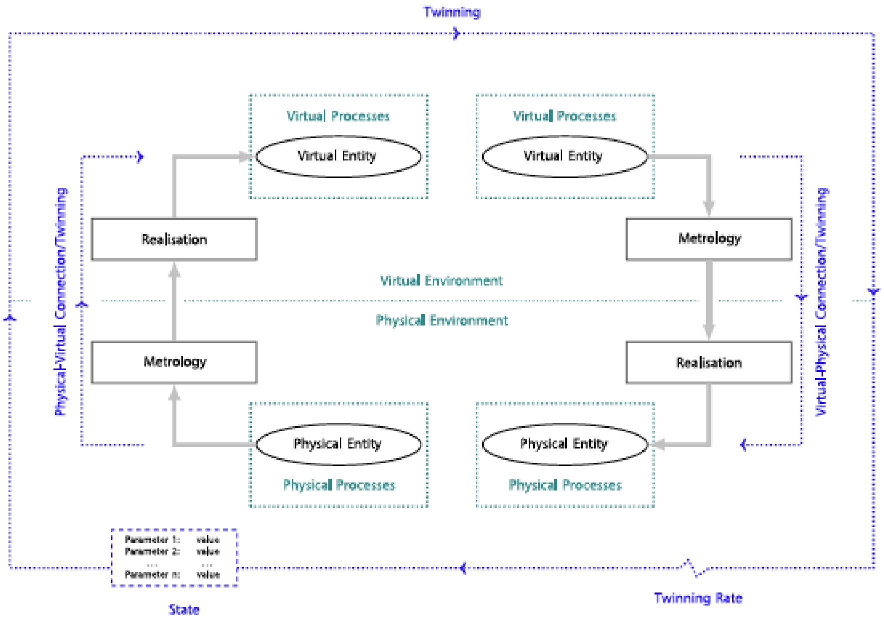


Figure 2.7: Twinning process and its characteristic inter-relations [12]

Therefore, the digital twin can be a controlling instance which is able to provide forecasting and decision making. Decision making is enabled by a set of actions which can be executed to optimally control the physical system, resulting in higher efficiency, accuracy and economic interest [27]. In addition, a digital twin can be seen as an integral part of CPS in a CPPS or another environment, and belongs to a relatively new system named Digital Family. Besides the digital twins, digital models and digital shadows belong to the digital family. Figure 2.8 presents a digital family with its systems and their elements.

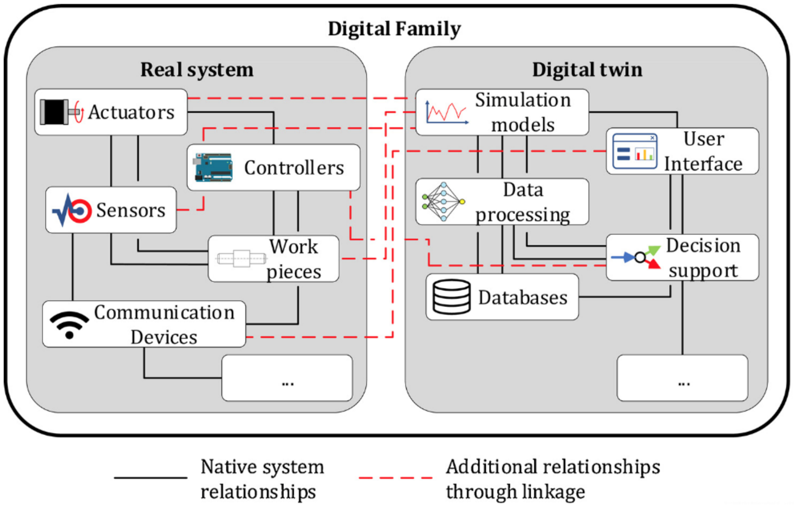


Figure 2.8: CPS and digital twin, in each level of integration, form a digital family [45]

As previously explained, CPS consists of transducers, such as sensors, actuators and IT systems. While the digital twin contains simulation models and decision support models. Furthermore, existing literature shows that systems and elements within a digital family are addressed to multiple disciplines, such as mechanics, software, communication and electronics.

2.4.3 State-of-the-Art

Although the concept is invented a while ago, the digital twin is seen as a relatively new research field. In literature multiple potential benefits are described relating the digital twin concept. D. Jones et al. [12] performed a systematic literature review by screening all existing papers by searching for the term 'digital twin' and categorized the perceived benefits. The benefits that come up are: reducing costs, risk and design time, complexity and reconfiguration time, improving after-sales service, efficiency, maintenance decision making, security, safety and reliability, manufacturing management, processes and tools, enhancing flexibility and competitiveness of manufacturing system and finally, the fostering of innovation.

In addition, in literature certain use cases for digital twin application can be found. D. Jones et al. [12] categorises and defines the identified use cases. The bulk of these use cases are manufacturing related, with a few cases that are linked to Industry 4.0, smart manufacturing and learning, product design (bicycle, pump and automotive wiring harness), model-based engineering and 5G communication for multiple systems whereof one paper addressed to digital twin application in the agriculture supply chain [26].

Briefly put, a CLSC supplied with RPM, can be seen as a material handling system with material flows. In literature, the majority of CPPS material handling systems focuses on shop-floor or entire manufacturing systems. Some work is done by Zhang et al. [20] by applying a digital twin for glass manufacturing line optimization. Bottani et al. [7] purposed a digital twin of a production system. Urbina Coronado et al. structured a digital twin of a shop floor for the production and control. M. Glatt et al. [45] modelled and implemented a digital twin of material flows based on physics simulation. However, research lacks in potential digital twin use cases in the supply chain, especially in the CLSC.

2.5 Conclusion

Because of the importance of describing how research is related to prior research, existing relevant scientific literature is reviewed in this chapter. By context and requirements analysis performed in the previous chapter, it can be concluded that performance improvement of Heineken's considered supply chain is necessary. Furthermore, the high-potential and state-of-the-art concept of a digital twin is found to be explored as a means of improving performance of physical entities or systems by supporting advanced growing technologies. Therefore, literature on how a digital twin is defined is reviewed, with its functions and characteristics, and state-of-the art applications.

Furthermore, literature is reviewed on how supply chains driven by returnable packaging are organized including their related performance measurements. In another section, literature regarding predictability in supply chains, is reviewed. This is done since the aim of this research is to explore how a digital twin can be used in order to control material flows in supply chains. Subsequently, existing supply chain performance measurements are inspected and explained. Supply chain performance indicators are important to identify, since performance measurements make explicit when supply chain improvement is gained.

This chapter has answered the following sub questions:

1. What are the characteristics of a supply chain driven by returnable packaging materials?

A supply chain driven by returnable packaging is generally a CLSC and utilizes two streams: 1. the classical forward logistics and 2. the reverse logistics with the intention to create value during the lifecycle of a certain product. The forward supply chain defines all the activities to meet customer requirements. But the reverse supply chain normally begins with the collection of products used by the end customers and thereafter, these used products are reintegrated into the supply chain. The latter has multiple key processes, such as item collection after use, inspection and sorting. Thereafter, the materials can be returned to the supply chain through repair, reuse, re-manufacturing and recycling or can be disposed [18].

For supply chain improvement and control, smart equipment items are deployed to supply information to the entire enterprise, resulting in better prediction, planning and scheduling decisions. Therefore, traceability and visibility of assets and RPM can be essential [34]. RFID technology is addressed as a fitting solution to improve visibility and information on the return of asset, which leads to better return predictability. Consequently, RFID implementation may support managing the RPM flow in a supply chain [33].

2. What are the key performance indicators of a supply chain driven by returnable packaging materials?

By measuring key performance indicators, a business can evaluate if its goals are being achieved. In literature, most performance analysis is done for forward logistics. But the increasing interest in extending the traditional supply chain to include reverse logistics, other performance measurements have become dominant, such as the occurrence of OOS situations, RPM cycle times, CAPEX and OPEX. The KPIs can be quantified with use of RFID measurements.

3. What is a Digital Twin?

The digital twin is generally a digital replica of a physical entity that contains its characteristics, parameters, conditions and behaviour through models and data. The latter refers to data connections between the physical and digital entity [56]. More specifically, a digital twin uses models combined with various data to interpret and to predict the behavior of a real system. They are described in literature mostly for the operations of a cyber physical production environment. Digital twins have the potential to increase the intelligence of such an environment by performance optimizations, analytical assessment and predictive diagnosis [15]. Digital twins have three main functions [45]: prediction, monitoring and diagnosis. Consequently, the objective of a digital twin is to facilitate decision-making processes and to enable decision automation through simulation of specific components and processes within the real system [45]. As the digital twin has significantly increased in interest over the last years, a consistent view on the digital twin is provided by twelve defining characteristics. These characteristics are: physical entity, virtual entity, physical environment, virtual environment, fidelity, state, parameters, twinning rate, physical-to-virtual connection, virtual-to-physical connection, physical processes and virtual processes [12].

In conclusion, despite the described importance and potential of digital twins in literature, few approaches leave the conceptual and theoretical level to indicate benefits of digital twins in practice. There are very few examples of validation, verification and quantification of potential benefits relating to existing processes and systems, including substantial improvement over the current norms, described. Therefore, it can be concluded that there is a lack of research regarding the connection between digital and physical worlds in supply chains and there is no digital control model from a digital twin perspective for RPM via RFID gateway measurements in a reverse supply chain found in literature. Hence, a research gap is found.

Part III

MODEL THE SYSTEM

Chapter 3

Analysis of Current State

In order to model a system, current system states are analyzed to determine how they operate and perform. This chapter provides an overview of the current structure of the investigated supply chain by analyzing current operations and processes, such as material and information flows, inventory and stock levels, planning and the stakeholders involved. By the end of this chapter the following sub question can be answered:

4. How does the supply chain driven by returnable packaging materials currently operate and perform?

3.1 Company Background: Heineken

In 1873, Gerard Heineken discovered he'd had a passion for brewing beer, started building a brewery in Amsterdam and worked hard to refine the recipe for the first 'premium' pilsener of the Netherlands. The news got around very quickly and before he knew, the name Heineken became a national symbol for quality. In the next 140 years the Heineken brand expanded and is worldwide known for its premium quality and excellent marketing. And today still, are there 25 million glasses of Heineken served in 192 countries in the world. Except for producing premium quality products, Heineken strives to drive E2E productivity across the operations in the company [23].

Heineken Netherlands Supply (HNS), the operating company (OPCO) of Heineken Nederland (HNL), is responsible for the production of all domestic and export products [22]. 70% of the produced volumes by HNS is for export. With an annual production of 18 mhL of beer in 2019, HNS has more than 1500 different types of Stock Keeping Units SKUs and brews in three different breweries in the Netherlands [43]:

- **Brewery in Zoeterwoude**: This brewery is named 'The Flexible Global Brewery' the largest of the three and mainly used to produce high volumes of beer.
- **Brewery in Den Bosch**: This brewery is the second largest and produces more than 40 sorts of beer. The beer production for the German export occurs in Den Bosch.
- **Brewery in Wijlre**: This brewery is the smallest one and produces mainly Brand beer.

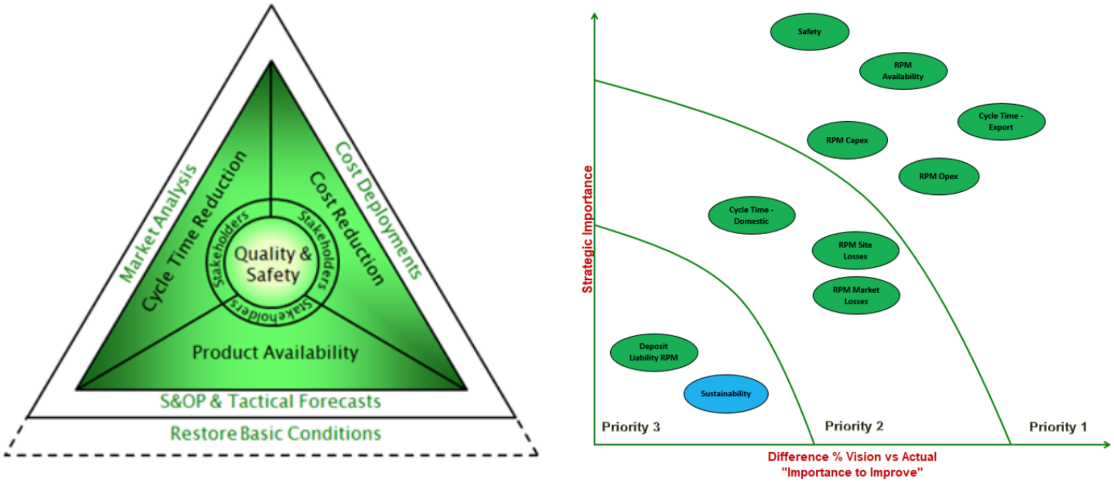
Heineken Germany (HGER) is one of the customers of HNS. HNS produces 92% of the German volumes and the volumes are expected to grow with 24% until 2022. HGER supplies the German market and was founded in 2008 in Munich. Today the head office is located in Berlin. Since

HGER does not brew Heineken products, their main activities are marketing and sales for the German market. HGER orders the required Heineken products for the German market through the HNS's CS&L department.

At HNS the department Customer Service and Logistics (CS&L) controls that all logistics and customer demands are met on time and with the highest level of service. The CSL department has various tasks and is organized in different sub- departments, such as market demand management, planning, export and operations. The planning department has a Returnable Packaging Materials (RPM) supply chain management division, that is responsible for all RPM development and investments. With regards to the volumes of beer sold on the German market, 96% is sold in RPM. The CS&L planning department responsible for RPM, has a multiple vision approach with strategic objectives with regards to the use of RPM, see Figure 3.1a.

One of the strategic objectives is reduction of the cycle time of the RPM based on market analysis. The reduction of the RPM cycle time results in lower maintenance costs and less capital investment since the pool size of RPM can be reduced. Product availability is another strategic objective and based on Strategic and Operational Planning S&OP and tactical forecasts. Ensuring RPM availability prevents out-of-stock situations (OOS). OOS situations lead to unmet customer demand and can damage the reputation of the Heineken brand. The last strategic objective is a constant drive towards further cost reduction based on cost deployments. The multiple vision approach has uses one overall vision which is the production of high quality products and ensure safe operations.

Under these visions, the RPM community at HNS ranks their yearly strategic priorities (Figure 3.1b). For 2020 the key priorities are consecutively, safety, RPM availability, RPM cycle time, RPM CAPEX and OPEX. For as far as product availability and safety is concerned, the RPM department has a zero OOS situation and a zero accident objective.



(a)

(b)

Figure 3.1: Visions (a) and priority graph (b) of the RPM department at HNS.

3.2 Returnable Packaging Materials at Heineken

RPM is usually reused and undergoes multiple cycles of usage throughout the CLSC. As explained in Section 2.1, in CLSC Forward Logistics (FL) and Reverse Logistics (RL) are combined. In this thesis FL includes Finished Products (FP), which refer to all products that are finished to be sold to customers after it is filled, labelled and packaged. A part of the RL includes the empty products, referred to as Empties. Empties are defined as RPM after consumption and transportation back to the brewery. Another important term used in this thesis is Stock Keeping Unit (SKU). In the inventory management discipline, a SKU is a particular type of item, which can be sold. The quantity of each SKU kept at a business is its stock inventory.

The RPM cycles through the supply chain. First RPM is filled at the brewery and is made a FP. The FP then is distributed to the market going through multiple stages of the supply chain. In the case of the HNS's production and distribution to the German market, FP passes through the distribution center in Den Bosch (LCDB), the Netherlands, the main warehouse in Werne, Germany and multiple regional distribution centers (DC) in Germany. Subsequently, after consumption, RPM is returned by consumers, redistributed and sorted. Sorting is the process during which empty RPM are being inspected for pollution. RPM pollution is the percentage of Empties that does not meet the required standards for reuse. After the sorting process, RPM returns back to the brewery. The RPM cycle throughout the CLSC is presented in Figure 3.2.

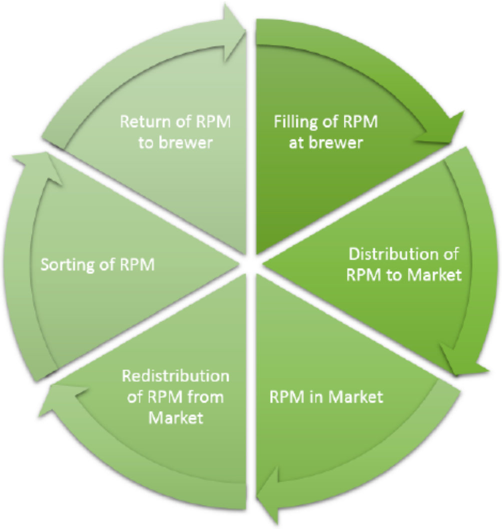


Figure 3.2: Use of RPM throughout the CLSC at Heineken.

RPM has several formats such as containers, pallets, kegs, shipping racks, crates and bottles. This thesis focuses on crates and bottles as RPM in CLSC. HNS delivers and sells five types of FP in crates and bottles to HGER which together make the main volume. Table 3.1 presents a description of each SKU with the sold volumes in hectoliters, the amount of crates and the percentage of the total sold volume to HGER. In this research study the focus is narrowed down to a specific crate type and its bottles the so called HKR Cluster Crates. This choice is made, because the largest percentage of the total volume for the German market is transported in Heineken HKR Cluster crate.

RPM SKU's for the German market.			
SKU no.	**Description**	**Crate quantity**	**Percentage of volume**
201488	Heineken 4x(6x330) HKR Cluster	1 087 753	33%
201934	Desperados 24x330 Plx	1 261 401	31%
201933	Desperados 4x(6x330) Plx	758 181	18%
200129	Heineken 28x250 HKR	278 957	9%
200148	Heineken 24x330 HKR	291 970	9%

Table 3.1: RPM crate and bottle SKUs at Heineken [43].

3.3 Process Description

3.3.1 System Structure

To provide a current state overview, the system structure is investigated and presented in this section with its locations and processes. Figure 3.3 visualizes the current stages in the CLSC between HNS and HGER and the crate flows between them. In this section RPM in the form of crates and bottles, are referred to as FP's or Empties. The grey colored box presents the German market. We have no insight in what happens to the RPM after it leaves Werne warehouse and as such the German market is considered a black box. The warehouse in Werne distributes to 31 different locations, where there are no data available. Inside this 'black box' Heineken has no direct influence on the logistics and therefore, the actual locations and amount of crate flows per week are not analyzed. The only relevant remark within the black box is the distinction between 'sorting' and 'unsorting' customers. The sorting customers sort out the bottles and corresponding crates,by means of discarding crown corks, straws and other pollution and make sure the returned crates have a sufficient quality for reuse. In conclusion, the scope of this research include the brewery and logistic center LCDB H&B in Den Bosch and the warehouse in Werne, Germany.

