The influence of risk on the design of a warehouse loading area

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Master of Science Thesis

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The influence of risk on the design of a warehouse loading area

Development of a parametric model to evaluate logistic design choices for the warehouse loading area

by

M.E. Tuijp

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This thesis is confidential and cannot be made public until February 5, 2025.

Preface

This thesis is the result of my graduation assignment at Heineken, from whom I have been given the opportunity to develop a parametric model which enables the evaluation of safety within the design of a warehouse loading area. After 9 months of research, this document contains the final report of my findings. During this period I have been challenged to think outside the box in order to properly evaluate the aspect of safety in the design process, which was a completely new field for me. However, I am grateful to be given the chance to familiarise myself with the associated concepts and to expand my knowledge in this field.

I would like to thank my TU Delft supervisor Wouter Beelaerts van Blokland for his support, the interest he has taken in the project and his encouragement to think outside the box. Also, I would like to express my thanks to Rudy Negenborn, who helped me improve my research with his critical questions and feedback during our meetings. Furthermore, it has been a great experience to be part of Heineken and get to know the positive environment in which they work. I am grateful that they have given me the freedom to perform my research as I wanted. Lastly, I would like to thank my friends, family and especially my boyfriend, who have supported me throughout the process.

M.E. Tuijp
Leiden, February 2020

Abstract

Heineken's goal with respect to safety is to reduce the number of accidents as close as possible to zero. Such a drastic reduction can only be achieved by considering safety as early as in the design phase, when the most impact can be made. Therefore, the purpose of this research is to enable the easy generation of different design concepts and evaluate them with regard to safety. Since most accidents currently occur in Heineken's warehouse loading areas, this is the area considered in this thesis.

In order to evaluate the generated designs with respect to safety, safety has been quantified into a single value, the risk level. This risk level is the result of the possible consequence of an accident (the impact), the number of times an activity is expected to occur (the frequency) and the chance that this activity results in an accident (the probability). These values depend on the type of accident, or hazard, which is any unsafe condition or potential source of an undesirable event with potential for harm or damage. The hazards corresponding to the top three most occurring accidents have been identified and have been evaluated. These accidents concern being injured due to manual loading of goods, being struck by a moving vehicle or striking against object, and being struck by falling object or trapped by overturning material.

For the generation and evaluation of design concepts, a parametric model has been developed. By changing parameters, designs with different operating processes, equipment types, layouts, and more, can quickly be generated and visualised for the designer. Also the movements that occur in the warehouse area can be simulated, and likewise be visualised. The model counts the number of times a hazard occurs to determine the corresponding frequency score. When the frequency score is determined, the risk level can be calculated, in which the scores for the impact and probability are based on expert opinion.

Using the parametric model, the risk level resulting from the twelve most occurring hazards in the warehouse loading area of Heineken is evaluated for different scenarios. The findings show that the current method that is used to determine the frequency score is not suitable for activities that typically occur a lot, which is the case in the warehouse loading area. Therefore, an alternative method is proposed, which uses an exponential distribution to score the number of times that a hazard can occur. In this method, the frequency score better reflects the number of hazards in the case of a warehouse loading area.

By analysing design choices regarding the type of picking process (directly from warehouse, using cross-docking or using pre-staging), the level of automation, the number of aisles, the distance between loading points and designing crossings on a different level, the preferred design choices have found. It is shown that, when taking safety into account, the design is influenced in the direction of:

- Small breweries would be designed to use the picking process using pre-staging;
- Medium breweries would be designed to either use the picking process using cross-docking or using pre-staging;
- Large breweries would be designed to either use the picking process directly from warehouse or using pre-staging;
- Equipment with a higher (combined) level of automation would be used;
- The use of forklift trucks would be eliminated;
- The loading points would be evenly distributed over the width of the warehouse;
- The number of aisles would be increased;
- All crossings between pedestrians and moving vehicles would be designed on a different level.

Abstract (Dutch)

Heineken's doel met betrekking tot veiligheid is om het aantal ongelukken te reduceren tot nul. Een dergelijke drastische vermindering kan alleen worden bereikt door veiligheid al in de ontwerpfase mee te nemen, wanneer de meeste impact kan worden gemaakt. Het doel van dit onderzoek is daarom om eenvoudig verschillende ontwerpconcepten te genereren en te evalueren met betrekking tot veiligheid. Aangezien de meeste ongelukken zich momenteel voordoen in het laadgebied van het magazijn, wordt dit gebied in dit onderzoek behandeld.

Om de gegenereerde ontwerpen met betrekking tot veiligheid te evalueren, is veiligheid gekwantificeerd in een enkele waarde, het risiconiveau. Dit risiconiveau is het resultaat van het mogelijke gevolg van een ongeval (de impact), het aantal keren dat een activiteit naar verwachting zal plaatsvinden (de frequentie) en de kans dat deze activiteit resulteert in een ongeval (de waarschijnlijkheid). Deze waarden zijn afhankelijk van het type ongeluk. De activiteiten die in de drie meest voorkomende ongelukken kunnen resulteren, zijn geïdentificeerd en geëvalueerd. Deze ongevallen betreffen letsel als gevolg van het handmatig laden van goederen, een botsing met of door een bewegend voertuig, en geraakt worden of bekneld worden door een vallend voorwerp.

Voor het genereren en evalueren van ontwerpconcepten is een parametrisch model ontwikkeld. Door parameters te wijzigen, kunnen ontwerpen met verschillende processen, transport- en laadvoertuigen, lay-outs, en meer, snel worden gegenereerd en gevisualiseerd voor de ontwerper. Ook kunnen de bewegingen die plaatsvinden in het magazijngebied worden gesimuleerd en worden gevisualiseerd. Het model telt vervolgens het aantal keren dat een gevaar optreedt om de bijbehorende frequentiescore te bepalen. Wanneer de frequentiescore is bepaald, kan het risiconiveau worden berekend, waarbij de scores voor de impact en waarschijnlijkheid zijn gebaseerd op de mening van een deskundige op het gebied van veiligheid.

Met behulp van het parametrische model wordt het risiconiveau voor verschillende scenario's geëvalueerd. De bevindingen tonen aan dat de huidige methode om de frequentiescore te bepalen niet geschikt is voor activiteiten die doorgaans veel voorkomen, wat het geval is in het laadgebied van het magazijn. Daarom wordt een alternatieve methode voorgesteld, die gebaseerd op een exponentiële verdeling, het aantal gevaren beter weergeeft voor het laadgebied in een magazijn.

Door ontwerpkeuzes te analyseren met betrekking tot het type proces (rechtstreeks vanuit het magazijn, met behulp van cross-docking of met behulp van pre-staging), het automatiseringsniveau, het aantal gangpaden, de afstand tussen laadpunten en het ontwerpen van kruisingen op een ander niveau, zijn de geprefereerde ontwerpkeuzes gevonden met betrekking tot veiligheid. Het is aangetoond dat, wanneer er in een vroeg stadium rekening wordt gehouden met veiligheid, het ontwerp wordt beïnvloed in de richting van:

- Kleine brouwerijen zouden pre-staging gebruiken;
- Middelgrote brouwerijen zouden ofwel cross-docking ofwel pre-staging gebruiken;
- Grote brouwerijen zouden ofwel rechtstreeks vanuit het magazijn laden ofwel pre-staging gebruiken;
- Transport- en laadvoertuigen met een hoger (gecombineerd) automatiseringsniveau zouden worden gebruikt;
- Het gebruik van vorkheftrucks zou worden geëlimineerd;
- De laadpunten zouden gelijkmatig worden verdeeld over de breedte van het magazijn;
- Het aantal gangpaden zou worden verhoogd;
- Alle kruisingen tussen voetgangers en bewegende voertuigen zouden op een ander niveau worden ontworpen.

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1 Introduction

This chapter provides a general introduction for this thesis. In Section 1.1, general background information is given about Heineken and their view with respect to safety. In Section 1.2, the research motivation is discussed. The main research question and the relevant subquestions are provided in Section 1.3. Subsequently, the scope is described in Section 1.4. Finally, the report outline is presented in Section 1.5.

1.1. Background information Heineken

Heineken is a company that brews beer for the global market and operates in more than 70 countries worldwide, providing work for more than 85,000 employees [HEINEKEN, 2019]. Heineken's goal is to provide a safe work environment for all those employees and to make sure no accidents happen which result in injuries, or even in fatalities. For this reason, they put 'Safety First' as their number one company behaviour. However, it is not always possible to prevent all accidents from happening, despite the constant effort that is made to prevent them from happening.

In Section 1.1.1, an explanation is given on the way Heineken registers the accidents that have occurred as well as the classification method they use to indicate the severity of an accident. Subsequently, in Section 1.1.2, this data is analysed to give an idea in which areas of the brewery most accidents occur. Finally, the area on which this thesis will focus is discussed in Section 1.1.3.

1.1.1. Accident registration

Every time an accident occurs, a case has to be written in the Accident Reporting Investigation Software (ARISO), which is a database in which accidents are registered from all breweries worldwide. Amongst others, information is given about where the accident occurred, about the cause of the accident and about the severity of the accident. The severity of the accidents is subdivided into five categories, which are presented in Table 1.1.

Table 1.1: Description of the subdivision of the severity of accidents.

Severity of accident	Description
Near miss	An accident that did not happen, but could have potentially resulted in a serious injury or death.
Incident	Injury but no lost days.
Minor accident	1 to 3 lost days.
Serious accident	More than 3 lost days.
Fatal accident	Accidents with a fatal result.

1.1.2. Accident distribution within the brewery

To see in which specific area in the brewery most accidents have occurred, data from the ARISO database is analysed from July 2013 (first registered accident) up to September 2019 (moment of analysis). It was found that a big part of the accidents occur off site, which include accidents on the public road or in the last mile to the customer. As these processes are outsourced to third parties, these will not be considered in this thesis. Also the accidents stated under ”Other” will not be considered, as these can apply to any location and are therefore not specific enough.

The remaining data is categorised into six overarching areas, which are packaging, warehouse, brewing, on site - outside, on site - inside office buildings, and utilities. In Table 1.2, an overview is presented of the percentage of the total number of accidents occurring in different areas (second column). The percentages corresponding to the top four show similar results. However, when the accidents are subdivided into accidents with a low severity (near misses and incidents) and accidents with a high severity (minor accidents, serious accidents and fatal accidents), presented in the third and fourth column respectively, the percentages differ significantly between the various areas. It can be seen that a substantial percentage of the high severity accidents occur in the warehousing area.

Table 1.2: Subdivision of the number of accidents that occur in the various areas. The second column shows the percentage concerning all accidents, the third column shows the percentage concerning the accidents with a low severity (near misses and incidents), and the fourth column shows the percentage concerning the accidents with a high severity (minor accidents, serious accidents and fatal accidents).

Area	Percentage of total number of accidents	Percentage of low severity accidents	Percentage of high severity accidents
Packaging	24%	25%	15%
Warehouse	24%	23%	43%
Brewing	20%	20%	14%
On site - outside	18%	18%	19%
On site - inside office buildings	9%	9%	7%
Utilities	5%	5%	3%

The warehousing area can subsequently be subdivided into two parts, which are the picking area and the loading area. The picking area is the part of the warehouse where the actual goods are brought to be stored to wait for transportation (see Figure 1.1a). The loading area is the area where the goods will be loaded onto, for example trucks, to be transported further to the customers (see Figure 1.1b). When looking to the number of accidents that occur in the respective areas, the number of accidents follows to be higher in the loading area.

(a) Warehouse picking area [Ancra Systems BV, 2012].

(b) Warehouse loading area [Europe Real Estate, 2015].

Figure 1.1: The warehouse can be subdivided into two main parts, the picking area (a) and the loading area (b).

1.1.3. Focus area of this research

Hudock et al. [1998] also emphasise the need for receiving and shipping docks to be operated in a safe way to be able to meet the customer requirements, but that these areas are usually neglected. Therefore, the main focus within this thesis will be on improving safety in the loading area. However, the loading area and picking area cannot fully be seen separate from each other as a lot of transport that needs to bring the goods to the trucks comes from the picking area. Therefore, the direct transport from the picking of goods to the trucks is included as well.

1.2. Research motivation

According to Zakaria et al. [2012], the design is one of the crucial parts in avoiding accidents in the workplace. An effective design and layout of a workplace can eliminate some hazards and help to get a job done safely and properly. When the design and layout of the workplace are done inadequately, this can frequently contribute to accidents by hiding hazards that cause injuries. Additionally, Booth [1979] indicates that the prevention of workplace transport accidents in the design phase of the workplace is not difficult, but once a dangerous layout is created it is much more difficult to correct. It is therefore imperative that more attention is paid to the design stage within the working environment.

In literature, the conceptual design phase is seen as the most crucial phase. Pahl and Beitz [1996] describe conceptual design as that part of the design process in which the basic solution path is laid down through the elaboration of a solution principle. According to them, conceptual design determines the principle of a solution. Hsu and Liu [2000] found that decisions made during conceptual design have significant influence on the cost, performance, reliability, safety and environmental impact of a product. They estimated that design decisions account for more than 75% of the final product costs. This is emphasised by Dieter and Schmidt [2009], who looked into the percentage of costs that are committed and incurred in different design phases: “Decisions made in the design process cost very little in terms of the overall product cost but have a major effect on the cost of the product”. The relation of the committed costs in different design phases, as presented in Figure 1.2, shows that it is important to make substantiated choices in an early design phase.

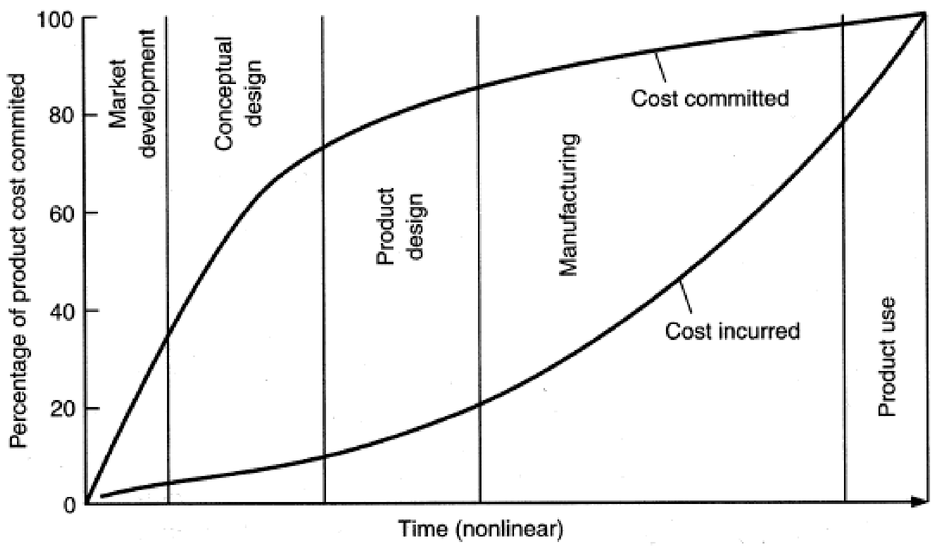


Figure 1.2: The relation between committed costs and incurred costs in different design phases [Dieter and Schmidt, 2009].

According to Wang et al. [2002], conceptual design is perhaps the most crucial task in an engineering development cycle, but it is also very difficult to accomplish. The impact of design decisions is initially very high, but there is not much information available to base decisions on. The impact that one can have declines steeply as the design matures, but the knowledge (or tools) that are available rises, as presented in Figure 1.3. In the beginning of a design process there is great opportunity. The concept generated at this stage affects the basic shape and material selection. In subsequent phases, it becomes very difficult to compensate the shortcomings of a poor design concept that has been formulated in an early phase.

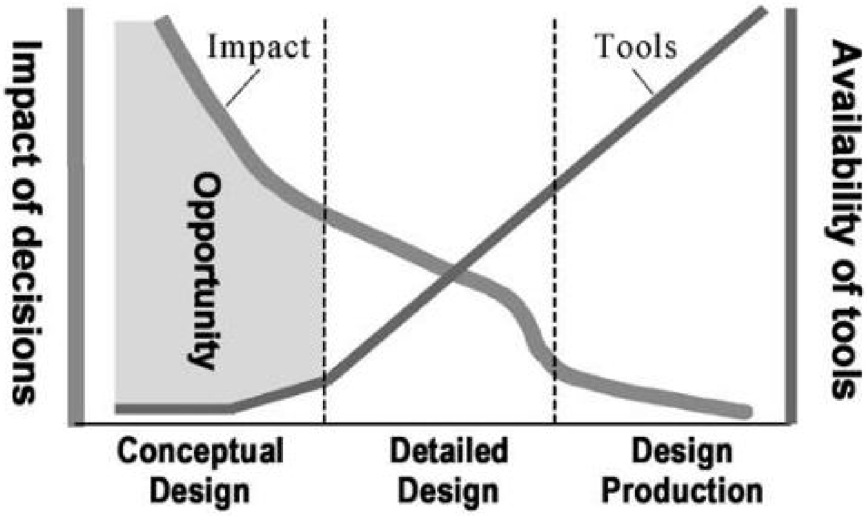


Figure 1.3: Relation between the impact of decisions and the availability of tools in different design phases [Wang et al., 2002].

The findings from the above described literature show that it is important to make good design decisions in an early design phase. Zakaria et al. [2012] and Booth [1979] especially emphasise the importance of a good design to avoid accidents. However, in the early design process of Heineken a lot of decisions are based on experience, rules of thumb and standards. They do not have a method in place to evaluate the actual impact a design has, in this case on the level of safety. Instead, the designs are heavily influenced by ones preference and personal experience, but do not necessarily have to result in the most optimal designs. For example, the person designing might be lacking some of the knowledge due to which a more suitable solution for a specific case is not found. As said by Stone et al. [2002]: "If the designer is experienced or works with experienced engineers, they could draw on their own knowledge or on the experience of others. However, relying only on knowledge gained from one's own past experiences limits the design possibilities and biases the design process".

Furthermore, the designs are largely made manually at the moment. A disadvantage of this is that designs are not easily adjustable in a later phase and therefore lack flexibility. The preference of designing manually is not unique though. Borg et al. [2003] and Lim et al. [2004] found that designers prefer freehand paper-based sketches during the early design phase, despite the availability of Computer-Aided Design (CAD) technology. Rigid user-interfaces, like CAD, are found to hinder freedom, intuitiveness and creative idea generation, and are therefore not suitable for the generation of various concepts [Naya et al., 2002, Roemer et al., 2001]. According to Balzan et al. [2008], designers need appropriate tools which integrate paper-based sketching with CAD, which would create the possibility to create a form concept which can subsequently be edited to explore form variation. They state that this design collaboration can only be effectively established if the generated model is a parametric model containing the geometric design intent of the designer. In this way, variations can be applied to the model while maintaining the unvaried geometric design intent.

The goal of this thesis is to develop a parametric model which enables the easy generation of design concepts and which creates the possibility to evaluate the impact of specific design decisions on the performance of a warehouse loading area, especially with respect to safety. The influence that the aspect of safety might have on design decisions will be shown by comparing different scenarios.

