

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Solving the facility layout problem in the wine industry

Bernardo Campos Leichsenring Franco



Mestrado em Engenharia Eletrotécnica e de Computadores (M.EEC)

Supervisor: Prof. Maria Beatriz Brito Oliveira

July 29, 2022

Abstract

Despite its long history, the wine industry is now, more than ever, a global business in expansion. Countries with long tracks of wine production, as is the case of Portugal, have been increasing their worldwide presence in the last decades, with clear cases of success in terms of export. For this reason, the wine supply chain needs to be adapted to support the increasing market expectations in terms of demand volume and the growing number of wine varieties and packaging formats.

At the center of the wine supply chain lies the bottling process, which concerns the packaging of the bulk wine into a medium that can be transported and sold to retailers. In the case of large companies with a large number of brands, bottling usually takes place in extensive facilities that comprise different functional areas. These include bottling lines and other supporting facilities, such as warehouses for the raw materials, storage tanks, and a distribution center for the incoming and outgoing flow of materials

This dissertation focuses on the expansion of the bottling plant of a Portuguese wine producer and the corresponding need to define a layout for the facility. This problem is a subset of the facility layout problem that has been the subject of significant study in the past years. The design of a new facility layout arises in response to the need to handle the forecasted increase in demand. The strategy developed for solving this project relies on modeling three candidate layouts using simulation. These were chosen for their expected viability following preliminary analysis.

The simulation work reflects the need to study the layouts regarding various key performance indicators, such as the utilization of resources, the storage capacity, and the overall efficiency of the operation. This allows the identification of flaws and strong points in the layouts, since each focuses on solving certain issues with the current operation. The resulting analysis serves as a decision support method to the stakeholders that needs to be balanced with additional factors such as the associated investment cost.

Following the simulation of the three layouts, one specific warehouse design is analyzed in depth using a multi-objective optimization model that aims to find a solution that balances storage capacity with the positioning of the various SKUs in the warehouse. The focus of this analysis is the warehouse of finished product, which represents the highest storage needs in the entire facility.

Both problems demonstrate the need for tools such as simulation and optimization in the context of facility design to ensure a competitive edge and to support the commercial activity of the company with a flexible and robust operation that can deal with the forecasted increase in demand. Despite the proven record of these techniques in aiding the decision process, there is room for improvements in several areas, that need to be addressed in the near future to allow for an optimized facility layout.

Resumo

Apesar da sua longa história, a indústria vitivinícola é agora, mais do que nunca, um negócio global em expansão. Países com longos percursos de produção de vinho, como é o caso de Portugal, têm vindo a aumentar a sua presença mundial nas últimas décadas, com nítidos casos de sucesso em termos de exportação. Por esta razão, a cadeia de abastecimento tem de ser adaptada para suportar as crescentes expectativas do mercado em termos de procura, do número crescente de variedades de vinho e formatos de embalagem.

No centro da cadeia de abastecimento do vinho encontra-se o processo de engarrafamento, que diz respeito ao embalamento do vinho a granel num meio que pode ser transportado e vendido a retalhistas. No caso de grandes empresas com um grande número de marcas, o engarrafamento ocorre em instalações extensas, que compreendem diferentes áreas funcionais. Estas incluem linhas de engarrafamento e outras instalações de apoio, tais como armazéns para as matérias-primas, tanques de armazenamento, e um centro de distribuição para o fluxo de entrada e saída de material.

Esta dissertação centra-se na expansão das instalações de engarrafamento de um produtor de vinho português e na correspondente necessidade de definir um *layout* para as instalações. Este problema é um subconjunto do *Facility Layout Problem* (FLP), que, nos últimos anos, tem sido objeto de estudo na literatura. A conceção de um novo desenho para as instalações surge em resposta à necessidade de lidar com o aumento previsto da procura. A estratégia desenvolvida para resolver este problema baseia-se na modelação de três *layouts* candidatos com base em simulação. Estes foram escolhidos após análise preliminar, pois apresentaram o maior potencial de viabilidade à implementação.

O trabalho de simulação reflete a necessidade de estudar os *layouts* relativos a vários indicadores-chave de desempenho, tais como a utilização de recursos, a capacidade de armazenamento, e a eficiência global da operação. Isto permite a identificação de pontos fortes e fracos nos *layouts*, uma vez que cada um deles se concentra na resolução de determinados problemas identificados na operação atual. A análise resultante serve como método de apoio à decisão, e tem de ser comparada com fatores adicionais, tais como os custos de investimento associados.

Após a simulação dos três *layouts*, o projeto de um armazém específico é analisado em profundidade, utilizando um modelo de otimização multi-objetivo, que visa encontrar uma solução que equilibre a capacidade de armazenamento com o posicionamento dos vários artigos no armazém. O foco desta análise é o armazém de produto acabado, que representa a maior necessidade de armazenamento em toda a instalação.

Ambos os problemas demonstram a necessidade de ferramentas tais como simulação e otimização no contexto do FLP, para assegurar uma vantagem competitiva e apoiar a atividade comercial da empresa com uma operação flexível e robusta, que possa lidar com o aumento previsto da procura. Apesar do registo comprovado destas técnicas no apoio ao processo de decisão, existe espaço para melhoria em várias áreas, que têm de ser abordadas para assegurar uma disposição otimizada das instalações.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to Professor Beatriz Brito Oliveira for your undivided support on an academic and personal level. This work would not have been possible without your profound insights and eagerness to help me at a moment's notice.

To Bruno Batista, for being my mentor for the past six months, for all the time you set aside for me and for ensuring my work corresponded to your high expectations. Our brainstorming conversations were some of the highlights of these past months. To Daniel Pereira, for your guidance and for teaching me what consulting is all about. To Inês Trovisco, for your patience and cooperation that helped make this work possible.

To Professor Bernardo Almada-Lobo, for your role in my professional life when you invited me to join LTPlabs almost four years ago and for challenging me to take part in the unique project that became the topic of this dissertation.

To all LTPeers, a group of some of the most brilliant, most interesting people I know. You took me in when I was barely starting the second year of my bachelor's and made me feel right at home. It has been a joy to work alongside you.

To Mom and Dad, the most sensible and loving persons I know and will ever know. Thank you for teaching me your values and always believing in me. Your drive and passion inspire me, and I hope to become one day as exceptional as you are. To Rita and Tomás, thank you for being there for me every day. To Grandpa with "saudade", and to Grandma, for your love, care and sense of humour that brighten up my days. And to Ginho, my faithful canine companion in these last few months.

To my "Bros", with a special note to Francisco Caetano, Guilherme Pinheiro and Tomás Araújo, who went with me through all the ups and downs of the past five years, from the days and nights at FEUP to the days and nights in Moledo.

Joana, I am very fortunate I could spend these past years with you. Your love, friendship and support made every step of this journey easier. Thank you for making my life better every single day.

Bernardo Campos Leichsenring Franco

*“A ideia nasce quando há sol...
Depois, cresce na sombra quente
E vive no sonho...*

*Às vezes passa, sem sorrir, sem chorar...
Mas um dia surge no papel branco
E é lançada para o vento do mundo...*

*Mas fui eu que a vi...
Sou eu que a vejo...
... E agrada-me tanto!...”*

Fernando Campos

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Scope of the project	2
1.3	Structure of the dissertation	4
2	Literature review	5
2.1	The context of a winery	5
2.2	Simulation	7
2.2.1	Digital Twin	9
2.3	Facility Layout Problem	10
2.4	Discussion	11
3	Winery facility and initial data acquisition	13
3.1	Understanding the facility and its functional units	14
3.1.1	The oenological operation	15
3.1.2	Bottling	16
3.1.3	Logistics	17
3.2	Gathering inputs for the simulation	18
3.2.1	Sales forecast and production plan for 2030	18
3.2.2	Required areas and loading docks	19
3.2.3	Pallet flow for all areas	26
4	Simulation model for the facility	27
4.1	Modeling the functional areas	27
4.1.1	The bottling lines	28
4.1.2	Warehouse for wine bottles and other containers	29
4.1.3	Warehouses of dry raw materials	32
4.1.4	Wine cellar	33
4.1.5	Warehouse for finished product and distribution center	35
4.1.6	Other warehouses	39
4.2	KPIs for evaluating the layouts	40
4.3	The layouts	41
4.3.1	The first layout - the Masterplan	43
4.3.2	The second layout – a variation of the Masterplan	45
4.3.3	The third layout - maximizing storage density with a vertical warehouse	46

5	Simulation implementation and results	48
5.1	Implementation of the simulation models	48
5.2	Results	49
5.2.1	Storage	49
5.2.2	Resources	50
5.2.3	Transporters	51
5.3	Discussion	54
6	Optimizing the finished product warehouse	56
6.1	Description of the problem	56
6.1.1	Methodology	57
6.2	Sets, indexes and parameters	59
6.2.1	Sets	59
6.2.2	Indexes	59
6.2.3	Parameters	60
6.3	Decision variables	60
6.4	Objective function	61
6.5	Constraints	62
6.6	Results	63
6.6.1	Discussion	64
7	Conclusion and future work	67
	References	70
A	Flowcharts of the modeled processes	74
B	Implementation of the layout simulation	76

List of Figures

2.1	Role of the wine producer in the supply chain	6
3.1	Structure of the project	13
3.2	Overview of the operations taking place in the facility	15
3.3	Flowchart of the process of the bottling lines	17
3.4	Daily arrival of trucks containing pallets with wine bottles to the facility in the year 2030 (the absolute values are anonymized for motives of confidentiality) . .	20
3.5	Implementation of the incoming operation of raw materials in Anylogic	22
3.6	Implementation of the incoming and outgoing operations of finished product (national or international distribution) in Anylogic	23
3.7	Ranking of the pallet flow for each of the warehouses	26
4.1	Process of the bottling lines modeled in Anylogic	30
4.2	Process mapping for the operation of the warehouses of raw materials	31
4.3	Processes used in the simulation of the bottle warehouse	32
4.4	Processes used in the simulation of the wine cellar	34
4.5	Layout for the operation of finished product, as implemented in the simulation model in Anylogic (L1 - Masterplan)	35
4.6	Processes used to simulate the shipment of finished product warehouse	37
4.7	KPIs ordered by topic, with a description of what they entail	41
4.8	Design of the upper floor in Anylogic in the first and second layouts	43
4.9	Layout of the lower floor for the second layout. The main change from the masterplan is the removal of the picking area and the introduction of a buffer storage area	45
4.10	Layout of the lower floor for the Vertical Warehouse layout	47
4.11	Layout of the upper floor for the Vertical Warehouse layout	47
5.1	Analysis of the total finished product pallet capacities of the three layouts. (The real number of pallets is not shown for reasons of confidentiality)	50
6.1	Sketch of the layout considered for this optimization problem. It is based on the lower floor layout of the Masterplan	58
6.2	Number of pallets that can be stored in the various storage layouts resulting from different α values	64
6.3	Total distance traveled by forklifts to transport pallets the storage layouts given different α values	65
A.1	Flowchart of the process of bottling to/from the wine cellar	74

A.2	Flowchart of the process of dispatching of pallets in the national distribution operation	74
A.3	Flowchart of process of reception of pallets of the finished product	75
B.1	Main parameters, schedules, storage units and functions of the simulation models	76
B.2	Process of reception of pallets of finished product	77
B.3	Processes related to the implementation of the logistic train in the facility	77

List of Tables

3.1	Simulation results for the loading docks of trucks with pallets of dry raw materials	24
3.2	Simulation results for the loading docks of trucks with pallets of wine bottles . . .	24
3.3	Simulation results for the loading docks of the national operation	25
3.4	Simulation results for the loading docks of the international operation	25
5.1	Occupation of the warehouses depending on the layout implemented in the year 2030 for the optimistic demand scenario	49
5.2	Man-hours by warehouse for each layout. The values are displayed in percentage of the the value for the Masterplan (layout 1)	52
5.3	Number of potential collisions at various critical points in the facility according to layout	52
5.4	Total monthly distance traveled by forklifts performing select activities	53
5.5	Loading time and time spent in the facility of the various outgoing operations. . .	53
6.1	Dimensions of the reduced MIP problem. The reduction is performed automatically by CPLEX.	63
6.2	Results of the solutions of the optimization model for the two instances, given various α values	64

Acronyms and Symbols

CAD	Computer-Aided Design
DTI	Digital Twin Instance
DTP	Digital Twin Prototype
FLP	Facility Layout Problem
FTE	Full-time equivalent
KPI	Key Performance Indicator
OOP	Object Oriented Programming
PDM	Product Data Management
PLM	Product Lifecycle Management
SCADA	Supervisory Control And Data Acquisition
SKU	Stock Keeping Unit
sqm	Square Meters

Chapter 1

Introduction

Over the past decades, the global wine market has been in clear expansion, driven by a worldwide increase in demand. This growth is especially noted in countries such as the US and Portugal, which featured growth rates of 7.6% and 29% between 2014 and 2018, respectively ([International Organisation of Vine and Wine, 2019](#)). This market development is driven by an increase in demand for existing wine products, as well as the introduction of new wine varieties and packaging mediums. Despite its ancient industry, the wine industry lies at the center of constant innovation in terms of product and production methods, incorporating many of the recent scientific developments in wine making, operations and supply chain management.

To capture the increase in demand, players in the wine industry have been adapting their supply chains to increase their production capacity and the variety of products they can output. Investments are made across the supply chain, ranging from the acquisition and plantation of new vineyards to the construction of larger distribution centers. The investment necessity is exacerbated by the fact that most businesses in this industry have centennial histories, with aging plants that are not suitable for large increases in production capacity.

1.1 Motivation

At the center of the wine-making operation lies the bottling plant, which takes in the prepared wine and bottles it for sale to the clients. Even in the case of large operations, the centralization of all bottling processes at a single facility is not uncommon. This results in large, complex bottling facilities featuring large intakes of raw materials and even higher quantities of outgoing finished products.

The creation of new bottling facilities or the expansion of existing ones often represent significant capital expenditure and require a large degree of planning. Since these endeavors often take years to be fulfilled and condition the operation of the whole company for years to come, there is an added incentive to ensure that the facility provides the necessary increase in production capacity. For this reason, one of the main aspects to consider is the facility's layout. It must satisfy the operation's space, storage and quality requirements while maintaining a high degree of efficiency.

Also called the Facility Layout Problem (FLP), it is a highly debated topic in the literature, with several solution possibilities being suggested by multiple authors. One of these methods is simulation which has become one of the central tools for providing stakeholders with methods to design and test layouts that satisfy their requirements. The ability to represent various designs for the layout of the facilities through discrete-event or agent-based models before applying them in the real world is an invaluable asset. Another feature of these models is the possibility of performing various what-if analyses corresponding, e.g., to different demand scenarios or number of bottling lines.

The ability to design appropriate layouts provides a clear competitive edge to businesses in the wine market, and ensures that their operations can scale up to meet the predicted increase in demand for decades to come. For this reason, the ability to solve the FLP in complex production environments such as bottling plants is a very relevant topic.

1.2 Scope of the project

This dissertation focuses on the application of simulation to solving the facility layout problem faced by a player in the wine industry. The central aspect of the solution is a facility-wide simulation model for its planned bottling plant, that aims to replicate the operation while being subjected to various types of layouts. During the design and execution of this model, an improvement possibility for the layout of one specific warehouse was detected, which gave rise to a second problem, for which a linear programming optimization model was developed.

The business in question is responsible for the sale of a large number of different wine labels under various brands. These range from low-end table wines to more premium wine varieties, spanning multiple geographies. The amount of wine varieties conditions several aspects of the company's operations, from bottling to distribution. The company is vertically integrated, being responsible for most wine supply chain operations, ranging from grape production to the distribution of the finished wine. It operates in the domestic and international markets, the latter of which represents the majority of the company's sales. The fact that it sells its products all around the world forces the company to make changes to the labeling and packaging of the product depending on the market. This adds an extra layer of complexity to the operations, especially regarding bottling.

The project was developed in the context of a consulting firm operating in close contact with the various stakeholders responsible for the implementation of this project. The development of this study is motivated by a long-term investment plan, which includes redesigning and expanding the existing bottling and distribution facilities at the company's main facility. Therefore, this project is integrated into a larger effort, consisting of various work streams. For this reason, the study presented here relies on various information sources, models and other types of analysis that preceded this project. Some relevant data sources and data sets are referred to and briefly explained, but they are largely kept out of scope. All remaining topics described in this study were developed by the author of this document in collaboration with the project team.

The plan intends to adapt the operations to the reality of the next decade and the forecasted sales growth, especially in the international market. The increase in operations at the main factory comes at the expense of closing a secondary facility. The production capacity at this secondary location needs to be transferred to the first one, with existing machines physically relocated or exchanged for newer ones. The combination of both operations places an additional strain on the main facility regarding bottling, storage, and distribution capabilities. However, it is also predicted that the condensation of both operations will generate synergies, increasing efficiency.

At the center of the projected increase in capacity lies the intention to expand the factory regarding its bottling throughput capacity, that is, the amount and variety of wine labels it can produce to satisfy the demand. Increasing the bottling operation impacts other parts of the factory – such as warehousing for dry raw materials and wine and the storage and dispatching of the finished product. The factory must also change several other aspects, such as the position and number of loading bays. Furthermore, the company intends to make several alterations in the factory's layout to better accommodate their business needs – such as making a clear physical separation between factory operations and the office buildings. All these restrictions must be factored in while designing potential layouts.

The second problem was identified during the creation of the various scenarios. Despite the high-level focus of the simulation - the most important part of the simulation model is the placement of the functional areas and how they interact - the layouts for each of the warehouses and bottling lines also needed to be designed, albeit in a simplified form. This simplification was deemed to be inaccurate in modeling the actual capacity of the warehouses. For this reason, a multi-objective optimization model was developed to maximize the storage capacity of the largest warehouse of the facility - the warehouse of finished product, while attempting to minimize the distance covered by forklifts for transportation.

Due to the sensitive angle of some of the aspects mentioned in this dissertation, certain values and figures needed to be anonymized in order to protect trade secrets. In particular operational KPIs that can be used to estimate the operational efficiency of the company, such as the absolute productivity of the working force, are not shown directly in this text. An effort has been made to use percentages instead of absolute values, especially when comparing scenarios and layouts.

In summary, the case arises from the need to assess the changes to the layout of the facility to make the increase in production capacity viable while tackling four central issues:

1. Existing problems in efficiency and quality, particularly in the second facility, which is to be dismantled
2. Limitations of space and capacity
3. Reduced flexibility of bottling lines
4. Unexplored synergies through the combination of both operations under one roof.

1.3 Structure of the dissertation

The dissertation showcases two problems related to simulation and optimization and is divided into seven distinct chapters. In the second chapter, a review of the literature regarding the topics of the wine supply chain, simulation, digital twin and the facility layout problem is presented. This part aims to contextualize the development of this project with the state-of-the-art. The third chapter provides an introduction to the facility and the strategies used for acquiring the necessary inputs. The fourth chapters focus on the simulation problem and the modeling of the various layouts. In chapter five, the results of the simulation model are provided and analyzed. In chapter six, the optimization problem that arises from the simulation is described in detail and its results shown. The last chapter features the conclusions from the work developed and presents improvement possibilities, as well as future work regarding the topics of the dissertation.

Chapter 2

Literature review

The literature review follows a top down approach to the problem, starting with the wine industry and a description of the operational problems faced by wineries. This is followed by an analysis of the topic of simulation, which is then described in the context of a Digital Twin and, more concretely, regarding the facility layout problem. A critical analysis of the relevance of the review to the problem at hand concludes this section.

2.1 The context of a winery

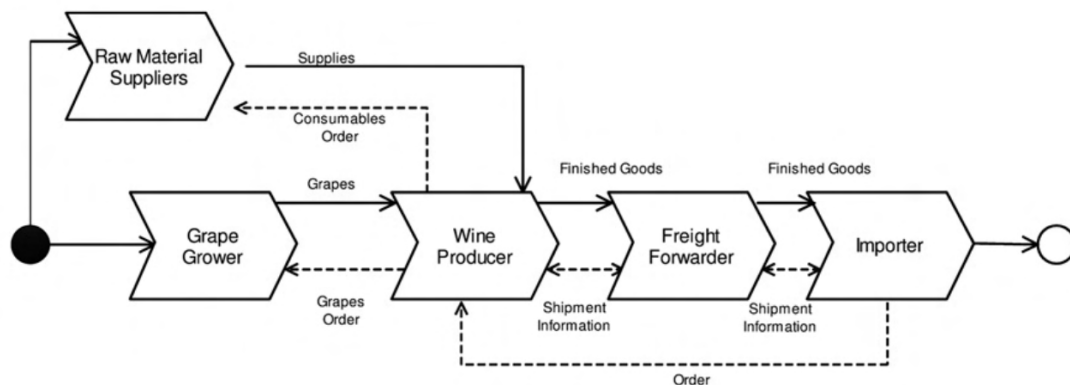
Wine is a complex product in terms of production and supply chain due to several factors, ranging from the effect of environmental conditions to a large number of wine classes and segments (Mac Cawley, 2014). Large wineries are usually responsible for many distinct Stock Keeping Units (SKUs), with different brands, wine types, harvest years and labels. The number of SKUs can reach up to 200 in a single production planning window, each requiring storage, lot-sizing, and production scheduling. The same wine type can be labeled and bottled differently according to the target market.

Garcia et al. illustrate the dimensions of the wine supply chain, while providing a framework for measuring the performance of logistics (Garcia et al., 2012). The winery's operation plays a critical role in this context. The wine supply chain includes 11 distinct layers; however, the same actor can be responsible for several simultaneously. The most critical roles for this analysis are the Filler/Packer role and, to a lesser extent, the role of Freight Forwarder and Importer.

The operations of the winery described here assume that the winery functions as a wine producer in the context of Garcia et al., while also filling the role of the freight forwarder (figure 2.1).

Wine either arrives in bulk and is stored in an appropriate tank, or in wine barrels. Tanks can vary largely in size, from several thousands to millions of liters, while barrels are typically smaller, with sizes in the range of hundreds or thousands of liters. The wine is kept in storage until it is ready to be bottled. Some wines go through a period of aging which can happen in the barrel (also denominated oak).

Figure 2.1: Role of the wine producer in the supply chain



Storage is then followed by the bottling process. According to Boulton et al., bottling is arguably the most important of all winemaking operations, as it determines the state in which the wine is delivered to the customer (Boulton et al., 1996). It requires a collection of input materials beyond the wine, which are typically designated dry raw materials and include the glass bottles, bag-in-box or cans, corks or bottle caps, labels, and cardboard boxes. This process can occur in multiple bottling lines in parallel, which may include labelling and packaging. First, the wine is pumped from storage to filling tanks and then to the bottling lines. The problem of efficiently routing the piping of wine from cellar to bottling line was analyzed by Cakici et al., who propose a network optimization algorithm especially for this purpose (Cakici et al., 2006). According to Basso and Varas, who provide a Mixed Integer Problem formulation for winery operation, large wineries have several bottling lines and intermediate bottling tanks are used for each production batch, where wine can remain for a limited time due to the risk of wine oxidation (Basso and Varas, 2017). The bottling lines are responsible for the filling of the bottles (or other storage material), their labeling and packaging. However, bottles may not be labeled immediately and stored undifferentiated, to be labeled later (Cholette, 2009). Likewise with the cardboard boxes: bottles can be stored in bulk in cellars, and packaged later, depending on demand. These postponement strategies are used to curb variations in demand, with a considerable part of the production held at the labeling and packaging levels. This strategy is typical in the global packaging industry, for which Twede et al. provide a good overview (Twede et al., 2000). One of the major problems faced in bottling process is the need for long setup times each time that the type of wine or bottle used changes. Both the filling tank and the filling device on the bottling line must undergo a process of washing, to ensure that the next batch is not contaminated with the previous one.

Since the main objective of this work is the prescription of an adequate macro-layout for the production center, it is fundamental to identify the necessary blocks of the production and storage processes. It is possible to distinguish between 5 main types of storage facilities:

- Storage of bulk material, requiring appropriate tanks
- Warehousing for the smaller wine barrels

- Warehousing for dry raw materials
- Cellars for undifferentiated and unpackaged final product
- Warehousing for finished cardboard boxes containing wine bottles, cans, and bag-in-boxes.

Meanwhile, the production itself includes the bottling lines and additional tanks used for cold stabilization and filling.

2.2 Simulation

When prototyping or interacting with an existing system is expensive or impossible, one possible solution is modeling (Borshchev and Filippov, 2004). This process allows for the mapping of problems from the real world through abstraction. In particular, complex interactions between different entities and agents make the definition of closed-form analytical solutions complicated or, in some cases, impossible (Swaminathan et al., 1998). Simulation can offer a good alternative in these cases, in particular when coupled with optimization. Although these two topics have traditionally been considered separate approaches, recent efforts have been made to combine both (Figueira and Almada-Lobo, 2014). Possible applications of this strategy are described in section 2.2.1. Other strategies include, for example, approximate solution methods.

Shannon (Shannon, 1998) defines simulation as the process of model design based on a real world system to allow for a better understanding of the system's properties and to evaluate different strategies for its operation. The possibility of testing various alternatives and scenarios for the operation of the system make it a valuable tool in the present manufacturing context. Simulation is especially well-suited when time dynamics of the system are important.

Simulation is one of the main tools used in the field of operations management, and has applications in manufacturing, logistics, services, and healthcare, among others (Jahangirian et al., 2010). The first publications relating to simulation technology in manufacturing date back to the 1960s and have accompanied the evolution of computers throughout the past 60 years (Mourtzis et al., 2014). They have since experienced an exponential growth in adoption.