For the latter, it is important to keep in mind that there is an additional input and output flow of material towards the three H.Leiter GmbH locations, which will be eventually modelled as one. The five relevant stages of the considered CLSC are:

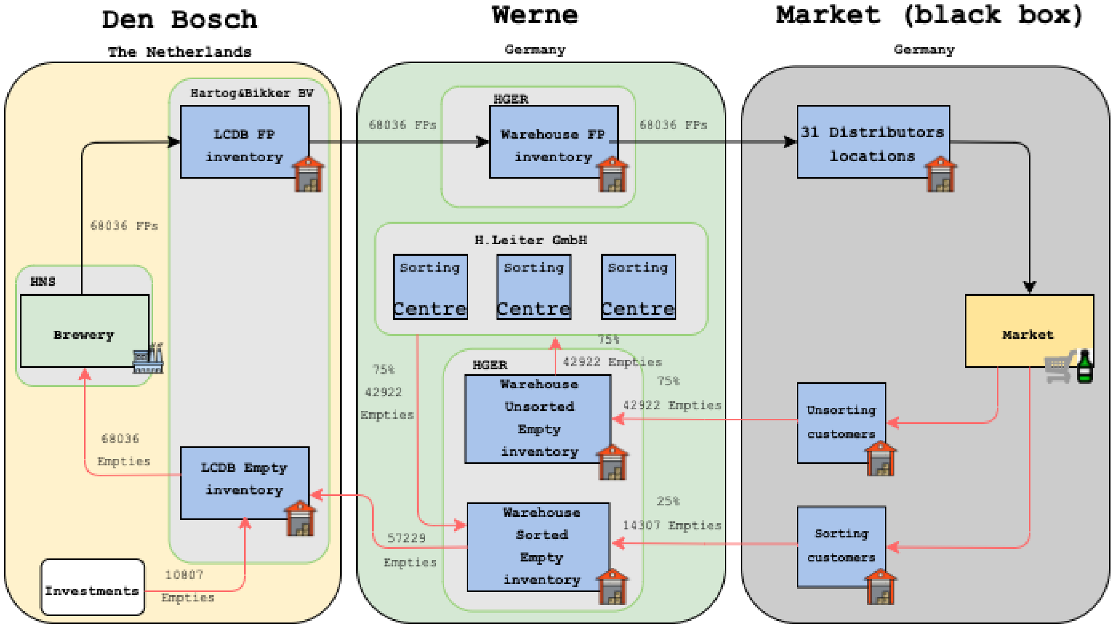


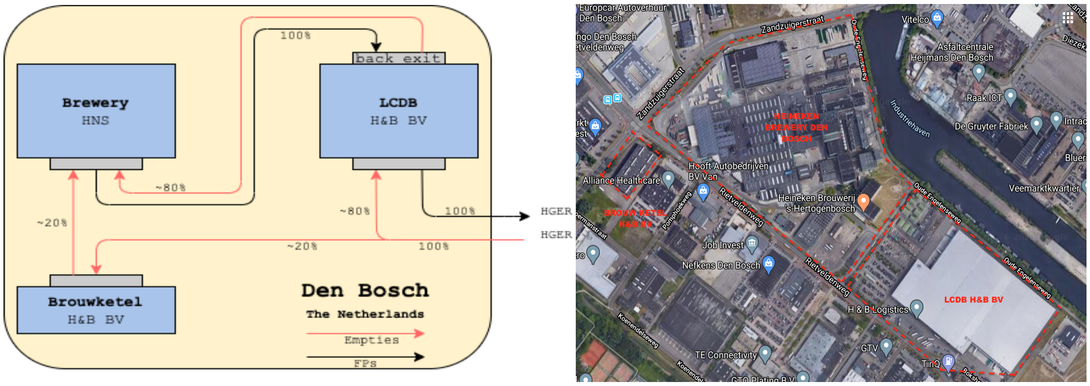
Figure 3.3: System structure including average crate flows per week.

- **Brewery in Den Bosch:** All the production for HGER occurs in the brewery in Den Bosch. FP are assembled by filling bottles with beer and subsequently packed in crates. After consumption sorted Empties eventually return to this brewery. After which they are being washed and maintained ready for being transformed into FPs again. The operation is executed by Heineken.
- **LCDB H&B in Den Bosch:** FPs enter the logistic centre in Den Bosch coming from the brewery. Transportation may occur by shuttle or truck. From the LCDB FPs are loaded into trucks and transported to Germany. In addition, Empties transported by truck coming from the warehouse in Germany enter the LCDB, where they are stored and transported to brewery. At the LCDB a third party is involved, H&B B.V.. They are responsible for the processes within the LCDB and provide the transportation between from and to the brewery.
- **Warehouse in Werne:** This warehouse belongs to HGER and at this location FPs and Empties are stored. All crate flows from and to the German market go through this the warehouse. Empties entering the warehouse location can be sorted or unsorted. The unsorted crates will be transported to a third party: H.Leiter GmbH.
- **Sorting Centers H.Leiter GmbH.:** H.Leiter GmbH. is a business which executes the crate sorting process. This process includes the unsorted Empties entering the sites and sorted Empties leaving the sites.
- **Market:** The German market includes distribution locations, wholesalers and retailers and is considered a black box in this thesis, as explained in 3.3.1.

From an analysis customer returns an average arrival rate of 57229 crates per week. Since, one pallet carries 40 Heineken HKR Cluster crates, this equals to 1430 pallets full of empties per week and can be divided in two crate flows: Empties entering the warehouse in Werne come from sorting customers and from unsorting customers. 25% of the total amount of customers sorts and 75% does not. This is contractual arranged. Hence, 75% of the total volume is transported to the sorting centers of H.Leiter GmbH.

3.3.2 Material Flows in Den Bosch

In Den Bosch H&B has multiple locations where trucks coming from HGER in Germany are unloaded and empty crates are being stored. Figure 3.5 presents the different locations and crate flows in Den Bosch. The left figure gives a schematic overview of the processes and the right figure gives the satellite top view of the territory gained via Google Maps. The LCDB is the main location and the largest one. Due to lack of capacity at the moment, H&B uses another storage location: de Brouwketel. Approximately, 80% of the total volume of crates used by the German market that enters the Den Bosch's sites is stored at the LCDB and 20% is stored at de Brouwketel. Subsequently, the Empties kept at the LCDB go to the brewery via another entrance of exit. The transportation between LCDB or de Brouwketel and the brewery is provided by H&B's logistic service. After both the streams enter the brewery, the Empties are checked, washed and reused by filling them with full bottles. From here it becomes FP again and will be transported to the LCDB again. The Brouwketel is only in use during RL. When, during FL FPs have to be transported to Germany, they do not go through the Brouwketel location. The process is shown by Figure 3.4a. Figure 3.4b gives an idea of the real distances between the various Den Bosch locations.



(a) (b)

Figure 3.4: Schematic overview of crate flows in Den Bosch (a) and real satellite top view by Google Maps of the locations in Den Bosch (b).

3.3.3 Material Flows in Werne

The warehouse of HGER is located in the region Werne in Germany. As previously described in Section 3.3.1, all the FPs produced for the German market come from HNS and go through HGER's warehouse in Werne. The market is considered a black box. The Empties picked up from the market can be sorted or unsorted. The unsorted Empties will go to sorting center of H.Leiter GmbH. All the logistic activities from and to this warehouse are provided by a third party, Bohnen Logistik. The warehouse has a capacity of storing 13800 pallets of FPs, which results in 45000 hL, and 10000 pallets of Empties.

After trucks enter the site, cargo is manually registered driven around the warehouse to their unloading and loading position. The material flows entering and exiting the warehouse location are presented in Figure 3.5a. In addition, Figure 3.5b shows the Google Maps top view of the warehouse terrain and gives an idea of how the actual location looks like.

(a) (b)

Figure 3.5: Schematic overview of crate flows in Werne (a) and real satellite top view by Google Maps of the Werne location of HGER (b).

3.3.4 Planning

Beer production is the main driver of the considered CLSC with both HNS and HGER involved. Production is planned on three different levels; strategic, tactical and operational. The planning departments cooperate, to ensure smooth planning operations. The strategic department performs long-term planning taking Heineken's visions and missions into account. This long-term horizon stretches several years. Market trends and historical seasonality fuel strategic decisions. Strategic plans form a framework for the tactical plans. The tactical planning department takes care of short-term planning with a time span of couple of weeks and estimates how the strategic plan can be achieved by certain short-term actions.

If HNS requires RPM, the tactical planning department of HNS in charge. The reference RPM demand is based on the historical demand of one year before. HNS's tactical department updates HGER on the required Empties a few weeks ahead. When production for the German market is scheduled, the RPM required can be determined as well. And last, operational planning is done with a very short time span of approximately three weeks and is very detailed.

3.3.5 Inventory and Stock Levels

In this system there are various warehousing locations for the FP or Empties, LCDB in Den Bosch, the warehouse in Werne and a H.Leiter GmbH. sorting center in Lutgendortmund. These locations have the ability to store products, while at the brewery location there is minimal to no storage capacity available. In this casus, inventory takes only FP, sorted and unsorted Empties into account. As previously described, 3PL are involved. The LCDB location is managed by HB Logistics, the warehousing in Werne is provided by Bohnen Logistik GmbH and the sorting center is managed by H.Leiter GmbH. At both the LCDB and the warehouse in Werne, SAP software systems gather and manage data.

The maximum storage capacity in the warehouse in Werne is 10 000 pallets. One pallet carries 40 Heineken HKR Cluster crates. The utilization rate of the storage capacity in peak season (March - October) is normally 50% to 60%, while in low season (October - March) is 100% to 150%. This means that in low season there is structurally a storage shortage and HGER leases storage space near the warehouse to compensate this shortage. Table 3.2 gives an overview of these values. In this table, for the peak season an average stock of 55% is given and for both Empties and FP, while the stock in low season is presented at full capacity utilization (100%) for convenience reasons. At the warehouse in Werne, the average storage time of a FPs, sorted and unsorted Empties are sequentially 3.5 weeks, 9.3 days and 7.7 days (Table 3.3). The inventory cost at the warehouse is €1,49/pallet/week.

The maximum storage capacity at the LCDB in Den Bosch is 46 000 pallets, which results in 1 840 000 crates. Crates destined for the German market are about 20% of this volume, which results in 368 000 crates, whereof 50% are FP and 50% are Empties. According to HB there are no insights on stock level differences between peak and low season. The values for stock levels are provided by Table 3.2. As for the crate inventory days at the LCDB, these can be from 1 day up till 3 weeks according to HB. Therefore the average inventory days for both storage of FP, sorted and unsorted Empties are taken to be 10.5 days. Furthermore, no distinction is made between peak season and low season in average inventory days at the storage locations. Table 3.3 gives an overview of the inventory days of both locations. The inventory cost at the LCDB is €1,75/pallet/week.

Stock Levels		
Location	**Warehouse in Werne**	**LCDB in Den Bosch**
Maximum storage capacity [#crates]	952 000	1 840 000
Average stock peak season [#crates]	220 000 (Empties)/303 600 (FP)	184 000 (Empties)/184 000 (FP)
Average stock low season [#crates]	400 000 (Empties)/552 000 (FP)	184 000 (Empties)/184 000 (FP)

Table 3.2: Number of crates stored at different warehousing locations.

Inventory Days		
Location	**Warehouse in Werne**	**LCDB in Den Bosch**
Average storage time FP [#days]	24.5	10.5
Average storage time sorted Empties #[days]	9.3	10.5
Average storage time unsorted Empties [#days]	7.7	10.5

Table 3.3: Storage duration at different warehousing locations.

3.3.6 Transportation

In the previous sections the relevant locations and the material flows within these locations are described. Therefore, the material flows between the locations have to be analyzed, which include between the brewery and the LCDB, the LCDB and the Werne warehouse, the Werne warehouse and the sorting center, and lastly the warehouse and a regional DC. First, the crate flows between the brewery and the LCDB in Den Bosch are analyzed.The two locations are positioned next to each other and the logistical operations between the two are exploited by HB Logistics. When production is scheduled HB will supply the required amount of Empties to the brewery with a Roll-on Roll-off trailer (RoRo). After the Empties are unloaded at the brewery, the RoRo trailer will be loaded with FP and transported to the LCDB. Here the FP are unloaded and stored in the warehouse. This cycle operates continuously.

The FP and Empties between the LCDB in Den Bosch and the warehouse in Werne are transported 220 km by trucks. This transportation is carried out by either by H&B Logistics or Bohnen Logistik GmbH. The third relevant transportation route is the one from the warehouse in Werne to the sorting centers of H.Leiter GmbH. H.Leiter GmbH has four sorting centers located in Berka/Werra, Hamminkeln, Wenden and Lutgendortmund. The largest volume of the total unsorted volumes is sorted by the location in Lutgendortmund. Therefore, unsorted Empties travel from the warehouse to this sorting center, where they are sorted and stored for approximately 2 weeks before they are transported back to the warehouse. The distance between the two is 52.3 km. The last relevant routes are between the warehouse in Werne and the DC. Since there are 31 DC in the system, only the largest one is considered: Winkels Getranke Logistik in Sachsenheim. This particular DC has the largest volume split of the total volume for the German market and the travelling distance is

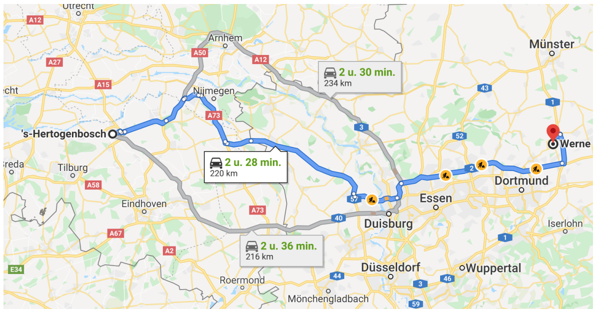
404 km. In Table 3.4 the relevant travelling distances in kilometers and the approximate travelling time in hours are summarized, while Figure 3.6 shows the routes. In both, the transportation information between the brewery and the LCDB are not included, since these are located next to each other.

Travelling times and distances		
Route	**Travelling distance [km]**	**Travelling time [h]**
LCDB - Warehouse	220	2.47
Warehouse - Sorting Center H.Leiter GmbH	52.3	0.65
Warehouse - DC	404	4.55

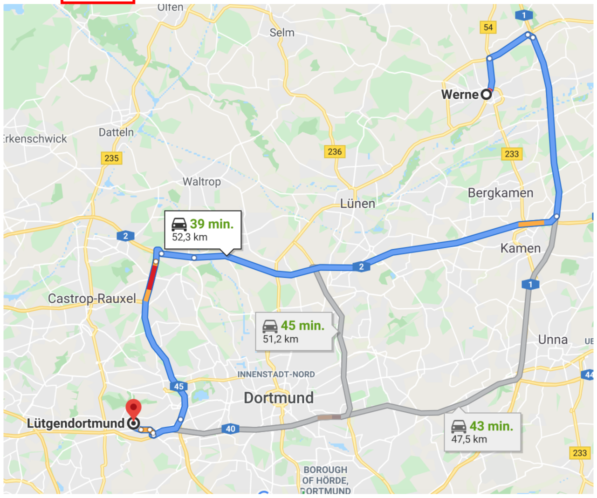
Table 3.4: Travelling times and distances between the different locations.

3.4 Information Flows

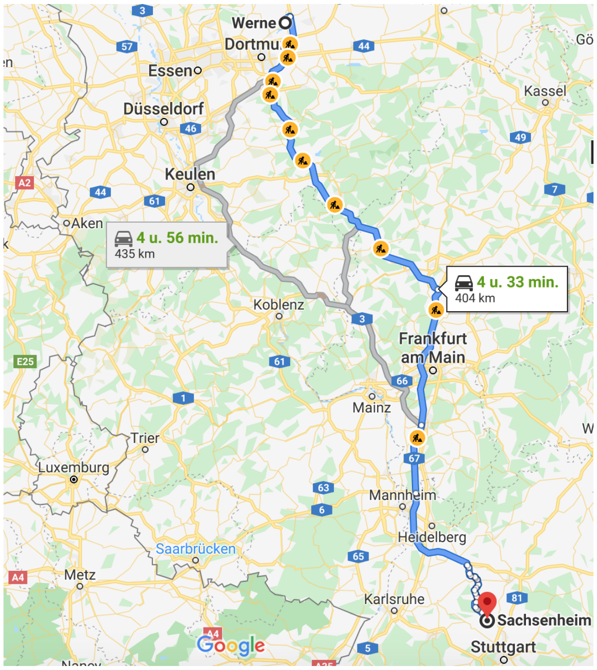
As mentioned in Section 3.3.4 production is the main driver of the relevant CLSC. Production is planned by the tactical department of CS&L of HNS in cooperation with HGER on basis of production information of the previous year. When production for the German market is scheduled, the amount of required crates can be determined. HNS manually updates HGER on the required Empties for the coming weeks. Between the brewery and the LCDB H&B in Den Bosch communication about short-term required Empties occur.



(a) LCDB in Den Bosch - the warehouse in Werne.



(b) The warehouse in Werne - H.Leiter GmbH. in Lutgendortmund.



(c) The warehouse in Werne - DC in Sachsenheim.

Figure 3.6: Route and travelling time between the locations by GoogleMaps.

3.5 Stakeholders

Table 3.5 gives an overview of the stakeholder involved in the system and is structured by location and organization.

Stakeholders	
Stakeholder	**Description**
Den Bosch	
HNS	
Tactical planning department	Provides all tactical planning decisions, scope is within the upcoming 6 weeks. Has interest in a shorter cycle time so that they can plan more accurately. Changes in the supply chain will change their planning operations.
Operational planning department	Short term operational planning has interest in a sufficient supply of empties in the LCDB.
RPM production and packaging department	Fewer changes in planning will affect performance of production positively. The quality of sorting and availability of empties is also of great importance to perform the production plan.
RPM development department	Responsible for all RPM of HNS, so also the SKUs used by HGER. Takes care of investments in RPM. Initiator of this research.
Customer service	Arranges all customer contact with HGER. Develops a customer supplier relationship. Is involved in all projects regarding products that are produced by HNS and shipped to HGER.
H&B BV	Provide logistical solutions at the LCDB. Changes in the supply chain will potentially change H&B it work methods.
Werne	
HGER	
RPM planning department	Arranges all contact with the planning departments of HNS. Provides them with stock levels and will take care of requests of HNS for empty returns to the LCDB. Arranges all contact with Sostmeier at the Wesel warehouse operation.
Customer service	Provides customer service on the German side. Has contact with all retialers, wholesalers and other customers that order products from HGER.
Other	
Bohnen Logistik GmbH.	The same as H&B all logistical operations in Wesel are provided by them. Any change will affect this stakeholders way of work.
H.Leiter GmbH.	The sorter that processes almost 75% of total volume of RPM

Table 3.5: Stakeholders involved in the system [43].

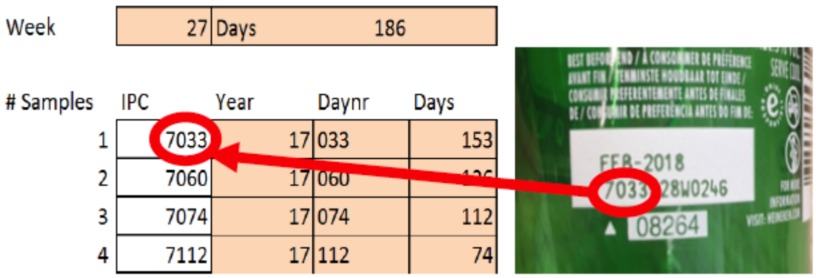
3.6 Current State Performance Analysis

In the previous chapter, Section 2.3, RL services such as customer satisfaction, internal businesses, financial performance, transport and warehousing and potential related KPIs are explained. In this section the performance of the supply chain driven by returnable packaging is analyzed using its KPIs. These performance indicators are determined by the combination of literature study, previous research done with analysis of the corresponding supply chain and interviews with RPM managers at Heineken. The KPIs relevant for this research are:

- Cycle time
- Inventory days
- Number of OOS situations
- Throughput
- CAPEX
- OPEX

One of the relevant performance measurements is cycle time. Cycle time represents the total time needed to complete the E2E process. In the case of the CLSC at HNS and HGER the cycle time refers to the duration of one RPM unit, in the form of a crate, from when it is filled at the brewery in Den Bosch to a FP to when it returns back to the brewery as an Emptie. An agile and efficient supply chain has a short cycle time.

One of the relevant performance measurements is cycle time. Cycle time represents the total time needed to complete the E2E process. In the case of the CLSC at HNS and HGER the cycle time refers to the duration it takes for one RPM unit to leave the brewery in Den Bosch as a FP and return back to the brewery as an Empty. An agile and efficient supply chain has a short cycle time. How the cycle time of crates circulating through the supply chain is measured currently, is as follows: at the brewery in Den Bosch, after the bottles are filled with beer, the bottles are labelled and placed in the corresponding crate. On every label the production date is noted. After the crate went through all stages of the CLSC and returns back to the brewery the label with the production date is noted again. This is shown in Figure 3.7. Consequently, the cycle time is measured. However, this is an estimation of the crate cycle time and not an accurate measure, since the cycle time of a bottle is measured and not the crate. The averaged cycle time measured this way is 25 weeks. The second performance measure is throughput rate and refers to the number of crates handled per operating hours per stage or location of the CLSC. This KPI enables us to check how fast the CLSC processes RPM at the LCDB and brewery in Den Bosch, Netherlands and the warehouse in Werne, Germany.



Week	27	Days	186

# Samples	IPC	Year	Daynr	Days
1	7033	17	033	153
2	7060	17	060	126
3	7074	17	074	112
4	7112	17	112	74

Figure 3.7: Cycle time measured by bottle production date registration.