1.3. Research questions

The aim of this research is to evaluate the influence of safety regarding design decisions in the warehouse loading area. The research question that will be answered in this research is therefore:

What is the influence of safety on design decisions regarding the warehouse loading area?

In order to answer the main research question, the following sub questions are defined:

- *How is safety defined and how can it be quantified?*
- *Which hazards occur in the warehouse loading area and how can they be prevented?*
- *What are the design requirements and parameters that determine the design of a warehouse loading area?*
- *How can the risk level of different design choices be calculated using a parametric model?*
- *What is the impact of different design choices regarding the warehouse loading area on the risk level?*

1.4. Research scope

The focus in this research is to improve safety in the warehouse loading area, as explained in Section 1.1.3. Because the loading process begins with picking goods from the warehouse, it was decided to include the picking process from the warehouse to the loading area as well.

When looking more specifically at the types of accidents that have occurred in the warehouse loading area, it can be seen that 15 accident categories can be distinguished, as presented in Table 1.3 (retrieved from the ARISO database). The relative percentages of their occurrence are given in the second column. Some type of accidents rarely occur in the warehouse loading area, like exposure to blood or injured by an animal. On the other hand, accidents like struck by a falling object or by a moving vehicle make up a high percentage of the total amount of accidents that take place.

Table 1.3: Overview of the type of accidents that have happened in the loading area with their respective relative percentages.

Cause of accident	All accidents	Low severity accidents	High severity accidents
Struck by falling object or trapped by overturning material	40%	43%	20%
Struck by moving vehicle or striking against object	23%	24%	21%
Injured while lifting or handling	14%	11%	37%
Slip, trip, fall same level	12%	12%	12%
Falls from height	4%	4%	6%
Contact with machinery / use of equipment / use of handtool	2%	2%	3%
Exposed to fire / explosion/smoke	1%	1%	0%
Equipment failure	1%	1%	0%
Exposed to extreme temperatures or a hot liquid / gas / surface	1%	1%	0%
Contact with electricity / electrical discharge	0%	0%	0%
Physical assault, acts of violence (by colleague or third party)	0%	0%	0%
Alcohol abuse	0%	0%	0%
Drowned or asphyxiated	0%	0%	0%
Injured by an animal	0%	0%	0%
Exposure to blood	0%	0%	0%

When a distinction is made between low severity accidents and high severity accidents (the third and fourth column, respectively), it follows that the top three types of accidents each account for more than 20% of the accidents. Together they account for 78% of the high severity accidents. Therefore, to limit the scope of this thesis, the focus on reducing the number of accidents is restricted to these three accident categories.

1.5. Report outline

This thesis is made up of three main parts. Within Part I, the literature and methodology are described. The way safety can be defined and quantified, and the hazards and possible prevention methods are discussed in Chapter 2. In Chapter 3, literature to investigate all relevant design requirements and parameters regarding the warehouse loading area is evaluated. In Part II, the development of the parametric model is described (Chapter 4) and subsequently verified to see whether the model works as expected (Chapter 5). In Part III, the model is used to evaluate various design choices. In Chapter 6, various scenarios are discussed in which typical design choices for the warehouse loading area are evaluated and compared. Because the results show a shortcoming of the method that is used, an alternative method is proposed in Chapter 7. Finally, a discussion and conclusion can be found in Chapters 8 and 9, respectively. An overview of the structure of this report can be found on the next page. It is also indicated where in the report which subquestion is answered.

Introduction

Chapter 1:
Introduction

Research question:
What is the influence of safety on design decisions regarding the warehouse loading area?

Part I: Literature and Methodology

Chapter 2:
Evaluation of Safety

Chapter 3:
Preliminary Model

Sub-questions 1 and 2:
How is safety defined and how can it be quantified?
and
Which hazards occur in the warehouse loading area and how can they be prevented?

Sub-question 3:
What are the design requirements and parameters that determine the design of a warehouse loading area?

Part II: The Model

Chapter 4:
Development of the Model

Chapter 5:
Verification Model

Sub-question 4:
How can the risk level of different design choices be calculated using a parametric model?

Part III: Findings

Chapter 6:
Scenarios and Results

Chapter 7:
Alternative Frequency Scoring System

Sub question 5:
What is the impact of different design choices regarding the warehouse loading area on the risk level?

Discussion and Conclusion

Chapter 8:
Discussion

Chapter 9:
Conclusion

Part I

Literature and Methodology

2

Evaluation of Safety

The goal of this thesis is to include the possibility to evaluate safety for different design choices for the warehouse loading area. But what exactly is safety? And maybe even more important; how can safety be quantified in order to compare different designs? In this chapter, answers are provided to these questions. First, a definition of safety is given in Section 2.1. In Section 2.2, the 'prevention through design'-methodology is explained, which is a systematic approach to evaluate safety. In the remaining sections of the chapter, the different steps of this design methodology are covered. This chapter provides an answer to the first two subquestions: *How is safety defined and how can it be quantified?* and *Which hazards occur in the warehouse loading area and how can they be prevented?*

2.1. Definition of safety

Within Heineken, safety is measured by looking at the probability that a situation can result in an accident. If a specific situation can potentially result in an accident, the situation is considered unsafe. Similarly, De Koster et al. [2011] describe safety performance as the extent to which companies are able to prevent accidents and errors. So to increase safety, the chance that an accident can happen should be reduced.

2.2. Prevention through design methodology

The American Society of Safety Professionals have developed a standard which provides specific guidelines for addressing occupational hazards and risks in design and redesign processes, which is the ANSI/ASSE Z590.3-2011 standard. This standard provides a systematic way to assess risks using the prevention through design methodology. In Figure 2.1, an overview of this methodology is presented (retrieved from [Lyon et al., 2016]). In this research, steps 1 to 5 are covered.

The first step involves data gathering and scope definition. Within this thesis, the data gathering relates to the available data in the ARISO database of Heineken, which was presented in the introduction already. Similarly, the scope has been defined in Section 1.4, in which it was described that the top three most occurring accidents in the warehouse loading area will be evaluated.

Subsequently, the second step concerns the identification of the specific tasks and hazards that can possibly result in an accident. Reniers et al. [2005] describe a hazard as "any unsafe condition or potential source of an undesirable event with potential for harm or damage". In this step, the hazards that can possibly cause one of the top three most occurring accidents will be identified. This identification is described in Section 2.3.

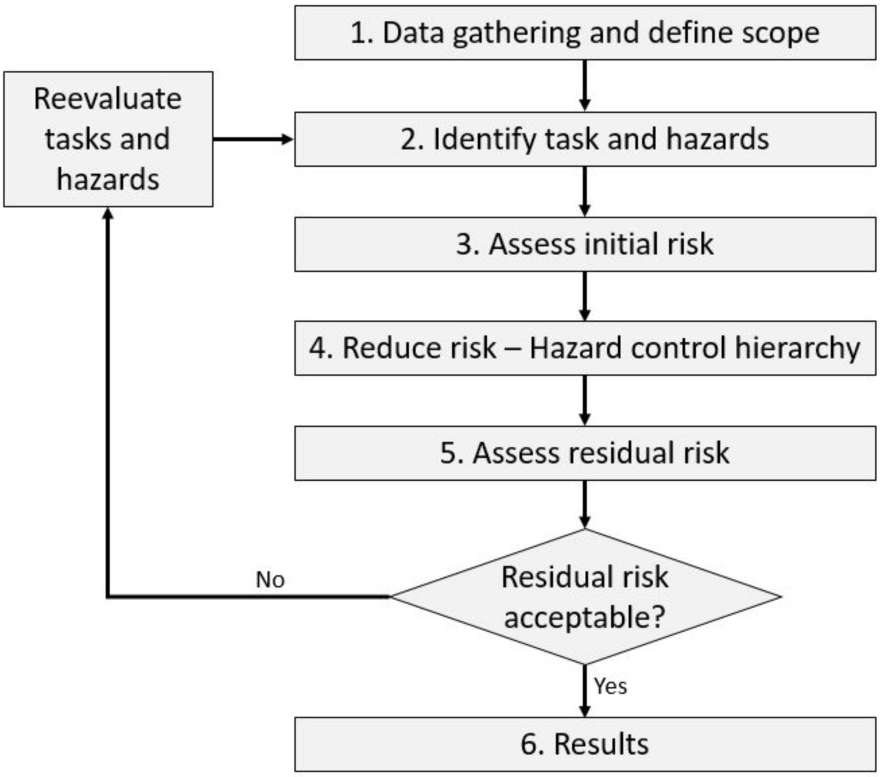


Figure 2.1: Hazard analysis and risk assessment process, based on the ANSI/ASSE Z590.3-2011 standard.

The risk corresponding to those hazards is determined for the initial situation in step 3. The methodology by which this risk can be determined, is explained in Section 2.4. The actual calculation of the risk is executed by the model, on which more is explained in Part II.

Next, solutions to reduce the risk are evaluated, which will follow the hazard control hierarchy. This is a methodology to systematically find solutions that will reduce the risk of a certain activity to result in an accident. More information on this hierarchy of controls is given in Section 2.5. Additionally, possible solutions are provided which can reduce the chance that the hazards, as described in Section 2.3, result in an accident.

Finally, step 5 concerns the assessment of the residual risk, in which the impact that the proposed solutions have on the risk level are evaluated, to see whether the situation indeed improved. The methodology on how this residual risk is assessed, is explained in Section 2.6. Similar to the assessment of the initial risk, the actual calculation is executed by the model.

2.3. Identify hazards

In this section, a more in depth analysis is conducted to find the hazards that can possibly result in one of the top three type of accidents in the warehouse loading area. This analysis is called a hazard identification, which is an attempt to discover, recognise and estimate the danger in a system, such as a workplace [Arimbi et al., 2019]. In the following sections, the top three most occurring accidents in the warehouse loading area are analysed. The order starting with the accident category with the highest percentage of high severity accidents is followed, which is:

1. Injured while lifting or handling;
2. Struck by moving vehicle or striking against object;
3. Struck by falling object or trapped by overturning material.

2.3.1. Injured while lifting or handling

In the warehouse loading area injuries due to lifting and handling mainly happen during the loading process, when people manually load the goods into trucks. With manual loading, a forklift truck (FLT) usually brings the pallet with stacked goods close to the truck from where workers subsequently load the goods into the truck. During this task, most injuries are caused due to the lifting of heavy loads or carrying the loads in a wrong way. Most injuries concern pain in the (lower) back, but also getting stuck between two packages or a cut finger are mentioned as causes. These latter ones happen due to breaking bottles while carrying them. Heineken is not the only company where these type of accidents occur. In the last ten years, comprehensive literature overviews concerning health risks due to lifting, especially low back pain, have been published [Kuijer et al., 2014, Lötters et al., 2003, Wai et al., 2010].

To summarise, the most common hazards that might cause injuries due to manual lifting or handling of goods are found to be:

- Carrying heavy goods resulting in back pain;
- Breaking bottles resulting in cuts in, for example, a finger;
- Getting stuck between two packages resulting in, for example, hurting a hand.

2.3.2. Struck by moving vehicle or striking against object

The hazards that might result in an accident in the category struck by moving vehicle or striking against an object are all concerned with a type of moving vehicle, either an FLT or a truck. These concern the collisions of a moving vehicle with another moving vehicle, a worker/pedestrian, or a stationary object. A moving vehicle colliding with another moving vehicle or a stationary object usually does not result in high severity accidents, but more in damages to the vehicle. A collision with a worker on the other hand usually results in a high severity accident. The worker is very vulnerable compared to the moving vehicle and it is therefore likely that the worker gets a bad injury.

In the case of Heineken, collisions between moving vehicles and a worker are to a lesser extent caused by a collision of a truck with a worker, but mainly due to a collision of an FLT with a worker. Miller [1988] found that a worker getting struck by an FLT is one of the two major causes of FLT accidents. Also collisions between an FLT and the truck driver commonly occur. Reiman et al. [2018] looked into the specific risks that truck drivers encounter when they have to leave their cabin to, for example, perform tasks like inspection and maintaining of equipment, load and unload cargo or do paperwork. When the truck driver is outside the cabin he/she exposes him-/herself to the potential dangers that are present at a loading area. These can, for example, include being close to an FLT or to other workers loading goods. Additionally, the truck driver is usually responsible for his/her own paperwork, which he/she usually does while the truck is being loaded. At a lot of breweries, there are no clear pedestrian paths for these type of activities. This causes a danger for the truck driver as he/she has to walk through the area where trucks are arriving and departing, and where FLTs are operating.

To summarise, the hazards that fall in the category struck by moving vehicle or striking against object are:

- FLT colliding with worker;
- Truck colliding with worker;
- FLT colliding with truck driver;
- Truck colliding with (other) truck driver;
- FLT colliding with other FLT;
- FLT colliding with truck;
- Truck colliding with other truck;
- FLT striking against object.

2.3.3. Struck by falling object or trapped by overturning material

This type of accident has the highest share of the total number of accidents, and it also has a high share in the high severity accidents. These accidents happen, for example, when an employee gets hit by an object that is not stacked correctly and therefore collapses on top of him/her. It can also happen that an object falls from an FLT onto a worker. Load dropping of an FLT or being shoved onto a worker was found by Miller [1988] to be the second major cause of FLT accidents, besides getting struck by an FLT. Similarly, Ellis [2003] found that struck by object falling from a vehicle is one of the most common types of accidents. Another cause that was highlighted by Miller [1988] were drivers driving off the loading dock. This could result in the danger that he/she gets stuck between the FLT and the wall or floor or that the FLT falls on top of a nearby working person.

To summarise, the hazards that fall in the category struck by falling object or trapped by overturning material are:

- Load falling from FLT onto worker;
- FLT falling off loading dock;
- Goods falling down due to improper stacking.

2.3.4. Overview of the hazards

Some accidents, like a collision between an FLT and a worker, can happen at multiple locations in the warehouse loading area. Other accidents, like falling off a loading dock, only occur in a specific location. To clearly show where the accidents usually occur, the loading area is divided into five smaller areas. In Figure 2.2, a schematic overview is presented of those five areas together with the hazards that can occur in each of the areas. A short description defining the different areas is:

- Picking up goods: the area where the goods are picked up from the storage.
- Transporting goods - inside: the area between the storage area and the doors to outside.
- Transporting goods - through the doors: the moment the goods are transported through the doors to outside.
- Loading process: the area where goods are loaded into the trucks.
- Truck area: the area where trucks arrive or depart.

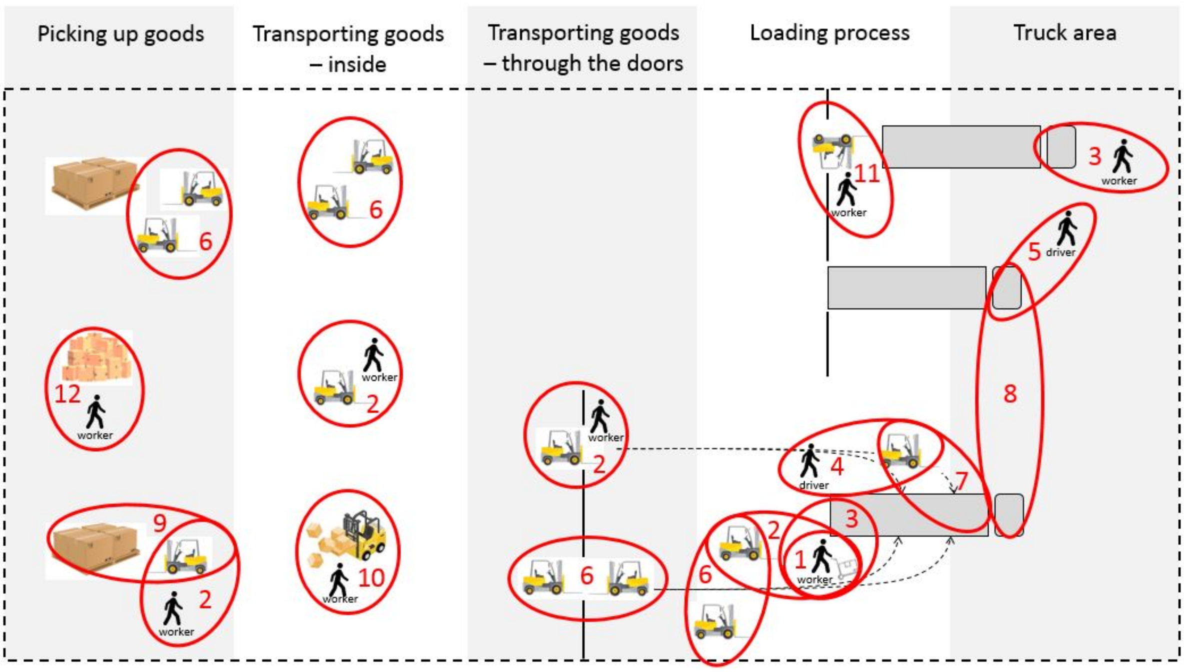


Figure 2.2: A schematic overview of the hazards possibly causing a top three type of accident.

All hazards, as described in the previous sections, are schematically shown in Figure 2.2. The respective numbers represent the following hazard:

1. Injuries due to manual loading of goods (including carrying heavy goods, breaking bottles and getting stuck between two packages).
2. FLT colliding with worker.
3. Truck colliding with worker.
4. FLT colliding with truck driver.
5. Truck colliding with (other) truck driver.
6. FLT colliding with other FLT.
7. FLT colliding with truck.
8. Truck colliding with other truck.
9. FLT striking against object.
10. Load falling from FLT onto worker.
11. FLT falling off loading dock.
12. Goods falling down due to improper stacking.

2.4. Risk assessment

In the previous section, the hazards that might result in an accident have been identified as possible dangerous situations. But how dangerous is dangerous? According to Lyon et al. [2016], the risk assessment methodology provides "a method to categorise combinations of probability of occurrence and severity of harm, thus establishing risk levels". This method enables safety to be quantified by calculating the risk level. In this way it provides the possibility to compare the risk levels of different situations.

According to the methodology, a risk matrix can be used as tool to show the risk based on the relation between the impact of an accident and the likelihood that a certain accident occurs. In literature, different classifications are used to describe the impact and likelihood of an accident [Arimbi et al., 2019, Azadeh-Fard et al., 2015, Marhavilas et al., 2011]. They adapt the risk matrix to a form that is suitable for them. As this research focuses on Heineken, the risk matrix that is used by Heineken is presented in Figure 2.3. In this matrix, a low risk level (the green boxes) is considered acceptable. When there is a medium risk (the orange boxes) corrective actions are needed, but no immediate actions are required. In case a high risk or major risk (the red and dark red boxes) is identified, immediate action shall be taken and corrective actions must be conducted. These actions may not lead to new hazards or increase the risk level of other already existing hazards.