However, simulation models can suffer from essentially two problems (Swaminathan et al., 1998):

1. They can take a long time to develop, since they require the real-world process to be modeled in sufficient detail.
2. They are highly specific to the problem at hand and their reuse is limited.

Several frameworks have been developed to tackle these issues. They form the basis of modern simulation software suites.

Modeling a real-world system with simulation can depend on varying levels of abstraction, from the strategic to the operational level. The level of abstraction is highly dependent on the topic. Borshchev and Filippov list several use cases for simulation models, ranging from marketplace and

competition models (high abstraction) to factory floor and warehouse models (low abstraction) (Borshchev and Filippov, 2004). Operational models such as the focus of this work will tend towards the lower end of the abstraction spectrum and require high levels of detail. Precise data acquisition is fundamental for the success of such a model.

Simulation models follow one of following three different methods (Grigoryev, 2021):

- System dynamics
- Discrete-event modeling (DE)
- Agent-based modeling (AB)

System dynamics is a high abstraction level method and is most often employed in high-level strategic modeling. It is based on the stock and flow diagram. Stock represents a quantity existing at one point in time while flow is characterized as the difference of stock over a given time frame. System dynamics models are deterministic.

Discrete event simulation models a system as a series of discrete events and processes that trigger actions. The occurrence of events leads entities to change state as time passes. No state change occurs between two consecutive events. DE models are stochastic by nature and need to be run multiple times to ensure full understanding of the system. Statistical methods are employed to condense the multiple runs (Maidstone, 2012).

Agent-based modeling is a more recent approach (Railsback, 2019) for simulation. Agents are defined as autonomous computation entities that find themselves in an environment and can interact with it and other agents. Five characteristics can be defined for an agent (Macal and North, 2005):

1. It is identifiable and discrete from other agents.
2. It is situated and lives in an environment alongside other agents.
3. It is goal-oriented, having objectives to achieve.
4. It is autonomous and self-directed, and act independently from other agents.
5. It is flexible, can learn and adapt its behaviors over time based on experiences.

However, different simulations show varying levels of sophistication in terms of the agent's characteristics and can be adapted according to the simulation's necessities. Therefore, AB is extremely flexible and can be used in a variety of levels of abstraction.

The choice of the most suitable simulation type is situation-dependent. A discussion about the feasibility of using one method over the other for the situation presented in this work is provided in the section.

2.2.1 Digital Twin

The concept of Digital Twin was first defined by Michael Grieves and John Vickers in 2002 as a digital equivalent to a physical product. It is composed of a physical entity, a virtual counterpart, and the corresponding data connections (Grieves and Vickers, 2017). This means there is a mirroring or “twinning” of the physical and virtual systems. Digital twins can belong to one of two types: (1) Digital Twin Prototype (DTP) and (2) Digital Twin Instance (DTI). A DTP describes the prototypical physical artifact, containing all information necessary to create the physical twin. A DTI describes a specific instance of a physical product that remains linked to an individual product. The DTP surges at the phase of product design, while the DTI is created for each manufactured product during the product realization phase.

Conceptually, Digital Twins can perform both physical-to-virtual and virtual-to-physical connections. However, most literature is concentrated on the first possibility – changes are controlled by Internet-of-Things sensors, web services or others (Jones et al., 2020). The measurement phase is denominated metrology. This phase triggers a further realization phase, which allows the virtual entity to be updated in the virtual entity. The virtual-physical connection occurs in similar manner, but changes occur in the virtual entity, triggering alterations in the physical world. They can be set off by changes in display terminals or production management. Both connections form the possibility of a continuous loop that can generate hypotheses that can be directly implemented in the physical world.

Digital Twins are used extensively in manufacturing scenarios (Kuts et al., 2017) where they are employed in modeling, simulation, and optimization (Kritzinger et al., 2018). Nikolakis et al. use a Digital Twin to simulate warehousing operations and significantly improve ergonomics of warehouse operations (Nikolakis et al., 2019).

Liu et al. (Liu et al., 2019) provide an application of a Digital Twin to an automated flow-shop manufacturing system. It is based on the concept of “iterative optimization between static configuration and dynamic execution”. Static configuration includes layout planning, equipment selection, assembly, among others. All these decisions are based on demand patterns. This information is modeled and fed into the execution engine (both digital and physical). System execution delivers the result of the static configuration, which enables the possibility to perform optimization on the operation mode in terms of various variables, such as load balance, utilization, stability, and robustness. This process allows adapting the initial design of the system accordingly.

Zhuang et al. suggest a new framework for a Digital Twin in the context of smart manufacturing, which includes the physical and a virtual shop-floor with an additional element: an application containing platforms for production management and prediction of the factory’s future operations (Zhuang et al., 2018). Big Data plays an important role in this area, providing data from ERP, MES, and other data sources for the prediction platform.

Boschert and Rosen describe simulation as a core part of the Digital Twin. It provides a framework for interacting with multiple manufacturing information systems, such as Product lifecycle management (PLM), Product data management (PDM), and Supervisory control and data acquisi-

tion (SCADA). The Digital Twin condenses this information and makes it available as simulation models. Furthermore, the Digital Twin is included in all the product's lifecycle and is intertwined with its evolution – it can be used during the design phase on a high-level, when the system's operations are not completely defined, but enjoys most use in the engineering phase. The possibility of testing many possibilities to solve a certain problem, such as layout optimization in a discrete manufacturing environment, makes it extremely effective for simulating a factory under varying degrees of load, which helps ensuring the viability of the system over a longer period. Furthermore, a model built during the engineering phase can be reutilized in operations to evaluate the performance of the system. The collection of data during this phase can also provide insights for the development of the next generation of the system (Boschert and Rosen, 2016).

Uhlemann et al. illustrate the possibility of coupling simulation and optimization in the context of a cyber-physical production system, illustrating the potential benefits of using a Digital Twin. According to the authors, a strategy for data acquisition is delineated, enabling the flow of data between the production system and its digital equivalent. This allows for optimization of the production process with a minimal delay between the time of data acquisition and the creation of the Digital Twin. This work is particularly focused on small and medium-sized companies and includes a strategy of multi-modal data retrieval (Uhlemann et al., 2017).

Including both simulation and optimization in the production process using the Digital Twin is particularly efficient. März et al. describe the possibility of combining these two steps, through the implementation of simulation before or after optimization, or as one process integrated inside the other. In the first possibility, that is, simulation-optimization, the output of a simulation is used in the optimization process, while in the case of optimization-simulation, simulation serves as an evaluation function of the optimization. The integration of optimization inside simulation occurs when simulation is performed before and after an optimization process. The opposite can also occur: the simulation step tests the result of optimization for feasibility (März et al., 2011).

Digital Twins can be employed in various scenarios, the more relevant of which for the case of this study is the facility layout problem. This topic is discussed extensively in the next segment.

2.3 Facility Layout Problem

Facility layouts are known to greatly impact the performance of a factory. One major subset of the field of operations management is concerned with the problem of the placement and sizing of production blocks in a plant, as well as the allocation of operators to each block. It is usually called Factory Layout Planning (FLP). The placement of facilities has a deep influence on the factory's processes and their overall efficiency. This problem is particularly critical when new production centers are being planned or existing ones restructured. Furthermore, the increasingly fast changes in customer demand requires factory planning to be agile in designing, planning, and changing layouts according to necessity (Mourtzis et al., 2014).

The FLP is generally an NP-hard problem and can be tackled using optimization techniques Drira et al. (2007). This work provides a good overview over several FLP varieties, ranging from

distinct shapes to layout configurations and material handling systems. Multiple formulations for the layout problems are also described. These range from discrete formulations to continuous, fuzzy, and multi-objective layout problems. Furthermore, it offers various solution possibilities for each of these problems. Larger problems require heuristics and metaheuristics to ensure viable, if not always optimal, solutions (Zhang et al., 2019). They range from simulated annealing (McKendall et al., 2006) to tabu search (Chiang and Kouvelis, 1996) and, more recently, genetic algorithms (Kia et al., 2014).

A simulation-based approach can also be used to solve the FLP. The method of simulation-optimization (Olafsson and Jumi Kim, 2002), arises, for example, when the performance of an optimization step is measured using simulation. The optimization step can follow several techniques, including metaheuristics (Jalali and Nieuwenhuyse, 2015).

Zhang et al. provide a framework for plant design using simulation (Zhang et al., 2019). It is divided into five major steps. First, it is critical to obtain data on the characteristics of demand and supply, as well as the equipment in use. The next step is the determination of essential factors and facilities. A hypothesis for the layout is then created, based on fixed-position, process-based, cellular or product layouts. The various simulation parameters, which range from deterministic to stochastic (with either continuous or discrete distributions) are defined using historical or equipment data. These include arrival rates of raw materials, the capacity of buffers and the processing time of the machines. The last step comprises the simulation itself and the statistical analysis of multiple runs, ensuring that the stochastic nature of the simulation is taken into consideration. Typically, KPIs such as resource utilization are provided as a statistical element, with a mean and a standard deviation (Grigoryev, 2021).

The result of previous simulations serves as input for a what-if analysis that can trigger modifications to the previous layout, which is then tested again. This process is repeated until a satisfying solution for the factory layout is obtained. Overall, this technique is manual and based on expert knowledge. It is particularly suited when the solution space, that is, the number of possible scenarios for the factory layout, is limited.

2.4 Discussion

With the objective of implementing a simulation for solving the FLP in the context of a winery, several aspects have to be considered. The first step towards finding an adequate solution for the problem encompasses an analysis of the current production process at the winery. This includes a detailed description of all the necessary production blocks, ranging from the tanks for the wine in bulk to the number and specification of the bottling lines. One key aspect is the size and number of distinct warehouses necessary for the storage of both raw materials and finished product. To estimate the size of each one of these blocks, it is fundamental to forecast demand of the different product segments over the next decade and to assess the coverage of raw input and finished product required by the company. The work of Garcia et al. (Garcia et al., 2012) is particularly important since it provides a framework for measuring KPIs over the full wine supply chain.

Selecting an appropriate simulation method is also critical. From the three options presented, a low-abstraction model should be selected to accurately depict the operations of the various production blocks. Hence, discrete event modeling, as described by Borshchev and Grigoryev (Borshchev, 2022) seems to be the more appropriate one. The stochastic aspect of this type of simulation suits this work particularly well, since it allows for a more granular analysis, regarding, for example, potential bottlenecks.

Although applying simulation to the FLP is not a new concept, it is a novelty in the complex world of the wine industry. Models based solely on optimization may be faced with several issues, especially due to the sheer complexity of the operations. Therefore, pure optimization methods (exact or approximate) might not be the most indicated for this problem. Simulation also has the added benefit of solving one of the problems posed by the company – the ability to easily measure the in- and output flows in the production process. One possibility is the integration of optimization in the simulation is an option worth considering. Of the ones suggested by März and Krug (März et al., 2011), the simulation-optimization method might be the most indicated for this problem. However, a simulation-optimization solution with a heavy optimization contribution, such as the one presented by Liu et al. (Liu et al., 2019) may not be the ideal course since the layout for the factory is heavily restricted by the existing facilities. Furthermore, the design process is subject to a large number of business constraints, such as the position of certain areas which significantly reduces the potential of an optimization algorithm. Therefore, a scenario-based approach is more adequate and was implemented in this project. This requires several scenarios to be designed manually and tested. Zhang et al. (Zhang et al., 2019) offer a good framework for this case.

In this literature review the topic of the Digital Twin is included. There is some debate as to whether the various simulation scenarios produced in the context of this project can be considered to constitute a Digital Twin. Especially when contemplating the definition of a Digital Twin for the design and engineering phases of a product's lifecycle, the simulation model developed in the project operates as a virtual counterpart to the existing real-world facility, which is currently under expansion. Furthermore, the simulation can be updated with ease to depict the evolution of the construction process and the introduction of new bottling lines. For this reason, one could consider the work developed as an example for a Digital Twin in its early phase. However, to avoid potential controversy, the solution method is designated from hereon as a simulation method.

The concept of using discrete-event simulation for solving the facility layout problem in the context of the wine industry is unprecedented in the literature; one can therefore say with a high degree of confidence that the implementation of such a solution to this context will not only help the design of the company's new facilities but will also contribute to the collective knowledge on facility design in the wine industry.

Chapter 3

Winery facility and initial data acquisition

The subject of this work is the development and assessment of a facility layout for a winery. When faced with a facility layout problem, there are various tools and strategies that can be used to identify viable solutions. However, the first step in any solution effort is the acquisition of the necessary input data.

The study follows a two-phase structure (figure 3.1), with each of the phases divided into multiple topics. This structure isolates the generation of input data from the simulation itself, allowing for a more robust approach.

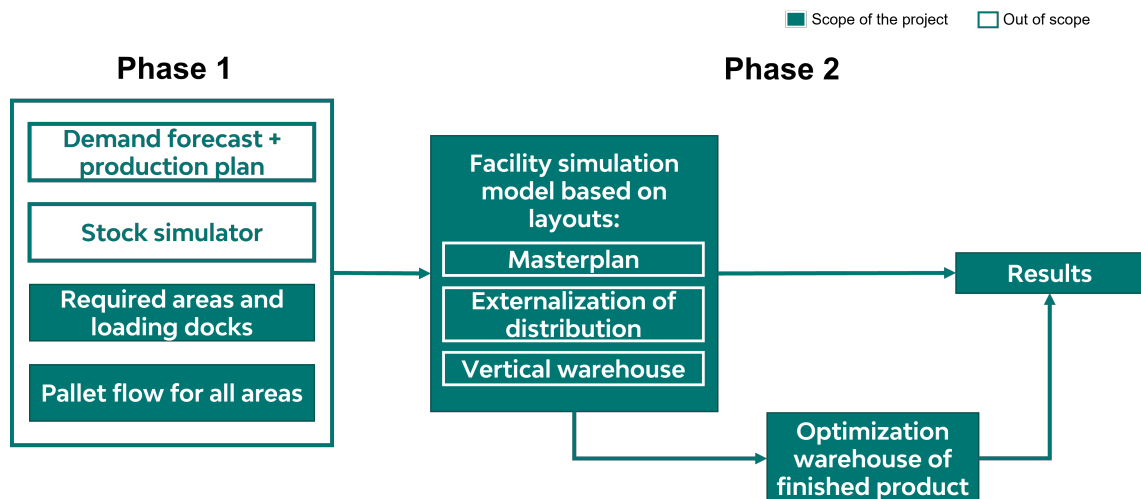


Figure 3.1: Structure of the project

The first phase concerns the creation of the necessary inputs for the simulation. It constitutes an essential phase of the project since the data it provides is common to all proposed layouts. This phase also requires a large amount of interaction between various stakeholders whose expertise is area-dependent. It includes four main tasks:

1. Development of a sales forecast for the company's operation and a resulting monthly production plan;
2. Creation of a simulator of stocks in the facility;
3. Calculation of the necessary space for each of the functional units of the factory using a stock simulator based on the production plan. It includes bottling lines, warehouses, the oenological operation and the number of required loading docks for the facility;
4. Estimation of the number of pallets transported from/to each facility.

The first and second topics are not the focus of this work and were addressed in previous studies. However, their relevance to this project is evident since they influenced many of the decisions that resulted in the layouts that were developed. Therefore, a brief explanation for these topics is presented in section 3.2.

The acquisition of this information allows a faster, more streamlined approach to modeling the facility in the context of discrete-event simulation. It is followed by a second phase, whose focus shifts to creating the simulation model and evaluating relevant KPIs. These will serve as the basis for the decision about the model to implement, guiding the construction project to restructure the facility accordingly. The second phase, therefore, focuses on the simulation itself, with four major tasks:

1. Design of candidate macro-layouts that accommodate the required increase in capacity and storage space to satisfy demand. This includes specific layouts for each functional unit, such as warehouses and bottling lines.
2. Creation of the simulation models for the proposed layouts using Anylogic® (www.anylogic.com);
3. Testing and comparing the distinct layouts through a set of KPIs defined beforehand;
4. Identification of potential improvements in the layouts of the warehouses and development of a strategy to optimize the layout of the warehouse with the highest potential - the warehouse of finished product.

The completion of this phase culminates in delivering the results to the stakeholders, who can make an informed decision regarding the appropriate layout to implement at the facility.

Although one of the most common approaches to solving the FLP using simulation includes the design of the current scenario for a more accurate comparison, this step was deemed unnecessary due to the possibility of confirming the model's accuracy using other factors.

3.1 Understanding the facility and its functional units

The facility in question is responsible for all the processes from the arrival of the prepared wine to its distribution in pallets. Most of the processes related to the preparation of this liquid raw

material are decentralized in various facilities that are typically built near the vineyards. Therefore, this facility functions as a bottling plant and distribution center for the domestic and international markets. Nevertheless, the possibility of externalizing part of this operation has been considered - this thought process gives rise to one of the layouts produced during the design phase. An overview of the functional areas and operations in the facility is provided in figure 3.2.

The operation at the factory is roughly divided into three parallel processes: the so-called oenological operation, which is responsible for the wine – a highly demanding and complex raw material – the operation of the bottling lines, and the logistics operation. This section is divided into these three parts, with significant weight placed on the last one since the possibilities for different space configurations are significantly higher.

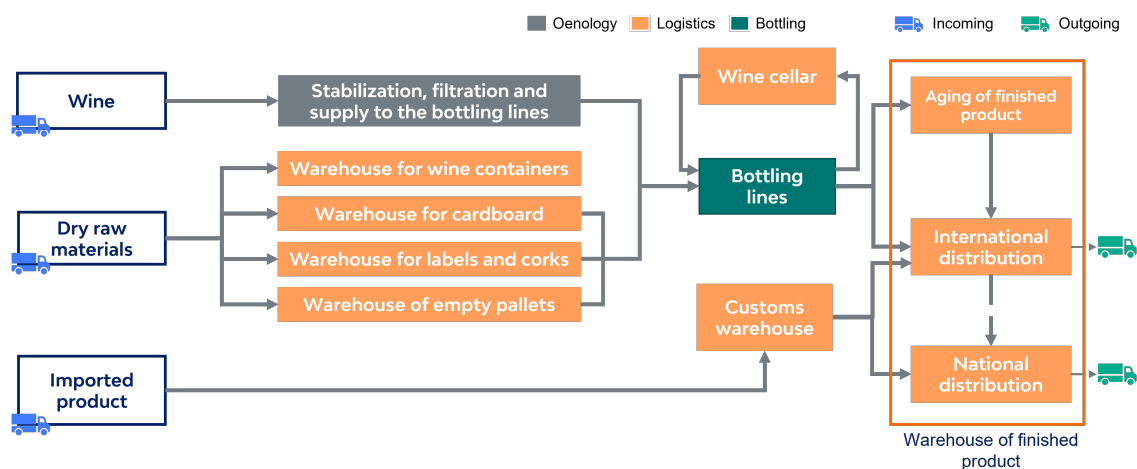


Figure 3.2: Overview of the operations taking place in the facility

3.1.1 The oenological operation

Wines arrive in lots of varying sizes, either in tank trucks or wine caskets. Upon arrival, the lots are unloaded in purpose-built docks and stored in tanks of various sizes, spread around the facility, depending on the volume and necessary conditions. Wine caskets are required for more demanding wines, which are more commonly denominated *fine wines*.

Each tank can hold wine from a single wine label. It can be subjected to additional treatment and quality control in these tanks. Despite its great complexity, this operation is essentially not within the scope of this study since the facility is predicted to continue operating within capacity, with the notable exception of the number of tanks by storage size. This analysis was performed before the onset of this project. One exception is, however, noted: the planned auxiliary warehouse must accommodate the warehouse for wine caskets and the bottling lines for the fine wines. They occupy most of the available room, with a small fraction used for a warehouse of dry raw materials in one of the layouts tested.

3.1.2 Bottling

One of the primary operations at the factory is the bottling operation. Counting between automatic, semi-automatic, and manual lines, the factory features various bottling lines with different throughput and bottling constraints. Some feature the possibility of filling a single wine variety with large throughput, while others offer more flexibility at a slower pace. Depending on the yearly seasonality, they can operate simultaneously, in up to two daily shifts.

Furthermore, some bottling lines can produce finished products directly, while other need to undergo a process of aging inside the bottle. The finishing process of the latter typically includes adding labels and counter-labels or other materials, as well as packaging and palletizing. Some wine labels go through the process of aging inside the bottle, ranging from one month to several years before they are deemed appropriate for sale and consumption. In some cases, the processes of bottling and finishing are separated. This happens due to the large variety of markets where the company sells its products (Cholette, 2009).

The possibility of adding region-specific labels and thus defining the SKU at a stage closer to expedition helps curb uncertainty and reduces the need for safety stock, which is calculated on an SKU basis. In other words, the bottles can be filled whenever the wine lot is ready, and the decision about the market can be made at a later stage when demand is less uncertain. From an operations point of view, however, this adds complexity to the operation since both the filling and the finishing processes can occur at the same bottling lines in parallel. This process needs to be accurately modeled by the simulation.

Automatic bottling lines take raw materials in the form of pallets or trays transported from the warehouses in forklifts or logistic trains (figure 3.3). Pallets are transported to one of the multiple depalletizing points at the lines, depending on the type of material. Pallets with the wine bottles or other containers are transported by forklift to the start of the bottling line, where they are first depalletized. Wine is then fed from the filling tanks and deposited in the bottles. After filling, the cork or capsule is added, depending on the wine.

Should the product be sent to intermediate storage in the cellar, the bottles are removed and stored in boxes. Otherwise, the wine bottles are packaged in cardboard boxes and assembled into pallets of predetermined sizes. These are lifted by forklifts and moved to their storage slot at the warehouse for the finished product. From the simulation perspective, this process is heavily simplified, since the main objective is observing the flow of pallets to and from the line. The critical elements are the rate of consumption of raw materials and production of finished products, and the SKU being produced. The SKU defines the parameters for production and therefore dictates the number of movements of forklifts to the lines and the distance that they cover.

Other lines are used for filling higher-value products or producing promotional bottles. Both operations require a more significant amount of manual labor. Although these lines do not feature particularly high throughputs, they occupy a relatively large amount of space in the facility, and are critical for the layouts. For this reason, they are included in the design of the layouts.

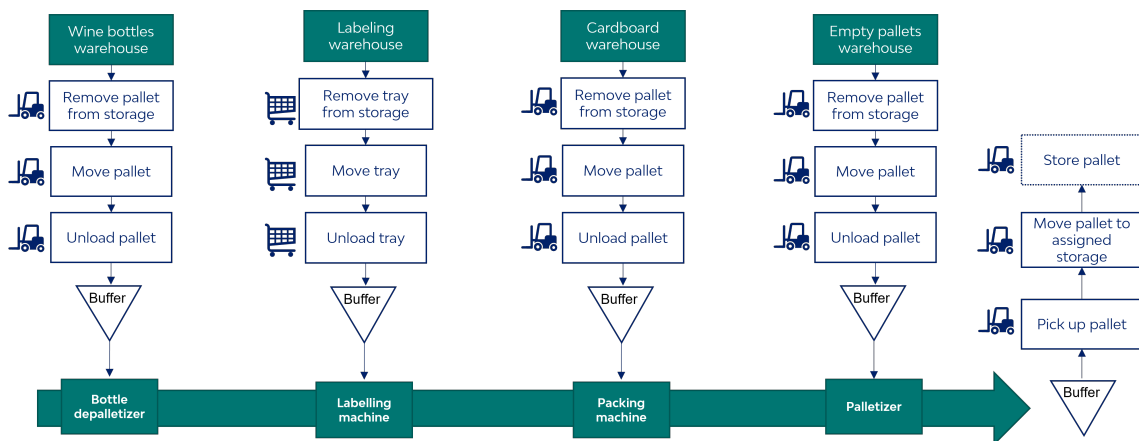


Figure 3.3: Flowchart of the process of the bottling lines

3.1.3 Logistics

The management of the storage facilities is the responsibility of the logistics department. This department controls every operation concerning the materials arriving in the facility, their storage and transport to the bottling lines. It also moves the pallets containing finished products from the bottling lines and loads the outbound trucks. The logistic operation occurs mainly using forklifts with different characteristics. According to the current operation, a certain number of forklifts is assigned to each warehouse and can be used in multiple tasks, such as unloading pallets from trucks or retrieving pallets from storage.

In the case of this facility, pallets are stored in stacks, either by floor or rack stacking, to minimize the floor area occupied by storage. Floor stacking refers to the stacking of pallets without any outside support; the first pallet is placed on the ground, and other pallets are placed directly on top, thus forming a stack. Rack stacking involves placing pallets on top of racks assembled vertically. Stacking pallets directly on the floor is significantly cheaper since it does not implicate the purchase and installation of a rack or other solutions and has lower space overhead, making them more efficient from the perspective of space utilization. However, this structure presents at least two disadvantages: large stacks can become unstable and specific measures must be undertaken to store and remove pallets, and a single storage bay can contain only one SKU. Meanwhile, this limitation does not exist in the case of the rack stacks. This is the result of a business decision to simplify warehouse management. This warehouse structure is referred to as single-product (as opposed to multi-product) and constitutes a constraint on the models developed.

In this case study, floor and rack stacking can be applied to all warehouses and exist simultaneously in different spaces. Certain parts of the warehouse require one structure, e.g., the picking area in the finished product warehouse requires racks. Apart from domain-specific uses, the choice between racks and floor stacking is dependent mainly on the floor space available and the CAPEX related to purchasing the racks. An example of the simultaneous use of both strategies in a single warehouse is the warehouse for the finished product, which includes rack stacking for SKUs with lower storage needs (C, according to the ABC classification), while single-product floor stacking

is used for the other SKUs (A and B). The decision on whether to apply racks or floor stacking is relevant to the layout problem discussed in this study since it heavily influences the space needs for each functional unit. This constituted part of the first phase of the project.