Inventory days is defined as the time one SKU is kept in stock at a location. The average inventory in this case study includes the FP and Empties of HKR Cluster crates. HGER targets a value of 5 inventory days at the warehouse in Werne. The sum of all inventory days, time for transport and time RPM is in the market is the cycle time. The values of these days of inventory per location are determined by analysis and interviews with stakeholders and are rounded to an integer in days and are presented in Table 3.6.

Inventory Days	
Location	**Days**
FL	
LCDB	11
Warehouse	25
RL sorted	
LCDB	11
Warehouse	9
RL unsorted	
LCDB	11
Warehouse	8
Sorting Center H.Leiter GmbH.	14

Table 3.6: Inventory Days of locations in the HNS and HGER clsc.

The third performance measure has to do with the ability to supply RPM. Availability of RPM is important to be able to transport beer. If crates are OOS, the beer production can as such can continue, but FPs are not able to be supplied to customers. Therefore, demand is not met and could result in unsatisfied customers, brand damage and loss of sales. The ability to supply RPM is not easy to measure. Therefore, the KPI taken is the number of OOS. At the inventory locations LCDB in Den Bosch and warehouse in Werne OOS occur. The throughput refers to the amount of SKUs handled at a certain location per hour. Currently, there is a lack of information available to determine the throughput at the relevant locations. CAPEX and OPEX are the financial KPIs. As previously explained the CAPEX refer to long-term investments, such as investments in RPM, while OPEX refer to short-term expenses such as rent, property taxes and Cost of Goods Sold (COGS). In this research the OPEX refers to the handling and storage costs. When CAPEX and OPEX are decreasing, the supply chain is performing better under the condition that no OOS occurs and customer demand is met.

3.7 Conclusion

This chapter provides an overview of the current structure of the supply chain that was investigated by analyzing its operations and processes, such as the material and information flows, inventory and stock levels, planning process and identifying its corresponding stakeholders. In addition the performance of the investigated supply chain was analyzed and consequently the sub question was answered:

4. How does the supply chain driven by returnable packaging materials currently operate and perform?

At the investigated Heineken CLSC, the RPM circulates through the supply chain. First, bottles are filled at the brewery and put into crates creating a FP. Then, FPs are distributed to the market going through multiple stages of the supply chain. In case of HNS's production for - and distribution to the German market, the RPM in the form of crates crosses the following stages: the brewery and a logistic center in Den Bosch, the Netherlands, a warehouse in Werne, Germany, a number of regional distribution centers in Germany, wholesalers and retailers in Germany. Subsequently, RPM will be in the market for some time and eventually returned by consumers. After the RPM is returned it is redistributed. Before redistribution the RPM needs to be sorted. Sorting is the process of crates filled with empty bottles being inspected for pollution. After the sorting process, crates are ready to be returned to the brewery. In this research, the market, as defined by the direct customers of HGER that pick-up FPs or return Empties, is considered a black box. This is because the company barely has any influence on performance related events in the market. Hence, it makes it difficult to predict occurrences in the market. In contrast, the operations at the brewery, the LCDB and warehouse are under direct control of the company and can as such be influenced or improved. Therefore process analysis is done at these three main sites of the supply chain.

From the current state analysis, it can be concluded that the planning period is relatively long. The process is done manually and with very little use of ICT possibilities. Additionally, prediction of crate returns is difficult since it depends on consumer behavior. Because prediction of the return rates is difficult, Heineken utilizes a large crate pool to prevent possible OOS situations. OOS situations can result in unsatisfied customers, brand damage and loss of sales, which should be prevented at all times. The use of the large amount of crates for the German market, results in large safety stocks, long average cycle times, many days of inventory and low throughput rates, and consequently, in high CAPEX and OPEX.

Nevertheless, not only for the FL but also for the RL of the supply chain OOS situations of Empties at the brewery occur. In this thesis, the reverse supply chain of the CLSC is primarily investigated. This part of the supply chain is driven by returnable packaging. Returnable packaging OOS should be prevented to avoid a production stop or excess RPM purchase. Heineken's reverse supply chain can be considered to be a push-model supply chain. Each supply chain agent at the various locations has its own priorities and preferred inventory level. Therefore the crates are pushed through the supply chain where it is stored till it needs to be available for production. It is very well possible that the current state is suboptimal and leads to unnecessary inventory costs. Table 3.7 provides the values of the current KPI. Unfortunately, several KPI could not be determined due to a lack of data provided. These are the occurrence of OOS situations and the throughput rate of the various locations. As a result the CAPEX for investments in additional crates to avoid OOS situations are unknown too. The OPEX is calculated by the storage costs per crate per day per location multiplied by the averaged inventory days per location and the average inventory level in peak and low season per location. All current KPI's are based on average values.

Moreover, a lack of data visibility and transparency for planning departments and coordination between supply chain agents was identified. It can be concluded that there is no centralized control of inventory levels. As digital twins have the potential to predict, monitor and diagnose physical material flows, they could lead to supply chain performance improvement. Development of a digital twin for this particular supply chain is driven by the motivation that quality and performance can be improved.

Current KPI values	
KPI	**Value**
Operational	
Cycle time	25 weeks
Inventory days warehouse RL sorted	25 days
Inventory days LCDB RL sorted	9 days
OOS situations	*
Throughput	*
Financial	
CAPEX: purchase new crate	*
OPEX (peak season, RL sorted) based on storage costs warehouse	€2.634
OPEX (peak season, RL sorted) based on storage costs LCDB	€12.650
OPEX (low season, RL sorted) based on storage costs RL unsorted warehouse	€4.789
OPEX (low season, RL sorted) based on storage costs RL sorted LCDB	€12.650

Table 3.7: Current operational and financial KPI based on analysis of the current state (*unknown).

Chapter 4

Method

In this chapter the link between the existing scientific literature discussed in Chapter 2 and the analysis of the considered current supply chain in Chapter 3 is made. By the literature research performed, it became clear that digital twins are found to be explored by means of improving performance of physical entities by supporting advanced growing technologies, while using models combined with various data to interpret and to predict the behavior of a real system. Therefore, digital twins have the potential to increase the intelligence of a specific environment, in this research case: a specific supply chain driven by returnable packaging. After the current state analysis of Heineken's relevant supply chain, it became clear that current prediction of crate returns is based on occurrences of the year before and there is a lack of information sharing within and between layers of the organization. In this chapter a method for first steps towards digital twin design for the considered supply chain is proposed, according to the 'Model the System' task of the SIMILAR approach of the Systems Engineering methodology. In this task the first steps towards system design will be done by model development for alternative designs and the model for the preferred alternative will be expanded. Therefore, system architecture is defined and functional analysis is performed. The sub research questions to be answered in this chapter is:

5. How can the RFID gateways contribute to supply chain control?

6. How can a Digital Twin be modelled for controlling returnable packaging material flows in a supply chain?

The proposed method for the digital twin design in this chapter, is combining the digital twin function requirements and characteristics with the knowledge obtained by literature research. And apply this in the supply chain that we are considering with the aim to manage asset control.

4.1 Digital Supply Chain Twin

A digital twin can be seen as a digital representation of an active and real object, machine or service that includes its characteristics, conditions and properties through models and is provided by sensor data and historical data to mirror its behaviours [45]. Application of a digital twin can be considered as key requirement for the operation of a CPPS, discussed in Section 2.4. In this research, first steps towards a Cyber Physical Supply System (CPSS) are made, with investigating the potential intelligence increase through analytical assessment, predictive diagnosis and performance optimization. Accordingly, to create a digital twin requires modelling which combines simulation, optimization and data analytics to enable its functions. The prediction function includes analysis of the behavior of the supply chain before actual run-time. Planned crate flow processes are simulated prior to the actual execution on the supply chain system. Consequently, supply chain parameters can be tested, while potential impacts on the supply chain performance can be evaluated. The monitoring function enables optimization when models are enriched with real-time data from physical sources, such as RFID, which allows tracking and supervision of the current state of crate flows, inventory and production. RFID data is able to feed live positional data from crates in the supply chain and can provide inputs to simulations. While, supply chain performance and behavior diagnosis is used after a certain process has occurred by applying data analytics. Information about the movement of crates and its result on the supply chain system including problems that might have occurred, allows for adjustments in crate handling actions. Connecting such a described digital model to a real supply chain system in order to derive performance optimization leads to the concept of digital supply chain twins.

4.1.1 Requirements

The basis for the requirement definition are these three previously described digital twin functions. However, there are further requirements that need to be met, which are real system, simulation-based decision support, connectivity and control of the real system [45].

- Real system: The real system refers to an experimental supply chain which needs to be developed in a virtual environment. This supply chain reflects the physical supply chain behavior with use of a model. In this model varying transportation and inventory parameters must be allowed and the system requires to be realized as a CPS to establish digital twin applicability.
- Model-based decision support: This is an approach to make evidence based decisions, imitating existing processes by models. Simulation is the process of using a model to study the behavior and performance of an actual and is the essence of the digital twin and for a digital twin application, must allow prediction and reaction to disturbances. Besides, automated decision processes is preferred to minimize human intervention.
- Connectivity: This refers to the communication between the relevant systems in both ways and is preferably automated as far as possible. The combination of both connections allow for a continuous optimization cycle. Future supply chain states are predicted in the virtual environment, using current states measured by RFID and are optimized for a specific purpose. After the optimal set of virtual supply chain parameters are determined, these will be passed on to the physical environment. Physical entities respond to the change and the delta between the optimal state and the current state will be measured and communicated to the virtual environment.
- Control of the real system: Control of the system refers to the decisions of the simulation are required to be modified in such a way that allows to derive control inputs for the real system.

Based on these requirements and the discussed digital twin functions, a data-driven supply chain modelling framework is illustrated in Figure 4.1 of a digital supply chain twin for model-based decision making support purposes [13].

4.1.2 Modeling Framework

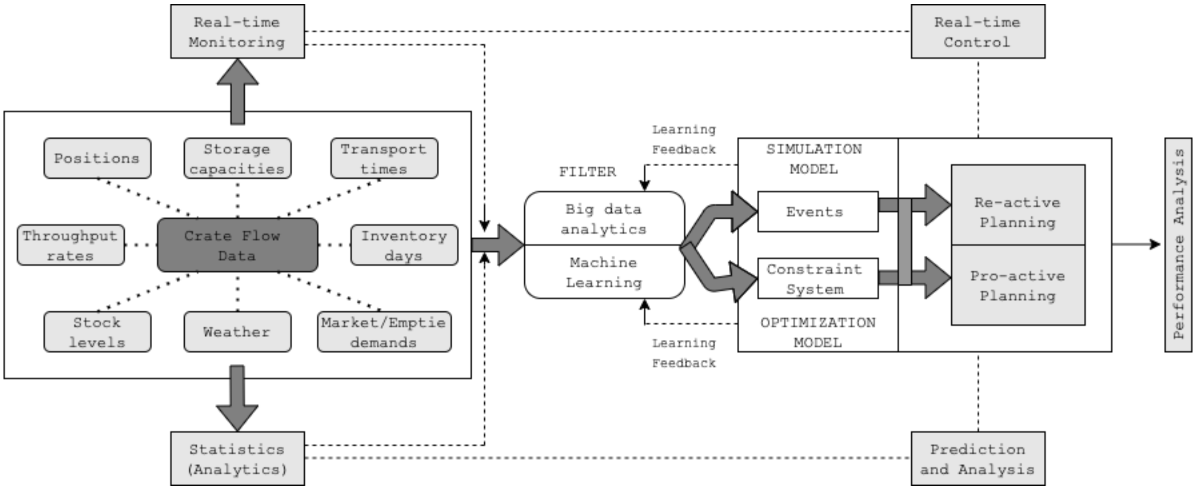


Figure 4.1: Digital supply chain twin for managing and controlling crate flows.

Figure 4.2 illustrates three domains of the supply chain digital twin for planning crate flows, which are crate identification and planning communication, the crate flow modelling in the supply chain and the performance impact analysis. The images used are from any LogistixTM software. The figure shows the mapping of relevant data gained by RFID measure gateways into the supply chain model. Besides historical data, real-time crate visibility data in the supply chain can enable proactive planning. After data is used as input in the supply chain model, the impact on the supply chain performance can be assessed.

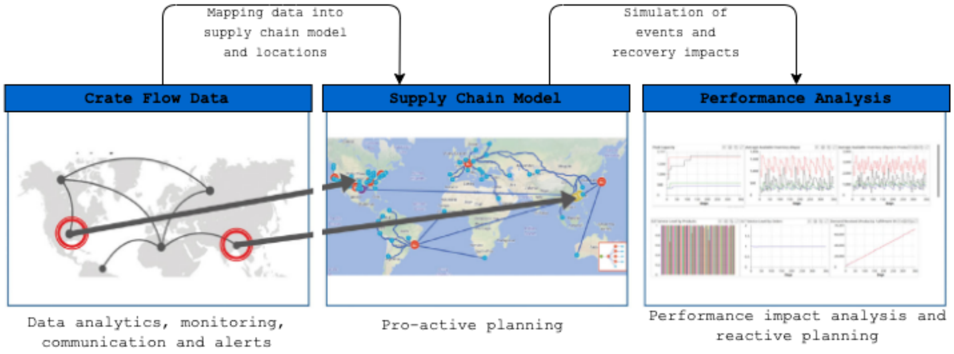


Figure 4.2: Interrelations between crate flow data, modelling, and performance analysis.

Digital supply chain twins for managing and controlling crate flows are found to have potential of improving the supply chain performance by using models to interpret and predict behavior and therefore, increase the intelligence of the system. In the considered supply chain crate returns are difficult to predict, since it depends on consumer behavior and this is hard to control. External factors such as weather and large events cause disturbances in the planned RPM flows. This can lead to OOS situations, longer delivery times and over-utilized storage capacities, which can result in additional costs and loss of sales as well as reduced consumer loyalty. Since the market and consumer behavior are difficult to control, it is the more reason to enable this control in those supply chain parts where it is possible to obtain information and manage actions. Crate visibility in the supply chain can be a first step in gathering relevant information on positional data. Obtaining positional data realized by application of RFID gateway measure points discussed in the next section.

The data provided by these RFID readers in the scanning gateways can be used as an input for the controller embedded in the digital twin. MPC is an advanced method of process control and used as a tool to capture and interpret the current state of the supply chain and use that current state to change future states. In the next chapter, a model predictive controller is designed and developed as a mean to control the processes in Heineken's supply chain.

4.2 RFID Scanning Gateways

As previously described and according to a papers found in literature (Section 2.2.1), RFID is proven to be a suitable technique for crate position measurements for the purpose of simulating material flows. In this thesis simulation is used as the process of using a model to study the behavior and performance of an actual system [55]. The crate position measurements can be made by identifying crates individually at specific locations in the supply chain, generating data and feeding this data into the digital supply chain twin model. RFID technology has the ability to make real-time measurements. Decision-making support models enriched with this real-time data can help to provide real-time model inputs for supply chain optimization. RFID readers can be fixed or handheld. The advantage of fixed RFID readers in gateways is that they can run fully automatic. In addition, RFID gateways have the ability to integrate a machine-learning model, that enables to identify the direction of materials going through the gateways, and as such determine whether materials are received or shipped out [17].

The tracking of crate positions in the supply chain, with use of these fixed RFID gateways, lead to reliable information on how many crates there are in the supply chain and at which stage. Consequently, these fixed RFID gateways provide information on storage capacity utilization at relevant locations, inventory days at relevant locations, transportation times between these locations, crate availability and improved information on the return of crates. The latter is caused by better return predictability as well as higher return rates [33]. Besides, information transparency within Heineken (HNS and HGER in this case) and their relevant stakeholders allows them to take actions to optimize the flow of crates. For the four stages in the supply chain, explained in Section 3.3, is analyzed what potential RFID reader positions could be for the design of RFID scanning gateways. Figures 4.3 and 4.4 on the next page, present images of the potential positions of the RFID gateways at the considered locations.

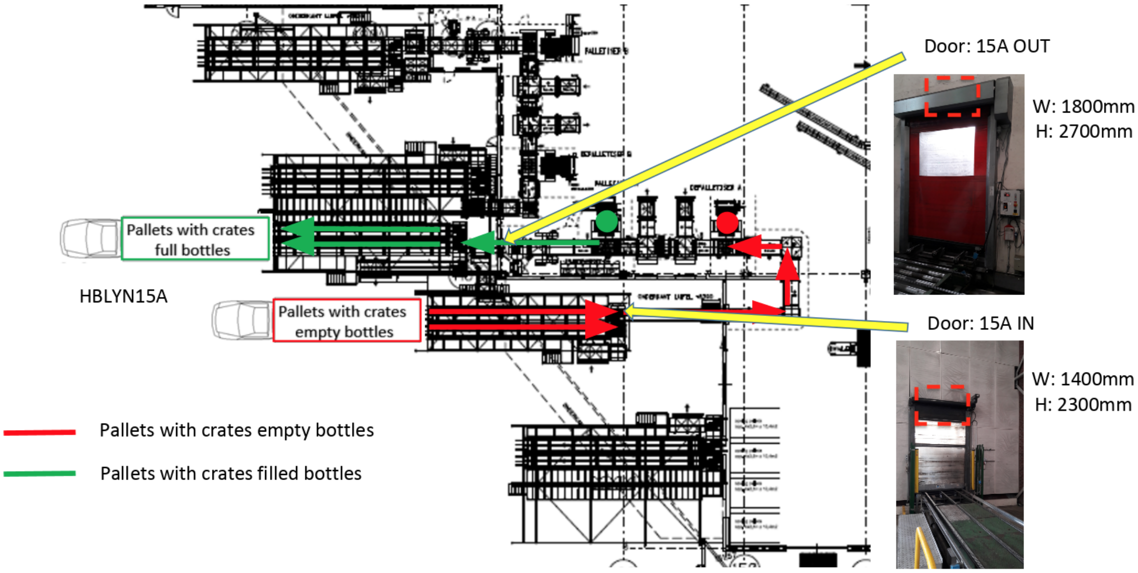
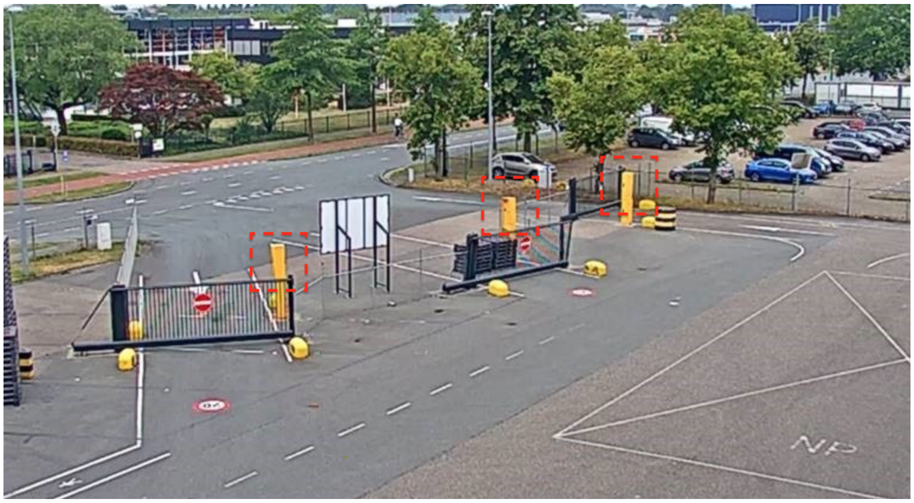
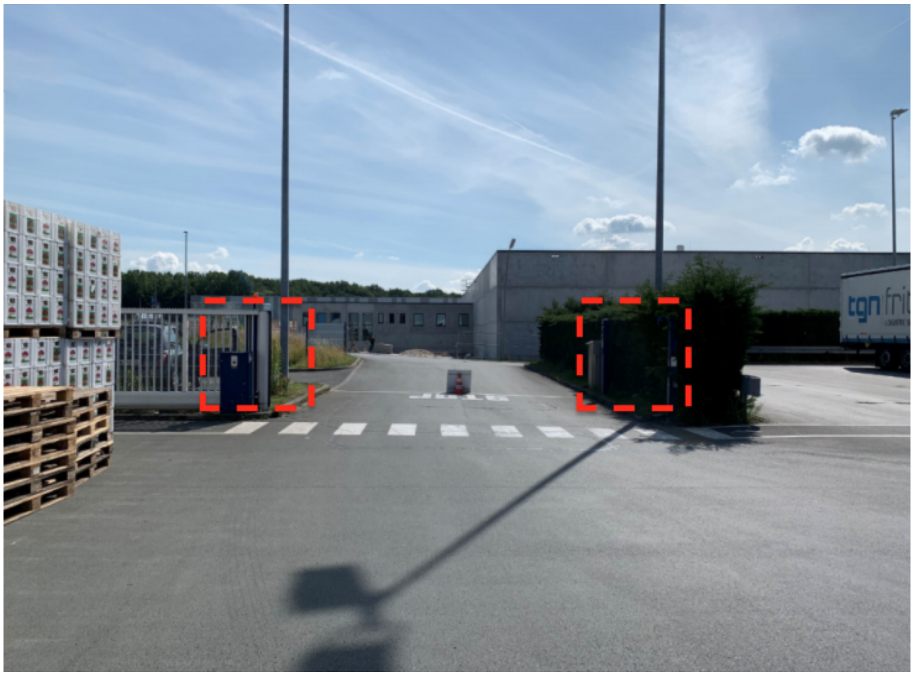


Figure 4.3: RFID gateway brewery in Den Bosch.