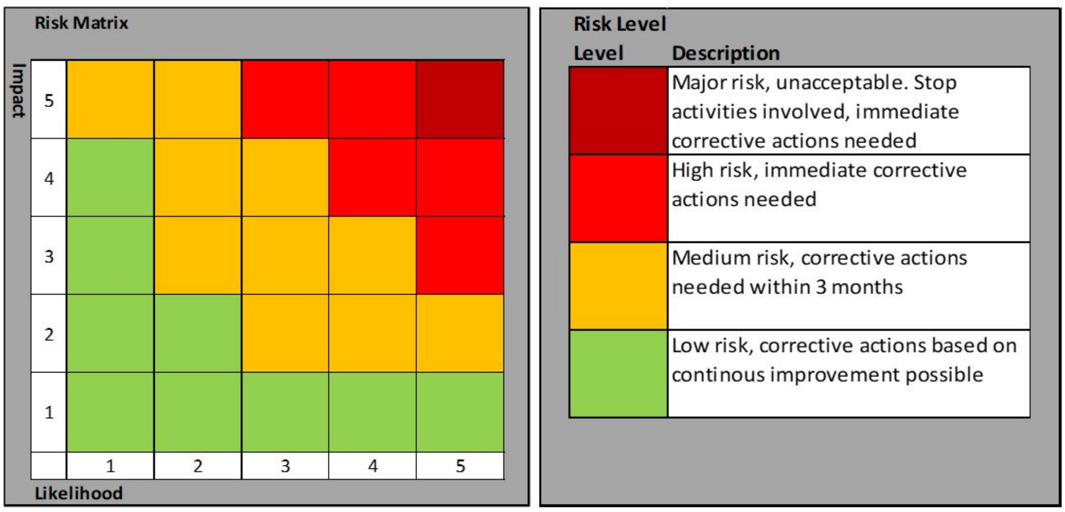


Figure 2.3: Risk matrix used within Heineken.

The above risk matrix can be translated into a risk level, according to formula 2.1 [Lyon et al., 2016]. In this formula, the risk level is calculated by multiplying the impact of an accident with the likelihood that an accidents occurs.

$$Risk\ level = Impact * Likelihood \tag{2.1}$$

Heineken uses a small variation on the formula of Lyon et al., as they describe the likelihood based on two other parameters, which are the frequency and the probability (see Formula 2.2). The frequency indicates the number of times a specific activity is performed. This can, for example, indicate that the activity is performed several times per shift, or only once per year. The probability describes the chance that this activity actually results in an accident.

$$Risk\ level = Impact * Frequency * Probability \tag{2.2}$$

The result of the risk assessment is a prioritised list of hazards [Popov et al., 2016], which ensures that the most serious hazards are identified first. In the method of Lyon et al. [2016] a similar score is given to both the impact and the likelihood (both from 1 to 5). However, they argue that a more conservative approach is desired to make sure that an accident with a very high impact is not scored lower than an accident with a low impact that occurs a lot. Within Heineken, a distinction is already made between the scoring systems for the different parameters. They use a more weighty score for impact than they use for frequency and probability. This results in the fact that the combination of an accident with a high impact, but a low probability results in a higher risk level than when all parameters would be rated equally. This is important as no accidents with a potential high risk are desired at all. This more conservative approach is in line with the advise of Lyon et al. [2016] and will therefore be used in this research. The ways the three parameters impact, frequency and probability are scored, are explained in Sections 2.4.1, 2.4.2 and 2.4.3, respectively.

2.4.1. Quantification of the impact of an accident

The impact of an accident is scored from 0.1 to 20, depending on the consequence of the accident. In Table 2.1, an overview is given of what type of accident corresponds to what impact number. In the first column the score is presented and in the second column a more extensive explanation is provided on the possible consequences that an accident can have.

Table 2.1: Definition of the score for the impact of accidents, as used by Heineken.

Score	Impact of accident
20	(Multiple) fatality, severe permanent effects on blindness, major amputation, paralysis.
15	Severe permanent effects as finger amputation, burn, multiple fractures.
10	Minor or serious but not permanent effects as broken bones, severe cuts.
5	Minor effects as small cuts, minor burns, bruises.
0.1	Negligible effects or no injury at all.

2.4.2. Quantification of the frequency of an activity

The frequency of an activity can be scored from 1 to 5, dependent on the number of times an activity is performed in a certain period of time. This can, for example, be an FLT that drives up and down to get goods to load a truck. If the FLT drives up and down a lot, the frequency would be high in this case. In the first column of Table 2.2 the scores are shown and in the second column an explanation is given on the respective number of times a specific type of activity is performed.

Table 2.2: Definition of the score for the frequency of an activity, as used by Heineken.

Score	Frequency of activity
5	Activity performed several times per shift.
4	Activity performed 1 - 3 times per day.
3	Activity performed 1 - 3 times per week.
2	Activity performed 1 - 3 times per month.
1	Activity performed 1 - 3 times per year.

2.4.3. Quantification of the probability of an accident

In Table 2.3, an overview is given of the score corresponding to the probability that a certain activity results in an accident. This score represents the fact that not all activities necessarily result in an accident. For example, a lot of FLTs driving around do not necessarily all collide, but a small number may. This is represented by the probability number, which is scored from 0.1 to 4.

Table 2.3: Definition of the score for the probability that an activity can result in an accident, as used by Heineken.

Score	Probability that activity results in an accident
4	Accident happens frequently.
3	Accident happens sometimes.
2	Event happened at least once in the past.
1	We don't know if the event happened in the past, we cannot exclude it.
0.1	It is not possible or hard to believe that this event can happen.

2.4.4. Acceptable range of risk level

As a different quantification is used to score the impact, frequency and probability than the 1 to 5 scoring system used the matrix (Figure 2.3), different values for which risk is seen as acceptable result. These are presented in Table 2.4.

Table 2.4: Range for which the risk level is assumed acceptable or whether actions are required, as used by Heineken.

Risk level	Required action
<35	Acceptable risk, situation can be kept as it is.
35-74	Marginal risk, attention required and countermeasures to be planned with lower priority.
75-119	Significant risk, countermeasures to be planned as soon as possible.
120-200	Very high risk, urgent action, countermeasures to be planned as soon as possible, consider to stop activity.
>200	Unacceptable risk, stop activity, restart only when effective countermeasures have been implemented.

2.5. Reducing risk

To reduce the risk level, the impact, frequency and/or probability should be reduced. The impact will not really change as an FLT hitting a worker always has the same impact. Therefore, the focus will be on reducing the frequency of the activity and/or the probability that this activity might result in an accident.

The frequency of an activity can be reduced by decreasing the number of times an activity needs to be performed. If, for example, an FLT can transport two pallets at a time instead of only one pallet, the number of times an FLT needs to drive up and down is divided by two. The probability that an activity results in an accident depends on the chance that this activity actually interferes with another activity. For example, if only one FLT is operating in an area, there is no chance for a collision with another FLT, whereas multiple FLTs operating in the same area do have a chance of colliding with each other.

Following the prevention through design methodology, possible solutions have to follow the hierarchy of controls, which is a means of determining how to implement feasible and effective control solutions [NIOSH, 2015]. More on this hierarchy of controls is explained in Section 2.5.1. Possible solutions on how to reduce the frequency and the probability are provided in Sections 2.5.2 up to 2.5.4.

2.5.1. Hierarchy of controls

A representation of the hierarchy of controls, as retrieved from the National Institute for Occupational Safety and Health [NIOSH, 2015], is shown in Figure 2.4. The idea behind the hierarchy is that the control methods at the top of the graphic are potentially more effective than those at the bottom. Elimination and substitution, so physically removing the hazard or replacing the hazard with something less dangerous, are the most effective methods to reduce hazards. In an existing process, these are the most difficult ones to implement. However, when they are considered in an early design phase, they may be inexpensive and simple to implement and subsequently reduce the risk significantly.

The third layer concerns engineering controls, which is a method to remove the hazard at the source before it comes in contact with the worker. Well-designed engineering controls can be highly effective in protecting workers as they will be typically independent of worker interactions. Lastly, administrative controls and people protective equipment are used when hazards have not been controlled well in the design phase. These methods have been proven less effective as they require significant effort by the affected workers.

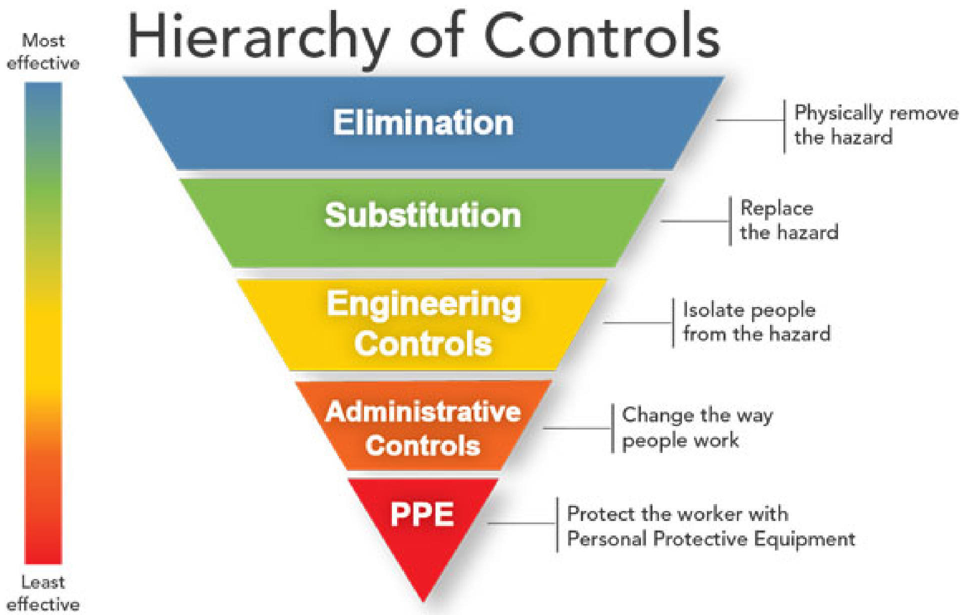


Figure 2.4: A representation of the hierarchy of controls, showing the effectiveness of various control methods [NIOSH, 2015].

In the following sections, possible solutions are discussed to reduce the frequency or the probability of a hazard, following the hierarchy of controls. In Sections 2.5.2, 2.5.3 and 2.5.4, possible elimination, substitution and engineering controls measures are described, respectively. As the design phase of the loading area is considered, the administrative controls and personal protective equipment will not be considered in this thesis as these are control measures that need to be taken if the design has not covered up for this.

2.5.2. Elimination

The most effective solution according to the hierarchy of controls is to eliminate the hazard, so to physically remove the hazard. When following the same sequence of the hazards as in Section 2.3.4, the first hazard to eliminate is the hazard caused by manual lifting and handling of goods. This type of hazard typically occurs during the (manual) loading process. Therefore, the elimination of this hazard can be achieved by eliminating the need to load manually. If the loading process can be done differently, due to which no manual loading is required anymore, injuries due to manual loading of goods cannot occur anymore.

The next eight hazards, number 2 up to 9 in Figure 2.2, all include a moving vehicle (FLT or truck). In the case of a truck, it is not possible to fully eliminate the truck as the truck is the common method to transport goods from the brewery to the customer and Heineken has no influence on this. When looking to the FLT, this is currently the most commonly used equipment within Heineken to execute transportation and/or loading operations. Although FLTs have many benefits, such as improving productivity and reducing manual handling, FLTs are seen as inherently high hazard vehicles [Larsson and Rechnitzer, 1994]. They especially cause occupational hazards when FLTs have a frequent interaction with pedestrians [Horberry et al., 2004]. Additionally, Williams and Priestley [1980] indicate that most of the seriously injured are pedestrians. These findings show that FLTs are a real danger for pedestrian workers when they work in close proximity to each other. The hazards resulting from FLTs can be solved in two ways, of which the first is by eliminating the FLT completely. However, the transportation of goods to the trucks should still be possible. Therefore, another method should replace the FLT to do this transportation task. More on possible substitution methods for the FLT is explained in the next section.

Instead of eliminating the moving vehicles, it is also possible to eliminate the possible crossings due to the moving vehicles. If no crossings can occur, no collisions can happen. For example, it can be an option to assign one FLT to every loading point. This FLT is only responsible to load the truck that comes to that loading point and does therefore not have to cross other FLTs' paths. The downside of this is that probably more FLTs are required.

Fully eliminating the movement of people from the area can also be a solution, considering both workers and truck drivers. If workers do not need to physically move in or through the area anymore, there is no chance of them getting hit. If the jobs performed by workers can be done in a different way, like automating processes, people can be eliminated. When looking to a truck driver, he/she is exposed to a couple of dangers because of the fact that he/she needs to do paperwork and needs to keep an eye on the loading process. Currently, they park their truck at the loading point, get out and walk to the point where their paperwork needs to be signed. To be able to get to the office, they need to cross the loading area by either having to walk between the trucks that arrive and depart or between the FLTs loading the trucks on the other side. Both have their respective dangers. If the paperwork can be done in a different way, due to which the truck driver does not need to get out of his/her cabin anymore, these crossings can be eliminated. A solution for this can be to do the paperwork digitally by using a QR-code, for example. The problem of truck drivers having to keep an eye on the loading process can be solved by providing a camera view on the loading process, which they can follow from within the cabin or maybe close to the cabin. They then do not have to stand near FLTs that are driving up and down to load the truck.

The hazard in which the FLT can possibly fall of the loading dock can be eliminated by removing the use of levelled loading docks. However, this causes the need for FLTs to drive through doors at the same level, due to which other hazards potentially arise. For example, an FLT can collide with another FLT or a worker because of not seeing them on the other side of the wall. It is therefore not necessarily better to remove a levelled loading dock. Additionally, Loading Dock Supply [2019] state that many of the risks associated with the use of loading docks can be alleviated when careful planning is done beforehand as common problems are often rooted in initial design elements.

The hazard concerning the improper stacking of goods can be eliminated by changing the stacking method. A first option is to only have one level of stacked goods. However, this will drastically increase the space that is required for the storage of goods. Another option is to use racks in which the goods can be stored. As the goods do not have to be positioned on top of each other directly, the chance of them collapsing decreases. A disadvantage of this is that additional height is required for a similar level of stacked goods, as there is now some empty space between the stacked goods.

Lastly, goods can fall off FLTs when they are not perfectly positioned. If the load is too heavy or the ballast of the truck is too light, the FLT may even tip forward [Lifschultz and Donoghue, 1994]. But even if the FLT is not tipping over, the load might be positioned in such a way that causes goods to fall off. If a more stable way of transportation is used, this hazard is eliminated. More information on the possible substitution of FLTs is provided in the next section.

2.5.3. Substitution

If fully eliminating the hazard is not an option, the second best option of risk reduction, according to the hierarchy of controls, is substitution. In this context substitution is the use of an alternative method to reach the same goal. For example, FLTs are most commonly used within Heineken but potentially very dangerous. But as the goods need to be moved from the storage area to the truck, transportation of those goods is inevitable and can therefore not be eliminated. However, the transportation of those goods can be done in a different way. Currently, new techniques are available to substitute FLTs. An example of these is a Lifting Guided Vehicle (LGV), of which a picture is shown in Figure 2.5a. According to White and Pence [2013], LGVs are becoming an important material handling tool in flexible manufacturing systems and they are able to replace FLTs. LGVs can take over the process of picking up goods, transporting them, and loading them into the truck. As these type of vehicles are able to operate in a fully autonomous way, people can be removed from the process. In this way, the crossings between workers and FLTs/LGVs are removed. The danger that remains is that LGVs might have to cross each others paths still. But as they can be in contact with each other, using e.g. sensors or via the server, they can see each other sooner and can avoid collisions [Bostelman et al., 2013]. Additionally, the danger of goods falling off an FLT due to a human error is taken away as LGVs move more smooth and also stop more fluently.

Another possibility to substitute the loading task executed by FLTs is the Automated Truck Loading System (ATLS), as developed by the Canadian equipment manufacturer Paco Corporation [Gobeil, 2003]. The ATLS is an automated alternative to FLTs to load finished products into regular semi-trailers without having to modify the semi-trailer. An example of such a system is shown in Figure 2.5b. The loading task that used to be done by FLTs is now taken over by the ATLS. This removes the variable movements of FLTs and makes sure they cannot collide with workers anymore or fall off a loading dock.

(a) LGV. Retrieved from [Conveyco, 2019]. (b) ATLS. Retrieved from [Ancra, 2019].

Figure 2.5: Examples of an LGV (left), and an ATLS (right).

The ATLS is also seen as the most effective way to prevent accidents resulting from the manual loading task [Smylie, 2019]. Reduced damage of goods and equipment due to controlled loading is a quantifiable benefit as well as creating a safer working environment for personnel, which generates employee satisfaction and retention. Similarly, the movement of goods from the storage could also be done using a conveyor system. This would substitute the transportation task executed by FLTs and remove the movements of FLTs from the area.

Instead of substituting the task with something different, it can also be evaluated to see how the frequency of an activity can be decreased. The higher the frequency of an activity, the higher the risk level is that a certain accident occurs. If a process can be changed in a way that the frequency of one or more activities can be reduced, the overall risk level will be reduced. The reason for FLTs to move through the area is to transport goods from the storage location to the loading location. If an FLT only has one fork, it has to drive up and down as many times as the number of pallets that need to go into the truck. If an FLT has two forks, the number of movements will be reduced by half, etc. So, in order to reduce the frequency of the FLT movements, single fork FLTs can be substituted by FLTs with a higher capacity. The same applies for LGVs.

2.5.4. Engineering controls

The last category from the hierarchy of controls that is considered in this research is the use of engineering controls. When it is not possible to eliminate the hazard or replace the hazard, it should be evaluated whether it is possible to implement engineering controls. To remove the danger of FLTs and pedestrians crossing each other, it is an option to arrange the crossing on a different level, as presented in Figure 2.6. In this way workers can safely cross the paths destined for FLTs.

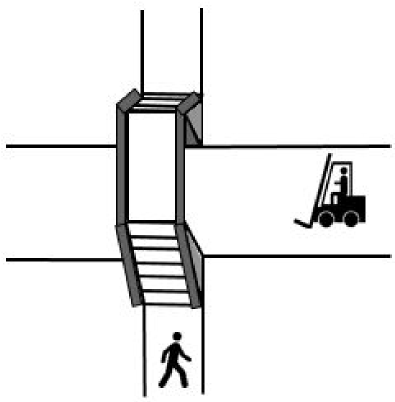
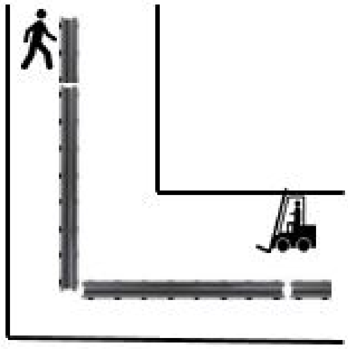
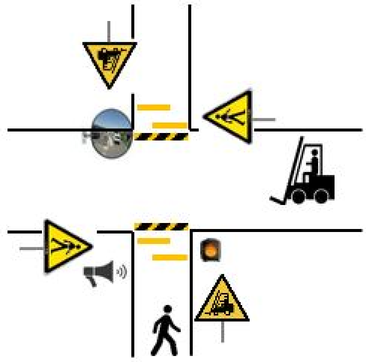


Figure 2.6: A crossing on a different level eliminates the chance of a collision between a worker and an FLT.