Calculating the space requirements for each warehouse requires finding an appropriate combination of rack vs floor stacks since both solutions offer different storage densities and are constrained by the number of distinct SKUs they can store. The choice between rack and floor stacking can be made in all warehouses to optimize space occupation. A solution for this problem using an optimization model, aiming to maximize the space occupation is provided in chapter 6.

3.1.3.1 The storage units

As noted, the logistics operation is divided into various warehouses.. They handle incoming material that arrives through loading docks that are mostly directly connected to the warehouses and outgoing pallets, either to the bottling lines or to satisfy client orders. These areas are detailed in chapter 4.

The warehousing operation can be divided into:

- Warehouses of raw materials, which follow a similar logic. Multiple different raw materials can be stored in a single contiguous warehouse in some of the designed layouts.
- The warehouse for unfinished filled bottles, which are undergoing aging or awaiting labeling, also denominated *wine cellar*.
- The warehouse of the finished product, featuring a distribution center for the domestic and international operations.
- Other warehouses.

3.2 Gathering inputs for the simulation

The case study outlined in this document is included in a more significant effort of the company to build an investment plan for the next decade. Therefore, this study stands on top of previous projects with this goal and employs data already acquired and generated as input for the simulation. Using already existing and validated data proved extremely useful and expedited the project's development.

3.2.1 Sales forecast and production plan for 2030

The first relevant topic, although part of a different project that will not be described in detail, is the demand forecast for the next decade, which is relevant for predicting the necessary increase in the size of the operations. To meet this growth in demand, the operation needs to scale up. This includes the increase in the bottling operation, which means more working shifts or the installation of more bottling lines. Moreover, the increase in production results in more stock to be stored and

shipped, which requires larger warehouses and more loading docks. The forecast is performed under three different scenarios – one pessimistic, one base, and another optimistic. The base scenario is considered the most likely result for the rise in sales over the next decade, while the pessimistic assumes that the increase in demand is minimal. The optimistic scenario predicts a more significant expansion of the operation.

The ability to navigate these different scenarios offers more confidence when building a simulation model intended as a decision support system for the stakeholder. During the project's development, it was understood that it had a long-term view in mind. For this reason, most of the analyses performed focus on best-case scenario in terms of demand increase.

The sales forecast allows for the construction of a monthly production plan. The plan already considers the increase in production and the introduction of new bottling lines and consists of the predicted number of bottles of each SKU to be produced monthly in 2030. The production plan is divided into bottling lines and provides a bill of materials for each of the SKUs. Since the bottling lines form the core of the simulation, triggering the entry of raw materials and the exit of the finished product to storage, this information is essential for the model.

Establishing a monthly production plan resulted in the creation of a monthly stock simulator, which provides insight into the stock that needs to be stored at the facility. It combines the production plan with the desired coverage of raw materials and finished product that the business requires to provide the evolution of stock throughout the year. Although the model is also outside the scope of this study, it forms the basis for calculating the necessary space for the different functional units in the factory.

One result of the monthly production plan is the possibility of measuring the number of pallets transported from and to each warehouse. This relies on the throughput of the bottling lines for each SKU and the corresponding number of pallets of raw materials that are necessary for producing each pallet.

3.2.2 Required areas and loading docks

Access to the amount of stock necessary to be kept in storage allows an estimation of the required maximum area for each functional unit. This analysis mainly focuses on the warehousing capability but also depicts the oenological operation, including bottling tanks and the loading docks that need to build for unloading batches of wine. Since the possibility of externalizing part of the operation is limited, each warehouse needs to accommodate the entire stock. Furthermore, as the optimistic scenario for demand results in the highest storage space requirements, it is used to calculate the required area of each warehouse. The conversion from the number of pallets to the required area must consider the storage strategy followed by the company in each of the warehouses, which includes floor or rack stacking.

Another central aspect of the preliminary analysis is the definition of the number of loading docks for arrivals and dispatching. Arrivals include trucks containing raw materials and wine, imported goods for sale in the domestic market and market returns. Dispatching refers to trucks loaded with pallets of the finished product to be transported to distribution centers, transshipment

points or directly to customers. Since they can only be loaded and unloaded at loading docks, a structured approach was developed to define the necessary number for every warehouse. Three separate sets of docks are considered – one for wine bottles, one for the dry raw materials, and another larger one for the totality of the finished product operation. The finished product operation was considered to be split into two distribution operations: national and international. An estimation for the necessary number of loading docks was performed using simulation, taking into consideration the operations of every warehouse, ranging from the preparation of orders in the case of the finished product to the type of forklift used at a given warehouse. This model was developed before the design of the layouts.

One critical step in modeling the operation concerns the arrival of trucks containing dry raw materials. These include materials such as bottles, boxes, and corks. Each truck carries a single material, whose number of pallets or trays is highly variable. Although the stock simulator provides a glimpse into the monthly needs of raw materials in 2030, it is necessary to disaggregate the number of trucks into a daily number to represent the possibility of monthly variation more accurately. It needs to maintain some degree of accuracy, despite the long planning horizon.

To solve this issue, the historically observed seasonality of arrivals of trucks in the year 2021 was considered. An example of the seasonality in the arrival of the trucks is shown in figure 3.4. This value was multiplied by the predicted total yearly percentage increase in the demand $\hat{d}_t$ of dry raw materials from 2021 to 2030, δ . This ensures that the number of trucks in the simulation respects the increase in demand while maintaining a degree of variability. The formula can be applied to any of the demand forecast scenarios.

$$\hat{d}_t^{2030} = d_t^{2021} \times (1 + \delta) \quad (3.1)$$

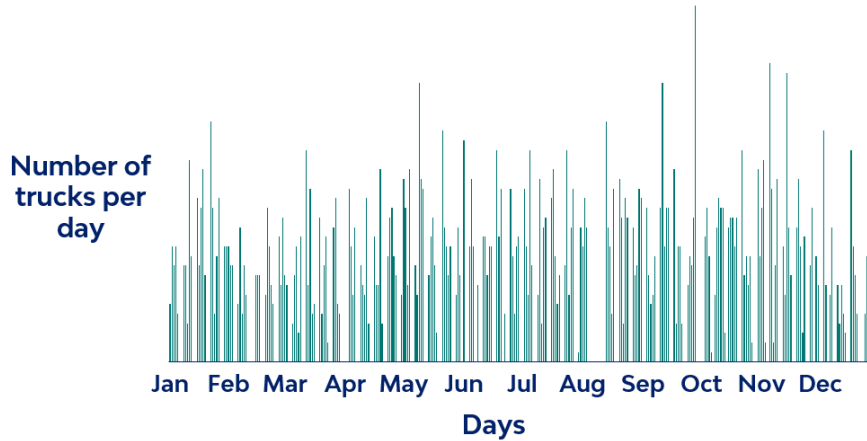


Figure 3.4: Daily arrival of trucks containing pallets with wine bottles to the facility in the year 2030 (the absolute values are anonymized for motives of confidentiality)

Accurately defining the number of loading docks is essential in ensuring that loading and unloading do not constitute a bottleneck in the operation. It is also fundamental to keep the turnover

time (that is, the time between entry and exit of the facility) of the trucks at a minimum. The number of loading docks is restricted by the length of the factory's walls.

Due to the relative simplicity in modeling the processes of truck loading and unloading using discrete-event simulation, this was the strategy used. This simulation is performed before the design of the complete factory simulation since its results influence the layouts for the facility. It was designed using Anylogic, which depicts the processes related to the unloading of raw materials separate from the finished product operation, divided into the national and international distribution.

The flow of dry raw materials starts with the arrival of pallets by truck to the facility, where they are unloaded, checked, and stored in their designated storage slot. The loading and unloading times are highly variable and depend on the number of pallets transported by the truck and the number of available forklifts for the task, which can vary with the number of operations occurring in parallel. More critically, for the factory layout's definition, the loading and unloading of trucks are limited by the number of available loading docks. They constitute the interface between the out-and indoor part of the factory regarding materials and finished products. The process of moving pallets in and out of the factory occurs through this area.

The unloading of raw materials is separated into docks for pallets of glass bottles and other wine containers and docks for the other types of dry raw materials. The simulation follows this structure, with two distinct models developed for the purpose. However, the general structure remains the same and is depicted in figure 3.5.

The discrete event simulation model describes the loading docks as resources which are occupied by arriving trucks. These trucks are agents, which navigate through the various blocks, controlled by time and conditions related to each specific agent. From an object-oriented programming (OOP) perspective, agents in Anylogic are objects, each with their own parameters Grigoryev (2021). Trucks are created according to an arrival schedule defined beforehand. After arrival, the truck is added to a queue, which it immediately skips if there are any free docks. The agent then passes through a delay block representing a setup time for the entry, which may involve both the maneuver to move the truck to the loading dock as well as for the bureaucratic work to be performed. The unloading process then follows, depending on the number of pallets the truck may carry.

Historical values confirmed by the stakeholders are used for the number of pallets per truck and for estimating the rate at which pallets are unloaded. It is assumed that a single forklift unloads each truck. The number of available loading docks conditions the number of parallel operations that can be performed and needs to be defined at the start of the simulation.

The process of loading and unloading of finished products is, in its essence, equivalent to the raw materials, but with some added complexity. This arises from the separation of the processes of preparation of the orders and their loading onto the truck. Due to the large number of trucks arriving on each day, the company implemented a two-step operation, which involves starting the preparation of orders the day before the shipment is due. Therefore, less time is spent retrieving

Incoming flow of pallets of dry raw materials

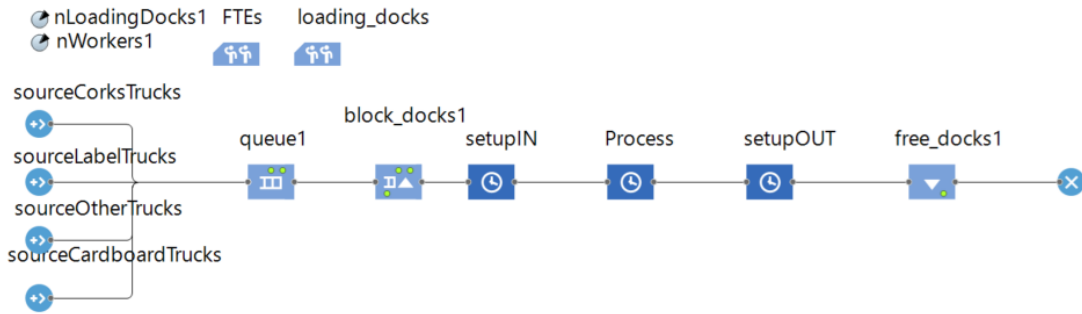


Figure 3.5: Implementation of the incoming operation of raw materials in Anylogic

the pallets from the warehouse on the day of the order. This allows workers to expedite the loading process and turnover of the truck.

Furthermore, there is a need to separate the national and international distribution processes. Due to business restrictions, both operations are considered separately. This needs to be replicated by the model. Another aspect to be taken into consideration is the arrival of trucks containing returns and imported products that are distributed by the company from this facility. This operation makes use of the same loading docks and needs to be considered to operate simultaneously.

Both operations are thus separated into two parts: one for the process of preparing and loading the orders onto trucks and the other for unloading pallets from arriving trucks. In both cases, there are two separate types of agents: orders and trucks. Workers are modeled as resources needed for certain operations to occur. Orders are generated according to a schedule and are fed into a queue where they await a worker to be free to process the order. Since the model heavily simplifies the process of pallet retrieving¹, while maintaining accuracy in comparison with the physical operation, historical productivity data is used to obtain an average time for retrieving each pallet from storage. As it will become clear in the full model, newly measured KPIs may vary significantly from the historical values due to significant changes in the layouts.

The activity of pallet retrieving may involve a process of picking, especially in the case of the national distribution, since multiple boxes, each containing different SKUs, may need to be assembled into a single pallet – a process that is more complex and time-consuming. This is followed by the release of the worker resource. Whenever the order preparation begins, the truck agent is created and put on hold for 24 hours. This modeling strategy ensures that the preparation of the order starts on the day prior to the arrival of the truck. It then leaves this block and is combined with the order agent, and a subsequent time delay for the loading of the truck takes place. The delay is defined by the number of pallets to be loaded. For this process, another worker

¹The full facility simulation takes this into account.

needs to be used. After the truck is loaded and a setup time equivalent to the truck driving out of the loading dock, it is removed from the simulation.

The operation relative to finished products also includes an incoming flow of pallets pertaining to returns from clients and imported products for resale. The number of arrivals and the number of pallets transported by each truck follows the historical data with an increase proportional to the predicted operation growth, as described by equation 3.1. The model is similar to the incoming operation of raw materials – a truck arrives and is first placed in a queue until servicing. The pallets are unloaded with the processing time depending on the number of pallets. This operation can only take place whenever a worker is available. The implementation of the process in Anylogic is shown in figure 3.6.

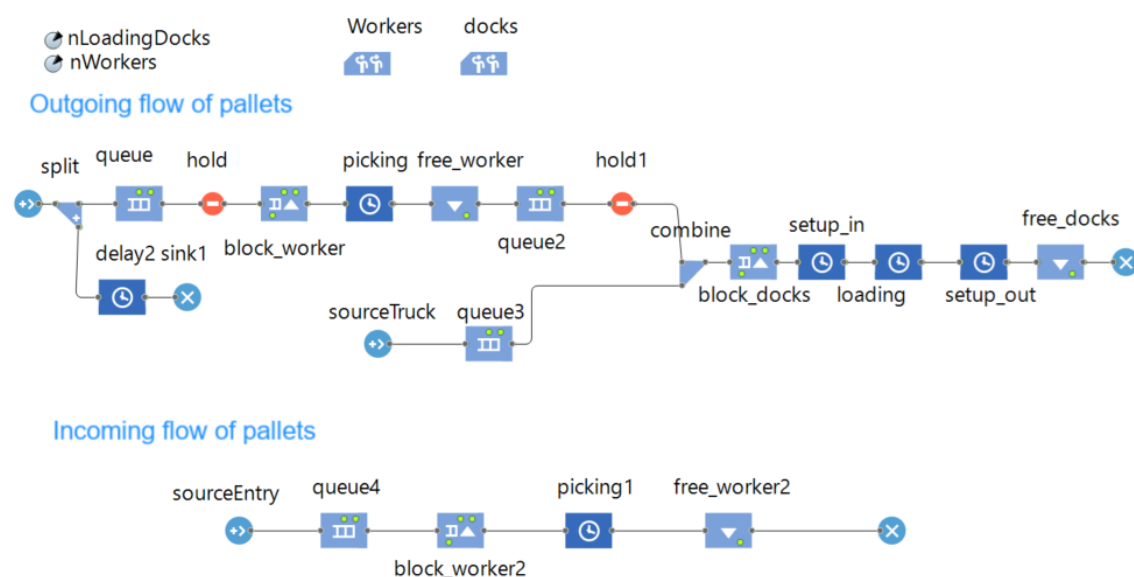


Figure 3.6: Implementation of the incoming and outgoing operations of finished product (national or international distribution) in Anylogic

Both models are run over a one-year time horizon to accommodate yearly seasonality variations. One of the main reasons for using simulation on this problem is the possibility of measuring KPIs for the modeled operation with relative ease. This factor is particularly important to make the necessary business decisions. The most important indicators to be measured by the simulation are the utilization of the docks, both for the average day and the 95%-percentile and the average waiting time of the trucks in the queue before processing. These values are measured for each parameter combination, which allows for a decision to be made.

The three simulation models are structured as follows: the number of loading docks and workers are given as parameters for each simulation instance. Several instances with a varying number of docks are simulated in parallel for each of the forecast scenarios. This allows the representation of the KPIs in a tabular form, which facilitates the decision-making process. The results for the three models are presented in tables 3.1, 3.2, 3.4, and 3.3.

Table 3.1: Simulation results for the loading docks of trucks with pallets of dry raw materials

Decision variables		Loading docks		Trucks
Loading docks	Scenario	Average daily utilization of the equipment	Maximum daily utilization (%)	Average waiting time by truck (min.)
1	Base	94%	177%	137
	Pessimistic	71%	160%	76
	Optimistic	107%	192%	212
2	Base	47%	100%	20
	Pessimistic	35%	80%	13
	Optimistic	54%	108%	24
3	Base	31%	67%	5
	Pessimistic	24%	54%	4
	Optimistic	36%	72%	6
4	Base	24%	51%	5
	Pessimistic	18%	41%	3
	Optimistic	27%	54%	5

Table 3.2: Simulation results for the loading docks of trucks with pallets of wine bottles

Decision Variables		Loading docks		Trucks
Loading docks	Scenario	Average daily utilization of the equipment (%)	Maximum daily utilization (%)	Average waiting time by truck (min.)
1	Base	65%	121%	59
	Pessimistic	45%	82%	10
	Optimistic	80%	173%	122
2	Base	39%	71%	9
	Pessimistic	27%	49%	1
	Optimistic	47%	86%	21
3	Base	22%	40%	0
	Pessimistic	15%	27%	0
	Optimistic	27%	48%	4

Using these results, it is possible to make a suggestion on the number of loading docks that the facility needs to feature. For that, certain minimum thresholds for each of the KPIs need to be defined and validated by the stakeholders. The decision criteria were chosen as follows:

- Consider the Optimistic scenario (the other scenarios are shown on the tables for comparison purposes);
- Maximum daily utilization below 100%;
- Average waiting time for the trucks under 30 minutes.

The solution with the lowest need for loading docks and worker FTEs that satisfies the requirements is the one that is considered to be ideal for the operation. This results in the following

Table 3.3: Simulation results for the loading docks of the national operation

Decision variables		Loading docks		Trucks
Loading docks	Scenario	Average utilization (%)	Maximum daily utilization (%)	Average waiting time per truck (min.)
7	Base	67%	116%	17
	Pessimistic	49%	82%	3
	Optimistic	82%	138%	52
8	Base	58%	101%	10
	Pessimistic	43%	72%	1
	Optimistic	71%	120%	37
9	Base	52%	90%	6
	Pessimistic	38%	64%	1
	Optimistic	63%	108%	18
10	Base	47%	81%	3
	Pessimistic	34%	58%	0
	Optimistic	57%	97%	11

Table 3.4: Simulation results for the loading docks of the international operation

Decision variables		Loading docks		Trucks
Loading docks	Scenario	Average utilization (%)	Maximum daily utilization (%)	Average waiting time per truck (min.)
10	Base	59%	106%	38
	Pessimistic	41%	82%	13
	Optimistic	73%	126%	70
11	Base	55%	102%	29
	Pessimistic	36%	75%	8
	Optimistic	67%	116%	56
12	Base	49%	92%	22
	Pessimistic	33%	72%	6
	Optimistic	62%	109%	46
13	Base	45%	87%	18
	Pessimistic	30%	67%	4
	Optimistic	57%	103%	38
14	Base	42%	82%	15
	Pessimistic	28%	64%	4
	Optimistic	54%	97%	33

numbers of necessary loading docks for each case to be defined: three for the dry materials (table 3.1), excluding bottles, two loading areas for bottles (table 3.2), and nine (table 3.3) and twelve (table 3.4) loading docks for the domestic and international finished product operations, respectively. These numbers for loading docks are used in the construction of the layouts and validated with simulation in the complete model.

3.2.3 Pallet flow for all areas

Before the layouts can be designed, one critical aspect needs to be considered: the flow of pallets for each warehouse. This metric predicts the frequency forklifts pass through a warehouse and, therefore, how critical it is for the warehouse to be placed closer to the bottling lines. Placing a warehouse with high flow intensity in proximity of the bottling lines ensures that the distance covered by the forklifts is reduced, diminishing the time to serve of the lines. For this reason, a ranking for the flow for each warehouse was created based on the number of trips the forklift makes to the warehouse. This ranking was created using the production plan and the stock simulator and can be observed in figure 3.7.

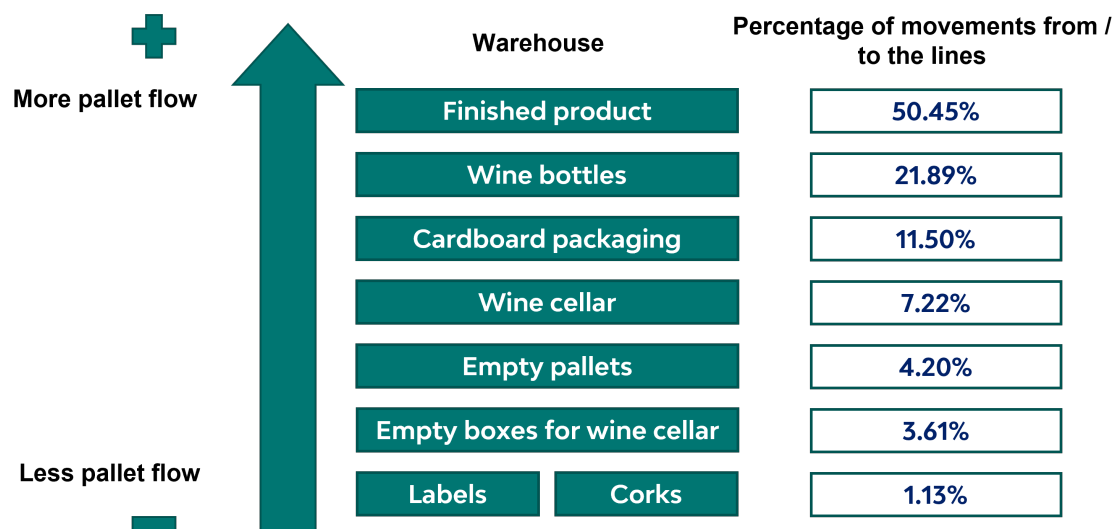


Figure 3.7: Ranking of the pallet flow for each of the warehouses

As the ranking shows, the most critical warehouse is the one for the finished products. However, due to its large size, there is a severe limitation regarding its placement close to the lines. Therefore, more importance is given to the remaining warehouses during the layout design phase. As it becomes clear in section 4.3, the warehouse for wine bottles is placed on a premium location, close to the bottling lines in all the layouts tested. The cardboard packaging warehouse also enjoys proximity to the bottling lines in the case of the first two layouts developed. The warehouses responsible for the remaining pallet flows are placed farther from the bottling lines, as is the case of the wine cellar and the warehouse for labels and corks in the third layout.

Chapter 4

Simulation model for the facility

As addressed in chapter 2, simulation is one of the main tools currently used to solve the facility layout problem. It enables the modeling and testing of multiple scenarios under various key performance indicators (KPIs) to help guide the stakeholders' decisions regarding the layout to implement since it conditions all further construction and facility design plans. Simulation is a particularly suitable strategy since it does not disrupt current operations and provides a quantifiable approach to the problem, allowing for more informed business decisions. Moreover, it is highly modular and enables many scenarios and layouts to be tested, with quick iterations between candidate solutions.

The facility enables the three primary operations of the factory. Therefore, it must accommodate various areas, each serving different purposes and having different needs in terms of total area and storage capacity. The number and size of the critical areas need to be defined accordingly.

To be able to define appropriate macro-layouts for the factory, it is relevant to delve into what composes the facility from the perspective of the areas within. The areas range from the warehouses for raw materials to those for intermediate and finished products. Furthermore, to simulate the operation of the factory as a whole, the processes at each of the functional units require previous assessment and modeling, which are the focus of this chapter.

4.1 Modeling the functional areas

Every functional area of the facility must be modeled separately since each may require distinct processes and actions while featuring significant variance in their micro-layouts. Therefore, this section focuses on describing the different warehouses and the decisions that need to be made to model them effectively and with a high degree of reliability. All operations that influence the flow of materials inside the facility are modeled, except for specific support tasks considered non-pertinent due to the low frequency or negligible impact on the layout. Other, more intensive support operations, such as stock count processes, can happen during off-peak times. Since different possibilities for the macro-layout of the factory are presented, some differences between these options may arise and are described in detail in section 4.3.

The simulation is performed in Anylogic, and makes use of the Material Handling Library, which enables the modeling of warehousing operations with high accuracy. This software abstracts some of the most complex processes from the user, expediting the development process. Anylogic conjugates process modeling with a corresponding graphical interface which includes roads, storage racks, and transporters.

Most of the preliminary work on the layouts was performed in CAD software, as it requires detailed measurements and the insertion of very fine features, such as the various machines on the bottling lines. The design process is not within the scope of this work.

Designs using CAD software can be exported to Anylogic. They are placed directly on the model's interface, resulting in a more friendly environment for development and presentation. This is one of the main features of this simulation software. The model can be simultaneously designed in 2D and 3D using the built-in graphical editor, which features textures for accompanying elements, such as walls, trucks, forklifts, or persons. This allows the user to record images and videos of the facility's operation, which facilitates the validation process and provides the stakeholders with a good visual overview of their operations in the next decade.

Although it is possible to design simulations without graphical interfaces, the suite is designed to interconnect the development of the model with its presentation. For example, it features racks and floor stacking with various depths and sizes, which can be controlled using specific programmable blocks. Some of these are used in this case study, such as the store and retrieve blocks, which abstract much of the work needed for the logistics of transporters and pallets. Additionally, an effort was made to measure the duration of many of the elementary tasks, such as lifting a pallet, placing it in a storage unit and removing it. The direct measurements resulted in a highly accurate model.

The modeling also occurs in the form of several other blocks that operate in conformity with the theory of discrete event simulation. For more complex actions, additional code can be added to perform more complicated steps, such as selecting specific pallets or measuring KPIs.

4.1.1 The bottling lines

From the operational perspective, the bottling lines at this facility are one of the central pieces since they trigger movements from and to every warehouse. The simulation, therefore, revolves around the bottling process and how it affects the flow of materials at the facility.