(a) LCDB H&B in Den Bosch.



(b) Warehouse in Werne.

(c) Sorting center H.Leiter GmbH. in Lutgendortmund

Figure 4.4: RFID gateways at three considered locations.

4.3 Base Case

In this section the base case is presented and explained. The base case is the model its expected case in the current state and is determined by various assumptions and the current state analysis in Chapter 3. The base case is used as a reference case and is based on historical data.

Due to the RFID gateways discussed in the previous section, the following crate flow measurements can be made:

- Position
- Times
- Quantities

The dashed vertical lines represent where (position) and when (time) measurements can be made. In Figure 4.5 the base case for inventory days at each location and the travelling times are presented. These values are determined in the current state analysis by interviews with stakeholders and are rounded to an integer in days. The transportation times are modelled to one day, since all transportation times can be done within one work day (8h). A distinction is made between the crate flows of unsorted and sorted Empties. At the LCDB in Den Bosch it is assumed that all crates are sorted after going through the sorting centers of H.Leiter GmbH.

Figures 4.6 and 4.7 present the based case for stock levels at the different locations for peak and low season. This distinction is not made for the LCDB location, as this data is not available. The same applies to the distinction between FP and Empties at the LCDB. In addition it is assumed that the sorting centers have the same crate stock levels as the warehouse. In this context, inventory is referred to the total amount of FP and Empties combined, while a stock level identifies them separately.

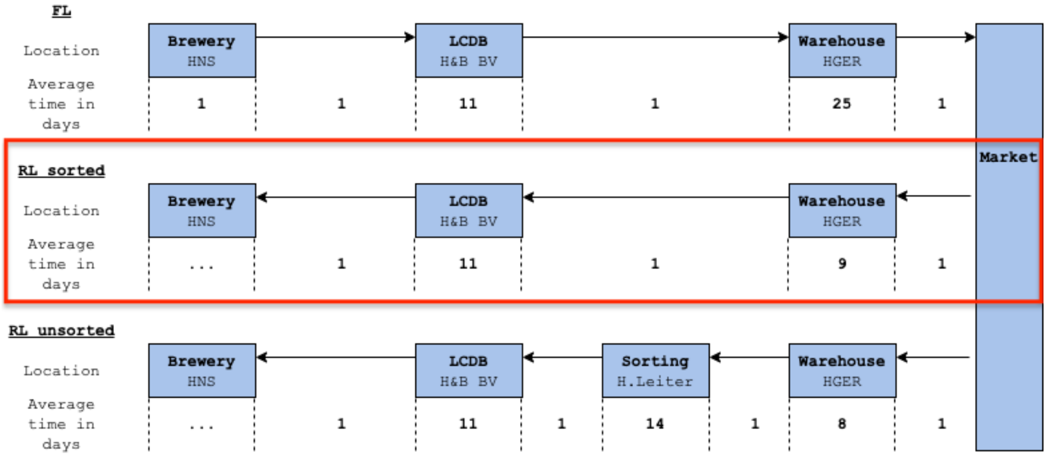


Figure 4.5: Base case: inventory days and transportation times HKR Cluster crates.

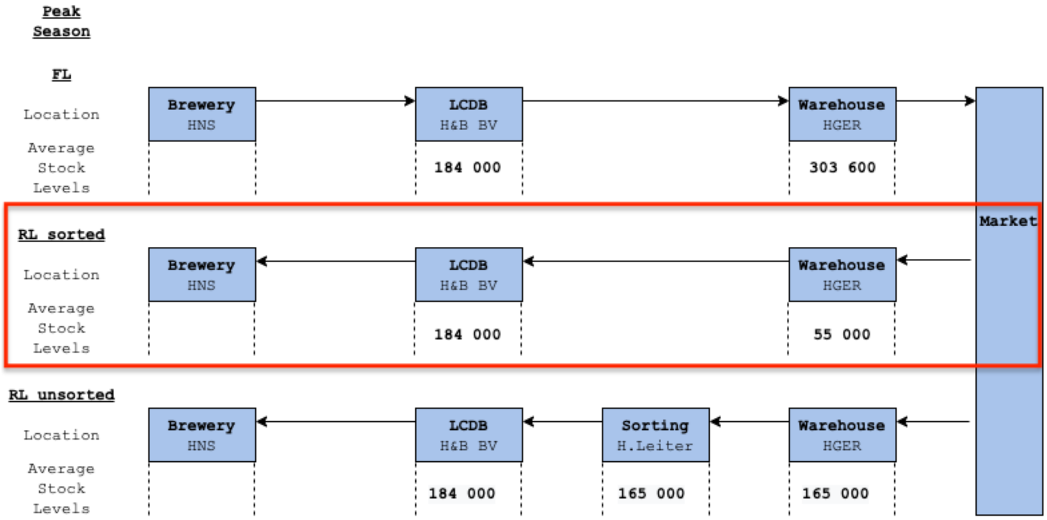


Figure 4.6: Base case: stock levels of HKR Cluster crates in peak season.

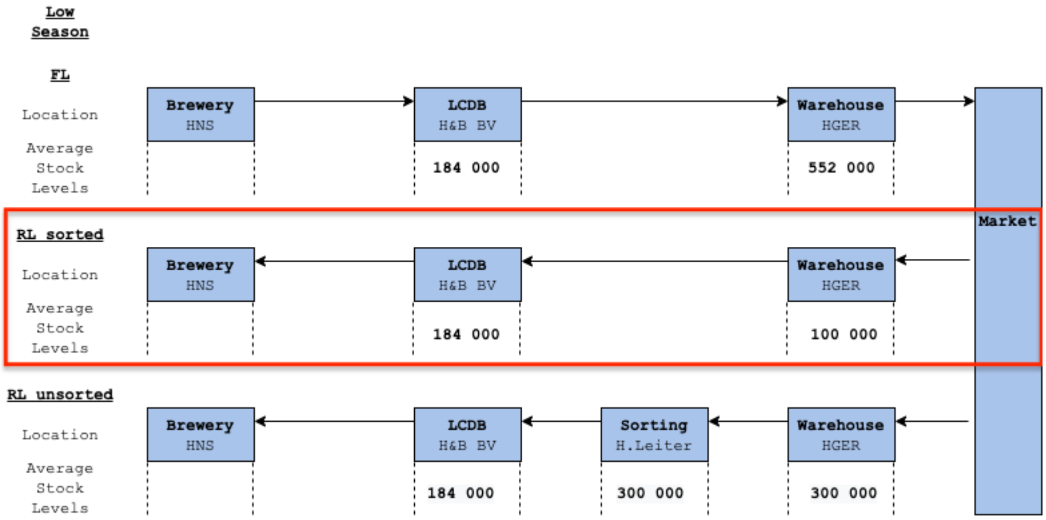


Figure 4.7: Base case: stock levels of HKR Cluster crates in low season.

4.4 Conclusion

This chapter describes a method for designing a digital twin framework for Heineken's supply chain. From the current situation analysis it can be concluded that supply chain control of the current supply chain will not be easy, because of a large black box in the system where flow of materials is hard to control and influence. This black box is represented by the market and consumer behavior. However this is reason the more over to enable maximum control on those supply chain parts where it is possible. This starts by providing reliable and accurate real-time or near real-time information on relevant parameters and KPIs in the supply chain. And hereby benefitting from fast developments in information, computation and communication technology. When information is transparent, supply chain agents have full knowledge at their disposal to make accurate predictions and optimal decisions. This could result in a better total supply chain performance, more profit and less costs. RFID gateways are designed for the relevant supply chain and described as a fitting solution for providing accurate and real-time supply chain data. This answers the sub research question:

5. How can the RFID gateways contribute to supply chain control?

RFID is proven to be a suitable technique for crate position measurements for the purpose of simulating the crate flows in a supply chain. With simulation of crate flow behavior, performance of a system can be studied and analyzed continuously. The crate flow measurements are made by identifying crates individually at specific locations in the supply chain, generating data and feeding this data into the digital supply chain twin model. The RFID data is used as inputs for supply chain optimization. The next part gives an answer to the sub research question:

6.How can a Digital Twin be modelled for controlling returnable packaging material flows in a supply chain?

A digital twin requires a real system, model-based decision support, connectivity and control of the real system to be able to function as intended. A digital twin modeling framework is provided for managing and controlling crate flows. The described RFID measurements by the gateways are fed into the model for real-time monitoring and data analytics. Thereafter, when data is filtered and analyzed it is fed into a simulation model for real-time control and prediction. The control system within the digital twin can plan decisions, re-active or pro-active, while analyzing supply chain performance. For example, external factors such as weather and large events cause disturbances in the planned material flows and can lead to OOS situations, longer delivery times and over-utilized storage capacities, which can result in additional costs and loss of sales as well as reduced consumer loyalty. The control model reacts to these occurrences in an optimal way.

In the next chapters a control model will be designed for the reverse supply chain of Heineken's CLSC. Crates are returned from the market at one end of the chain and at the other end the brewery is demanding empty crates for production. Currently, this reverse supply chain is performing on a push strategy, where each supply chain agent is managing their own inventory taking only their own objectives into account and pushing crates towards the production site. The future state supply chain will be demand driven, where information on crate returns and Empties demand will be transparent to all agents to optimize the entire supply chain performance.

Part IV

INTEGRATE

Chapter 5

Controller Design

A lack of data visibility , transparency for planning departments and communication among supply chain agents was identified in the current supply chain. Therefore these organizational agents along the supply chain need to be integrated and the coordination of material, information and financial flows should be improved. In this chapter the previously described methods will be integrated so they work as a whole. The system will be modeled and ready to operate.

MPC has shown to be useful for many process industry applications [59], therefore in this thesis MPC is used as a control tool within the digital supply chain twin framework. In this chapter a centralized MPC framework is designed to realize better coordination between the supply chain agents using RFID data in order to pursue RPM flow control by predicting supply chain behavior at future time instants.

5.1 Modeling

MPC is controlling a process, based on some form of model. The real supply chain processes are compared to a virtual supply chain model that is able to predict the future states and optimize the process. As such operations management of the supply chain and supply chain controllability will be enabled. MPC is a form of model-based prediction which is automated and robust [57]. Heineken's supply chain is modeled using state-space representation and in this model supply chain agents provide data regarding current inventory levels and available storage capacity captured with use of the RFID gateway measurements explained in the previous chapter (Chapter 4.2) over a specific horizon of prediction. Subsequently, the controller calculates the operational decisions using this information to minimize overall supply chain costs while fulling demand. The model of the supply chain will be demand-driven. This means the operating processes of the supply chain depend on the required demand of crate units.

Information exchange between supply chain agents is really important, such that the time remaining to deliver crates and inventory levels is transparent to multiple agents, while tracking RPM throughout the supply chain network. Consequently, this very transparent supply chain, where all relevant information can be accessed by all agents in the supply chain can lead to optimal decision making and execution in real time or nearly real time [57]. Therefore, MPC with real time data measurements have the potential to increase efficiency, reduce costs, increase reliability and provide supply chain agility.

In the next sections (Section 5.1.1 and Section 5.1.2) the representation of the relevant supply chain with the physical locations and material flows are explained. Thereafter, the state-space configuration is designed to model the dynamics of Heineken's reverse supply chain for the crates returned from market and to be supplied to the brewery.

5.1.1 Structure Representation

Supply chains consist of complex networks of nodes links. The nodes usually representing physical locations and the links corresponding to the transport between the nodes. The physical locations of Heineken's reverse supply chain taken into account in this section are consecutively a DC, warehouse, LCDB and the brewery, which are represented as main nodes. The various locations are managed by different agents. The crates entering and leaving these locations are the flows. This configuration is shown in Figure 5.1.

The transportation duration of crates between the main nodes is one day and the crates should be handled first before they can be transported to the next main node. Consequently, an additional node is modeled referring to a hypothetical location belonging to each main location, named a handling node. Because of this additional node, delays can be modeled and it makes sure crates are handled first before they can be transported to the next location. This configuration is shown in Figure 5.2.

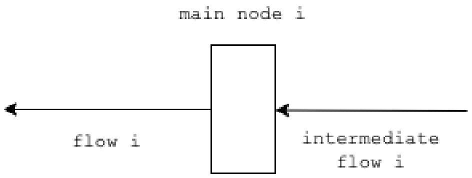


Figure 5.1: Main node configuration.

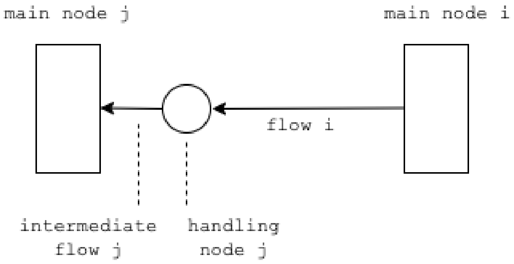


Figure 5.2: Connection between two main nodes.

As previously explained the future state of the supply chain will be demand-driven. Therefore, the objective of the system is to meet the Empties demand at the brewery in time. The operational decisions, made by the centralized controller, refer to the transportation decisions between the other agents. Therefore, the demand at the brewery is considered as a disturbance that affects the inventory of various agents. Besides, production at the brewery is planned by tactical management which carries out mid-term decisions and related distributions plans. While, the operational level of supply chain management is engaged with daily activities of the supply chain, such as warehouse management, incoming and outgoing products from facilities and routing [57]. The proposed approach in this thesis is focused on the operational goals of the supply chain, therefore, empty crate demand at the brewery is modeled as a disturbance. Additionally, the crate returns from market are modeled as a second disturbance, since it depends on consumer behavior and is difficult to predict.

The centralized MPC algorithm operates under the digital twin, which is modeled as a communication node that enables integrated operations and can control remotely the supply chain (Figure 5.3). The digital twin makes sure the agents at each main node in the supply chain can make collaborative decisions based on up-to-date information. The digital twin performs the supply chain management through the MPC, satisfying brewery demand, respecting infrastructural constraints and store crates so that desired inventory levels are allocated based on the beer production prediction. It is all about managing inventory levels, while tracking crates throughout the supply chain network and time needed before arriving the production location.

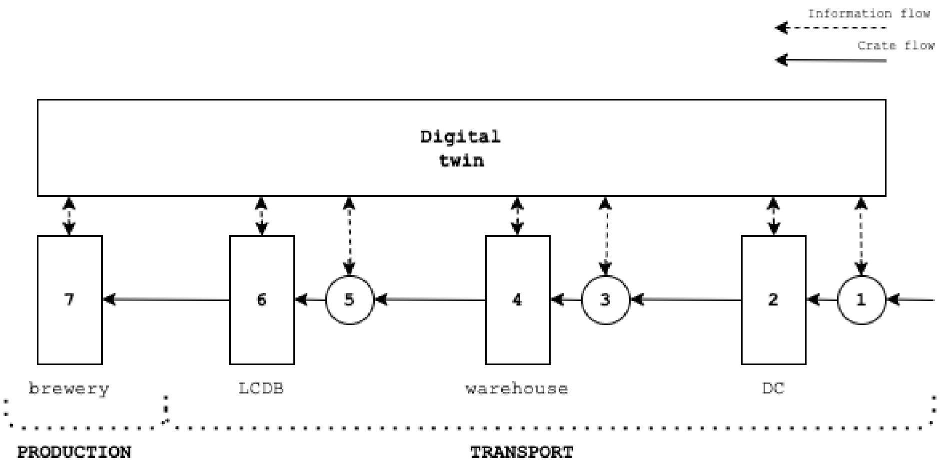


Figure 5.3: Supply chain configuration.

5.1.2 State-space Configuration

In the previous section the steps towards modeling the system are elaborated and are provided based on the case study. In this section a mathematical model of the case is presented that will be able to predict the system behavior. The system contains empty crates being transported through a supply chain by trucks. The mathematical model includes the system states, parameters and decision variables. In the next section the objective function and constraints are given considering the supply chain optimization problem from an operational management perspective.

First the equations for the systems states are given. The system states are the inventory levels of the various locations, modeled as the states in the main nodes (Section 5.1.1). The inventory at a main node is the inventory of this node at a previous discrete time step plus the inbound at the previous discrete time step minus the outbound at the previous time step (Equation 5.1). The inbound at a main node (i) at a particular time step (k) is equal to the outbound at a previous main node (i-1) at a previous time step (k-1), presented in Equation 5.2. This is under the assumption that there are no crate unit losses during transportation.

$$inventory_{\mathrm{i}}(k+1) = inventory_{\mathrm{i}}(k) + inbound_{\mathrm{i}}(k) - outbound_{\mathrm{i}}(k) \tag{5.1}$$

$$inbound_{\mathrm{i}}(k+1) = outbound_{\mathrm{i\text{-}1}}(k) \tag{5.2}$$

The operational decisions refer to the transportation decisions from one agent to another, managing the inventory levels at the main nodes. Therefore, the general state equation in state-space format can be presented as the following equation, Equation 5.3.

$$x_{\mathrm{i}}(k+1) = x_{\mathrm{i}}(k) + u_{\mathrm{i\text{-}1}}(k) - u_{\mathrm{i}}(k) \tag{5.3}$$

Taking the handling nodes into account, which are explained in Section 5.1.1, the first state is equal to the amount of crates entering the system (d_1) and is considered as the handling state of the first physical location of the supply chain. The second state presents the inventory of the first location of the supply chain. The third state represents the amount of crates during the handling state of the second location, while the fourth state represents the inventory of the second location of the supply chain and so on. The handling states can be seen as Work In Progress (WIP), which are included in total inventory. At the brewery crates cannot be stored, so there is no crate inventory at the production sight. Therefore, the seventh state does not depend on the previous time step, but is the difference in demanded amount of crates (d_2) at a time step and the supplied amount of crates. Equation E.2 presents the seven system states of Heineken's supply chain.

$$\begin{aligned}
x_1(k+1) &= d_1(k) \\
x_2(k+1) &= x_2(k) + x_1(k) - u_1(k) \\
x_3(k+1) &= u_1(k) \\
x_4(k+1) &= x_4(k) + x_3(k) - u_2(k) \\
x_5(k+1) &= u_2(k) \\
x_6(k+1) &= x_6(k) + x_5(k) - u_3(k) \\
x_7(k+1) &= d_2(k) - u_3(k)
\end{aligned} \tag{5.4}$$

The inventories ($\mathbf{y}$) of the various supply chain locations are measured by the RFID readers, positioned at the gateways. The total amount of crates in the supply chain system is always accessible through the state-space representation, either in storage, transport or WIP. The demand and the crates entering the system are seen as exogenous inputs ($\mathbf{d}$) and at every node it is assumed there is a FIFO policy. The decision vector ($\mathbf{u}$) relating to the transportation decision is integer. The state-space representation of the defined system is show in Equations 5.5 below, as are the corresponding vectors and matrices.

$$\begin{aligned}
\mathbf{x}(k+1) &= \mathbf{A}\mathbf{x}(k) + \mathbf{B_u}\mathbf{u}(k) + \mathbf{B_d}\mathbf{d}(k) \\
\mathbf{y}(k+1) &= \mathbf{C}\mathbf{x}(k+1)
\end{aligned} \tag{5.5}$$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} \tag{5.6}$$

$$\mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \tag{5.7}$$

$$\mathbf{d} = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \tag{5.8}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.9}$$

$$\mathbf{B_u} = \begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & -1 \end{bmatrix} \tag{5.10}$$

$$\mathbf{B_d} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{5.11}$$

$$\mathbf{C} = \begin{bmatrix} 1 \end{bmatrix} \tag{5.12}$$

5.2 Supply Chain Management

In the proposed design the digital twin communicates with all agents. These agents are responsible for the operations on the floor at the nodes. The digital twin receives information from all nodes measured by the RFID readers about the current inventory, current capacity, predictions on the crate availability, production at the brewery, crate returns from market and future inventory levels at specific time instants. When the digital twin in possession of the MPC controller receives this data, it will run the algorithm to find the optimal decisions with respect to stock levels. These optimal decisions will be communicated back to the agents at every supply chain node, so they can execute the related actions. Each iteration the controller receives updated data on the state of the system over a defined predictive horizon N_p. And formulates respectively evaluates the performance of the supply chain formulated in an optimization problem with respect to costs. The cost function of in this case is a function of the system states over the predictive horizon N_p, presented in Equation E.1.

$$J = \sum_{i=1}^{2}\sum_{k=1}^{N_\mathrm{p}} c_1 \cdot x_\mathrm{i}(k) + \sum_{i=3}^{4}\sum_{k=1}^{N_\mathrm{p}} c_2 \cdot x_\mathrm{i}(k) + \sum_{i=5}^{6}\sum_{k=1}^{N_\mathrm{p}} c_3 \cdot x_\mathrm{i}(k) + \sum_{k=1}^{N_\mathrm{p}} P_\mathrm{nc} \cdot x_7(k) \tag{5.13}$$

The cost function is a linear function depending on the system states multiplied by corresponding parameters, which refer to the storage costs per location (c_i). The last element of the cost function refers to costs of purchasing new crates (P_nc), when the demand at the brewery cannot be met. This can be seen as a penalty. The control objective is to minimize the cost function.