Another option to isolate people from FLTs and trucks can be realised by appointing dedicated FLT/truck driving lanes and pedestrian paths. It should be guaranteed that no vehicles can cross or enter the pedestrian walkways, and that no pedestrians have to enter the vehicle lanes. One option to isolate people from FLTs and/or trucks is to install a barrier between the path used by FLTs/trucks and the path used by workers. In this way, the paths of FLTs/trucks and workers can be positioned next to each other without having the danger of a collision, see Figure 2.7a. Another engineering control measure to prevent collisions from happening is to install a gate, as schematically presented in Figure 2.7b. This gate automatically closes if an FLT approaches due to which workers cannot enter the path of the FLT. If the FLT has passed, the gate opens and the worker is safe to cross.



(a) Schematic presentation of the use of a barrier.



(b) Schematic presentation of the use of a gate.

Figure 2.7: Examples of engineering controls. The use of a barrier (left) and the use of a gate (right).

2.6. Risk reduction assessment

In step 5 of the prevention through design methodology, the reduced risk should be assessed. All possible solutions that prevent a hazard from happening might change the frequency and/or probability of a specific hazard and result in a different risk level. This new risk level can subsequently be compared to the initial risk level. In this way, the difference in risk level between the initial and new situation can be assessed.

2.7. Overview Chapter 2

The first two subquestions *How is safety defined and how can it be quantified?* and *Which hazards occur in the warehouse loading area and how can they be prevented?* have now been answered. Safety has been described as the extent to which an accident can be prevented from happening. Using the risk level, which was a result of the multiplication of the possible consequences of an accident (the impact), the number of times an activity is expected to occur (the frequency) and the chance that this activity results in an accident (the probability), the level of safety of a certain hazard can be quantified.

Additionally, the hazards that correspond to the top three most occurring accidents in the warehouse loading area have been identified, which resulted in a total of twelve hazards. By following the hierarchy of controls, possible methods to prevent the hazards from resulting in an accident were found. Completely eliminating the hazard was the most effective method. However, when this is not possible, substitution of the hazard and the isolation of people from the hazard are also effective measures. By implementing the various prevention methods, a new risk level needs to be calculated. Subsequently, the change in risk level can be determined by comparing the new risk level to the initial risk level.

3 Preliminary Model

To be able to make a design of the warehouse loading area it must be known what type of design choices influence the design. Therefore, a design framework to systematically find the relevant design parameters and to set up a preliminary model is followed in this chapter. A general explanation of this framework is given in Section 3.1. In the remainder of the chapter, the different steps of the framework are discussed. This chapter will answer the third subquestion: *What are the design requirements and parameters that determine the design of a warehouse loading area?*.

3.1. Design framework

Over forty years ago, Heskett et al. [1973] already described the main aspects of warehouse design under three broad headings, which included determining the requirements, designing the material handling systems and developing the layout. The sequence of these three stages can be found in most of the subsequent literature. An extensive literature review on the proposed steps required in the design process of a warehouse has been conducted by Baker and Canessa [2009], who looked into available research done between 1973 and 2006. In their work, they both evaluated literature papers as well as information provided by warehouse design companies. By comparing the various design methodologies, Baker and Canessa developed an eleven step framework describing the required steps that need to be followed in the design process of a warehouse. These steps are:

1. Define system requirement.
2. Define and obtain data.
3. Analyse data.
4. Establish unit loads to be used.
5. Determine operating procedures and methods.
6. Consider possible equipment types and characteristics.
7. Calculate equipment capacities and quantities.
8. Define services and ancillary operations.
9. Prepare possible layouts.
10. Evaluate and assess.
11. Identify the preferred design.

In the remainder of this chapter, this framework is used to find the relevant requirements and parameters that determine the design of the warehouse loading area. As the model should enable the evaluation of designs for different breweries, the preliminary model described in this chapter is generic. No specific data or quantities are used yet, but the methods and/or calculations are provided by which the parameters will be determined. Steps 1 up to 9 are each individually discussed in the following sections. Steps 10 and 11, which concern the evaluation and assessment of the design, are examined using the parametric model and are therefore discussed at a later stage, in Part III.

3.2. Define system requirement

The system requirements are defined in the first step. According to Hassan [2002], the type and purpose of the warehouse should first be determined in order to provide designers with an initial conception of the expected levels of operations and requirements of the design. Therefore, the type and purpose of the warehouse are explained in Section 3.2.1 first. When these have been established, the requirements are discussed in Section 3.2.2.

3.2.1. Type and purpose of the warehouse

According to Rouwenhorst et al. [2000], specifying the type of the warehouse is important because relevant criteria vary for various types of warehouses. They distinguish between two types of warehouses, which are the distribution warehouse and the production warehouse. The function of a distribution warehouse is described as a warehouse that stores products and fulfils external customer orders, whereas the function of a production warehouse is described as a warehouse that stores raw materials, work-in-process and finished products associated with a manufacturing and/or assembly process. The warehouse of a Heineken brewery can be described as a production warehouse as it stores finished products that are associated with a manufacturing process. The purpose of this warehouse is to temporarily store finished products when there is no direct possibility to transport them further (to the customer).

Another distinction that can be made is whether single-command or dual-command operations are performed. Pohl et al. [2009] describe single-command operations as the operation in which workers travel from a pickup and deposit (P&D) point to a single location in the warehouse, where they store or retrieve a single pallet before returning. In a dual-command operation workers perform a storage operation and then continue directly to a retrieval location before returning to the P&D point. In the warehouse of Heineken pallets are typically stored and retrieved in a single trip. The respective picking operation therefore regards a single-command operation.

3.2.2. System requirements

The first system requirement concerns the capacity of the warehouse storage area and warehouse loading area. Regarding the storage area, there should be enough space to store the products. In the case of the loading area it is important that the number of loading points and transporters (e.g. FLTs) are sufficient to make sure the trucks can be loaded. These numbers need to be determined for the peak hour, as this is the critical hour.

Usually, a brewery makes an agreement with the respective truck companies to guarantee a certain service time for the truck. This service time has an influence on the number of loading points and transporters that is needed. To make sure the warehouse loading area can guarantee this service time, the time will be included in the model as a variable input. As these agreements can differ per country, it will be included as a variable input that can be adjusted for various breweries.

3.3. Define and obtain data

Step 2, defining and obtaining data, can be described as a forecast and analysis of the expected demand [Firth et al., 1988, Hassan, 2002, Hatton, 1990, Waters, 2003]. This includes the estimation of the demand, trends and changes in demand pattern and mix, and the volume of orders. This step is required for setting the capacity of the warehouse and preparing information which would be used in subsequent steps in determining inventory levels, equipment, and assignment of items to storage locations. Also the number of loading points depends on the expected demand as it needs to be possible to load sufficient trucks in order to transport all the products, possibly within a given service time, as explained in the previous section.

The first input for the model is the volume that the brewery needs to produce in order to meet the demand. This volume is defined in hectolitre per year, and is usually in the range of millions of hectolitres per year. If the demand is expected to change in the coming years, it is possible that a certain design is suitable at this moment in time, but not in the (near) future anymore. By taking the expected change in demand into account, this provides the chance to use this knowledge in an early phase to base decisions on. As Heineken currently experiences a shift from mass-produced beer to craft beer, which might have an influence on the transporting and loading operation, it is important to take this effect into account. The change in demand is going to be included in the model by providing the possibility to change the number of product types that are produced.

Additionally, the type of trucks that come to pick up the products need to be defined, which again varies per country. With respect to the design of the loading area it is required to know information about the amount of products a truck can take in order to determine the total amount of trucks that come to pick up goods. This influences the total number of loading doors that are required. Besides that, the dimensions of the biggest truck are critical for the dimensions of the loading area as the length of the biggest truck determines the area of the loading area and the width determines the required width of the loading doors. The height of the truck is relevant in case loading docks are used.

Lastly, products can be grouped with respect to their priority. This can have an advantage when storing the products in a warehouse using class-based storage, on which more is explained in Section 3.6. In inventory control, a classical way for dividing items into classes based on popularity is the Pareto's method [Koster et al., 2007]. Pareto Analysis is a statistical technique in decision-making, and the principle is named after the Italian economist Vilfredo Pareto, who observed that 80% of the income in Italy went to 20% of the population [Haughey, D., 2019]. The idea, as described by Koster et al. [2007], is to group products into classes in such a way that the fastest moving class contributes to about 80% of the turnover. Each class is then assigned to a dedicated area of the warehouse. The fastest moving items are usually called A-items, the next fastest moving category of products is called B-items, and so on. The number of classes is generally restricted to three. Within Heineken they use a similar approach of which the respective percentages of products that usually fall in a specific category are presented in Table 3.1.

Table 3.1: Subdivision of products in product classes A, B and C, based on Pareto's method.

Class	Percentage of products in a class
A	80%
B	15%
C	5%

3.4. Analyse data

Within this step, there are two important capacities that need to be determined, which are the capacities for the warehouse storage area and the warehouse loading area. To determine the required area for the storage of goods, it has to be decided what volume needs to be stored as this has an impact on the space requirements [Hassan, 2002]. Regarding the capacity of the loading area, the throughput in peak hour needs to be known, as explained in Section 3.2.2. The two calculation methods for the warehouse storage area and loading area are described in Sections 3.4.1 and 3.4.2, respectively.

3.4.1. Capacity storage area

The calculation method that is used in this thesis to determine the inventory level is derived from the calculation used by Heineken to make a first estimate of the required storage space. In this estimation, the expected volume that needs to be stored is dependent on the average sales per week, the average time a product is in stock and a seasonality factor (see Equation

3.1). The average sales per week is calculated using Equation 3.2, in which the average sales per year is divided by the number of weeks in a year. The average time a product is in stock depends on the product type and on the type of brewery. The seasonality factor varies per brewery and can be calculated using Equation 3.3, in which the average sales per month is calculated using Equation 3.4.

$$V_{in\ stock} = \sum^{p} (\overline{V}_{sales\ per\ week,\ p} * \overline{t}_{in\ stock,\ p}) * C_{seasonality} \tag{3.1}$$

In which:

$$\overline{V}_{sales\ per\ week,\ p} = \frac{V_{sales\ per\ year,\ p}}{52} \tag{3.2}$$

$$C_{seasonality} = \frac{V_{sales\ in\ peak\ month}}{\overline{V}_{sales\ per\ month}} \tag{3.3}$$

$$\overline{V}_{sales\ per\ month} = \frac{V_{sales\ per\ year}}{12} \tag{3.4}$$

Where:

$V_{in\ stock}$ = total volume of all product types that needs to be stored [in hL].
$V_{sales\ per\ year}$ = the total sales in a year [in hL].
$V_{sales\ per\ year,\ p}$ = the total sales of product p in a year [in hL].
$V_{sales\ in\ peak\ month}$ = the sales volume in the peak month [in hL].
$\overline{V}_{sales\ per\ month}$ = the average sales volume per month [in hL].
$\overline{V}_{sales\ per\ week,\ p}$ = the average sales of product p in a week [in hL].
$\overline{t}_{in\ stock,\ p}$ = the average number of weeks product p is in stock [in weeks].
$C_{seasonality}$ = the factor accounting for seasonality [-].

3.4.2. Capacity loading area

For the calculation of the required capacity of the loading area, like number of loading points and number of transporters, Heineken has learned from experience that this capacity should be calculated by multiplying the volume that needs to be transported in the peak hour by an additional peak factor. The calculation for the expected volume in peak hour is shown in Equation 3.5. From past experiences, Heineken has found that the constant factor to calculate the peak hour is 1.5.

$$V_{peak\ hour} = \frac{V_{sales\ per\ year} * C_{peak} * C_{seasonality}}{N_{days\ operating\ per\ year} * N_{hours\ operating\ per\ day}} \tag{3.5}$$

In which:

$$C_{seasonality} = \frac{V_{sales\ in\ peak\ month}}{\overline{V}_{sales\ per\ month}} \tag{3.6}$$

$$\overline{V}_{sales\ per\ month} = \frac{V_{sales\ per\ year}}{12} \tag{3.7}$$

Where:

$V_{peak\ hour}$ = volume in peak hour [in hL].
$V_{sales\ per\ year}$ = the total sales in a year [in hL].
$V_{sales\ in\ peak\ month}$ = the sales volume in the peak month [in hL].
$\overline{V}_{sales\ per\ month}$ = the average sales volume per month [in hL].
C_{peak} = the factor accounting for the peak demand [-].
$C_{seasonality}$ = the factor accounting for seasonality [-].
$N_{days\ operating\ per\ year}$ = the number of days per year a brewery is in operation [days].
$N_{hours\ operating\ per\ day}$ = the number of hours per day a brewery is in operation [hours].

3.5. Establish unit loads to be used

Different Heineken breweries make different products and use different packaging types, sometimes making up to 250 different product types. In the end they are all put together on pallets on which they are transported further. Therefore, the unit load in this case is pallets. The length and width of a pallet are 1 meter and 1.2 meter, respectively. The volume that fits on one pallet depends on the type of product. In this research, the volume per pallet is taken as an average of three common product types, which are presented in Table 3.2, and follows to be 7.5 hL/pallet.

Table 3.2: The average amount of hL that fit on one pallet for bottles, cans and kegs.

Product type	Volume on a pallet
Bottles	5.5 hL
Cans	9.0 hL
Kegs	8.0 hL

3.6. Determine operating procedures and methods

The operating procedures and methods are the high-level decisions that need to be made for each function of the warehouse. Decisions regarding the storage area (number of aisles, number of cross aisles, etc.) are discussed in Section 3.6.1. In Section 3.6.2, different ways on how to conduct the picking process are explained. Lastly, possible design decisions regarding the loading process are discussed in Section 3.6.3.

3.6.1. Storage area

The problem of arranging the storage area is called the internal layout problem or aisle configuration problem [Koster et al., 2007]. It concerns the determination of the number of blocks, and the number, length and width of aisles in each block of a picking area. A schematic overview of the typical layout decisions, as provided by Koster et al. [2007], is presented in Figure 3.1.

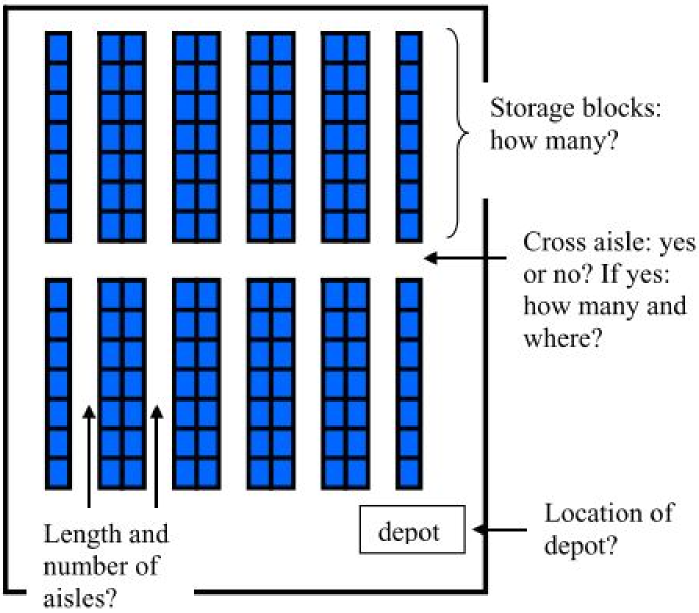
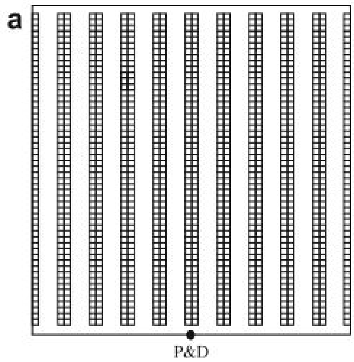


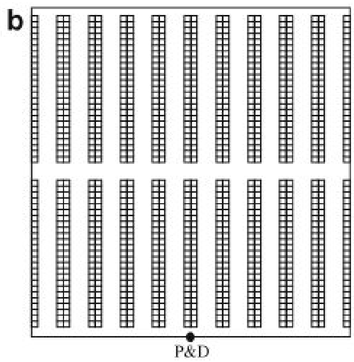
Figure 3.1: Typical layout decisions of a warehouse storage area, retrieved from [Koster et al., 2007].

Determining the number of aisles, their location, orientation, length, and width is an important step in designing a warehouse layout due to its impact on space requirements, operations, material handling, and storage assignment [Hassan, 2002]. These factors depend, amongst others, on the shape of the warehouse. For example, when a warehouse is wider with respect to its length, more but shorter aisles will be likely. In an early paper, Mayer Jr [1961] acknowledged that the optimal shape factor of a warehouse is a square when single-command travel is used and the dock door is located at a corner of the warehouse. In the case the dock door is centrally located, Pohl et al. [2009] has proven that the optimal shape factor of a warehouse with respect to single-command operations is that the warehouse wall containing dock doors should be twice as wide as the depth of the warehouse. This shape factor is often used as rule of thumb by warehouse managers [Tutam and White, 2019], and is also applied within Heineken.

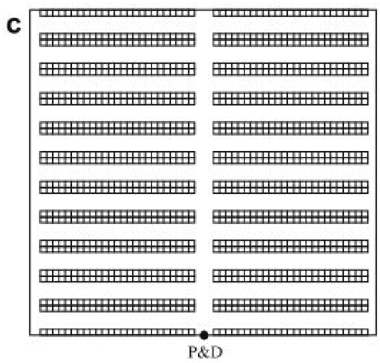
In the past years, many studies have been conducted to find the optimal design for the most efficient warehouse layout, of which more information is provided in Appendix B. These studies have all looked into the optimal layout in terms of efficiency, in which they optimised the layout in order to minimise the travel time that is needed to complete the picking process. However, the goal of this research is not to design the most optimal layout in terms of efficiency, but to evaluate the impact of a layout configuration on the risk level. Therefore, for the simplicity of the model that will be developed, the more simple layout configurations as presented in the figures below are evaluated.



(a) Layout A.



(b) Layout B.



(c) Layout C.

Figure 3.2: Three possible warehouse aisle layouts, retrieved from [Pohl et al., 2009].