Every line is modeled separately as its own agent. This modeling decision not only simplifies the design step but allows for several lines to be created once and reused multiple times. This is the result of the agent-based design featured in Anylogic that mimics objects. More complex bottling lines, such as the ones that output boxes containing unfinished products to the wine cellar, need to be modeled separately. Since the unit of product flow in the factory is the pallet (in some cases, trays may be used, but for simplification purposes, it is assumed that multiple trays behave as one pallet), every process is modeled with this in mind. Bottling lines, therefore, take in and output full pallets. The implementation of the bottling line is shown in figure 4.1.

The movements from and to the lines are controlled by an agent, denominated *Order*. Orders are created according to the production plan for the bottling line. Typically, an order goes through two phases: setup and production. Setup times can take considerable time and are the first step the agent goes through. They represent when a bottling line undergoes cleaning and preparation for receiving the next production batch. In particular, changes in the type of wine, e.g. from red to white, involve a cleaning process that delays the production of the subsequent batch. During the setup time, no raw material pallets are consumed.

Whenever the pre-determined setup time ends, the agent moves into the production block, which in turn triggers the consumption of the pallets of each raw material. This is modeled using the injection of an agent in a different process flow. This agent represents the pallet that is consumed by the bottling line. Each raw material follows its own process, from its arrival from storage, through a queue and a hold block that ensures that the pallet starts being consumed only when an order is in the production phase. A pallet spends a given time in the production delay block, according to the throughput of consumption. Whenever a pallet starts being consumed, a counter for the buffer of that raw material is decreased by one. An order for a new pallet is triggered whenever the buffer reaches a minimum threshold value. The quantity of pallets in the buffer is tested periodically by an event. However, if the transporters are unavailable when the buffer reaches the threshold, stockout events on the bottling line may occur, which causes the production to stop. Production stoppages are highly undesired in this type of an operation since setup times for the bottling lines can be high and significantly impact the ability to output enough finished products to satisfy demand. In the simulation, the bottling process does not stop when stockouts occur since it may influence the resource utilization of other operations. However, the number of events is counted and used as an indicator for evaluating the correctness of individual modeling decisions and the feasibility of the macro-layout.

This approach is used for the required raw materials per bottling line. All lines consume pallets with wine bottles, cardboard boxes, and stacks of empty pallets, while other lines may require boxes from the cellar, which adds a layer of complexity. This is exacerbated when the line has different possible configurations: either direct production, production of unlabeled bottles, or labeling of unfinished products. These two last operations can occur simultaneously, as they use different machinery. Otherwise, operations need to happen at different times. A possibility for modeling this operation involves replicating the structure already described for each of these processes. In effect, one bottling line is separated into three or four, each with its own raw materials and buffers. Control of the production is performed with a production order file for each of these sub-lines.

4.1.2 Warehouse for wine bottles and other containers

As described, the bottling lines are supplied by pallets of raw materials, which include wine bottles or other containers, such as cans, bag-in-boxes and barrels. The choice for the wine container can vary between products and markets and are aligned with the positioning of the business towards certain market segments. More recent efforts have been undertaken to market these new wine

Operation of the bottling lines

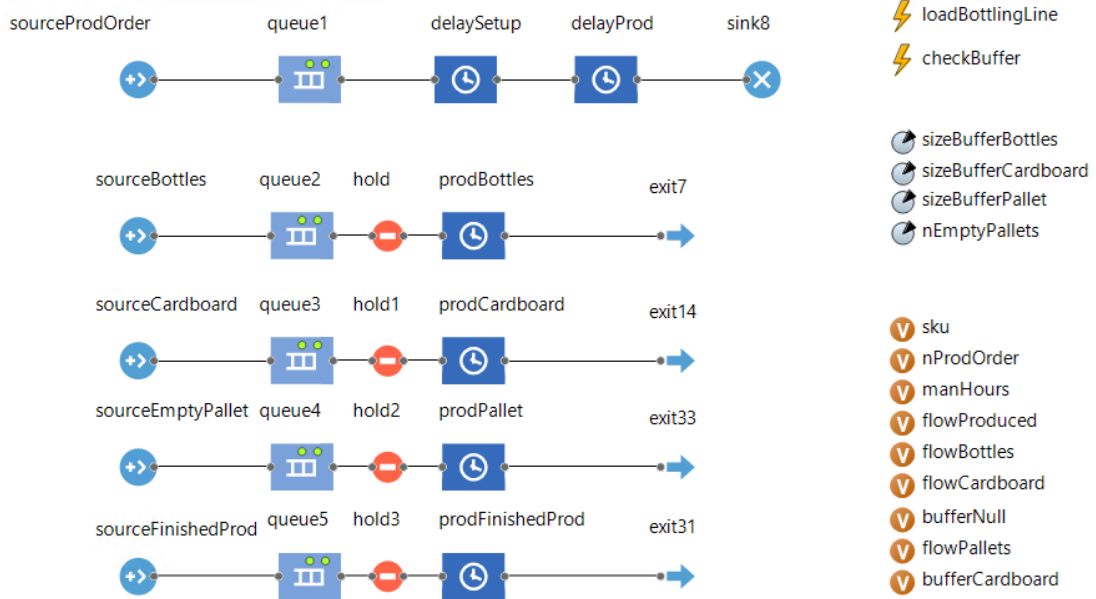


Figure 4.1: Process of the bottling lines modeled in Anylogic

container formats, that must feature in the new facility layouts. Each of these containers requires particular machinery on the bottling lines for making the filling process possible. However, the majority of the finished wine continues to be stored in bottles.

Despite their different characteristics and different storage requirements, all containers are stored in a single warehouse. Due to constraints regarding safety and quality, this warehouse is placed away from the rest of the operation and, in particular, from areas that may be crossed by factory workers. This reduces the possibility of broken glass contaminating other materials, which might constitute a safety hazard to the factory personnel. Furthermore, wine bottles are typically less demanding in terms of storage conditions and can be kept outdoors if necessary. However, this division effectively duplicates the operational needs – each warehouse requires their own forklifts, personnel and loading docks.

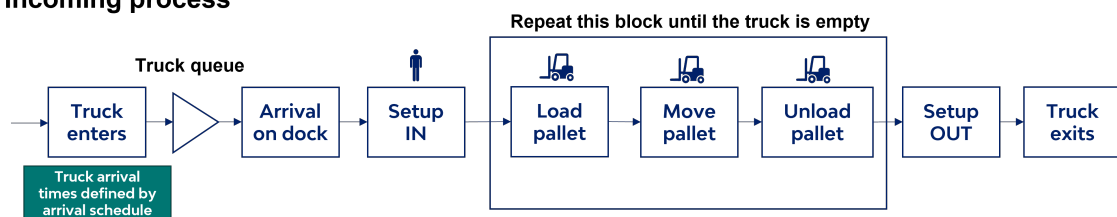
Similarly to the rest of the warehouses, the bottle warehouse is modeled in 2D with an appropriate layout that was designed with inputs from the stakeholders beforehand (figure 4.3). It mostly features deep floor stacking storage units, that allow for efficient packing at heights of 3 to 4 pallets. An area is reserved for lower density storage, generally for SKUs with lower rotation, such as the aforementioned new formats. These are kept at a larger distance from the loading docks and the entrance to the bottling lines, due to the more intermittent access.

The pallets containing the bottles arrive in trucks at the top end of the facility and are directly unloaded by forklifts onto their storage areas. The rate of arrival of the trucks follows the approach described by equation 3.1. If no docks are available, the trucks are placed in a queue, where they await their unloading process. After arrival to a dock, a setup time is introduced to simulate bureaucratic operations that need to take place, such as the confirmation of the order and the

material that is being transported. Only then does the unloading operation using forklifts begin. This includes the process of lifting the pallets, moving the pallets to their designated storage slot, and unloading of the pallet in that slot. The storage slot is selected at random, however, each storage unit (rack or floor stacking block) is assigned to one of the ABC categories according to the frequency that the SKU arrives at the facility and is used by the bottling lines.

The process is repeated until there are no pallets left inside the truck. Then, additional activities are performed, such as closing the doors of the truck, which take additional time and occupy the loading dock. This is included as an additional setup time in the simulation.

Incoming process



Outgoing process

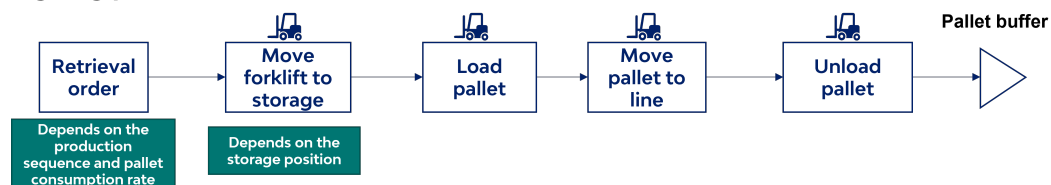


Figure 4.2: Process mapping for the operation of the warehouses of raw materials

This process is simulated in Anylogic using two distinct flows, one for the trucks, and one for the pallets. The operation is separated since both flows feature different agent types. The start of the process of unloading triggers the creation of agents that represent pallets in the simulation. These are fed into store blocks, which seize a transporter resource and select the desired destination of the pallet in the storage. A counter of pallets is set to the number of pallets that arrived on the truck and is decreased with each successive stored pallet. This releases the truck agent from its delay block and feeds it into a block for setup out process. The truck then moves to the exit of the facility through its designated path. This completes the incoming process of pallets in the bottle warehouse.

The outgoing process is responsible for the transport of the pallets to the bottling lines. Similarly, the ABC categorization for choosing the next pallet to be picked is used. The bottling orders for each line contain information on the wine bottle SKU that is needed next. Whenever the buffer for this material goes below a predetermined value, the picking process is triggered. From the simulation perspective, this leads to the selection of a random pallet from storage, triggering the pickup process by one of the available forklifts. In case no forklift is available, the pallet awaits transportation until one of the transporters finishes their previous task. The process is illustrated in detail in figure 4.2, with the corresponding simulation implementation in figure 4.3.

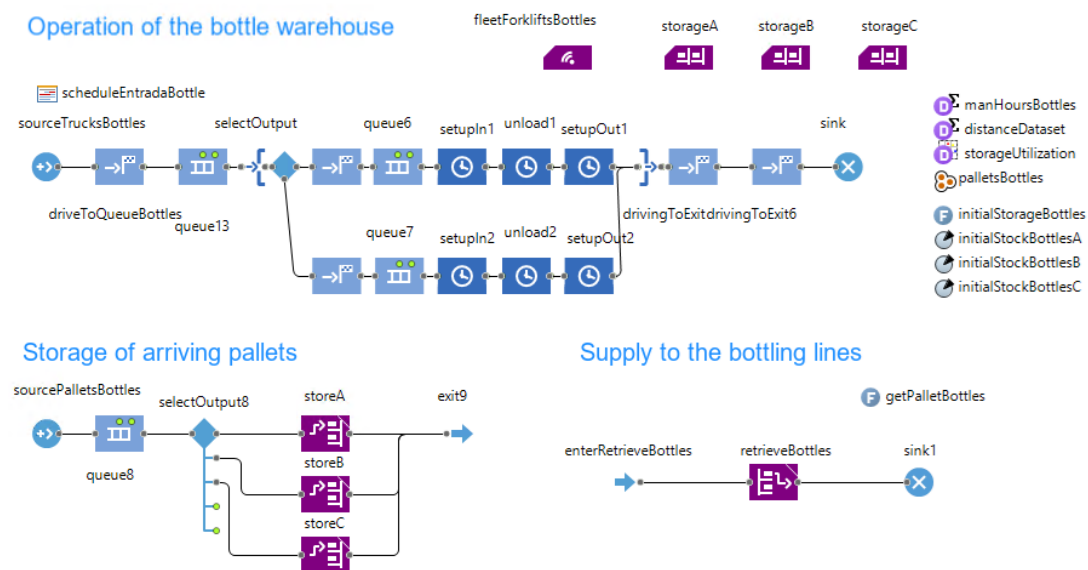


Figure 4.3: Processes used in the simulation of the bottle warehouse

The process of selecting a random pallet from any storage in Anylogic has some caveats that need to be addressed to make the simulation viable. Since no function or abstraction already developed is applicable, an ad-hoc algorithm was developed to solve the problem: a pallet is selected at random from all the available pallets, and a test is performed to assess whether the pallet is directly accessible. This may not be the case if pallets are floor stacked and there are pallets in front, which would cause an error in the simulation. Instead, the algorithm selects the pallet in front of the block.

The transport of these pallets occurs with the same pool of transporters that are used for the incoming process. Since it is fundamental that the bottling lines maintain constant operation, the simulation makes use of a feature of Anylogic when dealing with tasks that compete for the same resources - the task priority value. Higher priority values mean that certain tasks take precedence over lower priority actions, when two or more tasks await for a resource to be able to complete them. Therefore, all processes concerning the transport of pallets to the bottling lines are given higher task priority values.

4.1.3 Warehouses of dry raw materials

The other main warehouse to be considered is the warehouse of the other dry raw materials, which include cardboard packages, labels, and corks. Each is stored in their own racks and have different storage requirements. However, they share the same loading docks and points of supply to the bottling lines in two of the layouts designed. In the case of the third layout, the single warehouse is divided into two parts and placed in different buildings: cardboard is stored in the lower floor and the remaining raw materials are placed in the forest warehouse.

The warehouses operate in similar fashion as the warehouse for wine bottles (see figure 4.3). The storage structure, as well as the incoming and outgoing processes are similar to the bottle warehouse, with some notable exceptions. The first is the significant lower depths of pallets in the storage units. Cardboard boxes are unique to finished product SKUs, since they may contain details specific to the destination market as well as vintage year or other information. A second difference is the inclusion of a conference area where pallets are deposited immediately after unloading. Since the contents of the incoming pallets can vary highly, it is necessary to perform a confirmation step that takes additional time.

Effectively, the process for incoming pallets is split in two – unloading from the truck onto the conference area, followed by the storage of the pallets in their designated area. The distribution of the pallets to the bottling lines is not made directly from storage to the lines. Pallets are first moved to an order preparation zone, where they are picked from. Lastly, the process of transporting pallets to the line does not occur with a forklift that can transport only one pallet at a time but uses a logistic train that follows the mizusumashi principle. The logistic train follows a circular tour, collecting and delivering multiple pallets at the same time, according to the needs of the bottling lines. This process simplifies the operation of supply to the lines since fewer transporters need to operate simultaneously. Instead, two logistic trains cover the movement from the warehouse to the bottling lines, carrying a varying number of pallets according to the line's consumption rate.

The warehouse is modeled in the same way as the aforementioned bottle warehouse, following the exact same incoming and outgoing processes described in figure 4.2. However, the outgoing process occurs simultaneously with a process of order preparation. Pallets destined for the bottling lines are first stored in racks with the use of forklifts that place them close to the exit of the warehouses. Only then does the logistic train collect the pallet and transports it to the corresponding bottling line. This two-phase operation occurs in parallel and enables the use of the logistic train, which cannot navigate the warehouses' narrow corridors.

4.1.4 Wine cellar

Another warehouse that supports the operation of the bottling lines is the wine cellar. This warehouse is designed for storing unfinished products. This includes wine bottles that are conserved for later labeling and packaging. This process allows the time deference of the decision to differentiate the product in terms of destination market, resulting in the improved capability of reacting to changes in product demand at the expense of needing to move the product multiple times, which impacts the utilization of the forklift trucks.

Therefore, it features an incoming and an outgoing flow of material directly to and from the bottling lines, which may, furthermore, cause congestion in terms of transporters, especially in the area near the lines. Nevertheless, only a select number of bottling lines is designed to output undifferentiated intermediate wine bottles, which causes the total number of trips to the warehouse to be lower than the others. Furthermore, since most of the unfinished product is sent to this warehouse for aging inside the bottle, it may take several months before being brought back to the lines. Therefore, the incoming and outgoing flow from this warehouse is relatively small.

Bottles are stored in specially designed boxes with higher bottle density than normal pallets. Similar to pallets, they are transported one by one by each forklift. From the perspective of simulation, there is no significant difference, except for the fact that the bottling lines need to be supplied with empty boxes instead of empty pallets to be able to output the product.

The boxes are produced according to the output rates given by the production orders, which also control the start and end timestamps for their production. When a box is filled at the bottling line, a forklift picks it up and carries it to the wine cellar, storing it in the respective storage slot. The process works in a similar fashion to the other pallet storing operations and is performed by a group of forklifts assigned specifically to the wine cellar. From the point of view of the simulation, the incoming process is similar to the finished product, which is presented later in this section.

The outgoing operation of this warehouse is divided into the two main objects stored here – empty and full boxes. Empty boxes are transported to the bottling lines, where they are consumed as they are filled up. They can be transported two at a time by a forklift, also modeled in the simulation. Full boxes are taken as inputs for the bottling lines; however, they are only subject to a finishing process. The same set of forklifts transports them to the lines according to their needs. From the perspective of the Anylogic simulation, the picking process of full and empty boxes is triggered by the bottling lines, selecting a pallet according to the ABC category, which then passes through a retrieve block that utilizes a transporter to make the movement of the pallet to the line possible. The pallet is dropped and consumed as the line takes in the unlabeled bottles. The process modeled in Anylogic is featured in figure 4.4.

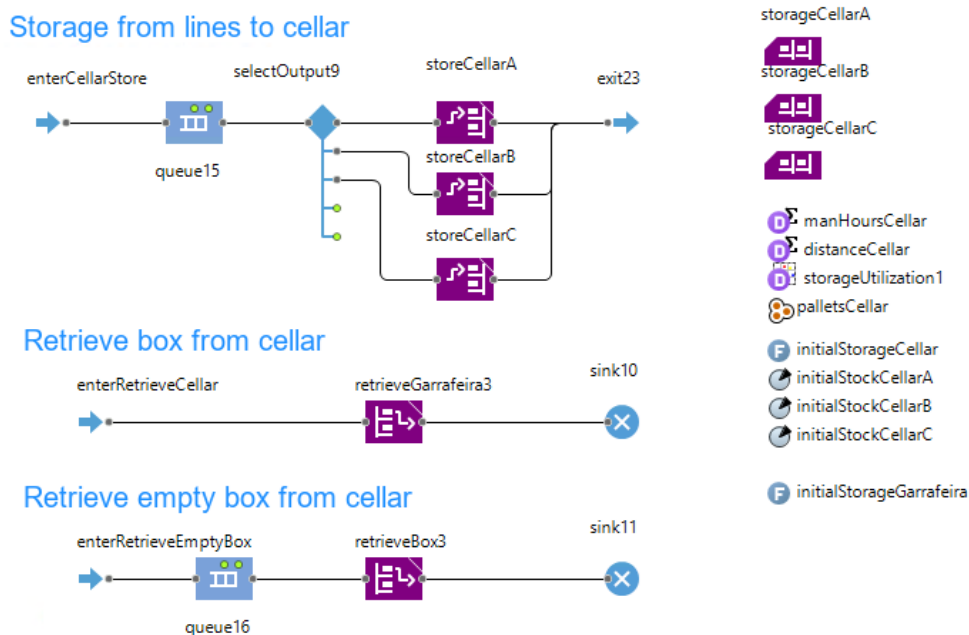


Figure 4.4: Processes used in the simulation of the wine cellar

Due to the relatively small number of trips that the transporters need to perform to the wine

cellar, the warehouse is placed in areas that are more distant to the bottling lines, with other warehouses enjoying placement in more privileged spots. This is the case in the three layouts that are considered for simulation.

4.1.5 Warehouse for finished product and distribution center

The warehouse for the finished products is composed of multiple different areas, each fulfilling different purposes. A facility design which condenses all these areas can be visualized in figure 4.5.

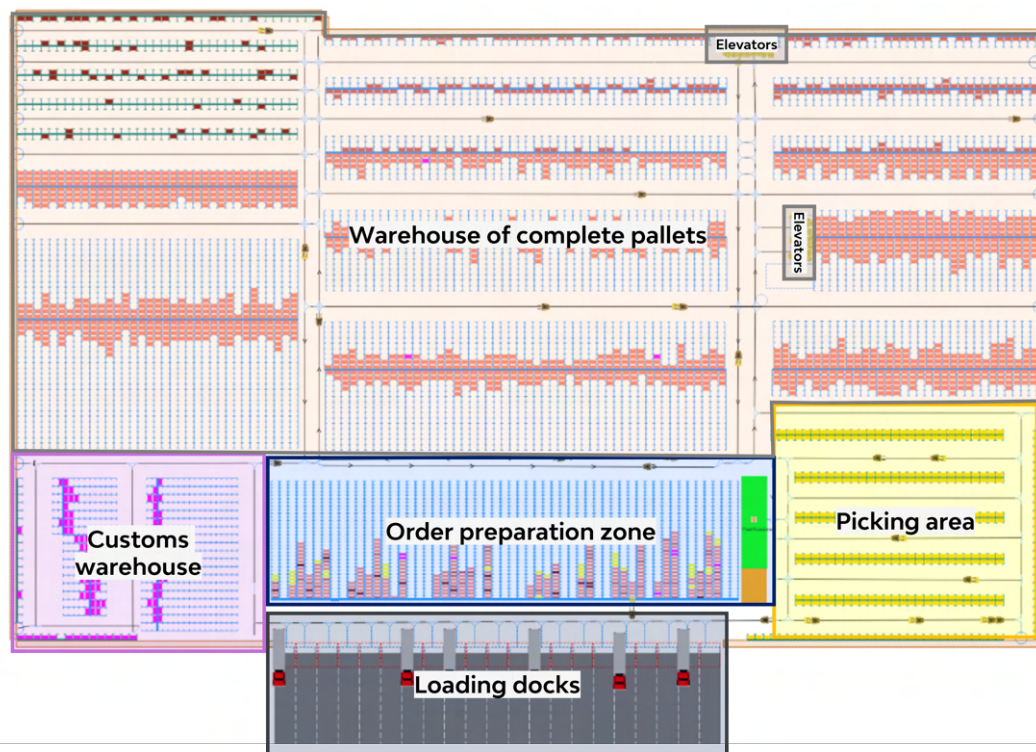


Figure 4.5: Layout for the operation of finished product, as implemented in the simulation model in Anylogic (L1 - Masterplan)

The warehouse is composed of the main storage area for complete pallets, which features a combination of racks and floor stacks. This is the largest of the areas since the majority of the orders feature the shipment of multiple complete pallets on the trucks. These complete pallets are received directly from the bottling lines, where the pallet is formed from multiple boxes containing wine bottles and leaves the warehouse without the need to be reduced to smaller units. Another area is reserved for the picking of boxes for small orders with multiple SKUs, where boxes of different SKUs need to be palletized together. Another area comparable in size is the customs warehouse, designed to store products imported from outside the Schengen area that are then re-sold.

The last two remaining areas for the warehouse include the order preparation area and the loading docks. The first area is designed for storing pallets that are being prepared for shipment.

In the case of the distribution operation, the process of shipping orders is divided into two steps. The first one includes a preliminary preparation of the orders, which typically occurs the day before the arrival of the corresponding truck. It is assumed that each truck carries a single order composed of at least 15 and up to 33 pallets stored in a specific aisle. Aisles can be accessed from two sides simultaneously – from the loading docks and the side of the main storage area. Ideally, each aisle would be composed of a single order. However, this is unfeasible given the predicted increase in the factory's operation. Therefore, multiple orders can be stored in a single aisle. In reality, orders are composed of multiple sub-orders with different destinations; however, for simplification purposes, a direct correspondence of one order to one truck is assumed.

After the order is prepared, a truck arrives, which triggers the loading process onto the truck. The loading docks allow for this process to take place. They require an additional clearance area in front, through which pallets can be carried from the orders the trucks. The loading docks are connected directly to the main road and are placed on the lower side of the warehouse (grey area in figure 4.5).

However, some orders can also be composed of quantities of each SKU which are smaller than the pallet unit. In this case, the process of picking boxes and forming them into pallets must take place. This is the case mainly in the national distribution, which serves smaller local clients that typically place orders composed of multiple SKUs. Hence, these boxes need to be formed into pallets, which is a slower process than lifting a single, complete pallet. The process takes place separated from the rest of the warehouse in an area composed of racks, using smaller stackers. It is a resource-intensive process which features many movements between racks since pallets can be composed of boxes of multiple SKUs. As each SKU has its own picking slot, the stackers move from rack to rack before finally depositing the boxes in the palletizing area. This process takes several minutes, and once it finishes, the pallet can finally be transported to the order preparation zone. Despite the facility's large size, some layouts require the externalization of at least part of the operation, as it becomes clear when the layouts are analyzed in more detail.

Due to the large number of distinct operations occurring at the same time, it makes sense to look in-depth at the various processes that make up this warehouse. Three different types of forklifts are used for various operations. Most processes are performed with larger forklifts that store the pallets arriving from the lines, transport them to the order preparation zone and load the trucks. Two smaller groups of stackers are used for the picking process and for the storage of unloaded pallets. Using one group of forklifts for multiple tasks requires processes to be modeled using the same pool of agents. This makes the management of priorities a critical aspect of the simulation.

The finished product arrives from the bottling lines, either directly using forklifts or through elevators, depending on the layout. Each pallet is allocated to a storage unit using the ABC categorization that is used in most of the warehouse models. The classification depends on the number of pallets of each SKU that are shipped from the facility. From the perspective of the simulation, it is similar to the process for storage from the lines in the case of the wine cellar (see figure 4.4).