In Equation E.4 the constraints are presented and guarantee that the supply chain behaves as it should. Non negativity of inventory states (nodes) and control actions (flows) are not possible. Additionally, the upper bounds show the storage capacity of each supply chain node, corresponding handling nodes and the transportation capacities per day. At the brewery (node 7) there is no storage of inventory possible, therefore the demand (d_2) always has to be larger than the supply

(u_3). Therefore,(x_7) remains a positive value. The MPC algorithm formulated in this chapter has a linear programming problem representing the desired pull-flow behaviour.

$$\begin{aligned}
&0 \leq x_{\mathrm{i}}(k) \leq x_{\mathrm{i,max}}, i = 1, 2\\
&0 \leq x_{\mathrm{i}}(k) \leq x_{\mathrm{i,max}}, i = 3, 4\\
&0 \leq x_{\mathrm{i}}(k) \leq x_{\mathrm{i,max}}, i = 5, 6\\
&0 \leq x_7(k)\\
&0 \leq u_1(k) \leq u_{1,\mathrm{max}}\\
&0 \leq u_2(k) \leq u_{2,\mathrm{max}}\\
&0 \leq u_3(k) \leq u_{3,\mathrm{max}}
\end{aligned} \tag{5.14}$$

5.3 Modelling Assumptions

Various assumptions have to be made when using this mathematical MPC model in the current supply chain case. First, all material flows refer to flows of the HKR Cluster crate. The leased extra storage space in low season right next to the warehouse has the same entrance/exit. Simulation is in weeks, which will be explained in the next chapter, and one week refers to 7 days. Inventory levels are expressed in quantities and not expressed in money units. Therefore, inventory days are referred to time crate units are in inventory.

In this model no distinction is made between sorted and unsorted crates and it is assumed all crates are sorted. Besides, it is also assumed the handling efficiency at the locations is optimal. The floors of the relevant locations are considered little black boxes, where no handling efficiency can be gained by other design lay-out or hiring more labour. It is also assumed no transportation accelerations between the nodes are possible. And last, with use of this model and running simulations it is assumed the RFID system elaborated in Chapter 4 is implemented and is used to support the tracking of crate positions in the supply chain. The use of RFID leads to improved information send to a centralized control node, a digital supply chain twin.

5.4 Conclusion

Digital supply chain twins are computerized supply chain models that represent the supply chain states for any moment in real time. Therefore, they can be used to support decision making and optimization of operational processes. MPC is a form of model-based optimization which is automated and robust. That is why it is used as a control tool in the digital supply chain twin framework of Heineken's supply chain. In this chapter the mathematical MPC model is presented and explained. First the structure representation is given by nodes and flows, representing the main locations and the physical crate flows. In addition, hypothetical handling nodes are modeled to create flow delays in the model. Further modeling of Heineken's supply chain took place using state-space representation and supply chain agents provide data regarding current inventory levels and available storage capacity captured with use of the RFID gateway measurements over a specific predictive horizon. After the controller receives this data, it calculates the operational decisions using this data minimizing overall supply chain costs, while fulfilling demand at the production location, explained in the supply chain management section.

Data flows and information transparency within supply chains are important. The effect of the importance and how the implementation of RFID gateways, which provide the digital supply chain twin of Heineken's supply chain with data, impacts the performance will be explained in the next chapter.

Part V

LAUNCH THE SYSTEM

Chapter 6

Simulation and Results

In this chapter the simulation results will be shown and explained. This chapter belongs to the Launch the System - step of the SIMILAR process approach, which is a SE method. Launching the system means allowing the system to do what it is intended to do. As a result the system is running and producing outputs.

In the previous chapter the mathematical model for Heineken's reverse supply chain is presented. The MPC controller presented optimizes the supply chain performance by reducing storage costs. It accurately keeps track of the crates within the supply chain, the related costs and the demand at the production site. At the same time the MPC controller is planning optimal storage time and corresponding transportation time at and between the various supply chain locations. The planning decisions are considered optimal if storage costs are low and demand is met. If demand is not met, new crates have to be purchased. This is considered a large penalty.

The digital twin with a MPC algorithm provides control of the crate flows in the supply chain case. The way the MPC algorithm works will be shown by the results from various experiments. And as such the sub-research question to be answered in this chapter is:

7. What is the impact of material flow control in a supply chain driven by returnable packaging materials?

In the experiments the controller reacts to disturbances and unforeseen events, while optimizing crate storage time at various locations and minimizing costs. This will be demonstrated by four scenarios. In the base case scenario the financial KPIs in the form of OPEX and CAPEX in the current state supply chain with no MPC control are calculated, while in the first scenario this is done for the current supply chain with MPC control. In the second and third scenario unforeseen situations in the supply chain are simulated to evaluate how the controller reacts and what the effects are on costs and whether or not there are cost savings.

Experimental Setup The experiments are done by feeding the model with multiple scenarios and the way the controller reacts will be evaluated. All the experiments are done using Matlab 2018a, on a laptop with a 2,7 GHz Dual-Core Intel Core i5 processor and are programmed using YALMIP, a toolbox for modeling and optimization. Furthermore the commercial mathematical optimization solver GUROBI was used. GUROBI claims to have the best performing optimization solvers.

6.1 Exogenous Inputs

The exogenous input explained in the previous chapter is derived from a data-set provided by Heineken. In this Excel data-set all information on the inbound and outbound RPM flows of the warehouse in Werne , Germany in 2019 is represented. For this research, we looked in particular at two specific RPM flow data from the data-set. The first are data of the materials entering the warehouse coming from the market. These are the Empties. And second are data on materials entering the warehouse coming from the LCDB, which are FP. After this information is extracted from the data-set, information on the HKR Cluster crates is filtered out and the entry date of the crates and the quantity is analyzed. Subsequently, the dates are sorted by week numbers and the two graphs, representing exogenous inputs, were made as shown in Figure 6.1 and Figure 6.2.

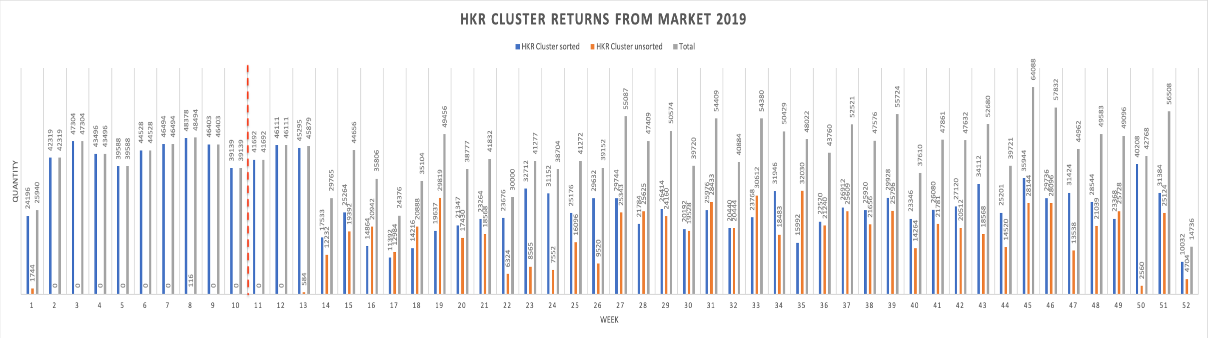


Figure 6.1: Data-set HKR cluster crate returns from market 2019.

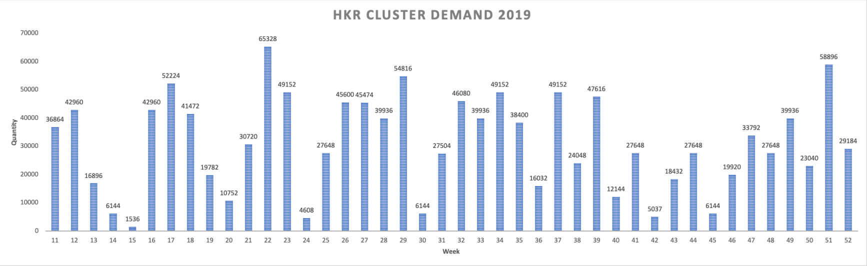


Figure 6.2: Data-set HKR cluster crate demand at production site 2019.

Because of the lack of data that we were able to use within the context of this research and the corresponding designed model, explained in both Chapter 4 and Chapter 5, two important assumptions had to be made. The first one assumes that the storage time at the DC is fixed. Therefore, the empty crate flow can be used for the flow entering the system and measured at the DC. The second assumption regards demand at the production site. Demand is assumed to be equal to the flow of crates (FP) entering the warehouse in the provided data-set, under the assumption that production at the brewery is equal to the market demand and this is supplied immediately with no delay. This FL flow passes the warehouse and therefore, this data can be used.

Remarkable is the difference between in bounds on the horizontal axis of the two input data-sets. This can be explained by the fact that no data was provided for the first ten weeks of 2019 for one of the crate flows. Therefore only data from week 11 to 52 will be used in the simulations because for these weeks the data are complete. Table (6.1 shows week numbers in 2019 with their respective months. Because there is only data available of the last three weeks of March, it is assumed that the first week of March has the same inbound and outbound input as the first week of April. Therefore data of week 14 in 2019 is used twice, in March and in April. For January and February there is no data available, as previously explained.

Peak season and low season	
Month	**Weeknumber 2019**
Peak season	
March	11-14
April	14-17
May	18-22
June	23-26
July	27-30
August	31-35
September	36-39
October	40-44
Low season	
November	45-48
December	49-52
January	-
February	-

Table 6.1: Week numbers and corresponding months 2019.

6.2 Parameters

The parameters values are presented in Table E.1. The simulation time N_{e} of all experiments is 4 or 5 weeks, depending on the month (Table 6.1). The prediction horizon of the controller N_{p} is 5 days. c_{i} refer to the storage costs per location, explained in the previous chapter. The values are derived from the storage costs per pallet per week at the different inventory locations. In the current state analysis is found that at this is €1.75 per pallet per week at the LCDB, €1.49 per pallet per week at the warehouse. The actual storage price for storage at the DCs is unknown and therefore assumed to be the same as at the LCDB, since it considers also a 3PL. Dividing this by the 40 crates on a pallet and 7 days in a week results in the values provided by the table. The price of a new crate is €7,20.

The maximum storage capacities of the warehouse and LCDB are given in Chapter 3. An assumption is made for the maximum storage capacity of the DC by assuming one DC to have a maximum capacity of 5% of a warehouse and there are 31 DCs in total (Chapter 3). Therefore the total maximum capacity of the DC is 1.475.000 crate units. The maximum transportation capacities are 200.000 crates per day between all locations.

Parameters	
Parameter	**Value**
N_{p}	4/5 [weeks]
N_{e}	5 [days]
c_1	€0,00625]crate/day]
c_2	€0,00532 [crate/day]
c_3	€0,00625 [crate/day]
P_{nc}	€7,20
$x_{\text{i,max}}$, i=1,2	1.475.600 [crates]
$x_{\text{i,max}}$, i=3,4	952.000 [crates]
$x_{\text{i,max}}$, i=5,6	1.840.000 [crates]
$u_{\text{i,max}}$ i=1,2,3	200.000 [crates]

Table 6.2: Parameters

6.3 Verification

Model verification ensures that the computer programming and implementation of the conceptual model are correct [51]. The model is designed and implemented in MATLAB software via structured programming. Validity of the simulation can be checked by evaluating how the simulation reacts to situations and if they match the expectations. Verification answers the question whether the model and its implementation for simulation is made right. In this thesis, verification of the simulations will be done by dynamic testing with a commonly used technique: investigation of input-output relations and consistency checks. This is to determine if the simulation program and its implementations are correct [51]. Correctness of the following supply chain properties in the simulation program are checked:

- Flow direction
- Inventory levels and corresponding costs
- Met and unmet demand
- Transportation
- Crate returns from market

6.3.1 Model including brewery, LCDB and warehouse

To determine if the simulation program is correct and represents the real supply chain, various input-output checks are done. The input values used for the verification are randomly chosen, but are easy to calculate with and have the same magnitude as the real inputs values. There is no initial inventory at the locations at the start of simulation. At day 1, 50.000 Empties are read by the RFID gateways at the warehouse and enter the system. At the same day 20.000 are demanded at the brewery. At day 8, these 50.000 Empties are demand at the brewery and at day 9, 100.000 Empties enter the system at the warehouse. Total simulation duration is 10 days.

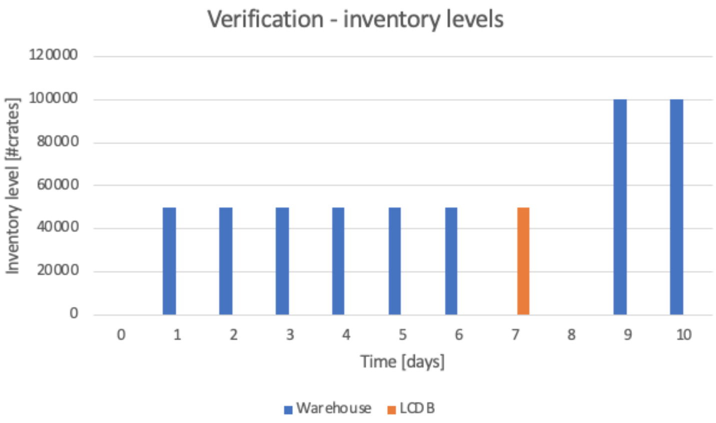


Figure 6.3: Outputs results (inventory levels) for verification.

Figure 6.3 shows that the simulation starts with no inventory, until the 50.000 crates enter the warehouse on day 1. On day 7 these crates are transported to the LCDB and on day 8 to the brewery, since this is required. These results are shown in both Figure 6.3 and Figure 6.4. On the 9th day, 100.000 crates are read at the warehouse and are included in the inventory. Figure 6.5 present the output results of the corresponding storage costs. On day 1 a demand of 20.000 Empties at the brewery could not be met. This results in CAPEX: €144.000. In Appendix C, the corresponding simulation results in MATLAB are shown. The given supply chain properties are checked based on the simulation results and are as expected. Therefore the model is verified.

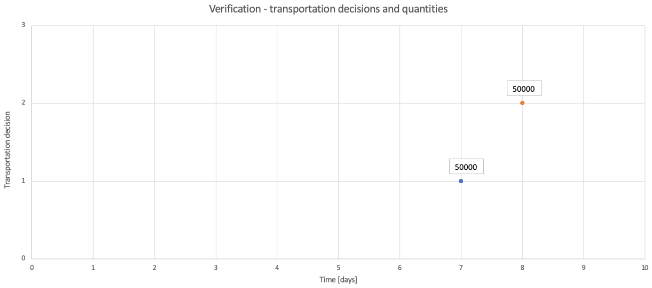


Figure 6.4: Output results (transportation decisions and quantities) for verification.

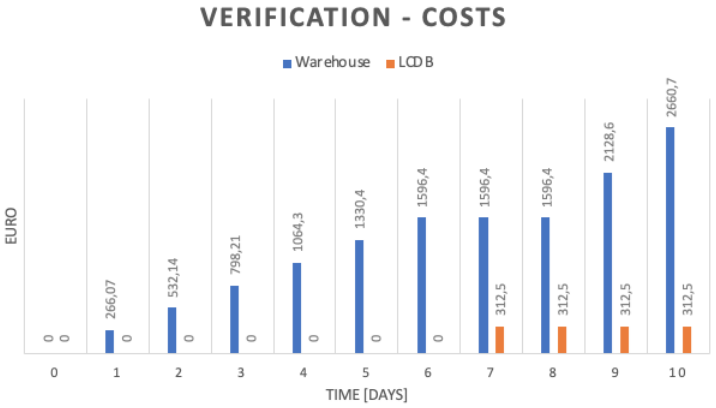


Figure 6.5: Outputs results (storage costs) for verification.

6.4 Base Case: Current state with no MPC

The first scenario is the base case scenario which is the current state without MPC control in the supply chain. This scenario is calculated based on the current KPI which are analyzed and defined in Chapter 4. The financial KPI of the current situation is calculated in Microsoft Excel. The financial KPI are the OPEX and CAPEX, which refer to the expenses for keeping inventory at the various locations and the purchase expenses for new crates to prevent OOS situations at the production site. For the current situation OPEX is calculated. This is done by using the current average crate inventory levels at the locations as initial states, taking the crate returns and demand per month (corresponding weeks in the data-sets Figure 6.1 and Figure 6.2) and the average inventory days into account, to calculate the inventory levels in units/crates of the two location. The inventory levels are multiplied by the storage costs per crate per day, which are €0,00532 per crate per day for the warehouse and €0,00625 per crate per day for the LCDB.

In the current situation of Heineken's supply chain there are no RFID measure gateways at the DCs and therefore, they are not taken into account. Besides, OOS situations do not occur since inventory levels were high enough during the simulation period for this scenario. Therefore, the CAPEX, which corresponds to the SKU investments if OOS situations happen, is not calculated for this scenario. Figures 6.6 and 6.7 show results of this calculation. While, Tables 6.3 and 6.4 show the total inventory costs per location for this current scenario with no MPC control.

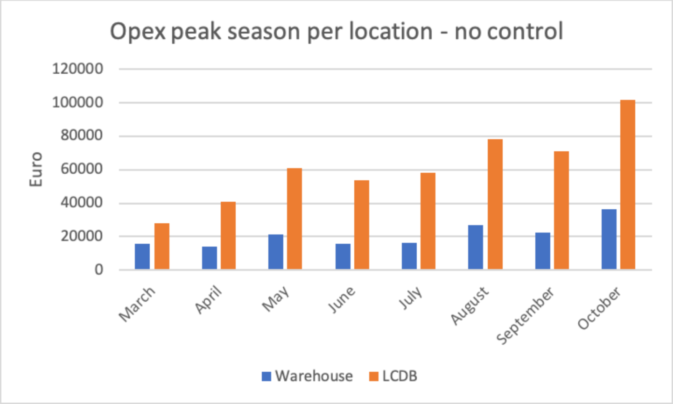


Figure 6.6: OPEX peak season per location with no control.

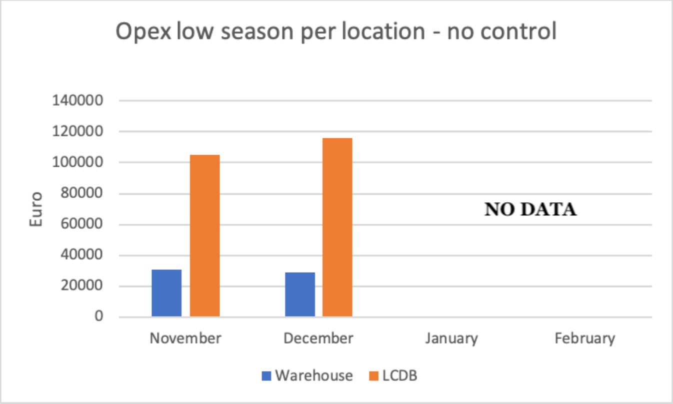


Figure 6.7: OPEX low season per location with no control.