When looking at these three layouts, Gue and Meller [2009] found that if single-command operations are concerned, which is the case for Heineken (as explained in Section 3.2), a traditional cross aisle confers no benefit when the layout configuration is like the configuration in Figures 3.2a and 3.2b. According to them it is easy to see why, as inserting a cross aisle moves approximately half of the locations farther away, and with that increases the corresponding travel distance to every location. Pohl et al. [2009] came to a similar conclusion with respect to these two configurations. However, they investigated an additional option in which the storage areas are rotated 90°, as presented in Figure 3.2c. It was found that this configuration, although least popular in practice, has an advantage in terms of single-command cycles provided that it is configured properly. However, when looking at the product flow within a Heineken brewery, this is typically a flow-through type of warehouse [Huertas et al., 2007], as shown in Figure 3.3. On the one side of the warehouse there are the packaging lines that produce the pallets, and on the other side there are the loading points where the trucks are loaded. As these packaging lines are distributed along the width of a warehouse, it is convenient to have the layout configuration from Figure 3.2a, as there are more points to enter the storage area. Therefore, this configuration will be used to evaluate the impact of different design decisions.

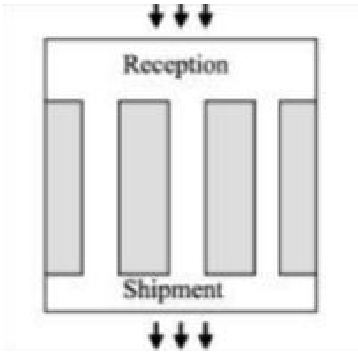


Figure 3.3: Schematic representation of the flow-through configuration, where goods enter the warehouse from one side and are shipped from the other side, retrieved from [Huertas et al., 2007].

Another important decision to make for the storage area concerns the class-based storage of different product groups, of which the concept was explained in Section 3.3. Different ways of class-based storage are explained in Appendix B. As the warehouse of Heineken is a flow-through warehouse, it makes sense to use the class-based storage method as displayed in Figure 3.4 so that the products with the highest demand are located close to the loading point.

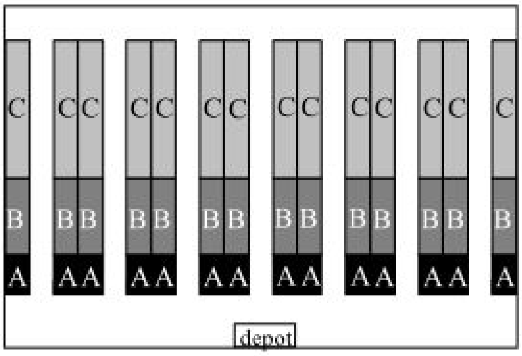


Figure 3.4: A common way to implement class-based storage, retrieved from [Koster et al., 2007]. The products with the highest demand, the A-products, are located close to the loading points. At the moment the truck arrives, these goods can be loaded into the truck quickly.

Finally, the required number of storage blocks can be calculated by dividing the total amount of pallets that need to be stored in the warehouse by the number of pallets that can be stored in one storage block. This latter one depends on both the amount of pallets that can be placed next to each other as well as behind each other. The amount of pallets that can be stored next to each other depends on the equipment type that picks up the pallets. For example, two pallets can be stored directly next to each other if a double fork FLT is used, whereas space is required between those two pallets if only a single fork FLT is used.

3.6.2. Picking process

There are different ways in which the general operation of transporting and loading goods can be executed. One method is to start picking the goods from the warehouse at the moment the truck arrives, and then load them directly into the truck. This is a commonly used method within Heineken. However, a disadvantage of this method is that the picking process can only start when the respective truck arrives.

Another option is to use pre-staging, or staged inventory, which is a method in which goods are transferred from the storage area to a location where they are ready to be loaded onto the truck [BusinessDictionary, 2019]. This location can be any random area between the storage area and the loading points, but it can also be an ATLS. In this way, goods can be picked from the storage area before the actual truck arrives and be temporarily stored in the pre-staging area. When the truck arrives, the distance that needs to be covered is only the distance from the pre-staging area to the truck or from the ATLS into the truck, and not the entire distance from the storage area. This results in a quicker loading time for the truck. A downside of pre-staging is that additional space is required to temporarily store the products. The required space is usually equal to the width times the length of the biggest truck in order to be able to pre-stage the goods for this truck.

Thirdly, the method of cross-docking can be used. The basic idea of cross-docking is to transfer incoming shipments directly to outgoing vehicles without storing them in between [Van Belle et al., 2012]. In the case of Heineken, this means that incoming goods from the packaging lines are directly transported, or cross-docked, to the shipping area from where they are loaded into the trucks. All goods that are directly cross-docked do not first need to go to the warehouse storage area. This means that the storage area can be much smaller, which is an advantage in terms of space requirements. Also the average distance that needs to be travelled is shorter as the goods are initially transported closer to the loading points.

Finally, a fourth option is to make the task of transporting goods from the storage to the loading points fully automatic. This can, for example, be done by installing a fully automated warehouse system. A review on the recent developments of robotised and automated warehouse systems is conducted by Azadeh et al. [2019], where they describe a typical automated warehouse for e-commerce operations. Most of the systems they describe can also be used for pallets and would result in the replacement of all FLT movements at once. When relating the typical material flow through a warehouse to the Heineken process, the following sequence can be derived (based on the information from Azadeh et al.):

1. Pallets arrive from the packaging lines via conveyor transport;
2. Pallets are stored in an autonomous storage and retrieval system;
3. When an order arrives, the pallets are retrieved and put in the correct sequence;
4. A conveyor system transports the goods to the shipping point;
5. Pallets are loaded into a truck.

The first three options are all variations that are present in one or more Heineken breweries. Currently, Heineken does not have a brewery that is fully automated. Costs highly influence the decision for a specific picking process and the level of automation that is used. For example, the labour costs in the Netherlands are relatively high and it is therefore interesting to substitute people with automated systems. The labour costs in third world countries on the other hand are low, due to which it is less attractive to automate because of the relatively high costs compared to manual labour. However, when considering the risk level of the different options, many injuries resulted from manual loading of goods. It is therefore interesting to compare the level of automation of the solutions with their resulting risk levels. More on this is explained in Section 3.7.5.

3.6.3. Loading process

When considering the loading process, the first decision to make is whether to load a truck via side-loading or end-loading. This choice both has an impact on the way the operation is executed as well as on the space that is required at the loading dock [Thomson, 1997]. Regarding the space usage, side-loading requires a lot more space than end-loading as FLTs need to be able to drive between the trucks. For this reason, Thomson advises to avoid side-loading if possible. Additionally, side-loading increases the chance that FLTs cross each others' paths if they share an aisle between trucks. Therefore, end-loading will be considered in this research from now on.

Subsequently, the loading berth itself should be specified. A decision that should be made is whether or not to use a loading dock, which is a recessed bay in a freight terminal or warehouse that allows for safe and efficient loading and unloading of trucks [Winnesota, 2018]. By enabling the use of specialised equipment when loading cargo, loading docks help increase the efficiency of the entire process, cutting costs and getting products to their destinations faster. Because of the functional requirements associated with the receipt and shipment of merchandise, the vast majority of industrial plants are equipped with a number of loading docks for trucks [Gauthier et al., 2007].

However, Gauthier et al. also found various studies that have shown it is fairly frequent for FLTs to fall or almost tip over from a loading dock, following a sudden movement of the truck. Usually the impact of such a fall leads to serious injuries for the FLT operator. But, as said earlier in Section 2.5.2, many of the risks associated with the use of loading docks can possibly be alleviated when careful planning is done beforehand [Loading Dock Supply, 2019]. Assuming that these risks can indeed be managed in the design phase, loading docks are used in this research because of the benefit this gives with respect to efficiency. Also, the available data with respect to equipment types, which is provided in Section 3.8, is based on the use of loading docks.

3.7. Consider possible equipment types and characteristics

The equipment types that need to be determined are the once that transport the goods from the warehouse to the truck and that load the goods into the truck. These do not necessarily have to be the same for the whole process, but a combination of systems can be implemented as well. The type of equipment influences the space required for the storage area and the loading area, as the aisle width and manoeuvring space depend on this (see Figure 3.5).

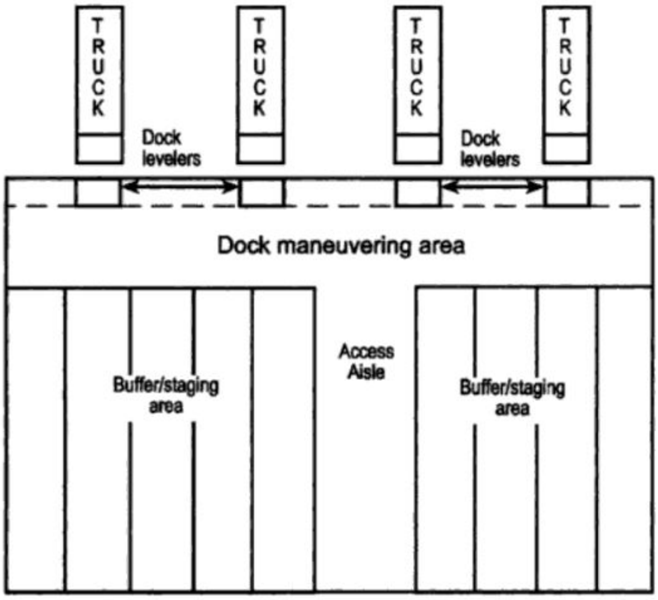


Figure 3.5: Shipping dock space requirements, retrieved from [Hudock et al., 1998].

In Section 2.5, multiple solutions were presented which could reduce the risk. Promising solutions were mainly automated solutions, like the LGV and the ATLS. As data is available of those two types of equipment, these will be included in the model. Besides those two, FLTs and manual loading will be included as they are currently most used within Heineken. In this way, it can be clearly shown what the impact of automation is on the risk level. Relevant characteristics regarding manual loading, FLTs, LGVs and ATLS and the space that they require are shortly described in Sections 3.7.1 to 3.7.4, respectively. Finally, a value for the level of automation is attached to the different equipment types in Section 3.7.5.

3.7.1. Manual loading

Manual loading is a method that is mainly applied in third world countries because of the cheap labour costs or in small breweries where only very few trucks arrive. It can be seen as a variant on pre-staging where FLTs are used to initially transport the goods from the warehouse to the loading area and someone then uses a hand cart to load the goods into the truck. Regarding the space that is required for manual loading, it is in this research assumed that this is the same as the space that a single fork FLT requires, which is 4 meter (based on information retrieved from Heineken). More on the space that is required for an FLT is provided in the next section.

3.7.2. Forklift truck

FLTs are available in different sizes, from being able to carry one unit load up to four unit loads. The more unit loads an FLT can carry, the wider the FLT gets. In this research, the single and double FLT are considered. An important distinction between the single fork FLT and double fork FLT is that the double fork FLT cannot perform the loading task, whereas the single fork FLT can do this. The reason for this is that it is too difficult for an operator to drive into the truck with a double fork FLT without damaging the truck as the width of the truck is too small for this. The minimum required width of an aisle for two way traffic is 4 meter for a single fork FLT and 6 meter for a double fork FLT, based on information retrieved from Heineken.

3.7.3. Lifting guided vehicle

The LGV is also available in different sizes. Again, both the single and double fork LGV are considered in this research. Similar to the double fork FLT, the double fork LGV is not able to perform the loading task. This was a result of an extensive feasibility study that Heineken performed on the use of LGVs in their operations. When looking at the space requirements, an LGV usually requires more space than an FLT. The minimum width of an aisle that is required for two way traffic when using a single fork LGV is 6 meter and 10 meter when using a double fork LGV. These widths are based on information received from Heinekens' logistics distribution centre in Den Bosch, where they use LGVs.

3.7.4. Automated truck loading system

The dimensions of an automated truck loading system are such that the biggest truck can be fully pre-staged. In the model, the system will therefore have the same dimensions of the biggest truck. An ATLS should be loaded using FLTs or LGVs.

3.7.5. Level of automation

As explained in Section 3.6.2, different picking processes can result in different risk levels. The type of equipment that is used within those processes influence this risk level. For example, LGVs have a lot of sensors and are able to communicate with each other, due to which the chance of a collision is much smaller compared to an FLT, which is reliant on the human operator. A measure of the interaction and task division between human and machine is the level of automation [Fasth et al., 2008, Frohm, 2008]. This level can be used to evaluate the impact that solutions with a different level of automation have on the risk level.

In Table 3.3, the seven levels of automation are presented with a general description. The equipment that is considered in this research, as described in the previous sections, is each given a level of automation. This is presented in the third column. Firstly, manual loading is given a 2 as it is assumed that they use a hand cart. Subsequently, a 4 is given to an FLT as it is considered an automatic hand tool. Lastly, a 7 is given to LGVs and the ATLS as they are fully automatic.

Table 3.3: Levels of automation, based on information retrieved from [Fasth et al., 2008, Frohm, 2008].

Level	Mechanical	Equipment
1	Totally manual	
2	Static hand tool	Manual loading
3	Flexible hand tool	
4	Automatic hand tool	FLT
5	Static workstation	
6	Flexible workstation	
7	Totally automatic	LGV, ATLS

3.8. Calculate equipment capacities and quantities

In this section, the equipment numbers that are necessary to perform the operation are determined. Firstly, the number of transporters (workers, FLTs, LGVs and/or ATLS) will be determined. Each of these has its own individual specifications which influences the required amount that is needed to fulfil the task. These specifications and the calculation method to determine the numbers are provided in Section 3.8.1. Additionally, the required number of loading points and pre-staging areas/ATLS needs to be determined. This approach is discussed in Section 3.8.2.

3.8.1. Transporter specifications

The various capacities for the transporters that are going to be included in the model, as explained in the previous section, are presented in Table 3.4. The specifications about the manual loading and the FLT are based on data from Heineken. Data regarding the LGV and ATLS is retrieved from the logistics centre in Den Bosch, which provides logistics services for the Heineken brewery in Den Bosch.

Table 3.4: Specifications for the different types of equipment, based on both information from Heineken and the logistics centre in Den Bosch.

Equipment type	Pickup time [in s]	Putdown time [in s]	Speed [in m/s]	Loading time [min]
Manual loading	15	15	1	-
FLT	15	15	4	-
LGV	54	54	1.5	-
ATLS	-	-	-	5

The number of transporters is calculated so that there is enough capacity to transport and load all goods in peak hour, within the agreed service time (as explained in Section 3.2.2). The capacity depends on the time it takes to transport or load the goods, which is the sum of the time it takes to drive or walk to the goods, to pickup the goods, to drive or walk to the right location (truck or pre-staging area/ATLS) and to put down the goods, as shown in Equation 3.8. Additionally, the number of pallets that can be carried by one transporter also influences the loading time as a double fork FLT or LGV can transport more pallets in a certain time than a single fork FLT or LGV.

$$t = t_{pickup} + 2 * \frac{s_{pallet\ to\ truck}}{v_{driving}} + t_{put\ down} \tag{3.8}$$

Where:

t = time to drive up and down once [in s].
t_{pickup} = time to pickup a pallet [in s].
$s_{pallet\ to\ truck}$ = distance to travel [in m].
$v_{driving}$ = driving speed [in m/s].
$t_{put\ down}$ = time to put down a pallet [in s].

As the travel distances vary in different layouts, the number of transporters required to guarantee a certain truck service time varies per layout as well. Therefore, the number of transporters will be calculated by the model based on the layout configuration. More on the way this is calculated, is explained in the next chapter.

3.8.2. Number of loading points

According to Hudock et al. [1998], the number of docks required is primarily a function of the time intervals between carrier arrivals at the dock and the time required to service the carriers upon arrival. The time it takes to load the trucks depends on the size of the truck as the more pallets fit in a truck, the longer it takes to load all pallets into the truck. For the calculation of the required number of loading points it is important to take into account the time it takes to make the truck ready for loading as well. This concerns the time to open the doors when the truck arrives and to close the doors when the truck is loaded. The total time that a truck is using a loading point can be calculated using Equation 3.9. More on the way this is determined by the model, is explained in the next chapter.

$$t_{using\ loading\ point} = t_{opening\ doors} + t_{loading} + t_{closing\ doors} \tag{3.9}$$

Where:

$t_{using\ loading\ point}$ = time truck is using loading point [in min].
$t_{opening\ doors}$ = time to open the doors [in min].
$t_{loading}$ = time to load all the pallets [in min].
$t_{closing\ doors}$ = time to close the doors [in min].

3.9. Define services and ancillary operations

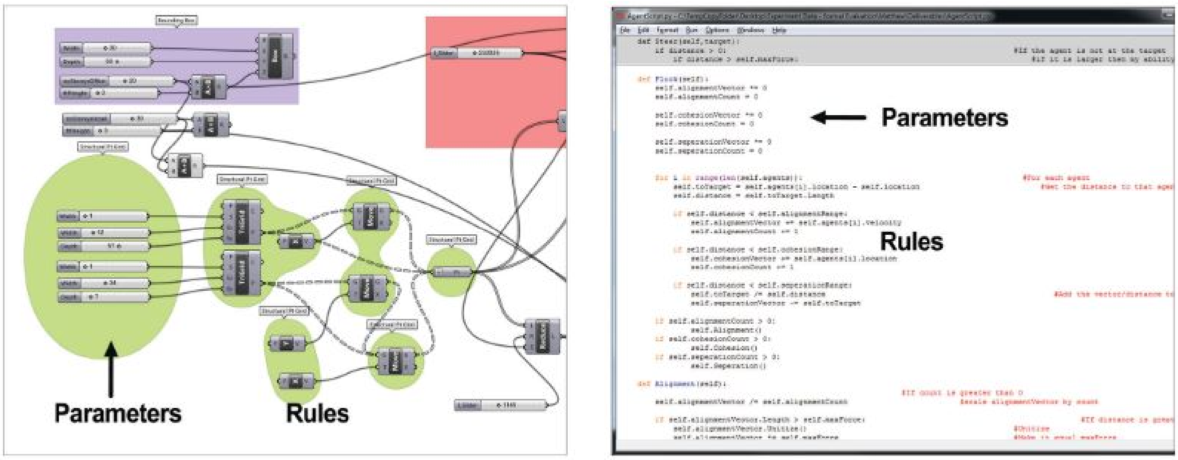
Services and ancillary operations are operations or services that, for example, are concerned with separately assembling smaller quantities or carrying out a unique step in the process [Hassan, 2002, Krauth et al., 2005]. In this research, these ancillary operations are not further evaluated.

3.10. Prepare possible layouts

As stated in the introduction of this thesis, the goal of this research is to develop a method which creates the opportunity to show what impact specific design decisions have on the performance of the warehouse loading area. For this, a parametric model is developed which enables the quick generation of concept designs of the layouts. In this way, multiple scenario's can quickly be evaluated and compared to each other. In Section 3.10.1, more information is provided about the concept of parametric design and why parametric design is appropriate to use to reach the goal of this research. The specific parametric design software that is used for this research is described in Section 3.10.2.

3.10.1. The concept of parametric design

Parametric design or parametric modelling is a design strategy associated with algorithmic scripting, in which geometric relations are represented by using relations between parameters, constraints and equations [Lee et al., 2014]. In parametric design form is shaped by values of parameters and equations are used to describe the relationships between the forms [Milena and Ognen, 2011]. According to Nagy et al. [2017], parametric design allows the designer to not only define a final geometric solution, but to describe the entire system behind how a design is generated. In Figure 3.6a, an example is presented of the relationships that describe a system using a graphical algorithm editor, like Grasshopper. In Figure 3.6b, these relationships are described using a text-based algorithm editor, like Python.