The shipping process is divided into two operations that function using the same resources –

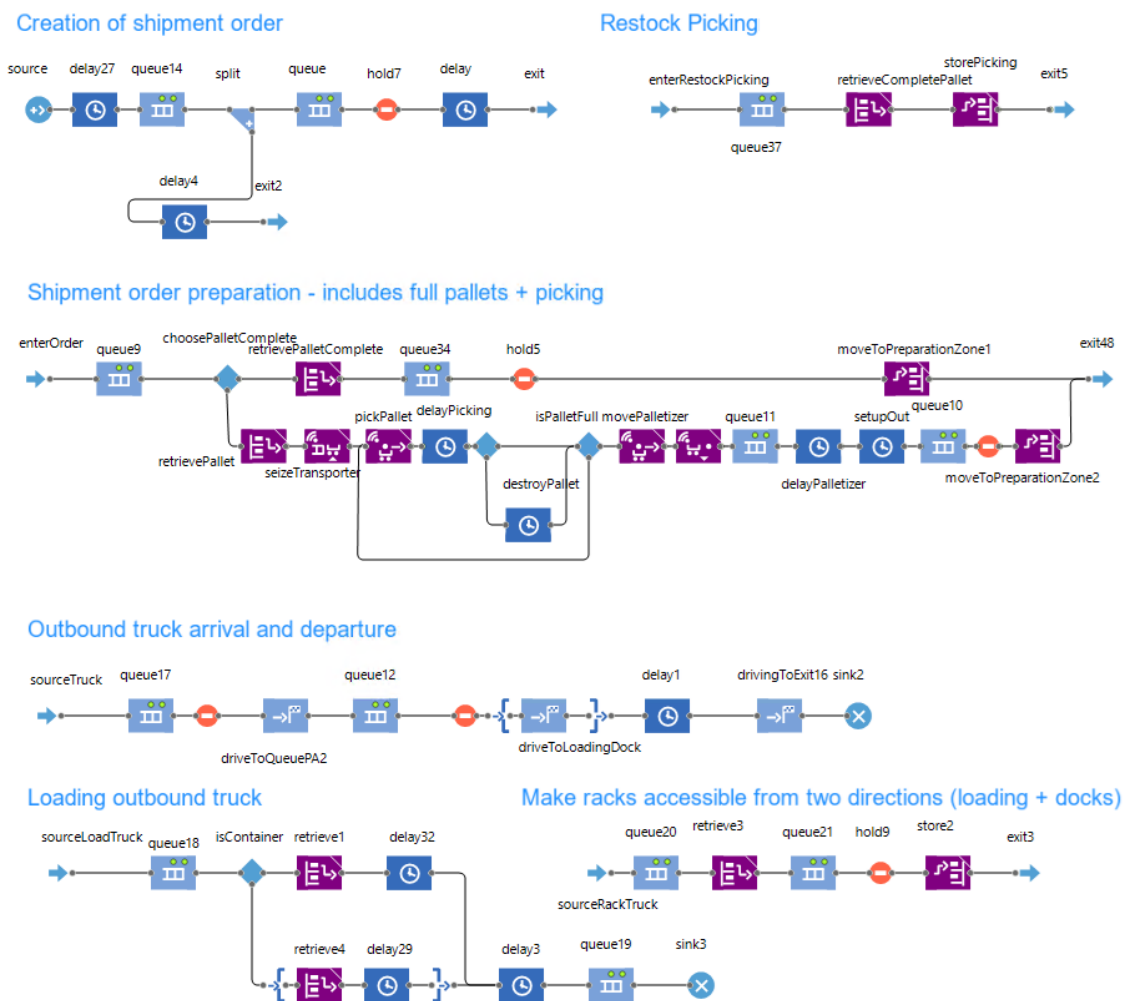


Figure 4.6: Processes used to simulate the shipment of finished product warehouse

the national and international distribution operations. However, as it has been made clear before, the national distribution operation relies heavily on the picking process and is, therefore, slower and more demanding from a resource perspective. The various processes composing this operation are represented in figure 4.6 as modeled in Anylogic.

From the simulation perspective, each operation has its own arrival schedule, which follows the scenario to be tested. The preparation of the orders for both operations is triggered on the day before the order is due to be shipped. It is controlled by the arrival schedule as described in section 3.2.2. The launch of an order calls a function responsible for the process of selecting the required number of pallets for each order, which is then fed into a second process flow. This process distinguishes pallets according to whether they need to be picked before being sent to the order preparation zone. In that case, an additional parameter is defined: each pallet must contain the number of distinct SKUs $n_{distinct}$. It follows a normal distribution with mean and standard deviation defined according to historical data. Since there is no direct indicator for this value, they are obtained from the number of distinct SKUs in each order, divided by the number of pallets shipped in the order. A normality test is conducted to ensure that the random variable can be approximated by a normal distribution.

$$n_{distinct} \sim N(\mu, \sigma) = N(2.863, 0.862) \quad (4.1)$$

The number of SKUs counts the number of movements the forklift for building the pallet, with the following constraint: $n_{distinct} \geq 2$. To simulate this process, the agent (pallet) first seizes a transporter and performs multiple sequential movements to different random picking points in the picking warehouse. Whenever one picking action occurs, the counter is decreased. The process is repeated until it reaches zero. The pallet is then transported to the palletizing area from where it can be brought to the order processing area, where it joins the complete pallets.

The complexity of the picking process is increased by the need to replenish the racks with complete pallets from the main warehousing area. The replenishment is triggered when the number of pallets in each rack falls below a certain value. From the simulation perspective, this is measured periodically. Whenever the number of pallets in a rack falls below the defined minimum value, a random pallet is selected from the complete pallet storage and transported by a transporter to the rack. Being able to perform this control rack-wise allows for a more detailed simulation which more closely emulates the real-world operation.

The pallets are transported to the order preparation area using retrieve and store blocks from the warehouse of complete pallets or the customs warehouse, similarly to other operations. However, in this case, the random assignment gives way to a function that attributes the target aisle for each pallet. The selection of the aisle for each order occurs randomly within the available racks, but each pallet in the order is transported to the same aisle. For this to be possible, it is necessary to maintain a log of all the aisles that are being used, either for order preparation or truck loading. Whenever any of these actions take place, no order can be prepared in this aisle. However, if both processes are not occurring and an aisle already contains one order, it is possible to store an

additional order in the same space. Ideally, this would not happen since it becomes more difficult to identify which pallets belong to which order; but, due to the heavy space constraints, it is necessary.

Pallets are fed from the top and removed from the bottom using an algorithm that automatically transports pallets to a virtual rack opposite the aisle, on the side of the loading docks. Since Anylogic does not allow racks to be accessed from two sides simultaneously, this technique is used to simulate this. Otherwise, transporters would need to circumvent the whole order preparation area to get the next pallet.

The arrival of the trucks depends on the operation type – national or international. In the case of the international operation, trucks arrive mostly in the morning, up until 2:00 pm. This is simulated using the aforementioned arrival schedule, although the truck arrives between 24 and 30 hours after the order starts being prepared. Trucks with national destinations arrive between 3:30 pm and 5:00 pm. This ensures complete fulfilment of all orders.

When trucks arrive in the facility, they select an empty loading dock, and the loading process of the order begins. There are two possibilities for this process: it can occur with a forklift via the virtual rack, where pallets are loaded sequentially onto the truck, with a delay simulating the loading process inside the truck; or by hand. This is a process that occurs when loading products inside containers. Instead of pallets, the boxes are arranged by hand inside the container, which is a process that may take several hours more than the typical loading process. This is why this operation is considered separately in chapter 4.

From the perspective of the simulation, the main moving agent is the pallet. Since the process of loading the containers occurs by boxes of wine bottles, it is necessary to find a way to abstract the pallet agent. This is performed through an automatic transfer of the pallet from the order preparation zone to the loading dock without the need for a transporter. Once the pallet arrives, however, there is a delay of several minutes until another pallet can be transferred to the truck. This simulates the process of loading the boxes onto the container box carried by the truck. Since the resulting process does not seize a resource, such as a transporter, it is necessary to log the number of hours spent on this process to ensure that it is modeled according to the real-world operation. This indicator is collected and displayed in chapter 5.

4.1.6 Other warehouses

Most of the operation, including the finished product, is made using pallets, assembled from a previously established fixed number of empty cardboard boxes filled with wine bottles and a pallet, usually covered in plastic to maintain structural integrity. The pallets considered here are flat wooden structures that support the cardboard boxes and come in two different dimensions: EUR-pallet (1,200 mm × 800 mm) and the so-called American pallet (1016mm × 1,219mm). Despite the difference, the simulation considers the EUR-pallet exclusively for simplification purposes, because it is the most common pallet type used by the company.

Pallets are stored in stacks of up to 30 units that are placed on the floor of the facility. Due to this efficient packing and the relatively low required area, it is not necessary to create a closed

warehouse specifically just for the pallets. Furthermore, they do not require any specific conditions besides fire-control systems and can, therefore, be placed virtually anywhere. In the layouts tested in this project, the empty pallets are placed in stacks close to the bottling lines to reduce the distance for transport. Furthermore, they can be transported in stacks of 15 by a single forklift at a time, which further reduces the congestion caused by this material.

Some promotional wine bottles require certain materials to be added to them, such as special boxes, labels or bottle collars. This process is called finishing and constitutes a relatively small part of the complete operation. However, it is a labour-intensive process that requires an additional warehouse for storing these additional raw materials. This warehouse is larger than the space required for empty pallets and is placed on the lower end of the facility, isolated from the rest of the operation. The reason for this is that this area requires a large number of workers that should not cross paths with forklifts or logistic trains for security reasons.

An additional area is planned for construction that is smaller in size than the main facility and is planned for the operation of wine varieties that are produced in smaller quantities, such as fine wines. This warehouse is connected to the main facility through an ad-hoc passage. In the preliminary analysis, it is predicted that this warehouse will have some free room after construction, which helps explain why this warehouse houses part of the operation of dry raw materials in one of the layouts analyzed in this project. However, the distance from the main facility and the intricate layout, which features several overlapping triangles place some limitations on the practicality of this decision.

4.2 KPIs for evaluating the layouts

Creating multiple layouts for simulation is only relevant insofar as they can be compared using indicators. The decision to implement the layouts in a simulation context makes this process relatively straightforward, especially since the tool used for the purpose, Anylogic, implements many shortcuts for making this process possible.

The first process in identifying the valuable KPIs to collect during the simulation relies on the definition of the overall comparison topics. Then, more detail can be placed on the exact metric that may help characterize the layout in this regard.

Following this process, the simulation covers three main topics, measuring five specific key process indicators: storage (storage density and occupation rate of each warehouse), resources (man-hours by warehouse), and transporters (distance covered by forklifts; and the congestion of critical points in the facility; and loading and unloading time of the trucks). An additional financial indicator that is independent of the simulation is also taken into consideration. Details on each KPI are provided in figure 4.7. After the construction of the layouts, additional code and process blocks are added to provide each of the required KPIs. Here, a brief explanation of this process is presented.

The storage density can be measured directly from the number of storage slots in each warehouse, divided by the area occupied by the warehouse. The occupation rate of each warehouse

needs to be measured over the simulation period and logged periodically since it varies according to the incoming and outgoing flows of each warehouse. Then, a mean value can be obtained that depicts the average occupation of the warehouse. However, even more, relevant is the peak this variable reaches. Should this value run above 100% on any day, then that would mean that the warehouse has insufficient space for the required number of pallets.

The man-hours by warehouse are measured exclusively for the transporters. Since the simulation mainly focuses on the logistics operation and other tasks outside the project's scope, the most critical metric in this regard is measuring the total time forklifts spend on the move, performing most various tasks. This metric is logged for each different task, including, e.g., preparing orders for the international shipment of the finished product or the transport of dry materials to the bottling lines. This ensures better comparability between layouts and with the historical data.

The layouts are created to scale, using the CAD designs as a reference, which makes the measurement of the number of kilometers traveled by the forklifts inside the facility possible. This is provided by Anylogic as a method called for each forklift object. The congestion is measured at several critical points in the layouts that are identified in the design phase. Each time a forklift passes through a point, it is logged, and posterior analysis is conducted to identify the points where forklifts cross each other with the highest frequency. The loading and unloading times of the trucks serve as a proxy for the correct modeling of both processes. They also ensure that the loading docks are placed sufficiently close to the storage units. The Anylogic software provides tools for logging these values, such as Data sets and collection data structures, which are written to Microsoft Excel files for further analysis.

Topic	#	KPI	Description
Storage	1	Occupation rate of each warehouse	Percentage of occupied area over available area by warehouse
Resources	2	Man-hours by warehouse	Necessity of man-hours by warehouse/task
Transporters	3	Distance covered by transporters	Distance in km, covered by transporters inside the facility. It is used as a complement to the number of man-hours.
	4	Congestion of critical points in the facility	Congestion metric, counting the number of forklifts that cross certain critical points within a given time of each other
	5	Loading and unloading time of the trucks	Average time spent loading and unloading pallets from trucks, in all operations

Figure 4.7: KPIs ordered by topic, with a description of what they entail

4.3 The layouts

The strategy for building the candidate layouts required meeting with the relevant stakeholders of the operation. They were designed with CAD software using inputs from the logistics and bottling operation teams. The design involved the creation of multiple drafts before layouts could be designed. This process followed an iterative approach, with more than 20 meetings between the project team and the stakeholders. After the discussion and presentation of more than ten candidate layouts, five were first selected and designed. Two further designs were eliminated due

to significant constraints detected during this work. The project then converged into three distinct, valid layouts, which were approved by the company's board for further analysis using simulation. The small number of valid candidate layouts is a directly consequence of the high number of business restrictions. These limitations include, e.g., the position of the bottling lines and the warehouse for wine bottles. Significant changes in the existing bottling lines require stopping the production for long periods, which causes disruption in the operation and should be minimized. Furthermore, they would represent a significant investment in machinery capable of performing such alterations, further increasing the necessary investment.

The design of the layouts was divided into two main areas: bottling and logistics. Due to the high complexity of the bottling process, the bottling operations team performed the task with input from the rest of the project team. The main focus of this work is the logistics aspect of the layouts, which most heavily affect the feasibility of a layout. This includes the placement of the required warehouses inside the planned constructed area. The warehouses that support the bottling process are given precedence over the warehouse for the finished product, meaning the storage space they require must be fulfilled entirely. If the area is insufficient, part of the warehouse of the finished product is sacrificed and transferred elsewhere outside the facilities. The layouts reflect this decision and feature warehouses of identical sizes, except for the finished product.

The three distinct layouts are designed separately using the underlying process modeling that is common to them all using Anylogic. The first layout, also designated Masterplan, serves as the basis for modeling the processes. These were reused for the rest of the layouts. Specific changes between layouts require processes to be redesigned and altered in conformity. These include the partition of processes into two parts, each occurring on a different floor of the facility, among others.

Following this first design, several improvement possibilities were identified, which reflect the existence of the two other layouts. The second layout provides the operation with an increase in the available storage space due to the externalization of the distribution operation for the domestic market. The third layout focuses on the optimization of space, through the implementation of a vertical warehouse, with high racks. This height storage solution provides a significant increase in available space at the expense of more complex flows.

The layouts were then compared according to their feasibility for future implementation in the facility, using the KPIs described in section 4.2. Regarding the layouts in specific, the Masterplan and the Externalization Layout are identical in the placement of the functional areas. However, with one significant change: due to the space constraints related to the predicted increase in the operation over the next decade, the national distribution operation is removed from this facility. This reduces the number of pallets stored in the facility and the related operations. These two layouts feature only small differences in the KPIs measured.

Meanwhile, the Vertical Warehouse Layout involves the redrawing of a major part of the facility. It includes a two-story-high warehouse and the warehouse's separation and relocation of dry raw materials. This layout deviates heavily from the designs mentioned above, which causes significant deviations in the measured KPIs.

4.3.1 The first layout - the Masterplan

The first layout formed the basis for the initial process modeling and was subjected to the most amount of work and discussion, which is reflected in the existence of two different solutions using the same basic design. Prior to the development of this project, a construction plan for the facility was laid out, which resulted in the available areas that were considered for the candidate layouts. At that time, the Masterplan was the only layout under discussion. For this reason, the first layout maintained this name, which is also used in this case study. Despite the similarities between the two first layouts, the Masterplan includes the maintenance of both distribution operations (national and international) under the same roof.

Similarly to the other layouts, this layout was designed in Anylogic, the result of which is shown on figure 4.8. The main features of the layout include the physical separation of the warehouses for bottles and dry raw materials by the bottling lines. These independent units supply the lines from the left and right sides, respectively. Placing the bottling lines in the center of the facility allows for a minimization of distance covered by the transporters since they are the central piece of the operation. This trait is common to all layouts, which some minor exceptions. Another feature of the layout is the concentration of all the operation of the finished product on the lower floor of the facility. From here, the warehouse enjoys the benefits from being completely separated from the rest of the operation, significantly reducing problems with congestion of transporters. The warehouse is connected to the top floor through two different elevator groups. Pallets arrive one by one to the warehouse through each of the elevators. One of the elevator groups is supplied directly from a palletization center on the top floor, while the other needs the pallets to be transported to the elevator by forklift.

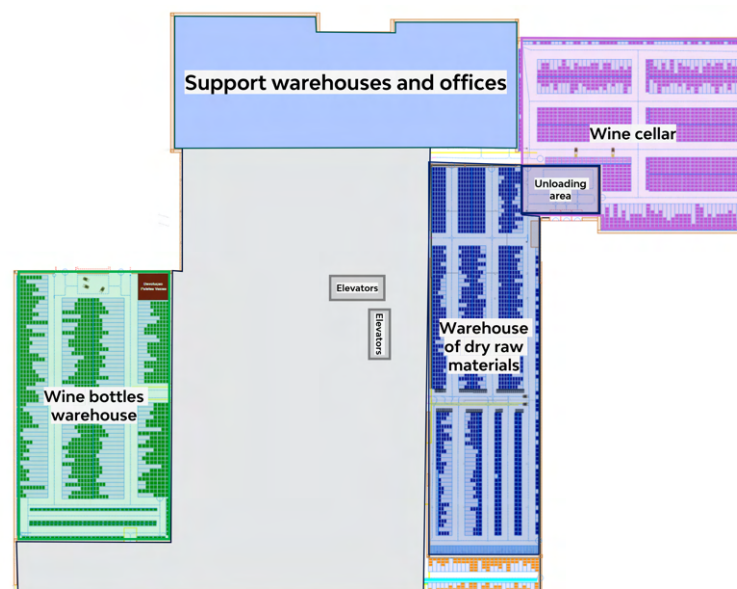


Figure 4.8: Design of the upper floor in Anylogic in the first and second layouts

The design of the bottle warehouse results from the constraints imposed by the stakeholders

regarding the separation of glass raw materials from the rest of the operation. Furthermore, there is enough room in this part of the facility to store pallets outdoors, if necessary, since these materials are less demanding from the perspective of storage conditions. For the incoming operation of the pallets, two areas were created where trucks can be stopped, parallel to the wall. This allows the truck to be unloaded from the side by multiple forklift trucks at the same time. The warehouse features deep storage units and a connection to the bottling lines in the middle of the warehouse to minimize the distance from the storage slots. An additional area is reserved close to the loading area for parking the forklifts whenever they are not in use.

This layout features also features a common warehouse for the remaining dry raw materials. It is composed of a long structure with major corridors connecting all the storage slots. Loading docks are placed on the top part of the warehouse. The storage units for cardboard are concentrated near this area to reduce the distance to the loading docks and bottling lines, which can be accessed directly from this area. Racks for the labels, corks and other materials are placed on the lower part of the warehouse, separated from the cardboard boxes. An area on the ground close to the loading docks is reserved for the conference of the arriving pallets. A secondary area near the second access to the main pavilion is filled with racks for preparing the orders to be transported to the lines on the milk run.

The wine cellar occupies the top-right part of the warehouse (see figure 4.8) and is connected directly to the bottling lines by a corridor for forklifts. This location was chosen because of the limited forklift movements necessary for this operation compared to the other warehouses (figure 3.7). The warehouse follows the same ABC structure described and features a combination of floor stacking storage units and racks. Some racks are reserved for storing empty boxes, which are transported to the lines to be filled with wine bottles for storage in the cellar.

The finished product warehouse is divided into the various areas described in section 4.1.5. The main feature is the block of loading docks through which the product is shipped. The order preparation zone is placed directly above, parallel to the loading docks. This allows multiple orders to be prepared and shipped from each dock and is featured in the two other layouts. Most of the area of the warehouse is used for storage of the complete pallets in storage units of various lengths and depths. The aisles are connected by two vertical corridors, one of which is directly connected to both elevators. They divide the warehouse into three major areas, where the storage units are placed back-to-back and can only be accessed from one side. The picking area occupies the bottom right corner, and the customs warehouse the bottom left corner. These areas benefit particularly from being physically close to the order preparation zone. The layout of this warehouse is shown in figure 4.5.

In general, this layout is a balanced option, with an emphasis on separating operations which may cause added complexity. The flow of pallets and movement of transporters is facilitated, and the positioning of the warehouses for support of the bottling lines is particularly convenient. However, it is predicted it will be unable to accommodate the total required number of pallets in 2030 - which limits the feasibility of the model without any corrections.

4.3.2 The second layout – a variation of the Masterplan

This design arises as a response to the main issue presented by Masterplan: the space limitation. Therefore, the major difference of this model is the attempt to address the problem of space constraints preemptively by externalizing the national distribution process to another facility.

As it became clear from the initial analysis, the Masterplan would not satisfy the required space for ensuring that the operation can support the predicted increase in sales. This drove the creation of this second layout, which assumes that it will be impossible to keep the whole operation in a single facility and aims to prepare the decentralization as soon as possible.

The main change in the layout is the substitution of the picking area by a buffer storage unit, which receives part of the produced pallets and loads them directly onto incoming trucks without the need for any order preparation (see figure 4.9). Although this does not allow for the storage of more pallets directly, all pallets for the national distribution operation are stored in a second location outside the facility. Although the second facility was not modeled, several possibilities were considered, ranging from the construction of a second warehouse to the outsourcing of storage area, each with its own benefits and associated fixed and variable costs.

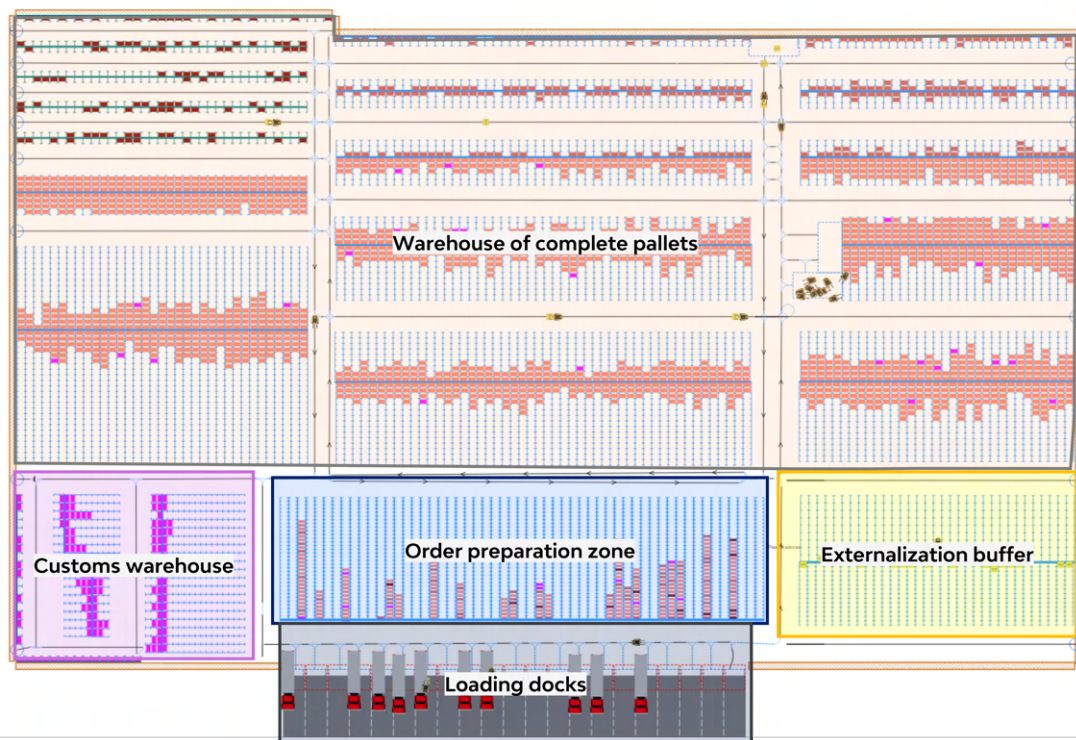


Figure 4.9: Layout of the lower floor for the second layout. The main change from the masterplan is the removal of the picking area and the introduction of a buffer storage area

The main implication of the decentralization is the need to transport the pallets to a second facility, which creates an additional operational effort. For each national order, pallets need to be loaded onto a truck twice instead of just once, resulting in a loss of efficiency. However, there might be additional gains in operational performance since the picking operation, which forms the

basis of the national distribution order preparation, is relatively constrained in the Masterplan layout. Furthermore, this alternative deals with space constraints, completely bypassing this problem in the near future since the freed area in the warehouse can be used to scale up the operation in the facility.

In summary, this layout offers the same benefits as the Masterplan while reducing the storage area requirements, ensuring the viability of the layout for the next decade.

4.3.3 The third layout - maximizing storage density with a vertical warehouse

The third and last layout considered in the case study involves a partial revamp of the facility. It also attempts to solve the space problem of the Masterplan, albeit maintaining both finished product operations inside the facility. A high ceiling, vertical warehouse spanning both floors makes room for more pallets of the finished product, allowing the complete operation to be maintained inside the facility. The decisions regarding the other functional areas are made on the sole basis of making this warehouse feasible.