OPEX peak season (March-October)	
Location	**Value**
Warehouse	€168.126
LCDB	€492.926
Total	€661.052

Table 6.3: OPEX peak season: current situation with no control.

OPEX low season (November-February)	
Location	**Value**
Warehouse	€59.975
LCDB	€221.532
Total	€281.507

Table 6.4: OPEX low season: current situation with no control.

6.5 Scenario 1: Current state with MPC

For the current state scenario with MPC control, a controller is built in MATLAB to simulate the inventory levels at different times. In this scenario no irregular disturbances occur, but the direct effect of centralized control with transparent information on SKU demand at the production site, the returns from market and the storage costs per SKU in the current supply chain result in these costs. The controller results are shown in Figure 6.8 for peak season per location and in Figure 6.9 for low season per location. The total OPEX costs are given in Table 6.5 and Table 6.6. OOS situations do not occur since the crate returns are higher than the crate demand at the production site.

When comparing the results of the same supply chain system but with control and without control, the most remarkable result is the difference in the location where inventory is allocated. In the base case scenario , the crate inventory levels are much higher at the LCDB. This is logical, since in the current situation the crates are 9 days in the warehouse and consequently are transported to the LCDB location. With MPC control, the results show higher inventory levels at the warehouse. This is explainable since the controller takes the storage costs into account per location. After the month April there it seems there is no inventory at the LCDB. This is because in April the initial stock at the LCDB is used for production and only a minimal quantity of crates will be left at this locations, since the maximum capacity at the warehouse is not reached yet and it is less expensive to keep inventory at this venue. The absolute difference in OPEX comparing the base case scenario and scenario 1 is for peak season: €94.511 and for low season: €41.184. The results are shown in Graphs 6.10 and 6.11.

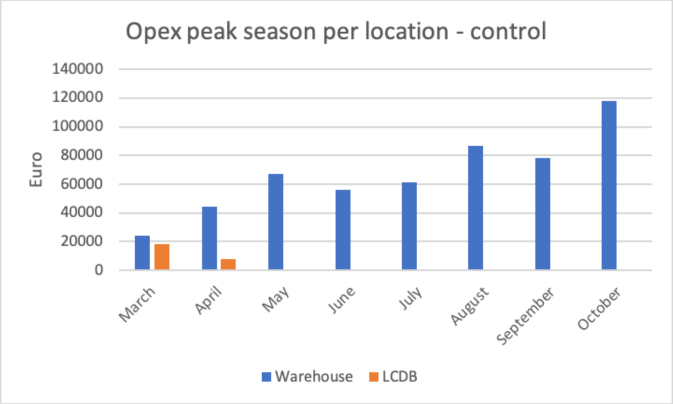


Figure 6.8: OPEX peak season per location with control.

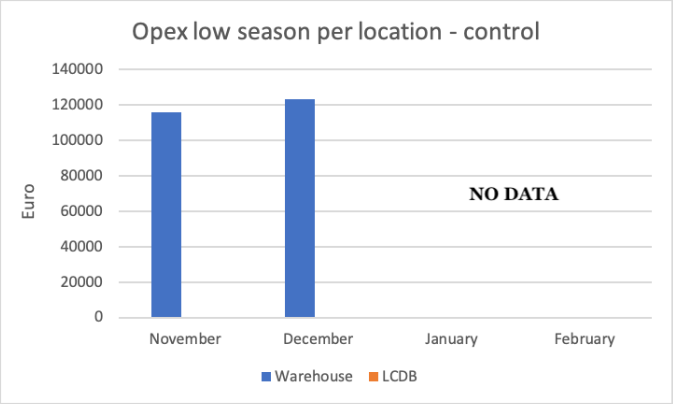


Figure 6.9: OPEX low season per location with control.

OPEX peak season (March-October)	
Location	**Value**
Warehouse	€535.973
LCDB	€30.568
Total	€566.541

Table 6.5: OPEX peak season scenario 1: current situation with MPC.

OPEX low season (November-February)	
Location	**Value**
Warehouse	€239.119
LCDB	€1.203
Total	€240.322

Table 6.6: OPEX low season scenario 1: current situation with MPC.

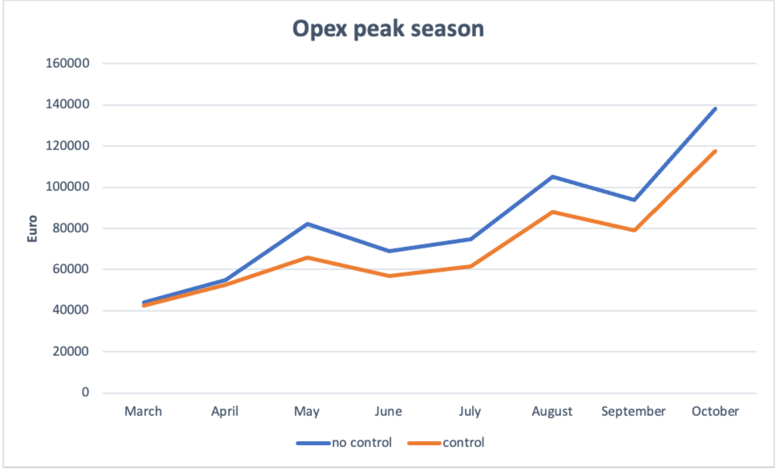


Figure 6.10: Comparison OPEX supply chain control and no supply chain control in peak season.

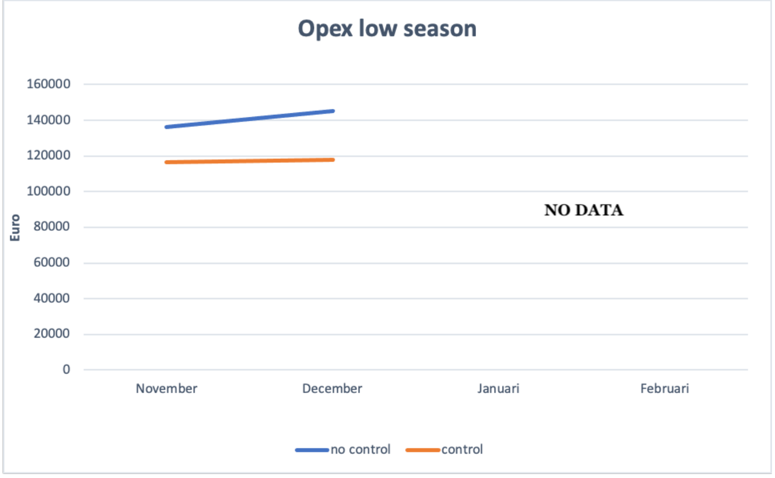


Figure 6.11: Comparison OPEX supply chain control and no supply chain control in low season.

6.6 Scenario 2: Peak in demand

Although the controlled supply chain is relatively short and without possibility for many transportation and allocation scenario's, with this scenario one of the advantages of MPC will be shown by presenting how the centralized supply chain controller will react to a possible unforeseen event and its corresponding quantified impact. One of the advantages of MPC control is that it can react to unforeseen events. In this scenario the unexpected or unplanned event occurs at the demand side of the supply chain. This is done because an unexpected occurrence on the crate return side will without MPC control only result in difference in inventory level at the warehouse. In this scenario an unforeseen high beer demand by hot weather is the occurring event. Heineken's tactical department has planned the beer production and the corresponding required RPM multiple weeks or months in advance, but due to this unexpected higher consumption and demand production need to be increased. As well as the supply of empty crates in the reverse supply chain. In this scenario there is little initial inventory at the LCDB, since the controller prefers low inventory levels at LCDB and is shown by scenario 1 in Section 6.5. This makes it unable to instantly meet demand at the brewery when requested. The impact of control will be simulated in this scenario.

For this scenario the month June is chosen to simulate, since the results of the first scenario (Section 6.5) show that in June there is little inventory at the LCDB which makes it easier to indicate the effect of control and in June heat waves are not uncommon, which makes this scenario realistic. For this scenario the initial inventory at the warehouse is 309.285 Empties and at the LCDB 49.152 Empties. The corresponding week numbers are 23 to 26 and crate demand in units at the brewery is consecutively, 49.152, 4.608, 27.648 and 45.600 (Figure 6.2). In this scenario in second week of June the crate demand goes up by 20% divided over 3 days. This results in an additional demand of 1843 crates on day 10, day 11 and day 12. It is assumed the weather forecast predicts this 2 days in advance. The relevant simulation results of this case are shown and compared to a situation where the heat wave is not predicted and been anticipated on.

In Figure 6.12 the controller plan is shown at day seven, at which point in time no information on increasing demand is yet available. The controller meets the demand at the brewery JIT. At day 8, the controller gets information on the increasing demand and acts on it. The actual control decisions by the end of the simulation are presented in Figure 6.13. In both figures the vertical axis presents the decisions taken, explained in the mathematical model in Chapter 5. Action 1 refers to transportation between warehouse and LCDB, while action 2 refers to transportation between LCDB and brewery. In Appendix C the relevant MATLAB results are presented and Table 6.7 gives the financial results of scenario 3.

OPEX and CAPEX Scenario 3	
OPEX	
Situation	**Value**
Control	€58.976
No control	€58.976
CAPEX	
Situation	**Value**
Control	-
No control	€39.809

Table 6.7: OPEX and CAPEX control and no control scenario 2.

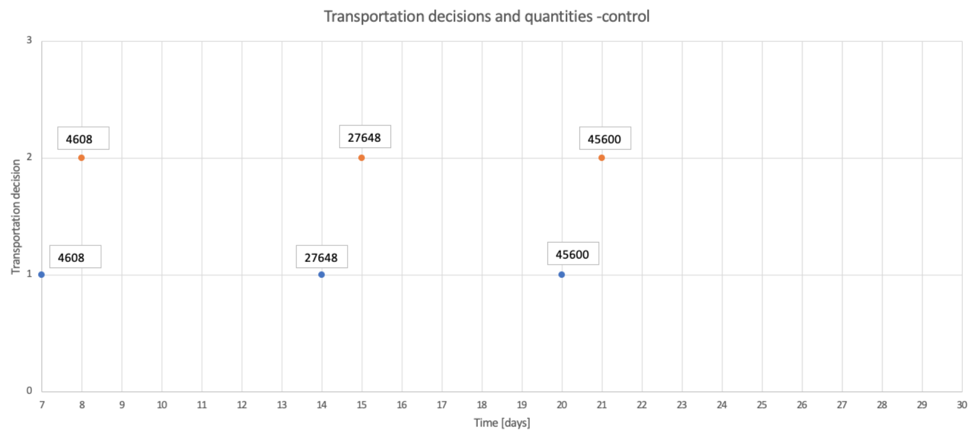


Figure 6.12: Control plan at day 7 (scenario 2).

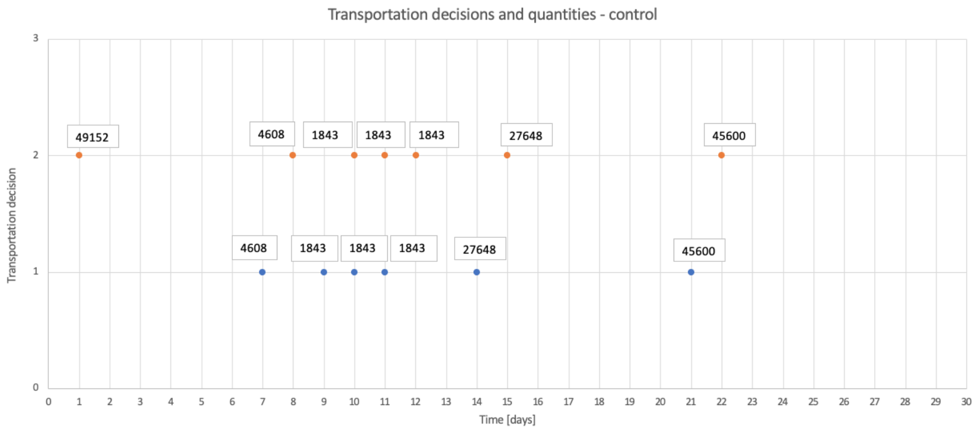


Figure 6.13: Actual control decisions (scenario 2).

6.7 Scenario 3: Additional RFID gateway location with capacity limitation

In this scenario the impact of information availability and transparency by including an extra location will be analyzed. Adding only one an extra measure location will not give much advantages in this supply chain case, since the controller does not have an influence on the crate returns. But creating a scenario whereby maximum storage capacity is reached, the impact of information transparency can be analysed for this scenario.

From the data in the two data-sets that include the empty crate demand at the brewery and the crate returns from market, it seems that the maximum storage capacity in 2019 at the various locations was not reached because in this thesis only the SKU HKR Cluster crate is taken into account. In reality it frequently occurs that due to a shortage of storage capacity external storage locations have to be rented. In this scenario the maximum storage capacity at the warehouse is reached and what the impact of supply chain control in such a situation is observed.

If such a scenario occurs, it is usually in low season since inventory levels are higher than in peak season. Therefore, the month November is chosen to simulate, which makes this scenario realistic. For this scenario the initial inventory at the warehouse 676.490 Empties, at the LCDB 6.144 Empties and at the DC zero Empties. The corresponding week numbers are 45 till 48 and Empties demand at the brewery is consecutively, 6.144, 19.920, 33.792 and 27.648 (Figure 6.2 and Appendix **??**). At day 8, day 9 and day 10 in November the maximum capacity at the warehouse is reached. Figure 6.14 and Figure 6.15 present the control plan results of day 7 and day 8.

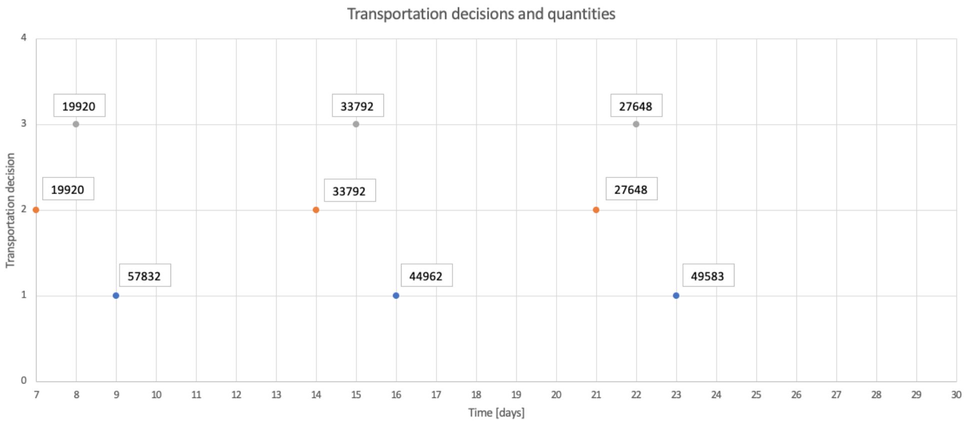


Figure 6.14: Control plan at day 7 (scenario 3).

In the figures the values on the x-axis are the days of the month November and on the y-axis the numbered transportation decisions. Transportation decision 1 refers to crate flow movements from DC to warehouse, transportation decision 2 refers to crate flow movements from warehouse to LCDB and transportation decision 3 refers to crate flow movements from LCDB to brewery, as explained in Chapter 5. It is shown by these results that the controller at day 7 plans to supply the demanded crates at the brewery and move the expected returned crates from the Market to the warehouse at day 9. At day 8 not all RPM supply from the DC to the warehouse are possible due to a capacity constraint (750.000 crates). The controller reacts to this by supplying the amount of crates up till this maximum capacity. The costs of this scenario and the scenario without control and the crates are yet moved to warehouse and an additional rented storage area has to be found is shown in Table 6.8. The costs of keeping inventory at the DC are based on the fact that is is also a 3PL and therefore is €1,75/pallet/week. And the costs for an additional storage area are based on the average venue renting costs in Germany and is taken €5,00/pallet/week.

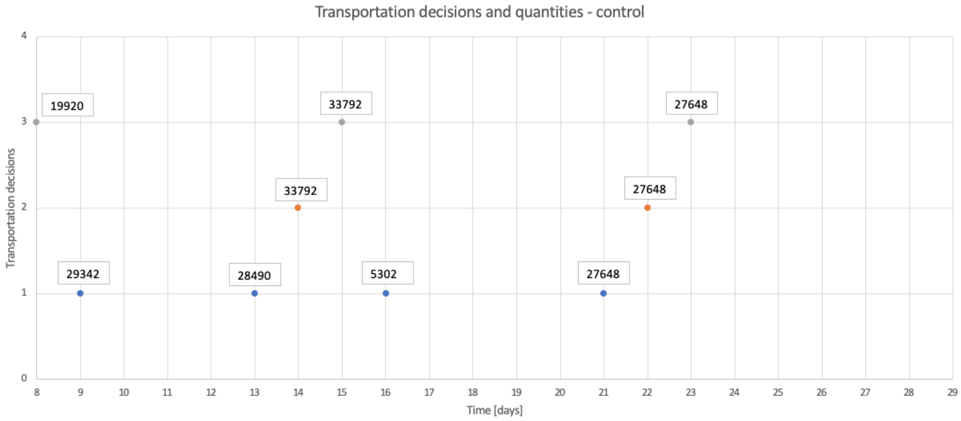


Figure 6.15: Control plan at day 8 (scenario 3).

OPEX and CAPEX Scenario 3	
OPEX	
Situation	**Value**
Control	€120.880
No control	€121.389

Table 6.8: OPEX and CAPEX control and no control scenario 3.

6.8 Conclusion

In this chapter the the simulation results are presented. Verification of the simulation model is done in advance. Model verification ensures that the computer programming and implementation of the conceptual model are correct. This is done by dynamic testing by investigation of input-output relations and consistency checks. Then the base case calculation is done followed by various scenarios in which the controller reacts to disturbances and unforeseen events. This chapter gives an answer to the sub research question:

7. What is the impact of material flow control in a supply chain driven by returnable packaging materials?

The answer to this question is given by simulating different scenarios and comparing the results of these scenarios. In the base case scenario the financial KPIs in the form of OPEX and CAPEX in the current state supply chain with no MPC control are calculated, while in the first scenario this same is done for the current supply chain but then with control. The results from both scenarios are compared. Due to the large crate pool circulating through the closed-loop supply chain, OOS situations of these SKU's at the brewery do not occur and the advantages of centralized control on the transparency of inventory levels do not affect the supply chain planning much. It has become more a solution for optimal crate allocation in the supply chain. Due to the non-occurrence of OOS situations in the base case scenario and scenario 1 there is no CAPEX calculation for these scenarios since no extra crates need to be purchased. The absolute difference in OPEX comparing the base case scenario and scenario 2 is for peak season: €94.511 and for low season: €41.184. These are the most important results of this thesis since the direct impact of the influence of control with an MPC controller is quantified with use of the empty crate demand and the crate returns over 2019.

In the second scenario an unexpected event occurs at the demand side of the supply chain and the impact of control is quantified. Due to control, the demand is met JIT at the brewery and when the unexpected event occurs the controller reacts and still minimizes costs. The absolute difference in costs comparing control and no control, both with the same occurring unforeseen event is €39.809. In the third scenario the impact of information availability and transparency by including an extra location is evaluated. An unforeseen capacity constraint event occurs in this scenario and the controller reacts optimally, while minimizing costs. The absolute difference in OPEX is €509.

In conclusion, in this chapter the impact of HKR Cluster crate flow control in the reverse supply chain of Heineken's supply chain driven by returnable packaging is quantified, expressed in CAPEX and OPEX. The optimization results in less operational costs, more profit, a smaller crate pool and less required storage space. The validation of the model is achieved by evaluation of the results of the scenarios simulated. The model is validated, since the results are reasonable for the intended purpose of the model.

Part VI

ASSES PERFORMANCE

Chapter 7

Conclusion

In this chapter of the thesis, the results will be evaluated in a more contextual manner in the research as a whole. The starting point of the research was given by the fact that Heineken Netherlands Supply realized that RPM cycle times measurements as an important KPI were based on assumptions and not real time data. Therefore Heineken Netherlands Supply intends to introduce RFID gateways at specific supply chain locations to measure actual crate cycle times. The question arose whether or not these RFID gateways, besides providing reliable and accurate cycle time measurements, also have the potential to contribute to supply chain control. A small analysis of the CLSC between Heineken Netherlands and Heineken Germany showed that there is little integral control of the supply chain and little automation of supply chain processes.