(a) Graphical algorithm editor (Grasshopper).

(b) Text-based algorithm editor (Python).

Figure 3.6: Examples of parameters and rules in two different parametric design environments, retrieved from [Lee et al., 2014].

Although it takes more work to describe such a model initially, Nagy et al. mention three main advantages that parametric design offers for the designer. Firstly, once the initial model is defined, the parametric approach makes it easy to create variations and custom adaptations of a design. Instead of manually creating multiple variations, the designer can change critical parameters that drive different variations and automatically generates different versions. A second advantage is that a well-structured parametric model is more adaptable to change in the future. Since it is defined by a series of operations, the design can be easily adapted to changing conditions instead of rebuilding the model from scratch each time. Lastly, it allows designers to think in a deeper and more dynamic way than possible with traditional methods. In the traditional approach, the designer usually studies the design problem, defines the constraints and objectives, and uses their skill and experience to craft a single design solution, or maybe a view at most. Instead of designing a single solution, the designer can generate a variety of solutions using the parametric approach. According to Iordanova [2007], Lee et al. [2013a,b], parametric design is fundamental to creativity through design exploration during the conceptual design phase, where variations can be generated by alternating design parameters, topological relationships, and rule algorithms.

A limitation of the parametric approach that is mentioned by Nagy et al. is that the exploration of the design space is still limited by the abilities of the human designer. The reason given for this is that the different options must still be investigated by the human designer by manually varying the parameters. Aish and Woodbury [2005] state that the downside of parametric modelling in the conceptual design lays in the fact that ”nothing can be created in a parametric system for which a designer has not explicitly externalised”. This is emphasised by Moussavi [2011], who state that ”parametric design as a style disposes itself of the restraints of external parameters and promotes the autonomy of architectural forms, while it cannot advance beyond new ways of shaping matter to produce unexpected spaces.”

A possible next step, to account for these limitations, is explored by Nagy et al., which is called generative design. Generative design explores the design space semi-autonomously and therefore allows a much deeper exploration of complex design spaces. Generative design is different from parametric design in that the rough outlines of the model are not known in advance. To go from a basic parametric model to a generative model, the parametric model must be extended in two ways [Nagy et al., 2017]. Firstly, the model must include a concrete metrics by which each design option can be evaluated in order for the computer to determine which designs perform better than others. Secondly, the model needs to be connected to a search algorithm that can control the input parameters of the model, get feedback from the metrics, and intelligently tune the parameters to find high performing designs while also exploring the full possibilities of the design space. A disadvantage of generative design, as stated by Moussavi [2011], is that although implicit low-level rule systems can offer wide design exploration due to their lack of structure, they often act as black boxes to human observers.

The goal of this research is to show what impact specific design decisions have on the performance of the warehouse loading area, specifically with respect to safety. Because of this reason, it creates more clarity for the designer if the designer can manually change the respective parameter(s) to see the direct impact of this. Within the generative approach it is less clear to the designer what happens, as the model is more like a black box than in the parametric approach. By using the parametric approach instead of the generative approach, the designer is more in control of what happens. In the case of this research, it means that the impact of a design decision can be clearly seen, which is the goal. For this reason, the designs are created using the (basic) parametric approach, without the generative component.

3.10.2. Parametric design software

Parametric modelling is now well established within the computational design community [Harding and Shepherd, 2017], and several software packages offer graphical algorithm editors [Milena and Ognen, 2011]. In the evaluated literature of Harding and Shepherd [2017], Kensek [2014], Krish [2011], Lee et al. [2014], Milena and Ognen [2011], the most mentioned parametric application is Grasshopper, which is a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators [Davidson, S., 2019]. And although with respect to architectural design, Grasshopper is one of the most commonly used generative design editors [Milena and Ognen, 2011].

The concept of Grasshopper can however also be applied for other design problems as the concept of establishing relationships stays the same. The advantage to use Grasshopper for this research is that it is tightly integrated with Rhino, which gives the opportunity to visualise the designs. This again reduces the influence of the black box, which Moussavi [2011] mentioned as possible disadvantage, and gives the chance to clearly show the designers intent. Another advantage is that the programming language Python is embedded within Grasshopper. In this way, the graphical modelling of Grasshopper can be combined with the advantages that scripting modelling provides, like simulation. This is useful in this research when showing, for example, the routes FLTs drive during operation.

3.11. Overview Chapter 3

By following the steps that are required in the design process of a warehouse loading area, as described by the eleven step framework, the relevant requirements and parameters have been found, therefore answering the third subquestion: *What are the design requirements and parameters that determine the design of a warehouse loading area?*. The type of data that needs to be available was explained as well as the methods to process this data. The important design decisions, like the number of aisles and the location of the loading points, have been discussed. Additionally, different picking processes of which it is interesting to evaluate their influence on risk (directly from warehouse, using cross-docking, using pre-staging and fully automatic) were described. Similarly, various types of equipment have been discussed which are expected to have an impact on the risk level in the area as well, which considered the use of manual loading, an FLT, an LGV and an ATLS.

Furthermore, it was explained that parametric modelling will be used to evaluate the different design choices as it gives the opportunity to quickly change one or more parameters. Because of the characteristic that a designer changes the parameters him/herself in the parametric approach, the impact of a certain choice can clearly be seen and it does not act like a complete black box to the observer. In the next part, the development of the parametric model is explained.

Part II

The Model

4

Development of the Model

In this chapter, it is explained how the model is developed and how it can be used to evaluate the risk level of different design choices, which provides an answer to the fourth subquestion: *How can the risk level of different design choices be calculated using a parametric model?*. First, the main options that are included in the model are described in Section 4.1. Next, the brewery specific parameters that need to be inserted into the model are provided in Section 4.2. In Section 4.3, the way the storage area and the required number of loading points and transporters are calculated is described. In Section 4.4, the generation and visualisation of the layout based on the input parameters is discussed. Subsequently, in Section 4.5, the simulation of truck arrivals, transporter movements and pedestrian movements is explained. Lastly, the calculation of the risk level is discussed in Section 4.6. The descriptions provided in this chapter are still generic, so that they can be applied for various breweries.

4.1. Setup of the model

To be able to design an appropriate model it needs to be determined what the model needs to be capable of. As stated in the introduction of this research, the goal of the model is to enable the possibility to evaluate the impact of design decisions on the risk level in the warehouse loading area. Therefore, it should be possible to choose various design options and see what effect these have. In the previous chapter, the relevant design decisions that should be considered have been established.

In Section 3.6.2, four picking processes were described, which were picking the goods directly from warehouse, using pre-staging, using cross-docking and using a fully automatic warehouse. The first three options are included in the model as such. However, due to the use of conveyor systems in a fully automatic warehouse, there are no movements of transporters or pedestrians present in this scenario. Therefore, this option is not included in the model. Instead, the impact that solutions with a different level of automation have on the risk level are evaluated by looking at the equipment type.

The four types of equipment of which their impact on risk will be evaluated are manual loading, using an FLT, using an LGV or using an ATLS, as described in Section 3.7. These should therefore be included in the model as options. As not all types of equipment are suitable for the transportation task as well as the loading task, a distinction has been made in which picking process which type(s) of equipment can be used. In Table 4.1, an overview is presented of the type(s) of equipment that can be chosen for a certain picking process. This is based on the information provided in Section 3.7. In case a scenario is using pre-staging, a distinction has been made between the transportation task (from the warehouse to the pre-staging area or ATLS) and the loading task (from the pre-staging area to the truck).

Table 4.1: Overview of the types of equipment that can be chosen for a certain picking process. The scenario using pre-staging is split into two parts, the transportation task (from the warehouse to the pre-staging area or ATLS) and the loading task (from the pre-staging area to the truck).

Picking process	Possible equipment types
Directly from warehouse	• Single fork FLT • Single fork LGV
Using cross-docking	• Single fork FLT • Single fork LGV
Using pre-staging (transportation task)	• Single fork FLT • Double fork FLT • Single fork LGV • Double fork LGV
Using pre-staging (loading task)	• Manual loading • Single fork FLT • Single fork LGV • ATLS

4.2. Input parameters

The input parameters that need to be inserted into the model concern the parameters that influence the expected volume that goes into stock and the expected throughput in peak hour. These parameters are specific for each individual brewery. A more extensive explanation of the required input values to determine those two values is provided in Sections 4.2.1 and 4.2.2, respectively.

4.2.1. Expected volume in stock

The expected volume that goes into stock influences the space that is required for the storage area. In Section 3.4, the method to calculate this volume was provided (using Equation 3.1). The parameters that need to be known are the expected sales volume per product type per year, the time a product type is expected to stay in stock and the expected sales in peak month. In this research, it is assumed that the different product types are always distributed in the three product classes A, B and C, based on Pareto's method (see Section 3.3). This means that the sales volume of class A, B and C products is 80%, 15% and 5% of the total sales per year, respectively. Likewise, the expected time that a product type is expected to stay in stock is determined for those three classes.

In the case the picking process is directly from warehouse or using pre-staging, it is assumed that all goods from the packaging department first go into the warehouse to be stored before they get loaded. In the case of cross-docking, only 15% goes into stock as the other 85% is directly cross-docked from the packaging hall to the loading area. This number is based on information from the Heineken brewery in Den Bosch, where they use a cross-docking system.

4.2.2. Expected throughput in peak hour

The expected throughput in peak hour is calculated using Equation 3.5. The parameters that are required are the expected sales volume per year, the expected sales volume in peak month and the number of days per year and the number of hours per day a brewery operates. Subsequently, the number of pallets can be calculated by dividing the calculated volume by the average amount of hectolitres that fits on one pallet.

Firstly, the expected throughput in peak hour influences the number of transporters that is required to transport and load all the goods into the truck. Secondly, it influences the number of trucks that is needed to pickup all the goods. The higher the throughput, the more transporters and trucks are required.

The number of trucks also depends on the type of truck. The bigger the truck is, the fewer trucks are needed to transport all the pallets. The truck type can vary per country. In some countries it is common to have very big trucks, whereas in other countries smaller trucks are more likely. Therefore, the truck type(s) need to be inserted as input in the model.

4.3. Calculations

Based on the input parameters described in the previous section, the required storage space, the number of transporters and the number of loading points can be determined. In Section 4.3.1, it is explained how the space that is required for the storage area is calculated. The calculation of the required number of transporters and loading points is discussed in Section 4.3.2.

4.3.1. Calculation storage area

As was explained earlier in Section 3.6, the general layout of the storage area follows the arrangement as (again) shown in Figure 4.1. The number of storage blocks that is required for each product class depends on the number of pallets that fit in one storage block. Usually, more pallets can be stacked behind each other, next to each other and/or on top of each other in one storage block. This can vary per brewery. Therefore, these numbers can be adjusted in the model to make them representative for the respective brewery. As example, if there is a total amount of 1000 pallets of A products that needs to be stored, five pallets can be stored behind each other and two pallets can be stacked on top of each other, then the number of storage blocks follows to be:

$$N_{storage\ blocks} = \frac{1000}{5 * 2} = 100 \text{ storage blocks}$$

These storage blocks are subsequently divided over the number of racks that are present. The number or racks depends on the dimensions of the warehouse, where the width to length ratio is initially set to be 2:1, which was found to be the most optimal ratio. For example, if there are ten racks, the number of storage blocks of class A products per rack would be:

$$N_{storage\ blocks\ per\ rack} = \frac{100}{10} = 10 \text{ storage blocks per rack}$$

Likewise, the number of storage blocks that are required to store the class B and C product is calculated in a similar way. Those storage blocks are also divided over the number of racks, which will subsequently be arranged according to the configuration in Figure 4.1 below.

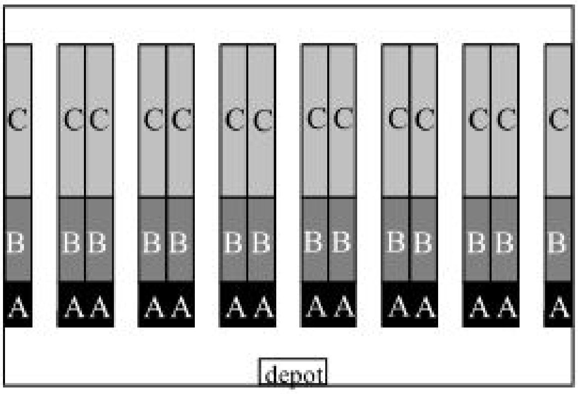


Figure 4.1: General layout of the warehouse storage area, retrieved from [Koster et al., 2007].

4.3.2. Calculation number of transporters and number of loading points

Based on the expected throughput in peak hour, the number of transporters and the number of loading points can be determined. Regarding the number of transporters, these are determined such that the maximum allowed time that trucks have to wait before they are loaded can be guaranteed, as was explained in Section 3.2.2.

The number of loading points depends on the number of trucks that arrive in peak hour. The number of trucks is calculated based on the number of pallets that need to be transported in peak hour, the size(s) of the truck(s) and the share of a truck type. This calculation is shown in Equation 4.1. In the model, these trucks are given an arrival time based on a random uniform distribution. Furthermore, it is assumed that the number of loading points needs to be sufficient so that there is always a loading point available when a truck arrives.

$$N_{trucks} = \frac{N_{pallets\ in\ peak\ hour}}{\sum^{t} N_{pallets\ in\ truck,\ t} * Share_{t}} \tag{4.1}$$

Where:

N_{trucks} = the number of trucks that arrive to pickup all the goods.
$N_{pallets\ in\ peak\ hour}$ = the total number of goods to be transported in peak hour.
$N_{pallets\ in\ truck,\ t}$ = the number of goods that fit in a truck type t.
$Share_{t}$ = the share of a truck type t.

4.4. Visualisation of the layout

The layout of the warehouse storage area as generated by the model for the three different picking processes directly from warehouse, using cross-docking and using pres-staging are presented in Figures 4.2, 4.3 and 4.4, respectively. The class A products are represented by the red boxes, the class B products by the orange boxes and the class C products by the green boxes. The red squares at the bottom of the figures represent the location of the loading points and the inside space that is required for them. The initial location of the loading points is set to be in the centre of the warehouse, as this was best for the 2:1 ratio. However, an option has been included to change the position of the doors to the left side or the right side of the warehouse when desired. Furthermore, the aisle width between the storage racks and the manoeuvring space needed between the warehouse storage area and the trucks (at the bottom) depend on the type of transporter that is used, of which the requirements were provided in Section 3.7. Lastly, the red crosses indicate the locations where transporters can pickup the goods. These locations are simplified to be one location per class per storage rack.

The cross-docking lanes, that are present in the scenario using cross-docking, are presented with grey lines, as shown in Figure 4.3. For the case when pre-staging is used, the pre-staging areas are visualised by rectangular boxes between the warehouse storage area and the loading points, as shown in Figure 4.4. These boxes have the same size as the biggest truck that arrives at the brewery. In the case an ATLS is used instead of pre-staging areas, the boxes are positioned against the bottom wall.

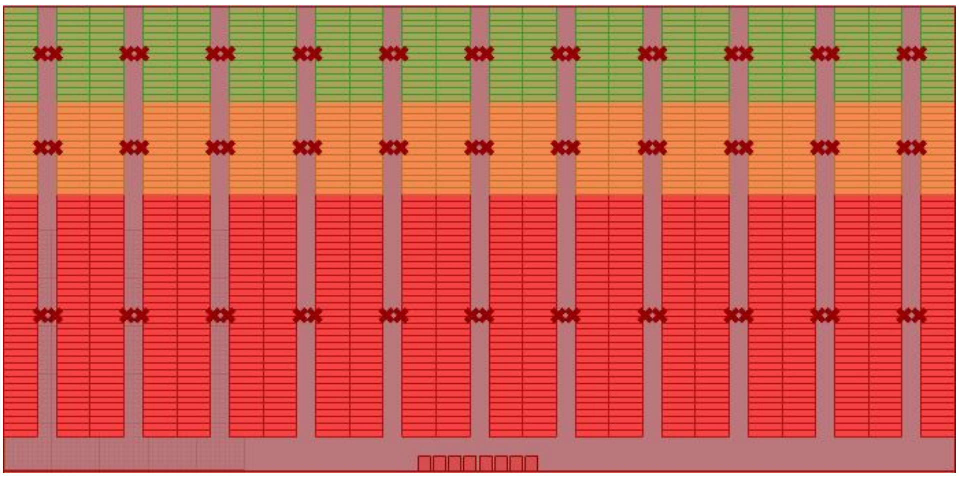


Figure 4.2: Visualisation of the generated layout by the model for the picking process directly from warehouse.

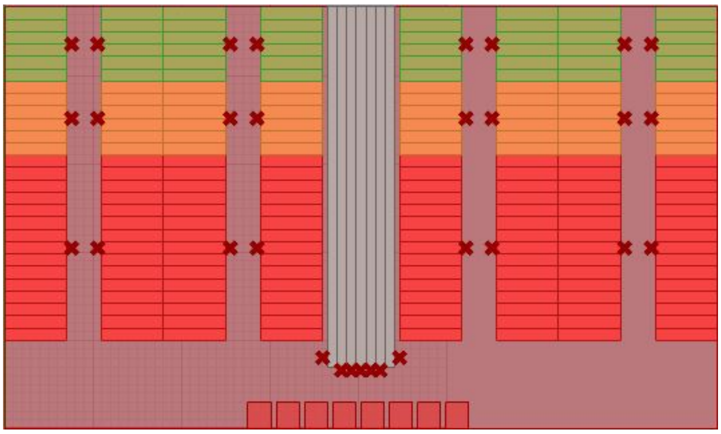


Figure 4.3: Visualisation of the generated layout by the model for the picking process using cross-docking.

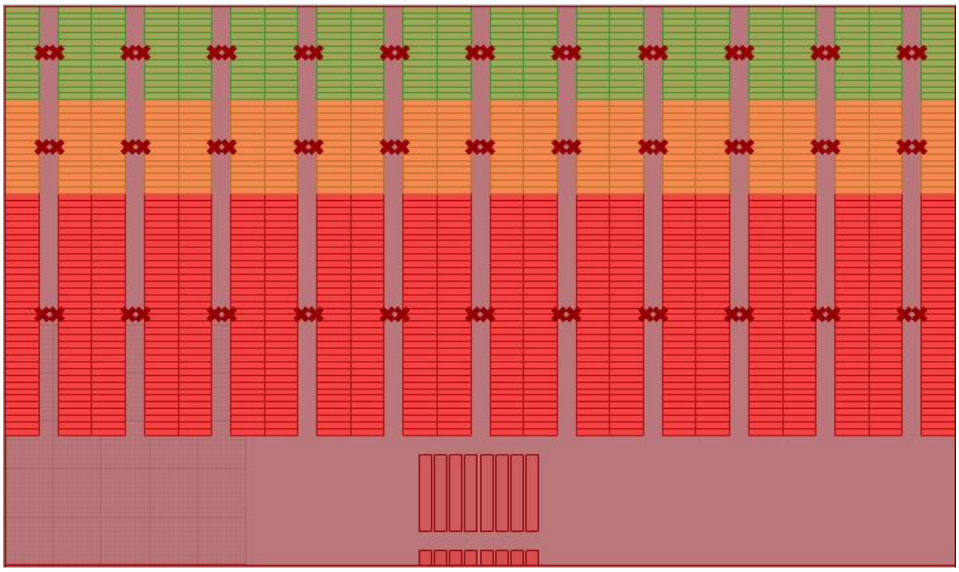


Figure 4.4: Visualisation of the generated layout by the model for the picking process using pre-staging.