The main change compared to the other layouts is the introduction of a 4000 sqm warehouse with racks that can support up to 8 pallets in height. This requires the warehouse to cover both floors in height. The racks can only be accessed from the lower floor. Meanwhile, multiple deep floor stacks cover most of the rest of the warehouse, making this solution particularly space-efficient. The loading docks are moved slightly to the left, taking up part of the space of the old customs warehouse. This area, in turn, grows, using part of the floor stacks. The implementation of the lower floor is depicted in figure 4.10.

The space that is occupied by the new structure forces the dry raw materials warehouse to be removed from its previous location and part of the bottling operation to be redesigned. The bottling lines that needed to be moved now occupy the area left vacant by the warehouse of raw materials (figure 4.11).

The cardboard warehouse is transferred to the lower floor. This represents a significant increase in the distance traveled by forklifts to supply the bottling lines with the required raw materials. The cardboard warehouse occupies the top-left part of the lower floor and uses the same elevators as the finished product but in the opposite direction. It uses the lower loading docks to receive pallets containing the cardboard boxes. The other raw materials (corks, labels, among others) are moved to the auxiliary warehouse, occupying the bottom part. Despite the unusual format of the warehouse, it has enough space to store the required materials. Meanwhile, the wine cellar, the warehouse of glass bottles and most of the bottling lines remain unaltered.

Despite its efficiency in space occupation, this solution drastically increases distances between warehouses. In particular, the supply of the bottling lines with raw materials is less efficient due to the larger distances from the lines. However, and as described in chapter 5, the total distance traveled by the forklifts actually decreases, mostly due driven by the warehouse of the finished product. The movement around the bottling lines becomes more convoluted, with pallets leaving the top floor through the elevators and others arriving. Overall, this layout provides the best

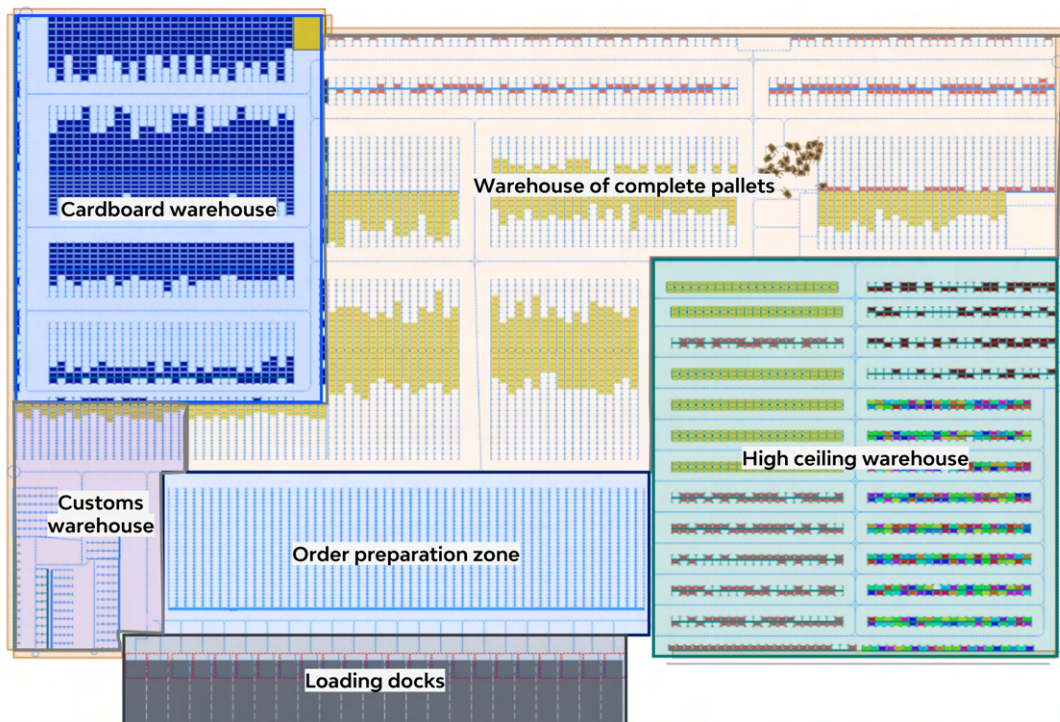


Figure 4.10: Layout of the lower floor for the Vertical Warehouse layout

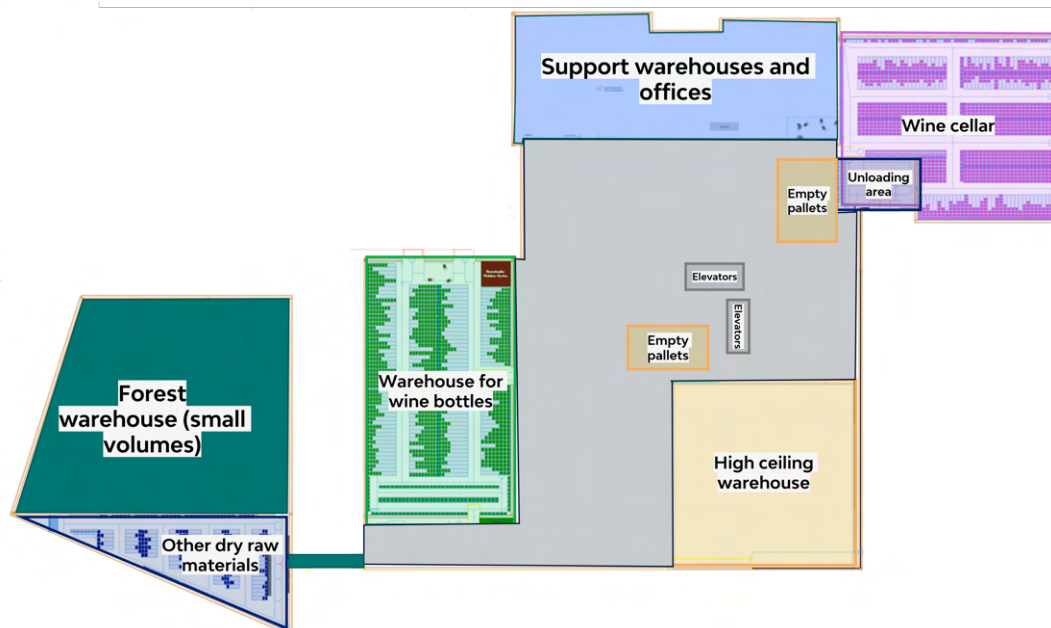


Figure 4.11: Layout of the upper floor for the Vertical Warehouse layout

solution in terms of space utilization but compromises in terms of the complexity of the flow of pallets.

Chapter 5

Simulation implementation and results

As stated in the last chapter, the three layouts were modeled in Anylogic using the same processes as the basis, as described in section 3.1. The model relies on the assumption that the layout must be able to support the operation in the year 2030. For this reason, the flow of material inside the facility is considered to operate at the levels of that year. This translates into an increase in the number of pallets arriving at and leaving the facility, as well as being consumed and produced by the bottling lines.

Furthermore, the main objective of the simulation is to consider the designed layouts in terms of their viability regarding implementation. Hence, the worst-case scenario of optimistic demand should be considered, since it forms an upper bound for the required storage capacity, the number of required man-hours and the number of trucks arriving and leaving the facility.

5.1 Implementation of the simulation models

The complexity of the real-life operation is reflected in the complexity of the model, which features hundreds of thousands of agents that are created and destroyed as they enter and leave the simulation, which takes a toll on its duration. Early estimates placed the duration of a single execution of the simulation model at over 12 hours for each run, which would be unfeasible in the design, test and final execution phases. The first effort to reduce the simulation duration is based on separating the simulation into two distinct models, one for each floor of the facility. The first two scenarios separate the bottling operation and the related warehouses from the finished product. This decision approximately halves the duration of each simulation run since they can be parallelized. Despite this, the simulation would still take over 6 hours to run, which despite being more realistic given the short time frame of the project, would still represent a significant effort. For this reason, the simulation is executed for the month with the largest in-and-out flow of product in the case of the optimistic demand scenario, June 2030. It is then possible to analyze the feasibility of the various layouts and understand how they operate at peak demand.

Despite some stochastic variation, such as the random parameters introduced at the level of the number of pallets arriving at the facility, the simulation is mostly deterministic. The number of

pallets produced, the number of arrivals of trucks at the facility and the number of pallets consumed at the bottling lines are constant parameters. Therefore, little variation is expected between runs.

The choice of the number of forklifts for each operation follows the number of units in utilization at the current facility. However, the values were updated iteratively in case their number could not deal with the increase in the operational demand. In this situation, their number increased proportionally to the forecasted increase in demand. The simulation is performed with a graphical interface, running at the fastest possible (virtual) time and can simulate a whole month of operation of each floor in under 30 minutes.

5.2 Results

Due to the large number of KPIs gathered, this section is divided according to the type of indicator, as described in figure 4.7: storage, resources, and transporters. For each layout the measured indicators are presented and compared with the other solutions.

Table 5.1: Occupation of the warehouses depending on the layout implemented in the year 2030 for the optimistic demand scenario

Layout	Finished Product	Glass Bottles	Cardboard packaging	Wine cellar	Labels and corks
1 - Masterplan	134%	102%	86%	98%	86%
2 - Externalization of distribution	91%	102%	86%	98%	86%
3 - Vertical warehouse	115%	102%	99%	98%	94%

5.2.1 Storage

This section condenses the usage of each warehouse as a percentage of the storage capacity needed in 2030, taking into account the optimistic demand scenario. The total storage capacity of the layouts is the direct result of the areas allocated to each warehouse. The values are presented as a percentage of the predicted necessary storage.

Since the major difference between the layouts is the storage space in the warehouse for the finished product, the increase in space is illustrated in figure 5.1. Here, the total pallet capacities are shown as a bar chart. Dotted lines represent the forecasted storage needs for this warehouse across the next decade. The third layout offers significantly more storage space than the Masterplan. In the case of the externalization of the national distribution, the size of the secondary facility is not determined yet. Therefore, no concrete numbers can be presented, and a grey bar is shown instead.

As expected, the Vertical Warehouse layout offers considerably more storage space for the finished product than the Masterplan (-19pp), while maintaining the necessary storage capacity for the remaining warehouses, with values under or around 100%. Despite the overall increase

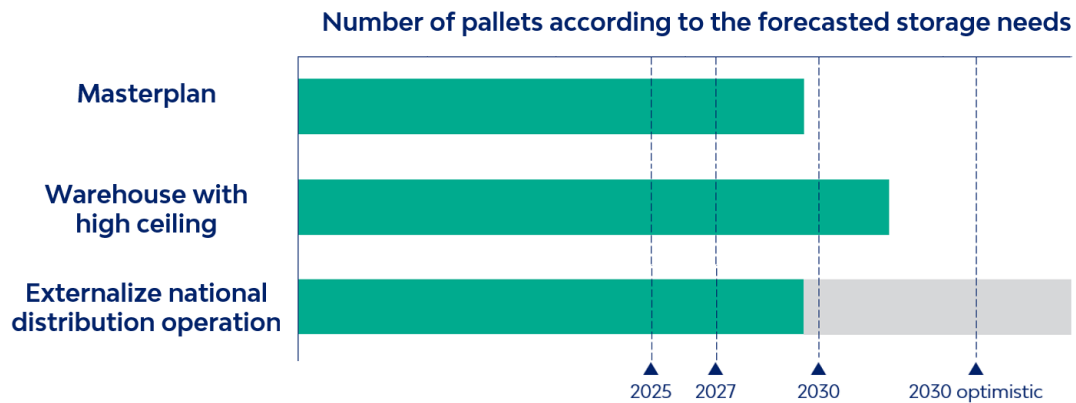


Figure 5.1: Analysis of the total finished product pallet capacities of the three layouts. (The real number of pallets is not shown for reasons of confidentiality)

in the number of pallets that can be stored, if the optimistic demand forecast scenario is achieved in 2030, part of the operation will have to be externalized. However, as shown in figure 5.1, this layout can successfully accommodate the increase in storage needs for the base demand forecast, which the Masterplan cannot. This last layout is unable to provide enough storage space for the finished product in 2030, even in the case of the base forecast scenario.

The externalization of the distribution operation presents a solution to this problem. Removing part of the operation reduces the necessary storage space to under 100% of its capacity, but it needs to be complemented by an external warehouse or distribution center. These and other possibilities are discussed in section 5.3.

5.2.2 Resources

As described already, most of the transport of materials inside the facility is performed using forklifts. For this reason, these are the main resources to consider when comparing the various layouts. Forklifts are divided according to their warehouse and, in the case of the finished product, their function. Forklifts in the warehouses of dry raw materials are responsible for both the incoming and outgoing flow of pallets, which is reflected in a large number of pallet movements.

The masterplan and layout 2 function in the same way on the top floor since the only difference is the externalization of the national operation of the finished product. For this reason, the only necessary comparison for this floor is between layouts 1/2 and 3.

One main aspect to keep in mind is that the third layout does not use the logistic train and uses forklifts to transport pallets of dry raw materials to the bottling lines. This is reflected in the markedly higher number of man-hours spent on this task in the case of the third layout. It is therefore clear: the logistic train is more efficient at transporting pallets, requiring just almost half the man-hours for the same task.

The clear increase in the average number of man-hours of the operation of dry raw materials is clear: +20% in the preparation of the orders and +89% in the supply to the bottling lines. These values are driven by the increase in distance from the warehouses to the bottling lines in the case of corks and labels, and from the placement of the cardboard warehouse on the lower floor. This is a clear case of how changes in the layout directly influence the performance of the operation.

In the case of the lower floor, the most apparent difference is between the first and the second layouts. Externalizing the national distribution operation eliminates the need for preparing orders for this operation, at least in this facility. This means there is no need to perform the picking operation. Furthermore, the restocking activity is also eliminated. Time spent with order preparation also goes down by 18%. Most of this reduction is, however, absorbed by the loading of the pallets destined for national distribution on the trucks. This operation requires 7% more man-hours than the equivalent in the Masterplan. Therefore, the only real efficiency gain is in the picking operation, which does not materialize in reality since it needs to be replicated in the other facility. For this reason, it is impossible to consider the Externalization of Distribution layout as a feasible alternative from the perspective of resource utilization.

One interesting aspect of the third layout is that the positioning of the vertical warehouse close to the loading docks corresponds to a significant decrease in the number of man-hours spent preparing orders. The reduced distance that the forklifts need to cover to prepare orders represents a decrease of nearly 22% in the average number of man-hours. Although this result is somewhat unintended (the objective of the high warehouse is the increase in storage space), it depicts the impact that the large distances have on the operational efficiency and the importance that needs to be given to their optimization.

The remaining parts of the operation display no real difference, which is expected since the positioning of their areas in the layout is similar. The indicators used in this analysis are shown in table 5.2.

5.2.3 Transporters

Transporters include the resources that can transport pallets: forklifts and trucks. This section analyses three different metrics: congestion and distance traveled (forklifts) and loading times (trucks).

Congestion

To measure the flow in the facility, four critical points on the upper floor of the facility were identified, and the number of conflicts was detailed. This allows the comparison between the layout of the upper floor found in the first two layouts and the layout with the vertical warehouse.

The main points are situated at the entrances/exits of the wine cellar, the warehouse of raw materials, the loading docks, and the main corridor that connects the warehouses to the bottling lines. The results are shown in table 5.3.

Table 5.2: Man-hours by warehouse for each layout. The values are displayed in percentage of the the value for the Masterplan (layout 1)

Warehouse	Transport method	Layout	Man-hours	
			Average	Maximum
Dry raw materials	Forklift	1	100%	100%
		2	100%	100%
		3	120%	104%
Supply to bottling lines	Logistic trains	1	100%	100%
	Logistic trains	2	100%	100%
	Forklifts	3	189%	208%
Finished product from bottling lines	Forklifts + Elevators	1	100%	100%
		2	113%	106%
		3	89%	92%
Picking	Stackers	1	100%	100%
		2	0%	0%
		3	98%	101%
Order preparation	Forklifts	1	100%	100%
		2	82%	88%
		3	77%	76%
Loading trucks	Forklifts	1	100%	100%
		2	107%	86%
		3	81%	82%
Restock picking area	Forklifts	1	100%	100%
		2	0%	0%
		3	106%	107%

Conflicts are counted when two forklifts pass through the same critical point at the same time and serve as a proxy for the congestion of the facility. This can be used as a metric for the likelihood of accidents, which is important to minimize.

Layout 3 represents an overall increase of more than 80% in the number of conflicts on the top floor. This is mostly driven by the transport of raw materials to the bottling lines using forklifts instead of logistic trains, which carry more pallets per trip, requiring fewer trips to the lines overall. The result is less congestion and a lower risk of actual collisions happening in the facility.

Table 5.3: Number of potential collisions at various critical points in the facility according to layout

Critical point		LAYOUTS 1 AND 2	L3 - Vertical warehouse	Difference (%)
1	Wine cellar	317	813	256%
2	Dry raw materials	1155	1320	114%
3	Loading docks raw materials	19	3	16%
4	Main corridor	184	979	532%
Total		1675	3115	186%

Distance traveled

Table 5.4: Total monthly distance traveled by forklifts performing select activities

Activity	Masterplan	Layout 2	Layout 3
	Total distance (km)	Total distance (km)	Total distance (km)
Dry raw materials	2 085	2 085	1 499
Supply to bottling lines	606	606	1 188
Finished product (complete operation)	16795	15410	12859
Customs warehouse	82	82	202
TOTAL	17483	16098	13061

The distances traveled by the transporters serve as validation for some of the indicators that have already been analyzed, such as the necessary man-hours for each operation. Table 5.4 provides the total distance traveled by all forklifts in the most critical month of the year.

As predicted, the third layout displays the lowest total distance traveled by its forklifts due to the aforementioned reduction in the distances that are covered between storage and the order preparation zone. The difference in the case of the finished product operation between layouts 1 and 2 is less clear, with a reduction of 1385km vs 3936km from the first to the third layout.

Loading times of trucks

Another set of KPIs measured by the simulation is the collection of loading times divided by the various outbound operations of finished product.

Table 5.5: Loading time and time spent in the facility of the various outgoing operations.

Layout	Zone		Loading time/ truck (min)	Time in the facility (min)	
			Average	Average	Maximum (97%)
L1 – Masterplan	International	Trucks	57.0	77.5	239.2
		Containers	189.4		
	National		50.0		
L2 - Externalization of distribution	International	Trucks	61.8	94.1	235.4
		Containers	192.1		
	National		90.7		
L3 - Vertical Warehouse	International	Trucks	46.1	73.7	241.3
		Containers	189.0		
	National		38.0		

In the case of this KPI, the main difference lies in the larger average time spent in the facility in the case of layout 2. This is a direct result of the way the simulation handles the externalization of the operation: trucks arrive periodically and are loaded until they are completely full with 33

pallets. In other cases, the trucks carry anywhere between 15 and 33 pallets. For this reason, the loading times are higher, so the trucks spend more time inside the facility.

Another interesting data point is the difference between the international operation loading times in the case of normal trucks. It reveals one major aspect of this simulation - the pool of forklifts that loads trucks also performs other tasks. Since the same number of forklifts is used in all three layouts for this operation and the forklifts need to cover less ground in layout 3 and are, therefore, more efficient, they can dedicate more time to loading the trucks more quickly. Especially when other higher priority tasks need to be performed, such as storing pallets arriving from the bottling lines, this operation takes less precedence.

However, it needs to be noted that the layout is only indirectly responsible for this. Should the number of forklifts in the masterplan layout increase, the operation would probably reach the same levels of loading times. However, the number of forklifts is kept constant between layouts for better comparison.

5.3 Discussion

Overall, the introduction of simulation strategies to test layouts for large facilities such as the winery presented in this work, has proven to be a helpful tool for providing a way to compare them according to KPIs that are deemed relevant for the operation. In this regard, it was possible to place three different layouts side by side, which at the onset of the project were difficult to compare regarding their viability. The KPIs focus on various parts of the operation and, when considered together, provide a holistic view of the overall fit of the layout to the needs of the company.

The decision to focus on the optimistic demand scenario for the simulation is the result of the necessity of evaluating the capacity of the facility in the next decade. The expansion of the facility is a process that can take several years, during which the operation requirements may increase, due to the forecasted growth in demand. Furthermore, the intention of the company is ensuring the viability of the facility for decades to come. Hence, simulating the worst case scenario in terms of storage necessity is based on this long-term view.

Regarding the three layouts described here, it is not easy to define which one is the most indicated for implementation. Each was developed as a response to problems identified in the current operation and serves different purposes. However, when considering the fact that one of the main objectives of the expansion of the facility is the need to store more pallets, more efficiently, the third layout, with its high warehouse spanning two floors, seems to provide a good solution in terms of space utilization. It also has the added benefit of performing better than the two other models regarding the total distance covered by its forklifts while requiring fewer man-hours for the same tasks. This is a direct consequence of the dense storage that is placed close to the elevators and to the order preparation zones. Since less distance seems directly proportional to a smaller requirement of man-hours, the final layout should consider this. From the perspective of resource utilization, it is very interesting to explore a possibility where the distance each pallet

travels in the warehouse is minimized. This is one of the focuses of the work developed in chapter 6.

Despite the favorable position of the Vertical Warehouse layout, some other aspects must be considered. First and foremost, the operation of raw materials is less efficient: it does not allow for a logistic train and places the warehouses far from the bottling lines. It also carries a higher risk of collisions of forklifts on the upper floor, which is a situation that should be avoided. Second, the Vertical Warehouse does not completely solve the storage necessity, especially considering the optimistic demand scenario. Only the externalization of the operation would provide a solution to this problem. Third, even if the optimistic scenario is not reached in 2030, there is a high chance it will happen in the following decade. In that case, the additional investment in the warehouse will prove less valuable, and the immediate externalization of the operation may prove less costly. Other relevant considerations are the required operation expenditure, the flexibility for future increases in production capacity and the potential for changes in the layout.

Despite all this, the recommendation of this work is for the third layout to be implemented. The cost of placing racks is lower than constructing a new facility elsewhere and prepares the operation better for the future while providing significant savings in terms of man-hours spent. An additional effort should be placed on implementing a logistic train despite the inherent space limitations of the design, as this could offset some of the productivity losses.

However, the business decision relies on more information than analyzed here. This simulation model is intended as a decision support tool that needs to be conjugated with several other decisions concerning the feasibility of the layouts. One point has already been mentioned - the investment cost for the various layouts. The acquisition of racks and the construction costs for a new facility represent significant investments and can therefore make or break a layout as a candidate. However, this financial analysis is yet to be performed but will play a part in the decision-making process, as is the case with all business decisions.

As shown in the next chapter, the simulation developed here has inherent limitations due to some abstractions steps that needed to be taken for the model to be successfully developed. For this reason, some work may still be necessary to accurately assess which layout is the superior solution for the facility layout problem faced by this company.

Chapter 6

Optimizing the finished product warehouse

The macro-layout that was defined with recourse to simulation makes use of particular micro-layouts for each warehouse. The most relevant decisions were made regarding how the warehouses interact with each other but did not place much effort on optimizing the internal operation of every single warehouse. The micro-layouts were developed with all the operational restrictions in mind and are comparable to what might be implemented in reality, but their development was not the main focus of the model, which means some abstraction decisions were made that may affect their feasibility regarding the actual operation. This presents an excellent opportunity for improvement.

6.1 Description of the problem

A solution is presented that tries to tackle the problems introduced by one of the abstractions from the simulation model. It consists of a linear programming model in the concrete example of the finished product warehouse that optimizes both space utilization and distance covered by transporters.

One of the shortcomings of the simulation model is the use of the ABC model for the distribution of SKUs in the various warehouses. The decision to employ such a simplification provides significant increases both in model development and execution time with minor changes in the flow of pallets, which is the main objective of the model. However, it may not provide a clear picture of how the different SKUs are distributed around the warehouses. The simulation works with a stochastic view of the factory, where pallets are selected randomly according to SKU from the appropriate stock category (A, B, or C) depending on the respective storage sizes. SKUs from the “A” category are items that are used (consumed or shipped) with the highest rate, “B” items are used with a medium rate, and “C” are more rarely moved. This means that pallets from SKUs in the first category are moved more often, e.g. to the bottling lines or the loading docks and have a more significant impact on the transporter needs. Due to the longer simulation horizon and the

relative uncertain reality of simulating a decade in advance, this strategy is deemed to produce viable results while maintaining the simulation complexity comparably lower.

Nevertheless, defining where each SKU is placed inside the warehouse is a relevant decision for the business. The distribution of SKUs impacts the number of pallets that can be stored in a warehouse since, in the case of the more efficient floor stacking method, storage bays can only store pallets of a single SKU. While racks have bays of a single depth, a choice of pallet depth has to be made in the case of floor stacking areas. Pallets are placed side by side in aisles with a given depth, which affects the capacity to store pallets of a given SKU. Furthermore, it also impacts the distance covered by the transporters. SKUs with higher loading and unloading rates benefit from being placed closer to bottling lines and loading docks, so transporters cover less distance to transport them. Since some of the warehouses can reach lengths of more than 100 meters, appropriate assignment of SKUs to storage units may provide significant benefits over a random assignment.

Assigning SKUs to bays can help maximize the number of pallets in storage and minimize the distance travelled by transporters – both crucial metrics for the operation of the warehouse. Since the layouts presented in this work display difficulties in storing all the necessary materials, the first consideration - the maximization of the pallets that fit in storage - takes precedence over the second one. Another benefit of such a model is the possibility of defining the need to acquire storage racks more accurately beforehand.

The primary constraint of this problem is the space limitation of the warehouses. Although various warehouses could benefit from such a model, the warehouse for finished product is the largest in terms of size and storage needs. Being able to maximize the space utilization for this warehouse, as well as minimizing the travel distance for transporters, could provide the most significant advantage. Furthermore, since it is a self-contained warehouse, receiving pallets from the bottling lines by elevator and shipping them through the loading docks, it is easier to develop an independent model compared to the other warehouses.