While the world of supply chain and its logistics has started its digitalization journey, including growing number of new technologies in their processes, still many areas are challenged to be transformed like automating manual processes and improving visibility and connectivity inside supply chains. Digitalization ensures creating flexibility, new efficiencies, lower cost and shorter response time to market demands. Since the Heineken's supply chain has potential to improve in these aspects, a modest literature research is done for potential digital solutions for improvement. One promising solution in particular came forward: the Digital Twin. This research was set out to investigate whether supply chain performance could be improved by control of RPM flows using data of the RFID gateway measurements from a Digital Twin design perspective. The problem that initiated this research was a lack of integral RPM flow control in the current supply chain. Therefore, this research could contribute to development of digital twins in supply chains, with use of a real-life case study with an application focus.

The research follows a structured methodology using the SIMILAR System Engineering process approach, in which the research problem and objectives are defined first. Then, a literature research is performed to investigate what is already done with regard to solving similar problems and what possible alternatives could be. From the literature review the importance and potential of developing digital twins became clear. Although very few papers are written indicating or quantifying the advantages of digital twins, let alone quantification of the potential benefits relating to real-life cases. After the literature review a current state supply chain analysis is performed, in which the current system structure is reviewed, data collected and problems identified. Subsequently a method is described for first steps towards digital twin design by proposing a framework for the relevant supply chain. The digital supply chain twin framework consists of three domains. One of these is the control domain, in which real-time control, prediction and performance analysis is enabled. Since the objective of this thesis is to enable supply chain control, this domain is examined in greater depth. MPC is used as control tool within the digital supply chain twin framework and a specific MPC controller design is proposed as the part of the SIMILAR approach that stands for integration. When the MPC controller was operating, simulation experiments are executed and results compared. This section is where all the other sections are combined and research is concluded.

7.1 Research questions

This thesis has created insights on what a digital supply chain is and what the effect of control can be on the supply chain performance. In particular, a reverse supply chain driven by returnable packaging using RFID technology to create flow visibility and information transparency. The main research question was formulated as:

How can real-time control in the reverse supply chain be enabled, with use of RFID data?

The main research question was answered with the help of the following sub-research questions:

1. *What are the characteristics of a supply chain driven by returnable packaging materials?*
2. *What are the key performance indicators of a supply chain driven by returnable packaging materials?*
3. *What is a Digital Twin?*
4. *How does the supply chain driven by returnable packaging materials currently operate and perform?*
5. *How can the RFID gateways contribute to supply chain control?*
6. *How can a Digital Twin be modelled for controlling returnable packaging material flows in a supply chain?*
7. *What is the impact of material flow control in a supply chain driven by returnable packaging?*

7.1.1 Research question 1

From the literature study performed, it was concluded that a supply chain driven by returnable packaging is often a closed-loop supply chain. A closed-loop supply chain utilizes two streams: the forward logistics and reverse logistics. The forward logistics in the supply chain is mostly driven to meet customer demand, while the reverse logistics with the intention to create value during the life cycle of a certain product, could be driven by returnable packaging demand at the production stage. Reverse supply chains normally begin with the collection of used products at the consumers end.

7.1.2 Research question 2

For reverse supply chains, driven by returnable packaging, other than the traditional supply chain performance measure have te be considered like number of Out-Of Stock situations, returnable packaging materials cycle times, inventory days, CAPEX and OPEX related to the reverse logistic activities.

7.1.3 Research question 3

A digital twin is generally speaking a digital replica of a physical entity and uses models combined with data to interpret and predict the behavior of a real system. In literature, digital twins are described as very promising having the potential to increase the intelligence of real systems. Digital twins have three main functions: prediction, monitoring and diagnosis. Besides, they facilitate decision-making processes and enable decision automation through simulation, which could lead to performance improvement of these real entities. Despite the described importance and potential of digital twins in literature, there are very few examples where the potential benefits are quantified related to actual real-world processes.

7.1.4 Research question 4

At Heineken's closed-loop supply chain, returnable packaging in the form of crates circulate through the supply chain. After the current state analysis, it was concluded that production planning is done relatively far in advance and the prediction of crate returns is difficult since this depends on consumer behavior. To manage this uncertainty Heineken utilizes an excess crate pool to prevent possible returnable packaging OOS situations at the production site. OOS situations result in extra costs, such as CAPEX when new crates need to be purchased and even more important loss of sales. The use of a large number of crates for the German market results in large safety stocks and consequently large OPEX in terms of inventory costs.

Furthermore, a lack of data visibility and transparency for the planning departments and coordination between supply chain agents was identified using interviews with stakeholders. It was concluded that there is no centralized control of crate flows in this supply chain driven by returnable packaging. As digital twins have the potential to control physical material flows, they are expected to lead to supply chain performance improvement. This is the reason why a digital twin of this supply chain is required.

7.1.5 Research question 5

Control of this supply chain is difficult, since there is a large black box (the German Market) in which it is hard or even impossible to control and influence material flows. However this is even the more reason to enable maximum control on supply chain parts where it is possible. This starts with gathering reliable and accurate real-time information on relevant supply chain parameters which can be received, in this case, by the RFID gateways. When information is transparent, supply chain agents have all the data at their disposal to make accurate predictions and optimal decisions. This could result in control, better total supply chain performance, more profit and less costs. RFID gateways are designed for this supply chain and described as an appropriate solution for providing crate flow measurements by identifying crates individually at specific locations in the supply chain, generating data and feeding this data into the digital supply chain twin model.

7.1.6 Research question 6

A digital twin modeling framework is provided for managing and controlling crate flows. The RFID gateways installed at the relevant supply chain locations create data which is fed into the model for real-time monitoring and data analytics. When the data is filtered and analyzed it is fed into a simulation model for real-time control and prediction. The control system within the digital twin can plan decisions, re-active or pro-active, while analyzing supply chain performance.

The control tool used for this control-part of the digital twin is Model Predictive Control. A mathematical control model for a centralized MPC algorithm is proposed for the reverse supply chain of Heineken's closed-loop supply chain, to realize better coordination between the supply chain agents using RFID data in order to pursue crate flow control by predicting supply chain behavior at future time instants.

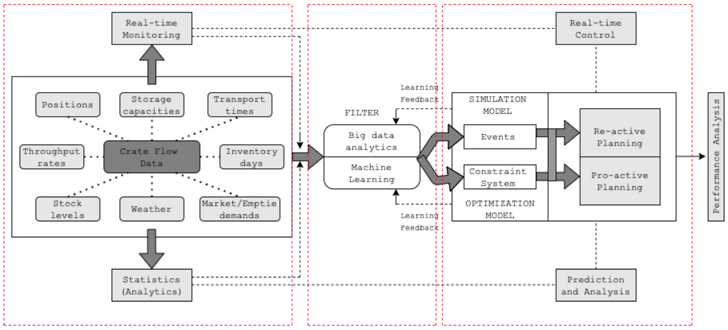


Figure 7.1: D-SC-T framework

7.1.7 Research question 7

The MPC controller in this thesis has the objective to optimize the supply chain performance by reducing costs relating storage. The MPC controller will accurately keep track of where crates are stored within the supply chain with use of the RFID gateways. As well as the related costs and demand at the production site, while planning optimal storage time and corresponding transportation at and between the supply chain locations. The planning decisions are considered optimal if the storage costs are low, while meeting demand. The digital twin with a MPC algorithm provides control of the crate flows. The impact is shown by various simulation experiments. The quantified impact of supply chain control results in less OPEX: €94.511 (peak season) and €41.184 (low season) with use of supply chain data over 2019.

7.1.8 Main research question

In this thesis it becomes clear that digital twins are found to be explored with the intention of improving performance of physical entities by supporting advanced developing technologies, while using models combined with data to interpret and to predict the behavior of a real system. A distinction can be made between a digital model, digital shadow and digital twin. The latter regulates data flows automatically and state changes of both the physical and virtual entity affect one another. When this function is enabled, control of the supply chain system can be empowered.

The controllability of the crate flows in Heineken's reverse supply chain driven by returnable packaging can be improved, using a centralized MPC control model within a proposed digital twin framework, combined with RFID data from the proposed gateways. These gateways measure crate positions and quantities per time. The controller uses this data to interpret and predict the supply chain behavior. The RFID data of the current supply chain states are fed into the model. The controller interprets the states and calculates which actions lead to less CAPEX and OPEX, while meeting all other the requirements. Due to the RFID measurements, data is visible and transparent for planning departments and other stakeholders and better coordination along supply chain agents can be made possible. This thesis does not claim to have developed a digital twin of a supply chain, but contributes to research of digital twin application in supply chains. This is done by proposing a framework including a control model and a solution to gain supply chain data, to enable real-time supply chain control. Furthermore, this thesis hopes to contribute to – and support the great digital twin visions of today, by an attempt to quantify the impact of a potential digital twin application within the supply chain field and contributes towards realization of digital supply chain twins.

Part VII

RE-EVALUATION

Chapter 8

Discussion and Recommendations

In this chapter a critical reflection on the performed research is shared, followed by recommendations for Heineken Netherlands Supply and for academic research.

8.1 Discussion

This thesis starts with a research of the entire closed-loop supply chain system and eventually simulates only the reverse logistics stream, to quantify the impact of control on this part. This is because in the current state analysis, the forward logistics and reverse logistics of the closed-loop system were analyzed, but two black boxes one at each end of system were considered: the production location and the market. These are the connections between the forward and reverse logistic material flows. Since these black boxes were considered, the effects of the two logistic streams on one another are not taken into account. In this thesis the control system is bounded to the reverse supply chain. More specifically, the reverse supply chain with sorted Empties including two main locations. The results are presented and are generalized. It should be kept in mind, that the results are representative for control over specific part of a supply chain. Not only the forward logistics but also the production and market relations will probably effect the reverse logistics in the real system. Although the focus of this research was mainly on the reverse flow, the forward flow is also included in the long cycle times and show relatively large inventory levels. Research on including improved planning, forecasting and interrelation between the two logistic flows could be beneficial for the total performance of the supply chain.

For this research data relating inbound and outbound at the warehouse in Werne was provided. With various assumptions this data could be used for the bounded control system. But this data was not the actual data regarding production and market returns. This is a large flaw of this research. To get the data required is currently not possible.

Furthermore, while analyzing the data used as exogenous input data for the simulations, an imbalance in crate flows has been noticed. The amount of crates entering the bounded system is for all weeks more than the crates leaving the system. This would mean increasing inventory levels at all locations throughout the years. In the real supply chain, this is not the case. Therefore, the data is not entirely representative for the situation. However in the research it is pointed out how the controller reacts to real-time data changes and therefore the noticed imbalance is not relevant. Since Heineken is planning on implementing the proposed RFID gateways to gather accurate data, for future research the influence of control can be investigated again with reliable data.

Since this research points out the importance of data transparency in a business and aims to quantify this for a real case where there is little, reasoning becomes a vicious circle. To be able to quantify the impact a base case is made, but due to a lack of information transparency and accessibility within the enterprise much assumptions have to be made to be able to quantify the impact. A multiplier effect is created, in which results based on assumptions are aiming to point out the significance of accurate results. Moreover, this contributes to the argument for Heineken to implement the RFID gateways to gather reliable, accurate and accessible data to stakeholders.

For this research MPC is the chosen control method for the control part within the digital twin. Therefore it only covers a small part of the wide variety of different control methods which could have been investigated and tested. Due to the similarities of digital twins and MPC in capturing and interpreting states and reacting by predicting the effect of possible actions on the states, MPC is chosen. Other control methods are still to be investigated. This research shows MPC is a control solution that works, but it is not argued to be the most suited solution.

8.2 Recommendations for Heineken Netherlands Supply

The starting point of this research was given the fact that the company is planning on introducing RFID gateways to measure actual crate cycle times. The first recommendation for Heineken is to carry out this project. Having real-time and reliable data enables decisions based on facts and not only on assumptions. Introducing the RFID could lead to better data transparency and accessibility to planning departments and other stakeholders. And stakeholder alignment and communications help solve simple problems. Better organization of information exchange helps planning departments to improve their planning and forecasts.

Another recommendation for Heineken is to further investigate what the optimal inventory levels are at the supply chain locations to meet the demand at the brewery, while preventing out of stock situations. A centralized information system containing real-time stock levels, orders, transport data will help provide this. When real-time information is available, inventory and logistic control of RPM can be enabled. When using a simulation model, optimal inventory levels can be determined. Feeding such a model with more data on market demand trends for example, make it more advanced and can improve better planning and forecasting.

8.3 Recommendations for academic research

In this research centralized planning and model predictive control is applied to the reverse logistic stream of the supply chain. A recommendation is to asses the influence of the forward logistics on the reverse logistic stream. Research on a complete CLSC with the proposed method could lead to new insights. In this research various black boxes were considered and left out of research. The market with its consumer behaviour and trends could be interesting to investigate and how it effects the entire CLSC. Moreover, what could be very interesting to study, is what the effect of control on the supply chain could be if the production is more flexible and can be adjusted to direct market demand and crate returns from market.

The processes within the supply chain stages itself were also considered black boxes in this research. The impact of information transparency and control on handling processes and material flows at these locations could be interesting to research. Another recommendation is to asses transport modes between the supply chain locations and how they could contribute to supply chain control.

In conclusion, this thesis offers a theoretical digital twin solution for the problems they have at Heineken's CLSC. But only a solution for the measure and control part has been brought forward. A digital twin also carries out big data analytics and machine learning possibilities. How these growing technologies fit into the digital twin concept could be interesting to study.

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`Some%20definitions%20include%20the%20human,connected%20to%20the%20cyber%20world.&text=The%20Digital%20Twin%20concept%20on,artificial%20intelligence%2Fmachine%20learning%20perspective.`

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Part VIII

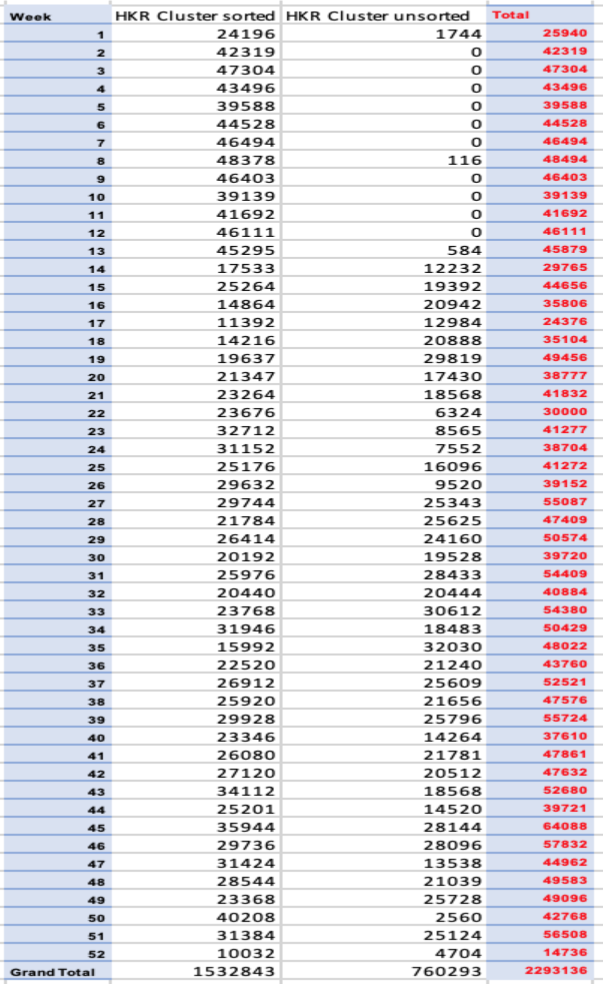
APPENDICES

Chapter A

Appendix A: Research Paper

Chapter B

Appendix B: Data



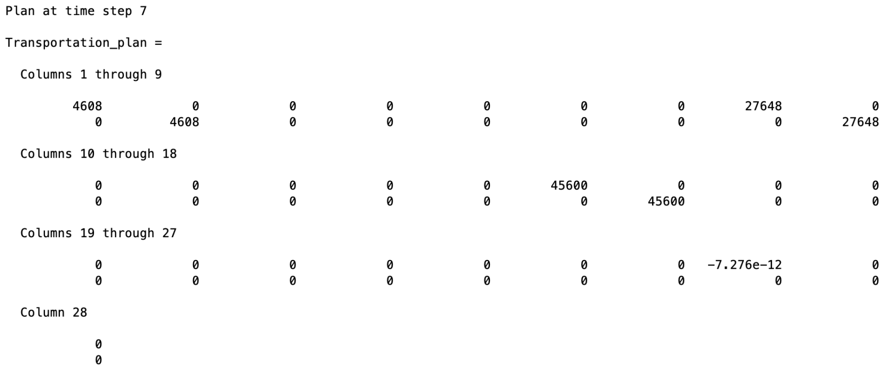
Week	HKR Cluster sorted	HKR Cluster unsorted	Total
1	24196	1744	25940
2	42319	0	42319
3	47304	0	47304
4	43496	0	43496
5	39588	0	39588
6	44528	0	44528
7	46494	0	46494
8	48378	116	48494
9	46403	0	46403
10	39139	0	39139
11	41692	0	41692
12	46111	0	46111
13	45295	584	45879
14	17533	12232	29765
15	25264	19392	44656
16	14864	20942	35806
17	11392	12984	24376
18	14216	20888	35104
19	19637	29819	49456
20	21347	17430	38777
21	23264	18568	41832
22	23676	6324	30000
23	32712	8565	41277
24	31152	7552	38704
25	25176	16096	41272
26	29632	9520	39152
27	29744	25343	55087
28	21784	25625	47409
29	26414	24160	50574
30	20192	19528	39720
31	25976	28433	54409
32	20440	20444	40884
33	23768	30612	54380
34	31946	18483	50429
35	15992	32030	48022
36	22520	21240	43760
37	26912	25609	52521
38	25920	21656	47576
39	29928	25796	55724
40	23346	14264	37610
41	26080	21781	47861
42	27120	20512	47632
43	34112	18568	52680
44	25201	14520	39721
45	35944	28144	64088
46	29736	28096	57832
47	31424	13538	44962
48	28544	21039	49583
49	23368	25728	49096
50	40208	2560	42768
51	31384	25124	56508
52	10032	4704	14736
Grand Total	1532843	760293	2293136

Figure B.1: Table of data HKR cluster crate returns from market 2019.