4.5. Simulation

Now that the locations of the storage areas and loading points are known, the different movements can be simulated. These movements include the movements of trucks, truck drivers, transporters and workers. In the following sections, a more extensive explanation of the respective simulations is provided. All movements are visualised by dark red lines as shown in Figure 4.5. In this example, a truck arrival and the movement of a transporter between the warehouse and the truck can be seen.

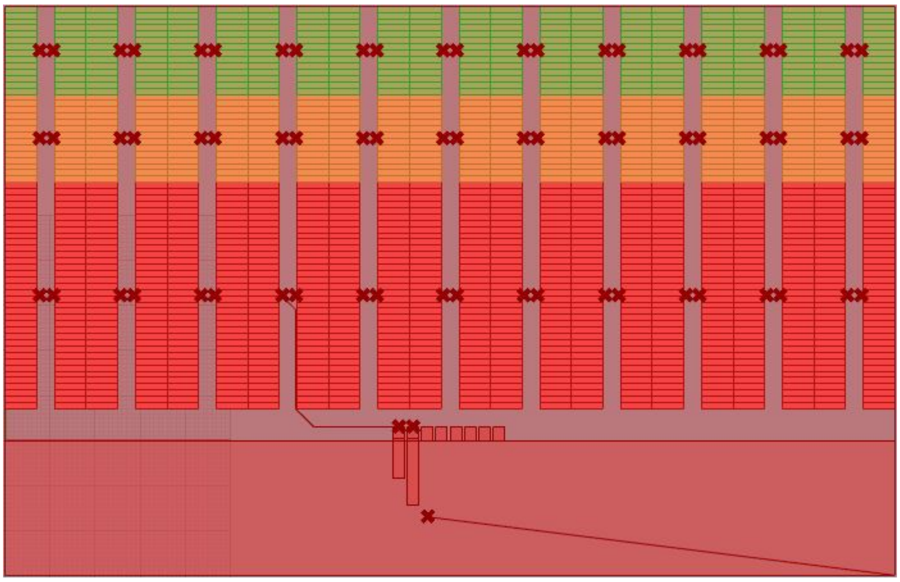


Figure 4.5: The movements of trucks, truck drivers, transporters and workers are visualised by a dark red line. In this example, a truck arrival and the movement of a transporter between the warehouse and the truck can be seen.

4.5.1. Simulation of truck arrivals and departures

When the simulation time is equal to the arrival time of a truck, a truck arrives at the brewery and goes to its assigned loading point. From the moment the truck is positioned at its loading point, it takes five minutes before the loading process can start. This represents the opening of the truck doors. When the truck is loaded, the doors need to be closed again, which is simulated to take another five minutes. After this, the truck drives away.

4.5.2. Simulation of transporter movements

Transporter movements occur between the pickup points of goods and the loading points. From the moment the doors of the truck are opened, the transporter drives up and down to load all the pallets into the truck. The choice for a specific loading point is based on the Pareto method, which means that 80% of the time a pallet is retrieved from the class A storage blocks, 15% from class B storage blocks and 5% from class C storage blocks.

In the brewery in Den Bosch they load trucks that arrive at the far left loading point as much as possible with goods from the left side of the warehouse. This chance has a huge impact on the number of crossings that occur in the area. However, as no data is available of this chance for the other picking processes, it is decided that in the model it is randomly chosen from which pickup point the pallet is retrieved. For example, if a pallet needs to be retrieved from the class A storage, it means that it can be any of the class A pickup points.

4.5.3. Simulation of pedestrian movements

The first type of pedestrian movement concerns the movement of the truck driver. When the doors of the trucks have been opened, the truck driver walks over the truck area to the office to sign his/her paperwork. Afterwards, the truck driver walks back to the truck again. This is simulated to occur at the moment that the truck has finished loading.

The second type concerns the movement of workers through the truck area (outside) and the loading area (inside). This is to take into account that in many breweries the walking paths of workers cross those areas. It is simulated that during peak hour one worker walks from right to left via outside and one worker does this via inside. Of course, when more workers would cross these areas the risk would be higher. However, the number of people walking in those areas is usually low and therefore it is representative to simulate one worker.

4.6. Calculation risk level

The main goal of the model is to calculate the risk levels of the twelve hazards that can possibly result in one of the three most occurring accidents, as described in Section 2.3. However, not all twelve hazards can occur in the model as a transporter never enters the area of a truck or truck driver in the model. Therefore, hazards number 4 and 7 cannot occur. These are left out from now on. For the hazards that can occur, the score for the impact, frequency and probability of the hazards need to be known in order to calculate the risk level. The scores for the impact and probability of the hazards are determined with the help of a safety expert within Heineken and are based on past experiences. In Table 4.2, the respective scores are presented. The probability depends on the type of equipment that is used and is given for both the use of FLTs and LGVs/ATLS. The score for the frequency is calculated by the model. In Table 4.3, an overview is given of what is calculated in order to determine the frequency score of a hazard. Based on the number of times a hazard can possibly occur, the model determines the frequency score according to Table 2.2. The crossings are only counted if a possible crossing of two paths occurs at the same moment in time.

Table 4.2: Scores for the impact and probability of the hazards, which are determined with the help of a safety expert within Heineken. The scores for the probability depend on the type of equipment.

	Hazard	Impact score	Probability score FLT	Probability score LGV/ATLS
1.	Injuries due to manual loading of goods	10	4	4
2.	Transporter colliding with worker	20	4	0.1
3.	Truck colliding with worker	20	2	2
4.	Transporter colliding with truck driver	20	3	0.1
5.	Truck colliding with truck driver	20	3	3
6.	Transporter colliding with transporter	10	3	0.1
7.	Transporter colliding with truck	10	1	1
8.	Truck colliding with truck	5	1	1
9.	Transporter striking against object	10	4	0.1
10.	Load falling from transporter onto worker	15	3	0.1
11.	Transporter falling off loading dock	20	2	2
12.	Goods falling down due to improper stacking	15	3	3

Table 4.3: Overview of how the different frequency scores for the hazards are determined by the model.

	Hazard	Calculated, number of times that:
1.	Injuries due to manual loading of goods	goods are transported manually.
2.	Transporter colliding with worker	path of a transporter crosses path of a worker.
3.	Truck colliding with worker	path of a truck crosses path of a worker.
4.	Truck colliding with truck driver	path of a truck crosses path of a truck driver.
5.	Transporter colliding with transporter	path of a transporter crosses path of another transporter.
6.	Truck colliding with truck	path of a truck crosses path of another truck.
7.	Transporter striking against object	a transporter needs to drive to or from the warehouse.
8.	Load falling from transporter onto worker	path of a transporter crosses path of a worker.
9.	Transporter falling off loading dock	a transporter drives in and out of a truck.
10.	Goods fall down due to improper stacking	goods need to be retrieved from the warehouse.

4.7. Overview Chapter 4

In this chapter, it has been explained how the model is developed and how it can be used to evaluate the risk level of different design choices, which provides an answer to the fourth subquestion: *How can the risk level of different design choices be calculated using a parametric model?*. The developed model enables the comparison of three different picking processes, directly from warehouse, using cross-docking and using pre-staging. Additionally, different equipment types can be compared, dependent on the type of picking process that is considered. By generating a layout and simulating the movements in the area, the number of times that a hazard can potentially occur can be calculated. Based on this number, the model determines the frequency score. By then multiplying the frequency score with the scores for the impact and probability, which were based on expert opinion, the risk level is calculated. In the next chapter, the model is verified to see whether it gives the results as expected.

5

Verification Model

To make sure the model, as described in the previous chapter, works as expected and provides the correct answers, the model needs to be verified. Therefore, the model is tested for the Heineken brewery in Den Bosch. The outcome of the model will be compared to the actual data in order to see whether the model generates a valid representation of reality. First, to give an idea on how the loading operation is executed in the brewery of Den Bosch, some general information regarding the brewery is provided in Section 5.1. Subsequently, the relevant input parameters are presented in Section 5.2. In Section 5.3, the calculations for the required storage area, number of transporters and number of loading points are verified. A comparison between the generated layout by the model and the actual layout is made in Section 5.4. The verification of the determination of the frequency score is discussed in Section 5.5. Finally, a discussion on the findings is provided in Section 5.6.

5.1. General information brewery Den Bosch

The brewery in Den Bosch is considered the innovation brewery of Heineken, where most of Heinekens' new products are being developed and where more than a hundred different types of products are being produced. The overall sales volume that the brewery is designed for is 6 million hectolitres of beer per year. Within their warehouse they use the cross-docking method to directly ship the products from the packaging lines to the loading area. On average 85% of all the pallets is cross-docked. Therefore, these pallets do not need to go to the warehouse storage area and for this reason their storage area can be kept relatively small. In Figure 5.1, the actual floor plan of the relevant area is presented.

At the bottom of the figure a total of twelve loading points can be seen where the trucks can dock to get loaded. The cross-docking system, which is shown in purple, has seven points where the goods can be picked from. The goods in the warehouse can be reached via four aisles. The transportation of goods from the warehouse or from the cross-docking lanes to the trucks is executed by single fork FLTs. Using levelled loading docks, the FLTs load the pallets into the truck. The maximum number of FLTs that is allowed to drive around at the same time is set to four.

Regarding the pedestrian movements, there are both walkways present that go through the area where transporters drive as well as where trucks arrive and depart. The transporter area is crossed by a walkway that can be used by workers when they have to move inside the warehouse. The walkway that goes through the truck area can both be used by workers as well as truck drivers (to walk to the office and do their paperwork).

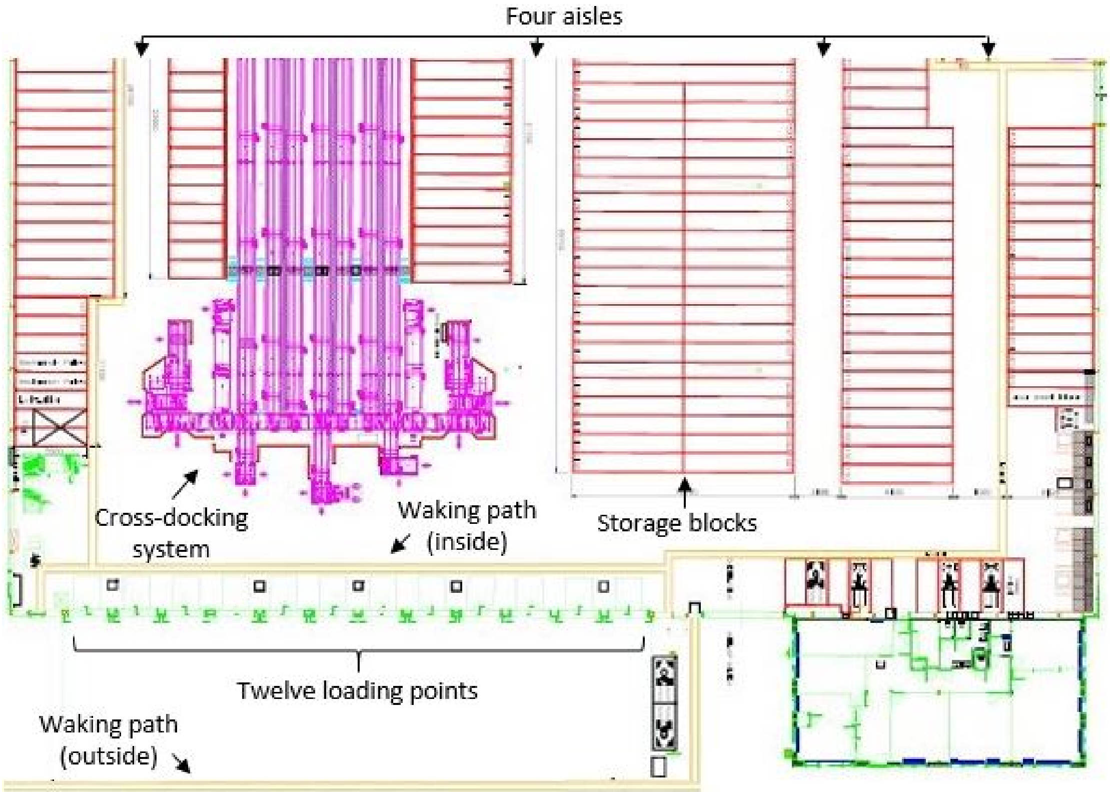


Figure 5.1: Actual floor plan of the warehouse loading area of the brewery in Den Bosch.

5.2. Input parameters - Den Bosch

In Section 4.2, the required input parameters that had to be inserted in the model have been described. The values of the parameters that are specific for the brewery in Den Bosch are presented in Table 5.1. Data about the respective trucks is separately presented in Table 5.2. The data regarding the volume per year and in peak hour is retrieved from data retrieved from the tactical planning department in Den Bosch and is based on the year 2018. The other values have been provided by staff members.

Table 5.1: Overview input parameters for the brewery of Den Bosch.

Input parameter	Data
Volume per year	$6.65 \cdot 10^6$ hL
Volume in peak hour	$0.63 \cdot 10^6$ hL
Number of operating days per year	365
Number of operating hours per day	24
Average time in stock:	
• Class A products	5 days
• Class B products	10 days
• Class C products	30 days

Table 5.2: Characteristics of the truck types that pickup the goods for the brewery in Den Bosch.

Truck type	Length	Width	Maximum number of pallets	Share
Container truck 40ft	15	2.5	22	60%
Container truck 20ft	9	2.5	20	30%
Conventional truck	16	2.2	24	10%

5.3. Verification calculations

The outcome calculated by the model with respect to the required number of pallets that needs to be stored, the number of trucks that comes to pickup the goods, the number of transporters that are needed and the number of loading points that are needed will be compared to the actual values. In the following sections, these calculations are more extensively discussed.

5.3.1. Verification of the space needed for the warehouse storage area

The actual number of pallet places in Den Bosch is 2852 in the current layout. Therefore, the number of pallet places that is calculated by the model will be compared to this number. Using the data from Table 5.1 in Equations 3.2, 3.3 and 3.4, the average sales per month, the seasonality factor and the average sales per week of each product class can be calculated. Subsequently, these values are inserted in Equation 3.1 to calculate the expected stock volume. As the number of pallet places for Den Bosch is known instead of the volume, the stock volume is converted to a number of pallets by dividing the volume by the average amount of hectolitres that fit on one pallet, which was 7.5 hL. The resulting values for the different parameters are shown in Table 5.3.

Table 5.3: Results of the average sales per month, the average sales per week of each product class, the seasonality factor and the expected stock volume. The expected stock volume is converted to a number of pallets.

Parameter	Result
$\overline{V}_{sales\ per\ month}$	$5.5 \cdot 10^5$ hL
$\overline{V}_{sales\ per\ week,\ class\ A\ products}$	$1.0 \cdot 10^5$ hL
$\overline{V}_{sales\ per\ week,\ class\ B\ products}$	$1.9 \cdot 10^4$ hL
$\overline{V}_{sales\ per\ week,\ class\ A\ products}$	$6.4 \cdot 10^3$ hL
$C_{seasonality}$	1.13
$V_{in\ stock}$	$1.4 \cdot 10^5$ hL
$N_{pallets\ in\ stock}$	$1.9 \cdot 10^4$ pallets

The calculated number of pallets follows to be $1.9 \cdot 10^4$. However, in this case it is not yet taken into account that in Den Bosch 85% of the pallets are directly cross-docked from the packaging lines to the loading area. These pallets will therefore not enter the storage area. The total number of pallets that needs to go to stock is therefore 15% of this calculated number and follows to be 2900 pallets. Comparing this number to the actual number of pallet places in Den Bosch, which was 2852, it follows that the deviation is smaller than 2%. Therefore, this calculation is assumed to be valid.

5.3.2. Verification of the number of trucks

Usually eight trucks are needed to transport all the goods during busy hours in the brewery of Den Bosch. The number of trucks that is calculated by the model should therefore match this number. As explained in Section 4.3.2, the number of trucks can be calculated using Equation 4.1. For this, the number of pallets that are transported in peak hour needs to be known. The way this number has to be calculated was explained in Section 3.4.

Using the data provided in Tables 5.1 and 5.2 in Equations, 3.5 and 4.1, the volume in peak hour, the number of pallets in peak hour and the resulting number of trucks can be calculated. The average sales per month and the seasonality factor were already determined in the previous section and followed to be $5.5 \cdot 10^5$ hL and 1.13, respectively. The resulting values for the different parameters are shown in Table 5.4.

Table 5.4: Results of the volume and number of pallets in peak hour and the resulting number of trucks that are needed to pickup all the goods.

Parameter	Result
$V_{peak\ hour}$	$1.3 \cdot 10^3$ hL
$N_{pallets\ in\ peak\ hour}$	173 pallets
N_{trucks}	8 trucks

The calculated number of trucks results to be the same as the actual number of trucks that arrive in busy moments. Therefore, this calculated number validly represents the number of trucks that come to pickup the goods in peak hour.

5.3.3. Verification of the number of loading points and transporters

In the brewery in Den Bosch there are currently twelve loading points and they allow a maximum of four transporters to operate at the same time. In the model, these numbers are calculated, as explained in Section 4.3.2, and it should therefore be checked whether the calculated numbers match the actual numbers.

In the model, the number of transporters is determined such that the maximum allowed time that trucks have to wait before they are loaded can be guaranteed. For Den Bosch, this time is 30 minutes. Based on this, the model determines the number of transporters that is needed to be four, which matches the actual number.

Similarly, the model determines the number of loading points such that there is always a loading point available when a truck arrives. Based on this, it follows that the required number of loading points is eight. This is four less than the twelve that are currently present. A reason for this can be that peak hour is considered on itself while the periods just before peak hour or after peak hour are not considered. This means that only the calculated number of eight trucks will arrive and that all loading points are available at the moment the first truck arrives. Besides that, no additional trucks will arrive when the eight truck has arrived. During a real day trucks come and go during the entire day. When this would be taken into account in the model, possibly more loading points would result as well.

5.4. Verification of the layout

The way the model generates the layout for the cross-docking scenario was presented in Figure 4.3 of the previous chapter. The required number of cross-dock lanes depends on the capacity per cross-dock lane. Currently, a number of seven cross-dock lanes is present in Den Bosch of which the capacity of one cross-dock lane is approximately 25 pallets per hour. Using the calculated throughput in peak hour, as calculated in Section 5.3.2, the number of cross-dock lanes that is required follows to be 7, which matches the actual number of cross-dock lanes.