6.1.1 Methodology

Similar to the main topic of this case study, the problem presented here belongs to the category of the FLP. As the literature review illustrates, optimization is one of the most common strategies for developing models for this category of problems, apart from simulation. Linear programming models allow modeling and solving complex combinatorial optimization problems such as the one presented here. This requires constraints to be written in linear form, which, in the case of this model, leads to the necessity to precompute several parameters.

The main output of the model is an attribution of the SKUs to be stored in the warehouse of finished products to a given rack or floor stacking block. Since layouts 1 and 2 use the lower floor in their entirety, the model developed here takes this macro-layout as an assumption. However, the intention while developing the model is that it can be applied to other layouts as well, even if some alterations are necessary.

Storage space is limited by the size of the warehouse and several areas that must be placed in the warehouse due to business restrictions. A simplified version of the warehouse considered for this model can be found in figure 6.1. This view excludes areas such as the customs warehouse and the picking area, keeping only the main storage areas. These need to be designed according to specific business requirements and were kept intentionally outside this model's scope.

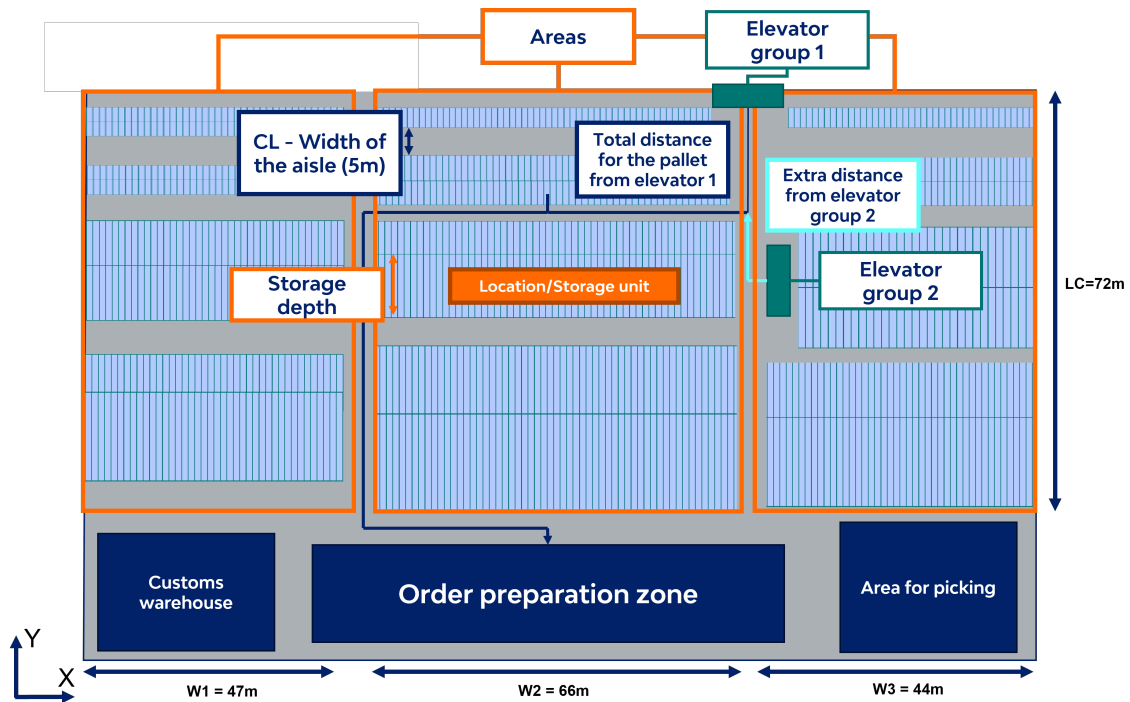


Figure 6.1: Sketch of the layout considered for this optimization problem. It is based on the lower floor layout of the Masterplan

The warehouse is divided into three main areas, which are connected by corridors that are placed vertically. Additional corridors for storage access run horizontally between racks and floor stacking blocks¹. In each of these three areas, the storage units are placed horizontally, preferentially back-to-back, which means they can only be accessed from one side. This allows for space optimization. However, it is also possible to place a single storage unit alone, although this is not a space-efficient solution, in light of the constraint of storing a single SKU in each of the storage bays. The storage units run for the length of the area, between corridors, or between a corridor and the outside walls of the warehouse.

The pallets arrive from one of two elevator groups, which connect the bottling lines on the upper floor to the warehouse. Both elevator groups are placed according to the figure, one on the upper part and the other further down the middle. Different bottling lines feed each elevator group. Since each SKU can only be produced in a single bottling line, the position of arrival to the warehouse is known beforehand. During the preparation of orders, the pallets are transported from their storage unit to the preparation zone on the lower part of the warehouse. Therefore, the

¹The storage racks/blocks are from here on denominated "storage units" for simplification purposes.

distance covered by the pallet is the sum of the distances covered while storing the pallets and preparing the orders. The distance considered by this model is the Manhattan distance, where the distance between two points $p_1 = (x_1, y_1)$ and $p_2 = (x_2, y_2)$ is calculated by the formula: $|x_1 - x_2| + |y_1 - y_2|$. This distance accurately depicts the movement inside this warehouse, which features only 90° turns, with aisles placed horizontally or vertically. In the case of arrivals through the second elevator group, there is an excess distance that needs to be covered to access storage units that are placed above its y-position. In this case, an extra average distance is considered to penalize the placement of pallets arriving through this elevator group.

The model considers the month with the most significant production amount, with two main indicators per SKU: amount in stock and throughput – the number of pallets shipped from the warehouse (also called flow). The amount in stock is the number of pallets that should be in storage in the warehouse at the end of the month. Furthermore, the model takes into account the dimensions of the warehouse and its three areas, and of the individual pallets. It is assumed that all pallets in the warehouse are EUR-pallets (dimensions: 1,200 mm × 800 mm × 144 mm). The number of pallets that can be stacked depends on the SKU, since it varies significantly with the bottle size. This is considered as one of the parameters of the simulation. Another parameter that is defined beforehand is the possible number of storage depths that be assigned to a storage unit. Instead of allowing the model to search over every possible combination, rack depths were defined to be one of a set including depths of either 1, 2, 5, 10, 15, or 20 pallets. This decision reduces the solution space and should expedite the process of solving the problem. Further possibilities were tested, such as a smaller combination of possible depths. These provide different results since the solution space is reduced.

6.2 Sets, indexes and parameters

6.2.1 Sets

$\mathcal{L}$	$= \{1, \dots, L\}$ - Set of all storage units
$\mathcal{L}_i \subset \mathcal{L}$	$= \{1, \dots, L_i\}$ - Set of all storage units in area i
$\mathcal{A}$	$= \{1, \dots, A\}$ - Set of all SKUs
$\mathcal{N}$	$= \{1, \dots, N\}$ - Set of possible pallet depths for a storage unit
$\mathcal{C}$	$= \{1, 2, 3\}$ - Set of areas
$\mathcal{A}^{EL2} \subset \mathcal{A}$	$= \{1, \dots, A^{EL2}\}$ - Set of SKUs that arrive to the warehouse from elevator 2

6.2.2 Indexes

a - SKU, which defines the type of pallet that is stored

l - Location (also called storage unit), which is organized according to the structure defined in section 6.1.1

n - Depth of the storage slot

6.2.3 Parameters

A - Number of different SKUs that are stored in the warehouse

L - Number of different Storage units/Locations in the warehouse

L_i - Number of different Storage units/Locations in an area

V_{an} - Number of bays that need to be reserved for SKU a for a given number of slots on the ground n . This value ensures that the SKU can be stored completely in a single rack. It is calculated for each combination of SKU-number of slots

C_l - Corridor of location l

RP_l - Index of the rack pair of location l

R_l - Index of the rack of location l

D_{al} - Total distance covered by a pallet from the elevator to rack/location l and then to the order preparation zone. It depends on the SKU a , since the elevator from which each SKU arrives is defined beforehand

D^{max} - Maximum possible distance covered by a pallet

S_a - Stock of SKU a that is stored if the SKU is placed in a storage unit

F_a - Flow of pallets of SKUS a . Counted as the number of pallets produced on the month of maximum production

P_a - Number of pallets of SKU a that need to be stored

WP - Width of a pallet. It is assumed that the operation uses exclusively EUR-pallet (dimensions: 1,200 mm $\times$ 800 mm $\times$ 144 mm). An excess of 10% is considered in this model to allow for some free space between pallets

LP - Length of a pallet. It is assumed that the operation uses exclusively EUR-pallet (dimensions: 1,200 mm $\times$ 800 mm $\times$ 144 mm). An excess of 10% is considered in this model to allow for some free space between pallets

LC - Length of the corridors

W_l - Width of a corridor, defined for location l

HP_a - Maximum number of pallets that can be stacked in each slot. This factor depends on the SKU, since the height of each pallet can vary, producing stacks between 2 and 3 pallets in height.

CL - Width of an aisle for storage access

Y^{EL2} - Y-position of the second elevator

z - Average extra distance that a pallet travels if it is placed over the elevator group 2

α - Weight of each part of the objective function. Allows modelling this multi-objective problem as a single-objective model, using the weighted sum method.

6.3 Decision variables

The output of the model is the location of the SKUs according to the storage unit. The decision variable also provides information on the number of pallets that can be stored on the ground per bay of each storage unit. The number of slots reserved for each SKU is kept constant for each

storage unit. The decision variables are binary and indicate if the SKU a is stored in storage unit l with a storage depth of n slots. The variable takes the value 1 when SKU a is stored in location l with depth n , and 0, otherwise:

$$x_{aln} \in \{0, 1\}$$

Auxiliary variables

Apart from the decision variables, additional variables were defined to simplify the formulation of certain constraints. This variable encodes the storage depth at each storage unit as a binary variable. An additional constraint is used to assign values to this variable.

The variable is binary and is 1 if the location l has depth n , and 0 otherwise:

$$y_{ln} \in \{0, 1\}$$

Another auxiliary variable is necessary for defining if SKU a , which arrives to the warehouse from the second group of elevators, is placed higher on the y-axis than the elevators.

The variable is binary and is 1 if SKU a is placed higher on the y-axis than the second elevator group, and 0 otherwise:

$$\delta_a \in \{0, 1\}$$

6.4 Objective function

As described in section 6.1.1, the objective function includes maximization of the number of pallets stored in the warehouse, as well as minimization of the distance covered by transporters.

The number of pallets stored in the warehouse is given by the multiplication of the decision variable by the stock stored on each rack per SKU, while the second component of the objective function is given by the multiplication of the decision variable by the flow of each SKU and the distance covered by the pallet to the slot and from the slot to the preparation zone.

One possible approach to solving this multi-objective problem is the weighted sum method (Marler and Arora, 2010), which involves multiplying one of the parts of the function by a factor α , that takes values between 0 and 1 and the other by $(1 - \alpha)$ and then combining them in a single function by addition of the resulting terms. The variation of the value α can lead to different solutions, depending on the importance given to each parameter. In section 6.6, sensitivity analysis is performed to assess the impact of changes in this parameter on the result of the model.

Additionally, both parts of the objective function are normalized to try to achieve some degree of comparability. In the case of the maximization of the number of pallets, the complete summand is divided by the maximum number of pallets to be stored in the warehouse. The other part of the objective function is divided by the worst-case scenario in terms of distances to cover, namely if all the pallets are placed in the top-left corner of the warehouse. This maximum distance is multiplied by the sum of all pallet flows. Even if this does not represent a feasible solution to the problem, it provides an upper bound for the distances that can be covered by the forklifts, providing some degree of comparability, which makes the process of choosing suitable values for

α more straightforward. This would not be the case if both parts of the objective function featured significantly different orders of magnitude.

Since the objective function includes the minimization of one term and the maximization of another, the model is presented as a minimization where both terms are included:

$$\min \left[\alpha \times \frac{1}{d^{max} \times \sum_{a \in \mathcal{A}} F_a} \left(\sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} \sum_{a \in \mathcal{A}} x_{aln} \times F_a \times (D_{al} + n) + \sum_{l \in \mathcal{L}} \sum_{a \in \mathcal{A}^{EL2}} \delta_{al} \times F_a \times z \right) \right. \\ \left. - \left[(1 - \alpha) \times \frac{1}{\sum_{a \in \mathcal{A}} S_a} \times \sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} \sum_{n \in \mathcal{N}} x_{aln} \times S_a \right] \right] \quad (6.1)$$

6.5 Constraints

The first constraint ensures that each SKU can only be stored in a single storage unit. The decision to restrict SKUs to a single unit ensures that the forklift operator spends less time in the process of locating the correct bay for each SKU and is the result of a specific business decision.

$$\sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} x_{aln} \leq 1, \forall a \in \mathcal{A} \quad (6.2)$$

As it has been set forth in section 6.3, the auxiliary variable y_{ln} needs to be defined. A constraint using big M notation is used to assign values to this variable. y_{ln} abstracts away information on what SKU is stored at each storage unit (given by x_{aln}) and allows for less constraints to be written later on when this information is necessary for further constraints.

$$\sum_{a \in \mathcal{A}} x_{aln} \leq y_{ln} \times A, \forall l \in \mathcal{L}, \forall n \in \mathcal{N} \quad (6.3)$$

The next constraint ensures that the storage depth at each location is constant, which means that, for each location, the number of distinct storage depths is less or equal than one.

$$\sum_{n \in \mathcal{N}} y_{ln} \leq 1, \forall l \in \mathcal{L} \quad (6.4)$$

The two following constraints include the space limitations of the warehouse, both in width and length. The width constraint is given by the multiplication of the number of occupied storage bays in each storage unit by the width of a pallet, which needs to be lower or equal to the width of the storage area. The process is repeated for each storage unit since the width is specific to each area.

$$\sum_{a \in \mathcal{A}} \sum_{n \in \mathcal{N}} x_{aln} \times V_{an} \times WP \leq W_l, \forall l \in \mathcal{L} \quad (6.5)$$

The length is restricted to the length of the warehouse (it is the same for each area, A1, A2 and A3). The occupied length is calculated using the storage depth of each rack multiplied by the length of the pallet, with an additional term being used to calculate the length used by the horizontal corridors for storage access. This part of the constraint is calculated using the number

of storage units. However, corridors can be used to access two different storage units if they are located opposite one another. Therefore, the number of units in use is converted to the number of corridors and then multiplied by the width of the corridor.

$$\sum_{n \in \mathcal{N}} y_{ln} \times CL \times (l - RP_l + 1) + \sum_{l \in \mathcal{L}} \sum_{n \in \mathcal{N}} y_{l,n} \times n \times LP \leq LC, \forall i \in \mathcal{C}, \forall l \in \mathcal{L}_i \quad (6.6)$$

The set of SKUs that have an additional distance to cover is defined using the auxiliary variable δ_a . For this, one has to assess if the location where the SKU is placed has a y-value that is superior to the y-value of elevator no.2. This is performed using the following equation:

$$\sum_{n \in \mathcal{N}} x_{aln} \times CL \times (l - RP_l + 1) + \sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}_i} x_{aln} \times n \times LP - Y^{EL2} \leq \delta_a \times LC, \forall i \in \mathcal{C}_i, \forall l \in \mathcal{L} \quad (6.7)$$

6.6 Results

The optimization model presented in this chapter was modeled in Python using the PuLP interface library, using IBM ILOG CPLEX as the solver. The model was solved on a system featuring an 11th Gen Intel® Core™ i7-1185G7, running at 3.00GHz, with 16GB of available RAM. The solver was limited to 4 available threads, and default CPLEX parameters were used.

The layout described in section 6.1 was used for testing the model. Regarding the parameters of the simulation, several aspects are considered, such as the possible depths for each storage unit. Varying this value produces problems that may be solved in shorter periods and produce significantly different results. For this reason, two different instances were tested: one where the predetermined pallet depths can vary between the set $[1, 2, 5, 10, 15, 20]$ (Instance 1) and another for the set $[5, 10, 15, 20]$ (Instance 2). This last instance prioritizes the storage of SKUs with larger depths and significantly reduces the solution space, as shown in table 6.1.

Table 6.1: Dimensions of the reduced MIP problem. The reduction is performed automatically by CPLEX.

Instance	MIP dimensions	
	Constraints	Binary variables
Instance 1	2079	472000
Instance 2	1983	316272

Both instances of the optimization model were executed for the different values of α using a time limit of 3600s. Since this model is not to be run periodically, e.g. every day, this was deemed an appropriate time limit for running this model. As it becomes apparent during the analysis, this has a clear effect on the results of the model. Especially if more importance is given to the storage capacity, the relative gap to the lower bound is particularly high, which points to the need to run the model over a more extended period of time.

The value α refers to the parameter used in the objective function to control the weight of each of the two parts. Low α values prioritize the space utilization, while larger values produce solutions that give more weight to the total distance traveled by forklifts in their activities.

Because this is a multi-objective model, it makes sense to consider various scenarios for the value α , which controls every term's impact on the objective function. With this in mind, the α parameter is varied in increments of 0.2 between 0 and 0.8. The results are displayed in table 6.2.

Table 6.2: Results of the solutions of the optimization model for the two instances, given various α values

Alpha	Instance	Result of the objective function	Total distance (km)	Total pallets stored (% of theoretical value)	Relative gap
0	Instance 1	-0.591	15033	76.1%	50.25%
	Instance 2	-0.658	15168	84.3%	31.89%
0.2	Instance 1	-0.603	996	77.3%	41.33%
	Instance 2	-0.452	1052	81.8%	30.99%
0.4	Instance 1	-0.301	185	68.8%	17.30%
	Instance 2	-0.315	306	74.6%	10.94%
0.6	Instance 1	-0.185	82	65.1%	9.19%
	Instance 2	-0.189	139	67.9%	7.82%
0.8	Instance 1	-0.089	22	60.3%	1.74%
	Instance 2	-0.087	19	58.6%	3.64%

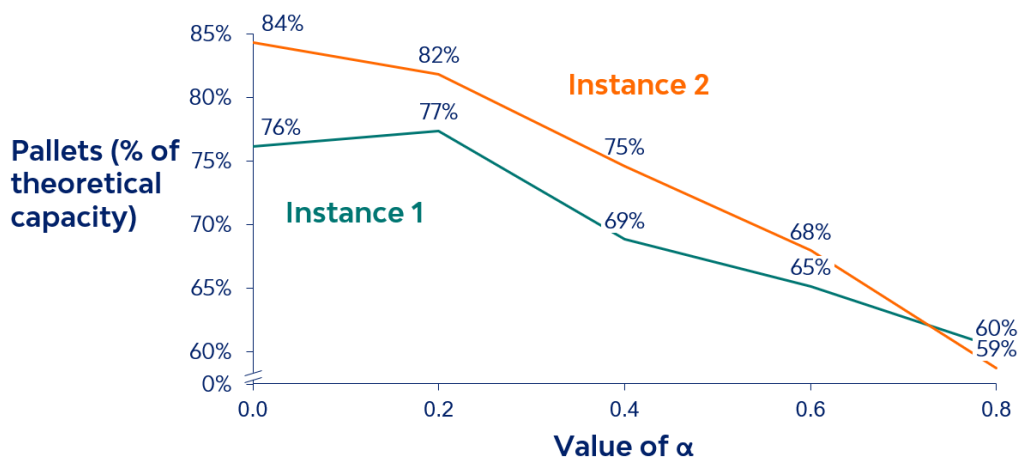


Figure 6.2: Number of pallets that can be stored in the various storage layouts resulting from different α values

6.6.1 Discussion

One of the first things to note in this model is that, especially for higher values of α , the relative gap is high, reaching 50.25% in the case of $\alpha = 0$ for the first instance. This means that the solutions for

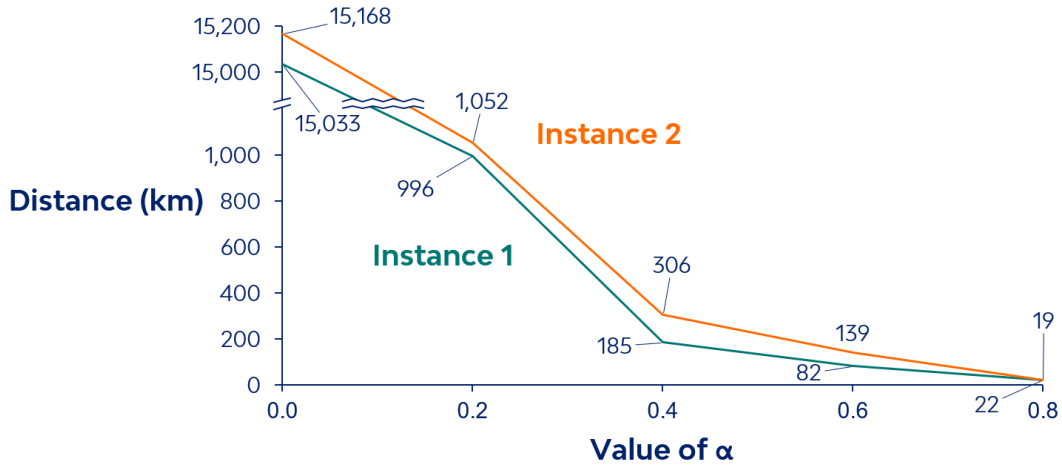


Figure 6.3: Total distance traveled by forklifts to transport pallets the storage layouts given different α values

these cases are likely far from the optimum. Furthermore, the relative gaps are larger for instance 1, which is probably the result of its larger solution space, caused by the choice of more possible values for the storage depths. A particularly interesting difference is the total number of pallets that can be stored by the resulting layout in the case of $\alpha = 0$. Despite the fact that the solution for instance 2 could theoretically be reached by instance 1 (since $N_2 \in N_1$), the time limit of one hour is insufficient for the model to achieve the same result. Nevertheless, and taking into consideration a preliminary analysis performed on the number of pallets that could be theoretically stored inside this warehouse, the difference is only about 15.7%. As one of the stakeholders pointed out during one of the preliminary discussions, when stock levels reach around 80-85% in the warehouse of the finished product, it becomes impossible to store only a single SKU in each storage bay. The target result is, therefore, hardly achievable since the optimization model measures the number of pallets that can be stored following this constraint. For this reason, there is a large degree of confidence that the results indeed correspond to a practical limit on the number of pallets that can be stored in the warehouse.

When considering the solution when $\alpha = 0$, there is an additional data point that allows for the validation of this model, namely the total distance traveled in the configuration given, that lies in the order of tens of thousands of kilometers for a whole month. The same order of magnitude is verified when looking at the results from the simulation model. For example, when considering the number of kilometers traveled by forklifts in the layout of externalization of the national distribution, it lies at around 15.1 thousand kilometers for the whole month. The value for the solution of instance 2 is about 15.2 thousand kilometers. This confers a certain degree of certainty regarding the results obtained using this model.

The same is not verified when α is increased - the distance traveled goes down dramatically, especially at $\alpha = 0.8$. In this case, due to the larger weight given to the distance part of the objective function, the solver prefers the solution to have pallets with SKUs of low rotation, that

display low probabilities of being shipped during that month. SKUs with higher rotation are completely eliminated from storage. Lower values of α show less of a preference as to what category of items to store.

Following the logic mentioned in the discussion section of chapter 5, there is a clear margin for improving the total distances measured by the simulation. For example, when comparing $\alpha = 0$ and $\alpha = 0.2$ in the case of the second instance, the dramatic decrease from around 15 thousand to one thousand kilometers, while reducing the amount of total pallets stored by only 2.5% clearly illustrates this fact.

In summary, the choice for the value of α needs to be made with the business aspect in mind. The possibility of modeling different scenarios in terms of preference offers an advantage to the decision-making process. In this case, the decision lies between which SKUs should, e.g., be stored outside of this facility, where storage is denser and less distance needs to be covered by the pallets. One possibility for comparing these values and finding the optimum is considering the investment aspect, which needs to answer the following question: is the reduction in utilized storage space compensated by the savings due to the reduction in distances traveled?

However, and from the understanding that outsourcing the storage of pallets is an expensive endeavor, one would recommend the solution provided by $\alpha = 0.2$, since it provides a balanced solution in terms of the total number of pallets while producing a significant reduction in the distance traveled by the forklifts in comparison to the distance-agnostic version.

Overall, this study illustrates how certain problems can require various tools for providing a solution that helps stakeholders make decisions. The simulation provided good insights into several aspects, such as the resource utilization and the potential number of collisions of transporters, but, as a standalone tool, it is insufficient to solve the facility layout problem completely. As this optimization model shows, there are many potential improvements in the various layouts, which may need to be taken into account to provide a complete picture to the decision-makers.

Chapter 7

Conclusion and future work

The first part of the final chapter aims to enumerate the key takeaways from the project while providing critical analysis of the impact of the work. Additionally, possibilities for continuing to develop the topics in this dissertation are discussed.

From the perspective of a stakeholder that needs to make a decision that significantly impacts the complete operation of a business, the ability to test the outcome of various potential solutions is a fundamental tool. This is especially the case when the decision concerns a highly complex topic such as the layout of a facility that is central to achieving the company's objectives in the long term. Evaluating various scenarios gives more support in the search for technological solutions and offers more confidence in deciding what solution to pursue.

Designing a facility for the wine industry relies on a combination of specific domain knowledge spanning various areas, from oenology, to bottling and logistics, each featuring different, sometimes conflicting requirements and constraints. For this reason, the project's first step needed to be acquiring inputs from all these areas. Only then did it become possible to develop layouts that correspond to the various stakeholders' expectations. However, comparing different layouts that place warehouses in different areas or completely remove parts of the operation from the facility is difficult to assess, even for stakeholders with decades of experience. For this reason, the simulation models developed in the context of this work are invaluable assets that can help make better, more informed solutions. They provide a degree of reality to an abstract problem. This work intends to show that they can model real-world operations with the required degree of precision while abstracting information that may not be relevant for solving the problem.