Chapter C

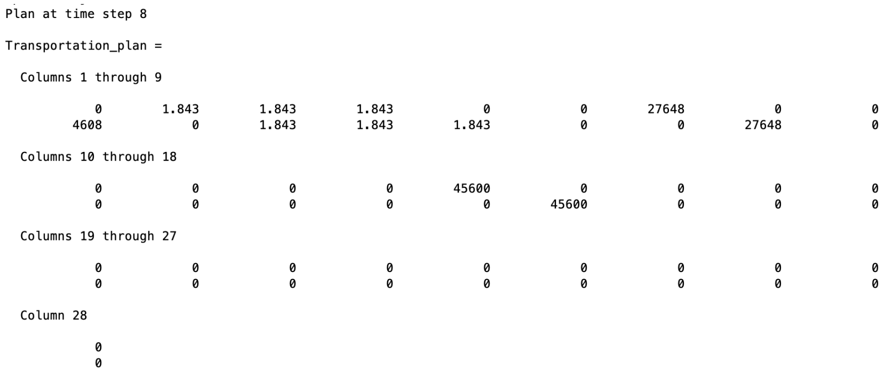
Appendix C: Simulation Results of Inventory Levels

C.1 Scenario 3



```
Plan at time step 7

Transportation_plan =

  Columns 1 through 9

        4608           0           0           0           0           0           0       27648           0
           0        4608           0           0           0           0           0           0       27648

  Columns 10 through 18

           0           0           0           0           0       45600           0           0           0
           0           0           0           0           0           0       45600           0           0

  Columns 19 through 27

           0           0           0           0           0           0           0  -7.276e-12           0
           0           0           0           0           0           0           0           0           0

  Column 28

           0
           0
```

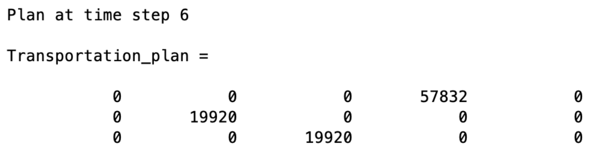
Figure C.1: Output results: scenario 3, day 7



```
Plan at time step 8

Transportation_plan =

  Columns 1 through 9

           0       1.843       1.843       1.843           0           0       27648           0           0
        4608           0       1.843       1.843       1.843           0           0       27648           0

  Columns 10 through 18

           0           0           0           0       45600           0           0           0           0
           0           0           0           0           0       45600           0           0           0

  Columns 19 through 27

           0           0           0           0           0           0           0           0           0
           0           0           0           0           0           0           0           0           0

  Column 28

           0
           0
```

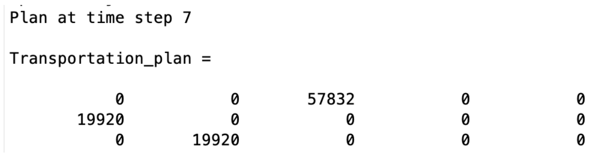
Figure C.2: Output results: scenario 3, day 8

C.2 Scenario 4



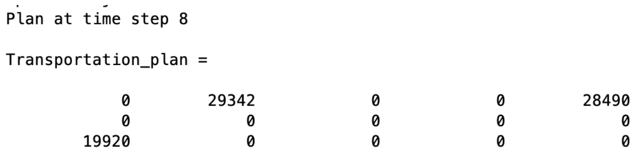
```
Plan at time step 6

Transportation_plan =

           0           0           0       57832           0
           0       19920           0           0           0
           0           0       19920           0           0
```

Figure C.3: Output results: scenario 4, day 6



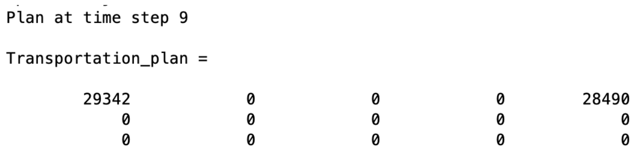
```
Plan at time step 7

Transportation_plan =

           0           0       57832           0           0
       19920           0           0           0           0
           0       19920           0           0           0
```

Figure C.4: Output results: scenario 4, day 7



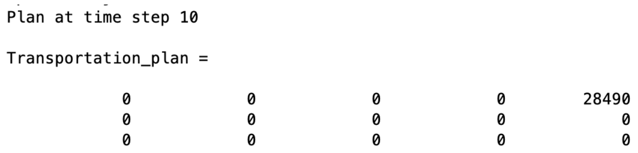
```
Plan at time step 8

Transportation_plan =

           0       29342           0           0       28490
           0           0           0           0           0
       19920           0           0           0           0
```

Figure C.5: Output results: scenario 4, day 8



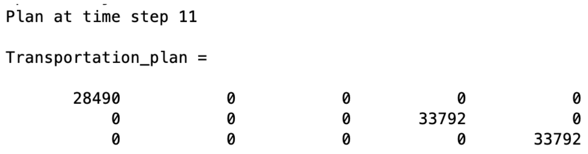
```
Plan at time step 9

Transportation_plan =

       29342           0           0           0       28490
           0           0           0           0           0
           0           0           0           0           0
```

Figure C.6: Output results: scenario 4, day 9



```
Plan at time step 10

Transportation_plan =

           0           0           0           0       28490
           0           0           0           0           0
           0           0           0           0           0
```

Figure C.7: Output results: scenario 4, day 10



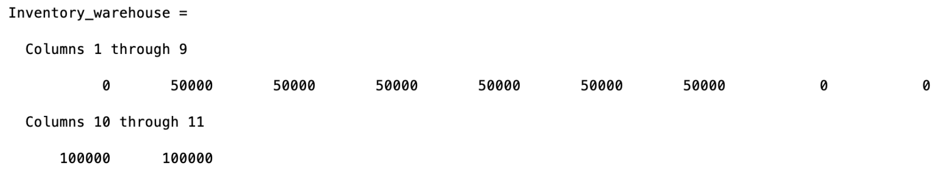
```
Plan at time step 11

Transportation_plan =

       28490           0           0           0           0
           0           0           0       33792           0
           0           0           0           0       33792
```

Figure C.8: Output results: scenario 4, day 11

Chapter D

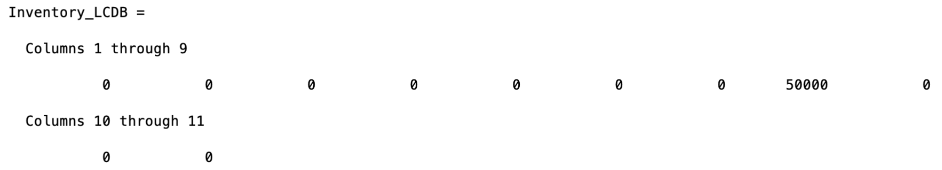
Appendix D: Verification

MATLAB output results: model including brewery, LCDB and warehouse



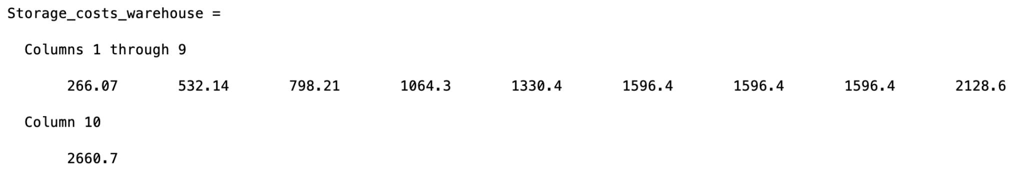
```
Inventory_warehouse =

  Columns 1 through 9

         0       50000       50000       50000       50000       50000       50000           0           0

  Columns 10 through 11

    100000      100000
```

Figure D.1: Output results: inventory level warehouse (day 0 - day 10)



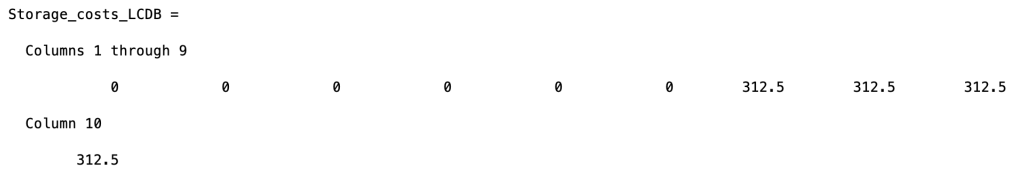
```
Inventory_LCDB =

  Columns 1 through 9

         0           0           0           0           0           0           0       50000           0

  Columns 10 through 11

         0           0
```

Figure D.2: Output results: inventory level LCDB (day 0 - day 10)



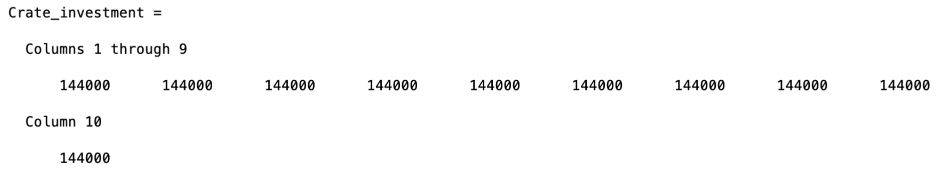
```
Storage_costs_warehouse =

  Columns 1 through 9

      266.07       532.14       798.21       1064.3       1330.4       1596.4       1596.4       1596.4       2128.6

  Column 10

      2660.7
```

Figure D.3: Output results: storage costs warehouse (day 1 - day 10



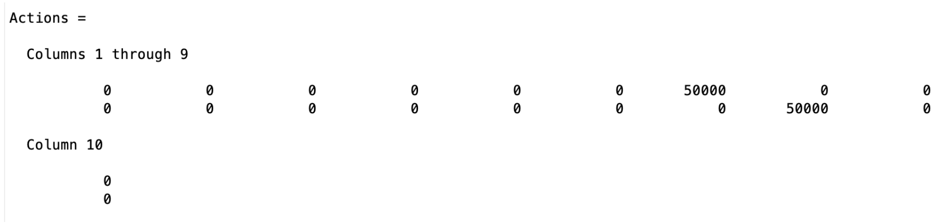
```
Storage_costs_LCDB =

  Columns 1 through 9

         0         0         0         0         0         0    312.5    312.5    312.5

  Column 10

     312.5
```

Figure D.4: Output results: storage costs LCDB (day 1 - day 10)



```
Crate_investment =

  Columns 1 through 9

    144000    144000    144000    144000    144000    144000    144000    144000    144000

  Column 10

    144000
```

Figure D.5: Output results: CAPEX (day 1 - day 10)



```
Actions =

  Columns 1 through 9

         0         0         0         0         0         0     50000         0         0
         0         0         0         0         0         0         0     50000         0

  Column 10

         0
         0
```

Figure D.6: Output results: transportation decisions (day 1 - day 10)

Chapter E

Appendix E: MPC Control Problem

E.1 Parameters

Parameters	
Parameter	**Description**
N_{p}	Prediction horizon [days]
N_{e}	Simulation duration [days]
c_{i}	Inventory costs location i [€/crate/day]
P_{nc}	Price per new crate
$x_{\mathrm{i,max}}$	Maximum capacity location i [crates]
$u_{\mathrm{i,max}}$	Maximum transportation capacity [crates]

Table E.1: Parameters

E.2 Control objective

minimize

$$J = \sum_{i=1}^{2}\sum_{k=1}^{N_{\mathrm{p}}} c_1 \cdot x_{\mathrm{i}}(k) + \sum_{i=3}^{4}\sum_{k=1}^{N_{\mathrm{p}}} c_2 \cdot x_{\mathrm{i}}(k) + \sum_{i=5}^{6}\sum_{k=1}^{N_{\mathrm{p}}} c_3 \cdot x_{\mathrm{i}}(k) + \sum_{k=1}^{N_{\mathrm{p}}} P_{\mathrm{nc}} \cdot x_7(k) \tag{E.1}$$

E.3 Prediction model

subject to

$$
\begin{aligned}
&\underline{x_1}(k+1) = \underline{d_1}(k)\\
&\underline{x_2}(k+1) = \underline{x_2}(k) + \underline{x_1}(k) - \underline{u_1}(k)\\
&\underline{x_3}(k+1) = \underline{u_1}(k)\\
&\underline{x_4}(k+1) = \underline{x_4}(k) + \underline{x_3}(k) - \underline{u_2}(k)\\
&\underline{x_5}(k+1) = \underline{u_2}(k)\\
&\underline{x_6}(k+1) = \underline{x_6}(k) + \underline{x_5}(k) - \underline{u_3}(k)\\
&\underline{x_7}(k+1) = \underline{d_2}(k) - \underline{u_3}(k)\\
&\underline{\mathbf{y}}(k+1) = \underline{\mathbf{x}}(k+1)\\
&...\\
&\underline{x_1}(k+N_{\mathrm{p}}) = \underline{d_1}(k+N_{\mathrm{p}}-1)\\
&\underline{x_2}(k+N_{\mathrm{p}}) = \underline{x_2}(k+N_{\mathrm{p}}-1) + \underline{x_1}(k+N_{\mathrm{p}}-1) - \underline{u_1}(k+N_{\mathrm{p}}-1)\\
&\underline{x_3}(k+N_{\mathrm{p}}) = \underline{u_1}(k+N_{\mathrm{p}}-1)\\
&\underline{x_4}(k+N_{\mathrm{p}}) = \underline{x_4}(k+N_{\mathrm{p}}-1) + \underline{x_3}(k+N_{\mathrm{p}}-1) - \underline{u_2}(k+N_{\mathrm{p}}-1)\\
&\underline{x_5}(k+N_{\mathrm{p}}) = \underline{u_2}(k+N_{\mathrm{p}}-1)\\
&\underline{x_6}(k+N_{\mathrm{p}}) = \underline{x_6}(k+N_{\mathrm{p}}-1) + \underline{x_5}(k+N_{\mathrm{p}}-1) - \underline{u_3}(k+N_{\mathrm{p}}-1)\\
&\underline{x_7}(k+N_{\mathrm{p}}) = \underline{d_2}(k+N_{\mathrm{p}}-1) - \underline{u_3}(k+N_{\mathrm{p}}-1)\\
&\underline{\mathbf{y}}(k+N_{\mathrm{p}}) = \underline{\mathbf{x}}(k+N_{\mathrm{p}}-1)
\end{aligned}
\tag{E.2}
$$

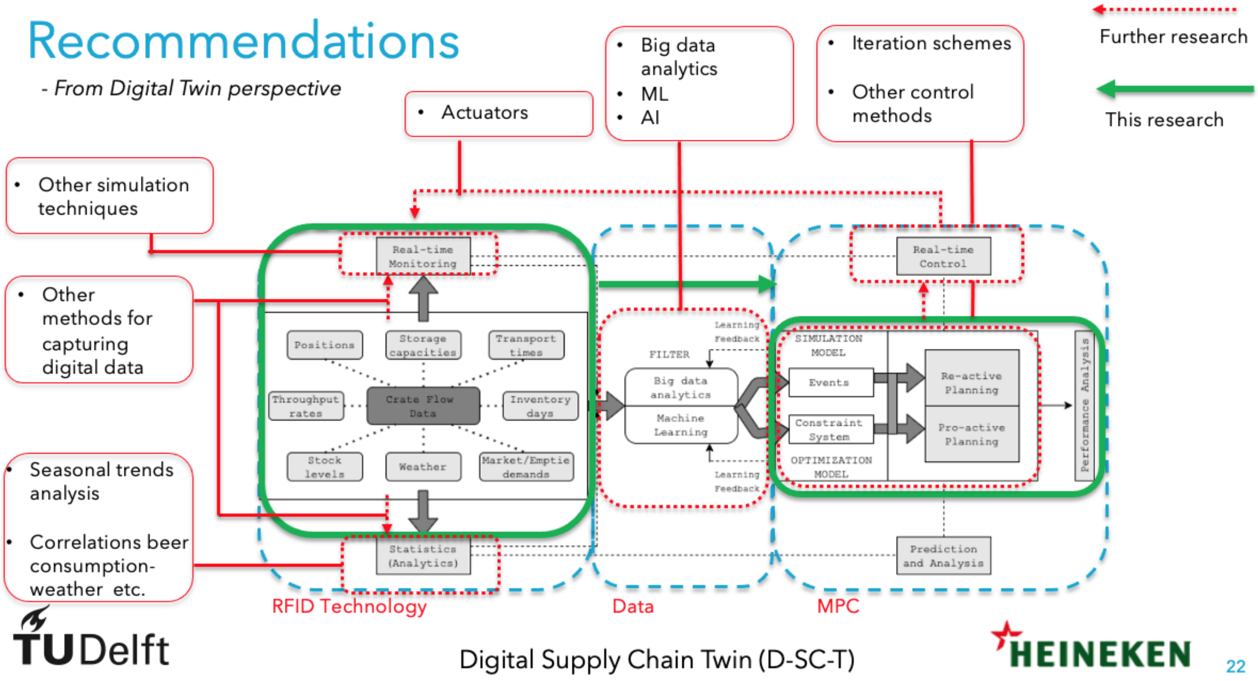
$$
\begin{aligned}
&0 \leq \underline{\mathbf{u}}(k) \leq \underline{\mathbf{u}_{\mathrm{max}}}\\
&0 \leq \underline{\mathbf{x}}(k+1) \leq \underline{\mathbf{x}_{\mathrm{max}}}\\
&0 \leq \underline{\mathbf{y}}(k+1) \leq \underline{\mathbf{u}_{\mathrm{max}}}\\
&...\\
&0 \leq \underline{\mathbf{u}}(k+N_{\mathrm{p}}-1) \leq \underline{\mathbf{u}_{\mathrm{max}}}\\
&0 \leq \underline{\mathbf{x}}(k+N_{\mathrm{p}}) \leq \underline{\mathbf{x}_{\mathrm{max}}}\\
&0 \leq \underline{\mathbf{y}}(k+N_{\mathrm{p}}) \leq \underline{\mathbf{u}_{\mathrm{max}}}
\end{aligned}
\tag{E.3}
$$

$$
\begin{aligned}
&\underline{\mathbf{x}}(k) = \underline{\mathbf{x}_{\mathrm{k}}}\\
&\underline{\mathbf{d}}(k) = \underline{\mathbf{d}_{\mathrm{k}}}\\
&...\\
&\underline{\mathbf{d}}(k+N_{\mathrm{p}}-1) = \underline{\mathbf{d}_{\mathrm{k+N_p\text{-}1}}}
\end{aligned}
\tag{E.4}
$$

Chapter F

Appendix F: Figures for Recommendations for future research

F.1 From a Digital Twin perspective



Recommendations

- From Digital Twin perspective

- Actuators

- Big data analytics
- ML
- AI

- Iteration schemes
- Other control methods

Further research

This research

- Other simulation techniques

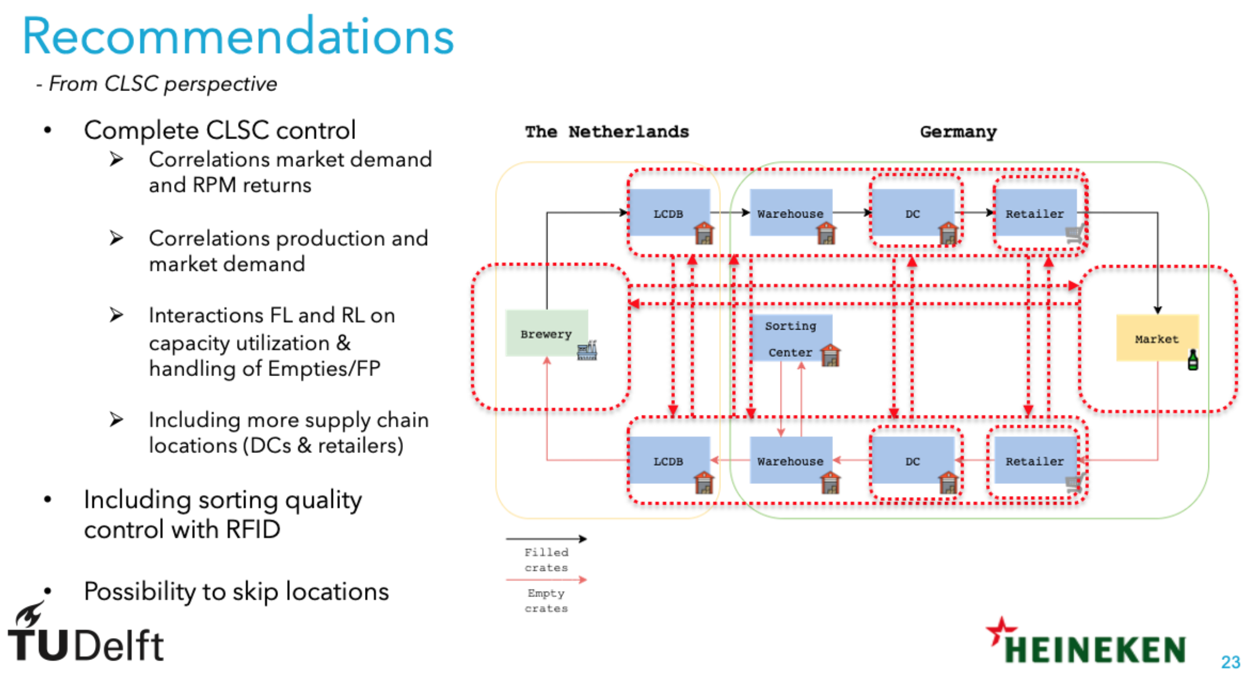
- Other methods for capturing digital data

- Seasonal trends analysis
- Correlations beer consumption-weather etc.

Digital Supply Chain Twin (D-SC-T)

Figure F.1: Recommendations from a digital twin perspective

F.2 From a Closed-Loop Supply Chain perspective



Recommendations

- From CLSC perspective

- Complete CLSC control
  - Correlations market demand and RPM returns
  - Correlations production and market demand
  - Interactions FL and RL on capacity utilization & handling of Empties/FP
  - Including more supply chain locations (DCs & retailers)
- Including sorting quality control with RFID
- Possibility to skip locations

Figure F.2: Recommendations from a CLSC perspective

Chapter G

Appendix G: Project Implementation Plan at Heineken