Furthermore, simulation provides the ability to extract key performance indicators from the designed layouts that aid the decision-making process. These range from high-level indicators, such as the total storage capacity, to more specific values, such as the total distance covered by forklifts in the specific warehouses. Despite the need to implement certain simplification measures to model the layouts in a simulation context, it provides an accurate representation of the real-world operation, should a given layout be implemented.

Regarding the simulation results, the main takeaway is that from a purely operational perspective, both the masterplan and the layout featuring the vertical warehouse are particularly well

suited. The masterplan is particularly well balanced considering the first floor, while the other performs better in the context of the operation of the finished product. Since this part of the operation represents the most significant effort in terms of forklifts and storage space, it may be beneficial to implement the latter. This analysis also needs to consider the layout involving the externalization of the complete national distribution operation. Despite providing the warehouse with much-needed free storage space, the remaining indicators point to no significant improvement in the operation besides the reduction in the man-hours spent on the picking process. Since this activity needs to occur at the second facility, the operation would be more complex and less efficient overall.

Making a final decision regarding the layout depends on more information than just the performance indicators collected from this simulation model. For this reason, the second problem was formulated. It provides an optimized layout for the warehouse of the finished product that considers various business restrictions that were not modeled using simulation. The possibility of choosing between different strategies of storage inside the facility gives the stakeholder additional control over the model and its impact. Since one of the significant limitations of the layouts described is the inability to store all pallets of finished product inside the facility in the coming decade, it is necessary to strike a balance between which pallets to store in another facility, depending on various factors. This model, therefore, provides an additional decision-making tool to the stakeholder if and when he needs to externalize the storage operation.

Future work

One of the major shortcomings of the work developed is the reduced focus placed on other solutions of externalization of pallet storage beside the removal of the national distribution from the facility. Since the complete occupation of the warehouse of the finished product is a probable event in the next decade, it makes sense to start studying the various possibilities to accommodate this increase. Viable solutions include

1. Outsourcing part of the storage capacity
2. Building a second warehouse just for the pallets of finished products
3. Further expanding the facility towards the surrounding areas

These could then be coupled with the existing layout models developed in the context of this work. One additional improvement possibility is the implementation of similar optimization models to the various warehouses. Although it was tested on the warehouse that represents the largest burden on the facility, for example the wine bottle warehouse could benefit from a better placement strategy for the pallets that minimizes the distance covered by the forklifts to load and unload pallets from storage.

From the perspective of the facility layout problem, another improvement potential is the introduction of optimization-simulation tools to generate more candidate layouts based on the restrictions of the business. The long design times for each layout could therefore be reduced, and

the position of the various warehouses could be optimized using preliminary analysis. The optimization model could then be applied to a simulation model similar to the ones described in this work. Overall this could also reduce the need for the degree of interaction between the stakeholders and the members of the project while designing each layout. Other optimization-simulation models could be created to optimize specific parameters, such as the attribution of SKUs to each storage unit, as shown in chapter 6. This could provide the simulation with optimized parameters, resulting in a more accurate simulation whose results could be directly implemented in the existing facility.

Despite the possibilities for further analysis that strengthen the decision-making capabilities of the stakeholders, the two models described here highlight the importance of simulation and optimization in understanding the processes underlying the operation of complex facilities and how they can be improved in the future. Simulation is handy for modeling real-life situations with a significant amount of detail, even decades ahead, especially when coupled with good forecasting models, as was the case in this project. The optimization model built upon the shortcomings of the simulation model and provided a solution to a more specific problem regarding the optimization of the position of the pallets inside the facility.

Simulation is expected to become a more constant presence in the decision-making process at companies due to the various possibilities and use cases. Furthermore, simulation can be coupled with solutions such as optimization models to improve companies' operations beyond just their operations and guide strategic decisions.

References

- F. Basso and M. Varas. A MIP formulation and a heuristic solution approach for the bottling scheduling problem in the wine industry. *Computers & Industrial Engineering*, 105:136–145, Mar. 2017. ISSN 03608352. doi: 10.1016/j.cie.2016.12.029. URL <https://linkinghub.elsevier.com/retrieve/pii/S0360835216305071>.
- A. Borshchev. Big book of simulation modeling, 2022. URL <https://www.anylogic.com/resources/books/big-book-of-simulation-modeling>. Accessed on 2022-06-29.
- A. Borshchev and A. Filippov. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. page 23, 2004.
- S. Boschert and R. Rosen. Digital Twin—The Simulation Aspect. In P. Hehenberger and D. Bradley, editors, *Mechatronic Futures*, pages 59–74. Springer International Publishing, Cham, 2016. ISBN 978-3-319-32154-7 978-3-319-32156-1. doi: 10.1007/978-3-319-32156-1_5. URL http://link.springer.com/10.1007/978-3-319-32156-1_5.
- R. B. Boulton, V. L. Singleton, L. F. Bisson, and R. E. Kunkee. *Principles and Practices of Winemaking*. Springer US, Boston, MA, 1996. ISBN 978-1-4613-5718-6 978-1-4615-1781-8. doi: 10.1007/978-1-4615-1781-8. URL <http://link.springer.com/10.1007/978-1-4615-1781-8>.
- E. Cakici, J. Jia, P. Yu, S. J. Mason, C. Richard Cassady, L. Pohl, and A. J. Lachowsky. Cellar Tank Piping Network Analysis at E. & J. Gallo Winery. *Journal of Wine Research*, 17(3): 145–160, Dec. 2006. ISSN 0957-1264, 1469-9672. doi: 10.1080/09571260701286585. URL <http://www.tandfonline.com/doi/full/10.1080/09571260701286585>.
- W.-C. Chiang and P. Kouvelis. An improved tabu search heuristic for solving facility layout design problems. *International Journal of Production Research*, 34(9):2565–2585, Sept. 1996. ISSN 0020-7543, 1366-588X. doi: 10.1080/00207549608905045. URL <http://www.tandfonline.com/doi/abs/10.1080/00207549608905045>.
- S. Cholette. Mitigating demand uncertainty across a winery’s sales channels through postponement. *International Journal of Production Research*, 47(13):3587–3609, July 2009. ISSN 0020-7543, 1366-588X. doi: 10.1080/00207540802320156. URL <https://www.tandfonline.com/doi/full/10.1080/00207540802320156>.
- A. Drira, H. Pierreval, and S. Hajri-Gabouj. Facility layout problems: A survey. *Annual Reviews in Control*, 31(2):255–267, Jan. 2007. ISSN 13675788. doi: 10.1016/j.arcontrol.2007.04.001. URL <https://linkinghub.elsevier.com/retrieve/pii/S1367578807000417>.

- G. Figueira and B. Almada-Lobo. Hybrid simulation–optimization methods: A taxonomy and discussion. *Simulation Modelling Practice and Theory*, 46:118–134, Aug. 2014. ISSN 1569190X. doi: 10.1016/j.simpat.2014.03.007. URL <https://linkinghub.elsevier.com/retrieve/pii/S1569190X14000458>.
- F. A. Garcia, M. G. Marchetta, M. Camargo, L. Morel, and R. Q. Forradellas. A framework for measuring logistics performance in the wine industry. *International Journal of Production Economics*, 135(1):284–298, Jan. 2012. ISSN 09255273. doi: 10.1016/j.ijpe.2011.08.003. URL <https://linkinghub.elsevier.com/retrieve/pii/S0925527311003240>.
- M. Grieves and J. Vickers. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In F.-J. Kahlen, S. Flumerfelt, and A. Alves, editors, *Transdisciplinary Perspectives on Complex Systems*, pages 85–113. Springer International Publishing, Cham, 2017. ISBN 978-3-319-38754-3 978-3-319-38756-7. doi: 10.1007/978-3-319-38756-7_4. URL http://link.springer.com/10.1007/978-3-319-38756-7_4.
- I. V. Grigoryev. Fifth edition 2021 - Anylogic, 2021. URL <https://www.anylogic.com/upload/al-in-3-days/anylogic-in-3-days.pdf>. Accessed on 2022-06-29.
- International Organisation of Vine and Wine, 2019. URL <https://www.oiv.int/public/medias/6782/oiv-2019-statistical-report-on-world-vitiviniculture.pdf>.
- M. Jahangirian, T. Eldabi, A. Naseer, L. K. Stergioulas, and T. Young. Simulation in manufacturing and business: A review. *European Journal of Operational Research*, 203(1):1–13, May 2010. ISSN 03772217. doi: 10.1016/j.ejor.2009.06.004. URL <https://linkinghub.elsevier.com/retrieve/pii/S0377221709004263>.
- H. Jalali and I. V. Nieuwenhuyse. Simulation optimization in inventory replenishment: a classification. *IIE Transactions*, 47(11):1217–1235, Nov. 2015. ISSN 0740-817X, 1545-8830. doi: 10.1080/0740817X.2015.1019162. URL <http://www.tandfonline.com/doi/full/10.1080/0740817X.2015.1019162>.
- D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks. Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, 29:36–52, May 2020. ISSN 17555817. doi: 10.1016/j.cirpj.2020.02.002. URL <https://linkinghub.elsevier.com/retrieve/pii/S1755581720300110>.
- R. Kia, F. Khaksar-Haghani, N. Javadian, and R. Tavakkoli-Moghaddam. Solving a multi-floor layout design model of a dynamic cellular manufacturing system by an efficient genetic algorithm. *Journal of Manufacturing Systems*, 33(1):218–232, Jan. 2014. ISSN 02786125. doi: 10.1016/j.jmsy.2013.12.005. URL <https://linkinghub.elsevier.com/retrieve/pii/S0278612513001283>.
- W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 51(11):1016–1022, 2018. ISSN 24058963. doi: 10.1016/j.ifacol.2018.08.474. URL <https://linkinghub.elsevier.com/retrieve/pii/S2405896318316021>.
- V. Kuts, G. E. Modoni, W. Terkaj, T. Tähemaa, M. Sacco, and T. Otto. Exploiting Factory Telemetry to Support Virtual Reality Simulation in Robotics Cell. In L. T. De Paolis, P. Bourdot, and A. Mongelli, editors, *Augmented Reality, Virtual Reality, and Computer*

- Graphics*, volume 10324, pages 212–221. Springer International Publishing, Cham, 2017. ISBN 978-3-319-60921-8 978-3-319-60922-5. doi: 10.1007/978-3-319-60922-5_16. URL http://link.springer.com/10.1007/978-3-319-60922-5_16. Series Title: Lecture Notes in Computer Science.
- Q. Liu, H. Zhang, J. Leng, and X. Chen. Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. *International Journal of Production Research*, 57(12):3903–3919, June 2019. ISSN 0020-7543, 1366-588X. doi: 10.1080/00207543.2018.1471243. URL <https://www.tandfonline.com/doi/full/10.1080/00207543.2018.1471243>.
- A. F. Mac Cawley. *The international wine supply chain: challenges from bottling to the glass*. PhD thesis, Georgia Institute of Technology, 2014.
- C. Macal and M. North. Tutorial on agent-based modeling and simulation. In *Proceedings of the Winter Simulation Conference, 2005.*, pages 2–15, Orlando, FL, USA, 2005. IEEE. ISBN 978-0-7803-9519-0. doi: 10.1109/WSC.2005.1574234. URL <http://ieeexplore.ieee.org/document/1574234/>.
- R. Maidstone. Discrete event simulation, system dynamics and agent based simulation: Discussion and comparison. pages 1–6, 03 2012.
- R. T. Marler and J. S. Arora. The weighted sum method for multi-objective optimization: new insights. *Structural and Multidisciplinary Optimization*, 41(6):853–862, June 2010. ISSN 1615-147X, 1615-1488. doi: 10.1007/s00158-009-0460-7. URL <http://link.springer.com/10.1007/s00158-009-0460-7>.
- A. R. McKendall, J. Shang, and S. Kuppusamy. Simulated annealing heuristics for the dynamic facility layout problem. *Computers & Operations Research*, 33(8):2431–2444, Aug. 2006. ISSN 03050548. doi: 10.1016/j.cor.2005.02.021. URL <https://linkinghub.elsevier.com/retrieve/pii/S0305054805000778>.
- D. Mourtzis, M. Doukas, and D. Bernidaki. Simulation in Manufacturing: Review and Challenges. *Procedia CIRP*, 25:213–229, 2014. ISSN 22128271. doi: 10.1016/j.procir.2014.10.032. URL <https://linkinghub.elsevier.com/retrieve/pii/S2212827114010634>.
- L. März, W. Krug, O. Rose, and G. Weigert, editors. *Simulation und Optimierung in Produktion und Logistik*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011. ISBN 978-3-642-14535-3 978-3-642-14536-0. doi: 10.1007/978-3-642-14536-0. URL <http://link.springer.com/10.1007/978-3-642-14536-0>.
- N. Nikolakis, K. Alexopoulos, E. Xanthakis, and G. Chryssolouris. The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. *International Journal of Computer Integrated Manufacturing*, 32(1):1–12, Jan. 2019. ISSN 0951-192X, 1362-3052. doi: 10.1080/0951192X.2018.1529430. URL <https://www.tandfonline.com/doi/full/10.1080/0951192X.2018.1529430>.
- S. Olafsson and Jumi Kim. Simulation optimization. In *Proceedings of the Winter Simulation Conference*, volume 1, pages 79–84, San Diego, CA, USA, 2002. IEEE. ISBN 978-0-7803-7614-4. doi: 10.1109/WSC.2002.1172871. URL <http://ieeexplore.ieee.org/document/1172871/>.

- S. F. Railsback. *Agent-based and individual-based modeling: a practical introduction*. Princeton University Press, Princeton, NJ, 2nd edition edition, 2019. ISBN 978-0-691-19082-2 978-0-691-19083-9.
- R. Shannon. Introduction to the art and science of simulation. In *1998 Winter Simulation Conference. Proceedings (Cat. No.98CH36274)*, volume 1, pages 7–14 vol.1, Dec 1998. doi: 10.1109/WSC.1998.744892.
- J. M. Swaminathan, S. F. Smith, and N. M. Sadeh. Modeling Supply Chain Dynamics: A Multi-agent Approach. *Decision Sciences*, 29(3):607–632, July 1998. ISSN 0011-7315, 1540-5915. doi: 10.1111/j.1540-5915.1998.tb01356.x. URL <https://onlinelibrary.wiley.com/doi/10.1111/j.1540-5915.1998.tb01356.x>.
- D. Twede, R. H. Clarke, and J. A. Tait. Packaging postponement: a global packaging strategy. *Packaging Technology and Science*, 13(3):105–115, May 2000. ISSN 0894-3214, 1099-1522. doi: 10.1002/1099-1522(200005)13:3<105::AID-PTS503>3.0.CO;2-9. URL [https://onlinelibrary.wiley.com/doi/10.1002/1099-1522\(200005\)13:3<105::AID-PTS503>3.0.CO;2-9](https://onlinelibrary.wiley.com/doi/10.1002/1099-1522(200005)13:3<105::AID-PTS503>3.0.CO;2-9).
- T. H.-J. Uhlemann, C. Lehmann, and R. Steinhilper. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. *Procedia CIRP*, 61:335–340, 2017. ISSN 22128271. doi: 10.1016/j.procir.2016.11.152. URL <https://linkinghub.elsevier.com/retrieve/pii/S2212827116313129>.
- www.anylogic.com. Anylogic - simulation modeling software tools; solutions for business. URL <https://www.anylogic.com/>. Accessed on 2022-06-29.
- Z. Zhang, X. Wang, X. Wang, F. Cui, and H. Cheng. A simulation-based approach for plant layout design and production planning. *Journal of Ambient Intelligence and Humanized Computing*, 10(3):1217–1230, Mar. 2019. ISSN 1868-5137, 1868-5145. doi: 10.1007/s12652-018-0687-5. URL <http://link.springer.com/10.1007/s12652-018-0687-5>.
- C. Zhuang, J. Liu, and H. Xiong. Digital twin-based smart production management and control framework for the complex product assembly shop-floor. *The International Journal of Advanced Manufacturing Technology*, 96(1-4):1149–1163, Apr. 2018. ISSN 0268-3768, 1433-3015. doi: 10.1007/s00170-018-1617-6. URL <http://link.springer.com/10.1007/s00170-018-1617-6>.

Appendix A

Flowcharts of the modeled processes

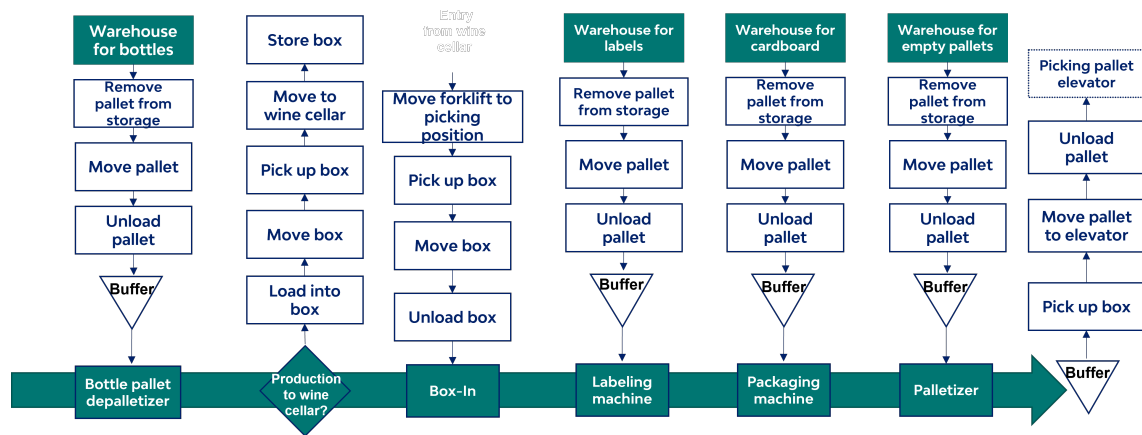


Figure A.1: Flowchart of the process of bottling to/from the wine cellar

Flow of trucks

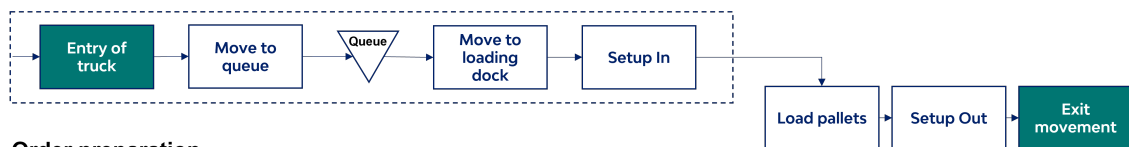


Figure A.2: Flowchart of the process of dispatching of pallets in the national distribution operation

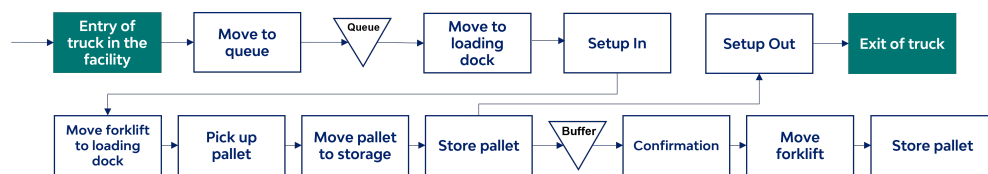


Figure A.3: Flowchart of process of reception of pallets of the finished product

Appendix B

Implementation of the layout simulation

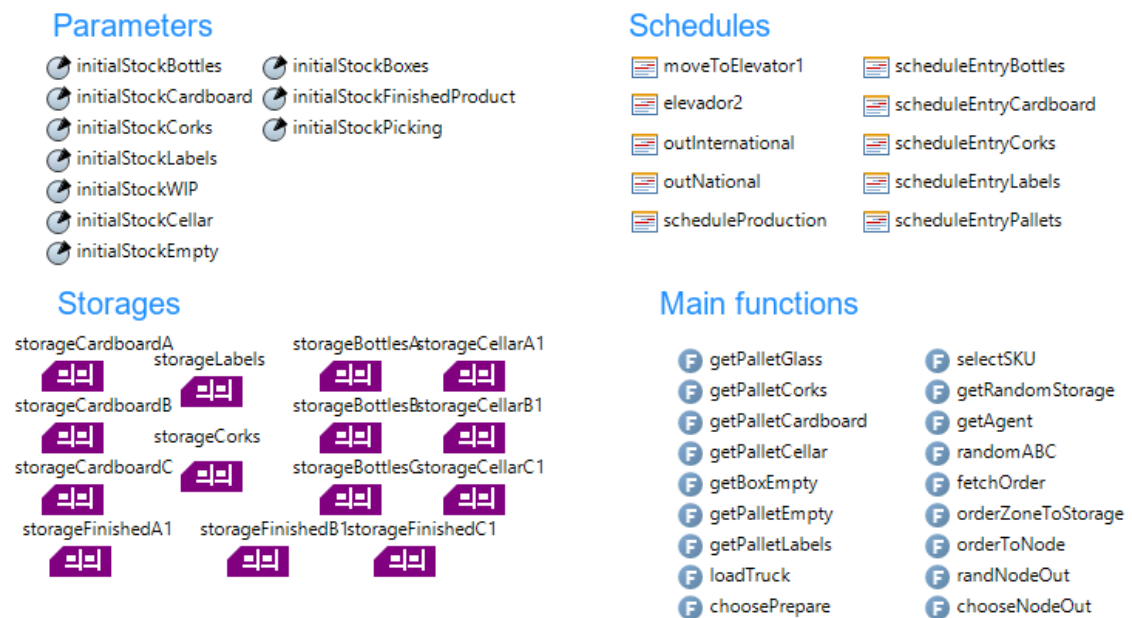


Figure B.1: Main parameters, schedules, storage units and functions of the simulation models

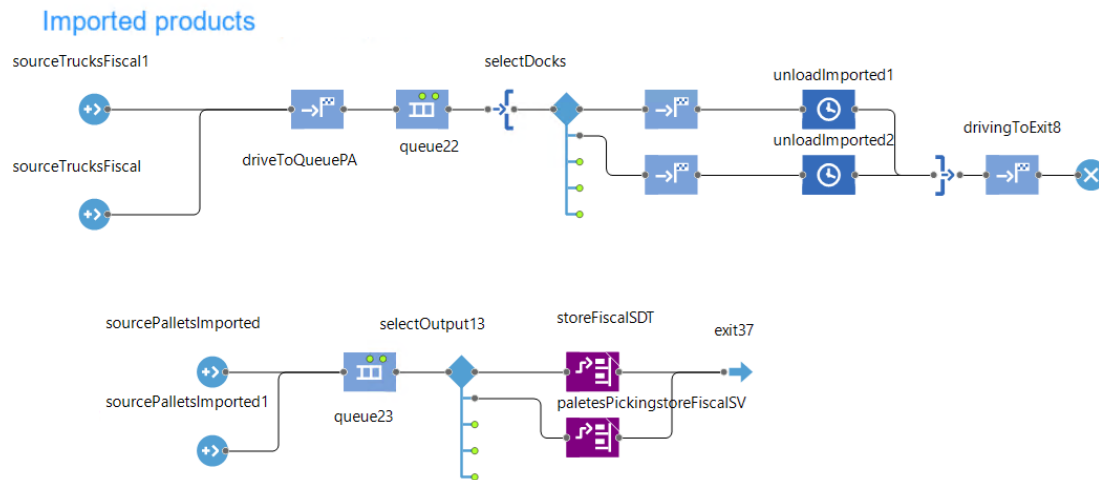


Figure B.2: Process of reception of pallets of finished product

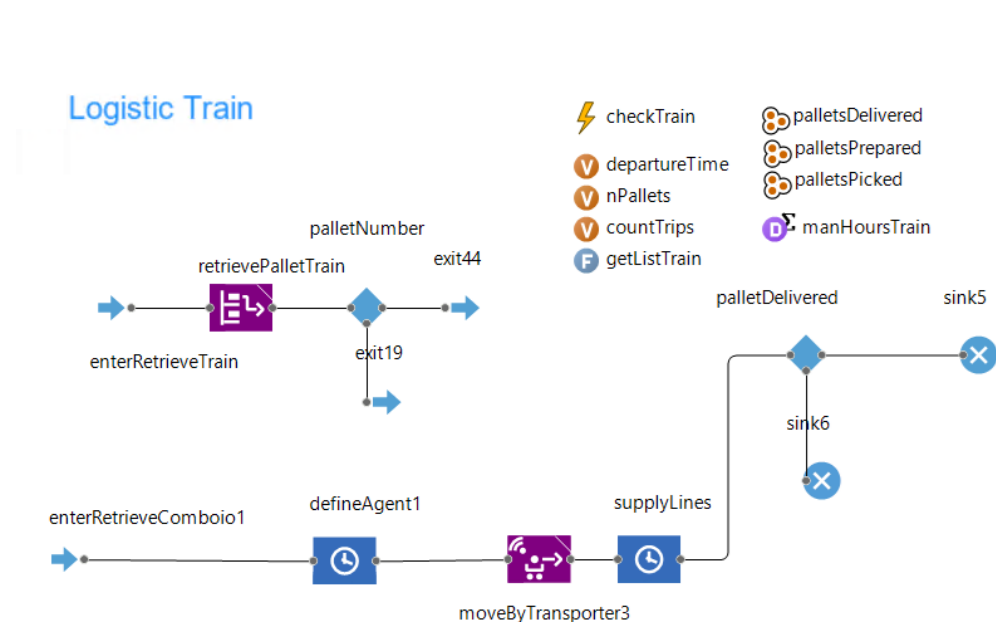


Figure B.3: Processes related to the implementation of the logistic train in the facility