In Figure 4.3, the cross-docking system was centrally located in the warehouse. However, in the brewery of Den Bosch it is positioned more to the left side of the warehouse, between the second and the third storage rack. In the model this has been adjusted, as it is possible to position the system wherever is desired. The resulting layout representing the layout of Den Bosch, as generated by the model, is shown in Figure 5.2.

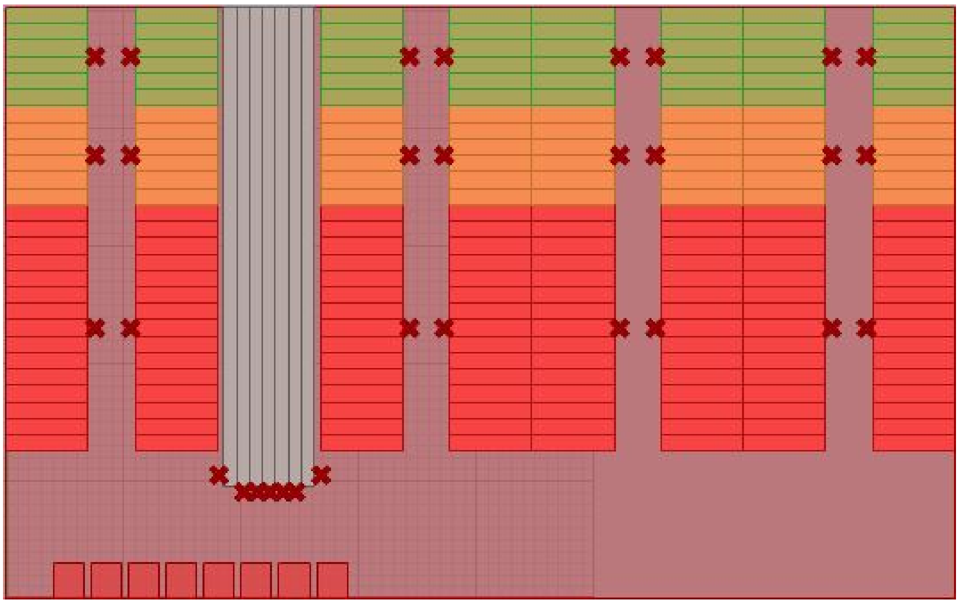


Figure 5.2: The generated layout representing the floor plan in Den Bosch.

Comparing this layout to the actual layout, as presented in Figure 5.1, there are two main differences. The space that is used by the cross-docking system is smaller than in the actual floor plan and the storage area is displayed in a more orderly way. However, it is assumed that this is not a problem for the simulation as the number of pickup points from the cross-docking lanes is the same and also the number of aisles is the same. Therefore, the routes that a transporter needs to drive are almost the same. Due to this, the potential locations where collisions can happen are similar.

Considering the dimensions of the configured layout, the width follows to be 80.7 meter and the length 50.3 meter. The actual width and length of the brewery in Den Bosch are 82 meter and 50 meter, respectively. So, the resulting width in the model is only 1.6% smaller than the actual width and the length is only 0.6% bigger than the actual length. Therefore, the dimensions of the layout are assumed to be valid.

5.5. Verification of the determination of the frequency score

As the scores for the impact and probability are manually inserted into the model, the only score that is determined by the model is the score for the frequency. During the simulation the individual occurrence of the activities are counted by the model, according to Table 4.3. In Table 5.5, the ten hazards are presented together with their frequency score. For clarity, the number of crossings as calculated by the model is also included for each hazard. As no manual handling takes place in Den Bosch, the frequency of this hazard is given a 0, to show that this hazard cannot occur in this specific scenario.

The frequency scores of all hazards have the maximum frequency score. However, this is not necessarily strange as the peak hour is considered, which is the busiest hour. Following the definition for the frequency scores, as provided in Table 2.2, a hazard is soon given a high score. Besides that, the activities that occur in the warehouse loading area are typically activities that occur often. Therefore, all frequency numbers can in principle be substantiated and it is therefore assumed that the model determines them accordingly.

Besides the fact that the model determines the frequency scores as it is supposed to do, one might wonder why a hazard that occurs 4 times (FLT colliding with worker) and a hazard that occurs 348 times (FLT falling off loading dock) are both given the same score. More on this is discussed in the next part.

Table 5.5: Overview of the calculated number of times a hazard can potentially occur and the resulting frequency scores, as determined by the model.

	Hazard	Number of times hazard can potentially occur	Frequency score
1.	Injuries due to manual loading of goods	0	0
2.	FLT colliding with worker	4	5
3.	Truck colliding with worker	1	5
4.	Truck colliding with truck driver	2	5
5.	FLT colliding with FLT	94	5
6.	Truck colliding with truck	0	3
7.	FLT striking against object	46	5
8.	Load falling from FLT onto worker	4	5
9.	FLT falling off loading dock	348	5
10.	Goods fall down due to improper stacking	23	5

5.6. Discussion

Most of the calculations executed by the model are very close or similar to the actual numbers. These include the number of pallet places (deviates less than 2%), the number of trucks that arrive to pickup the goods (matches the actual number) and the number of transporters that is needed (matches the actual number). On the other hand, the number of loading points was calculated incorrectly. The reason that was already given for this was that the model considers peak hour only, it does not consider the hours before and after, while trucks can possibly arrive then as well. Besides the fact that the number of loading points calculated is too low, it also influences the number of crossings that occur. In the current model, the loading area is empty when the first truck arrives and this truck will therefore never cross the path of another truck, whereas this could possibly occur when trucks that arrive in the hour before would be taken into account. Similarly, this applies for the movements inside the warehouse as well. In the current model, no FLTs are yet driving around when the first truck arrives, while this would possibly be the case when the hour before is considered. If the simulation would be run for a longer period of time, instead of just peak hour, a more realistic representation would be made.

Considering the generated layout, there were differences with the actual layout. However,this was found not to be a problem as the number of pickup points of goods is the same and the potential locations where crossings can occur are similar. Furthermore, the calculation of the number of crossings was determined correctly by the model, based on the frequency scoring system (see Section 2.4.2). However, a side note was made about the general method by which the frequency score was determined. The reason for this was that hazards that occur 4 times or 348 times were both given the maximum frequency score of 5. A more in depth discussion on this is provided in the next part.

Except for the fact that the number of crossings is underestimated for some hazards due to considering the peak hour on itself, the model proves to be a proper tool for determining the risk. It can evaluate all hazards, determine the frequency score and calculate the corresponding risk. In the next chapter, the model is therefore used to evaluate different design choices.

Part III

Findings

6

Scenarios and Results

Now that the model has been developed and verified, the impact of different design choices can be evaluated. This chapter will answer the last subquestion: *What is the impact of different design choices regarding the warehouse loading area on the risk level?* In Section 6.1, critical design choices that are expected to affect the risk level are provided. These are based on the findings from Part I. Subsequently, in Section 6.2, different scenarios are described to be able to evaluate the impact on risk of each of the design choices. The results of those scenarios are discussed in Section 6.3. Finally, a discussion of the results is provided in Section 6.4.

6.1. Critical design choices

In this section, critical design choices that are expected to affect the risk level are provided. In Part I, various design choices and possible solution methods have been described. In this section, it is explained which once will be evaluated. A total of five choices is explained.

Firstly, the choice for which picking process (directly from warehouse, using cross-docking or using pre-staging) needs to be made. Currently, the risk level is hardly an important factor in the choice for a picking process within Heineken. Instead, efficiency and costs are the leading factors. It is therefore interesting to demonstrate which picking process actually results in the lowest (and highest) risk. This is therefore the first design choice that will be evaluated.

Secondly, the type of equipment with which the transportation and/or loading operation is going to be executed needs to be determined. In Chapter 2, it was found that most hazards that occur are injuries due to manual loading or are a result from an interaction with an FLT. However, these are still the most commonly used methods within Heineken. This is mainly due to their relatively low costs and high flexibility. These two methods have a relatively low level of automation, especially the manual loading. It is therefore interesting to compare those with equipment types with a high(er) level of automation, like an LGV and an ATLS. Does an increase in the level of automation cause a decrease in the risk level? To investigate this impact equipment with different levels of automation will be compared.

The third design decision concerns the number of aisles that are present in the warehouse storage area. In Section 3.6, it was mentioned that the shape factor of the warehouse has a big influence on the efficiency of the warehouse. The 2:1 ratio, which means that the length of the warehouse is half the width of the warehouse, is most optimal in terms of efficiency. This rule of thumb is also used by Heineken. However, as the shape factor has an influence on the efficiency, it might also have an influence on the risk level. The wider a warehouse is, the shorter the aisles become. Additionally, the more aisles a warehouse has, the smaller the chance is that two or more transporters need to pick goods from the same aisle and the smaller the chance of a collision is. Therefore, it is interesting to evaluate the impact of the number of aisles regarding the risk level of the warehouse.

When looking more closely to the location of the collisions in the case of Den Bosch, it was found that most collisions occur in the area where the FLTs drive in and out of the trucks. The reason for this is that all FLTs need to travel to and from the same small area as the loading points are usually positioned next to each other as close as possible. Therefore, the influence that the distance between loading points has on the risk level will be evaluated.

Lastly, the biggest dangers resulted from a collision of a moving vehicle with a pedestrian. The solution of arranging the crossing on a different level was provided in Section 2.5.4. The impact of this control measure is going to evaluated to see what the difference in risk level is when this measure would be implemented.

To summarise, the five design decisions that will be evaluated are the:
1. Picking process;
2. Level of automation;
3. Number of aisles;
4. Distance between loading points;
5. Crossings on different level.

6.2. Scenarios

In this section, it is described how the different design decisions, as explained in the previous section, will be evaluated. In Sections 6.2.1 up to 6.2.5, the five design decisions are discussed, following the same sequence as in the previous section. A short description of which hazards the decision has an impact on is provided as well.

6.2.1. Picking process

Heineken has a big variety in brewery sizes and it might be the case that a certain picking process works fine for a small brewery but not for a large brewery. Therefore, the different picking processes are evaluated for small (1 million hL/year), medium (6 million hL/year) and large (11 million hL/year) breweries. This comparison will show whether the size of the brewery has an impact on the risk level and for what size which picking process is best.

The type of picking process is expected to have an effect on all ten hazards. The transportation and loading operations inside the warehouse are directly influenced by a different arrangement whereas the hazards that occur outside, in the truck area, are indirectly influenced. The type of picking process influences the loading speed. The faster a truck gets loaded, the sooner it can drive away again. This increases the frequency of trucks arriving and departing in the truck area. If more trucks arrive or depart in a shorter time, a worker or truck driver that needs to cross the area has a bigger chance of getting struck by the truck.

6.2.2. Level of Automation

The level of automation is evaluated using the picking process pre-staging. The reason for this is that most combinations of different equipment types can be chosen within the pre-staging process. Therefore, this one gives the most possibilities to evaluate the impact of equipment types, and also the impact of a combination of equipment types.

In Section 4.1, it was explained that not all types of equipment can be used for all operations. Therefore, a distinction has been made in the equipment types that are used for the transportation task and for the loading task. For the transportation task from the warehouse to the pre-staging areas the double fork FLT and double fork LGV are considered. For the loading task manual loading, the single fork FLT, the single fork LGV and the ATLS are considered. Both the FLT as well as the LGV for the transportation part will be combined with each of the four options for the loading part. This results in a total of 8 scenarios that will be evaluated.

The hazards that arise in the area where the goods are transported from the warehouse to the pre-staging area or ATLS are the chance of two transporters colliding with each other, a transporter colliding with a stationary object in the warehouse and goods falling down due to improper stacking.

The hazards that arise due to the loading of goods depend on the loading method. In the case of manual loading, the injuries due to manual loading of goods should be taken into account. As workers are assumed to move very slow, it is assumed that no collisions between workers occur. However, a worker, can just like an FLT or LGV, fall off the loading dock due to a sudden movement of a truck. With an ATLS this cannot happen as it is a stationary device inside the warehouse. Furthermore, in the case of FLTs and LGVs, additional hazards that can occur are a collision with a worker, a collision with each other or load falling off the transporter onto a worker.

6.2.3. Number of aisles

The influence of the number of aisles will be evaluated using the picking process directly from warehouse as in this variation the change in number of aisles can most clearly be seen. For this scenario, the same input data as used for Den Bosch will be inserted. When the shape factor 2:1 is applied, the number of aisles within the warehouse storage area results to be 11. This situation is used as base case and will be compared to the situation where the number of aisles is either (approximately) doubled or halved, so when 22 and 5 aisles are present.

Changing the number of aisles is expected to have an influence on the number of crossings inside the warehouse, as the more aisles a warehouse has, the smaller the chance is that two or more transporters need to pick goods from the same aisle and the smaller the chance of a collision is. Therefore, it concerns the hazard of two transporters colliding with each other when transporting goods from the warehouse to the trucks.

6.2.4. Distance between loading points

In the case of Den Bosch, the loading points are positioned next to each other with a distance of 0.6 meter in between the loading points. This distance will be compared to the case in which the loading points are equally distributed over the warehouse. The impact of the distance between loading points will be evaluated for the same three scenarios as described in the previous section. Therefore the 11, 22 and 5 aisle configurations are considered.

Similar to the previous scenario, changing the distance between loading points is expected to have an influence on the number of crossings between transporters. Therefore the hazard of two transporters colliding with each other is concerned. However, in contrast to the previous scenario, this is expected to influence the number of crossings in the area where transporters drive in and out of the trucks.

6.2.5. Crossings on different level

To evaluate the impact that the engineering control measure of designing crossings on a different level has on the risk level, a path that currently crosses another path at the same level should be substituted. In this research, the crossings of workers and transporters inside the warehouse are removed.

The hazards that are concerned in this scenario involve the hazards in which a transporter interacts with a worker. These are the once in which a transporter collides with a worker and in which goods can fall off a transporter onto a worker.

6.3. Results

The results of the different scenarios, as described in the previous section, are provided in this section following the same sequence. The scores for the impact and probability are based on the information provided in Table 4.2. An overview of the results is provided at the end of the section. In Appendix C, the respective layouts of the described scenarios can be found.

6.3.1. Results picking process

For each size of brewery (small, medium and large), the results have been collected for all three picking processes (directly from warehouse, using cross-docking and using pre-staging). These concern the results regarding the number of times a hazard can potentially occur, the resulting frequency score, the risk level and other relevant data per scenario. This other data includes, amongst others, the number of loading points and number of transporters that are needed. In Tables 6.2 and 6.3, the results are presented for the small sized brewery. The results for the medium sized brewery are shown in Tables 6.4 and 6.5. Lastly, the results regarding the large sized brewery are provided in Tables 6.6 and 6.7. It can clearly be seen that the values for the required numbers of trucks, loading points, transporters, etc. increase with an increasing brewery size. Likewise, the number of crossings increases as well when the brewery gets bigger.

In Table 6.1, an overview is presented of the total risk level of each scenario. According to the safety expert within Heineken, it is allowed to sum the risk levels to be able to compare the combined risk level in one scenario to that of another. However, this is only allowed if the hazards in the different scenarios are similar. When considering the small brewery, the pre-staging process has the lowest risk level. This difference is mainly due to the fact that only one FLT was required for the transportation task and one for the loading task. Therefore, no crossings could occur between them. When the brewery gets bigger, the pre-staging process looses this advantage and it follows that the picking processes directly from warehouse and using cross-docking are more favourable.

Interesting is that for all brewery sizes the risk levels of the scenario directly from warehouse and using cross-docking are the same. Similarly, the medium and large breweries have the same risk level for those two picking processes as well. This would indicate that these four scenarios are equally safe. However, when looking at the actual number of crossings, significant differences can be found. For example, the number of times that a transporter crosses the path of another transporter is 95 for the medium brewery considering the picking process directly from warehouse, whereas it is 290 for the large brewery considering the picking process using cross-docking. Although there is a significant difference, they both fall in the highest scoring level of the frequency score as they both happen ‘several times per shift’. However, the cross-docking process contains in this case more dangers than the directly from warehouse process. This shows that the frequency scoring system does not have a sufficient number of scales to be able to make a distinction between frequencies of such magnitudes. It is therefore important to look at the actual number of times that a hazard can potentially occur as well. In the subsequent scenarios, they will therefore both be evaluated. At the end of this chapter, this apparent shortcoming of the method used will be discussed in more detail.

Table 6.1: Overview of the results of the risk levels regarding the three brewery sizes for the different picking processes.

	Small	Medium	Large
Directly from warehouse	1715	1835	1835
Using cross-docking	1715	1835	1835
Using pre-staging	1655	1895	1905

Table 6.2: The results for the potential number of times that a hazard can occur (#), the resulting frequency score (f) and the risk level for the small brewery (1 million hL/year) considering the three picking processes.

	Hazard	Directly from warehouse			Using cross-docking			Using pre-staging		
		#	f	Risk	#	f	Risk	#	f	Risk
1.	Injuries due to manual loading of goods	0	0	0	0	0	0	0	0	0
2.	Transporter colliding with worker	1	5	400	2	5	400	1	5	400
3.	Truck colliding with worker	0	3	180	0	3	180	0	3	180
4.	Truck colliding with truck driver	0	3	180	0	3	180	0	3	180
5.	Transporter colliding with transporter	1	5	150	1	5	150	0	1	30
6.	Truck colliding with truck	0	3	15	0	3	15	0	3	15
7.	Transporter striking against object	84	5	200	84	5	200	42	5	200
8.	Load falling from transporter onto worker	1	5	225	2	5	225	1	5	225
9.	Transporter falling off loading dock	84	5	200	84	5	200	84	5	200
10.	Goods fall down due to improper stacking	42	5	225	13	5	225	21	5	225
				1715			1715			1655

Table 6.3: The results of the number of trucks that arrive in peak hour, the required number of pre-staging areas, loading points and transporters, and the average pre-staging time, loading time and truck service time for the three picking processes in the case of a small brewery (1 million hL/year).

	Directly from warehouse	Using cross-docking	Using pre-staging
Number of trucks	2	2	2
Number of pre-staging areas	-	-	2
Number of loading points	2	2	2
Number of transporters	2	2	-
Number of transporter to pre-staging	-	-	1
Number of transporters from pre-staging	-	-	1
Average pre-staging time [min]	-	-	11
Average truck loading time [min]	21	21	21
Average truck service time [min]	31	31	31

Table 6.4: The results for the potential number of times that a hazard can occur (#), the resulting frequency score (f) and the risk level for the medium brewery (6 million hL/year), considering the three picking processes.

	Hazard	Directly from warehouse			Using cross-docking			Using pre-staging		
		#	f	Risk	#	f	Risk	#	f	Risk
1.	Injuries due to manual loading of goods	0	0	0	0	0	0	0	0	0
2.	Transporter colliding with worker	3	5	400	4	5	400	4	5	400
3.	Truck colliding with worker	0	3	180	0	3	180	0	3	180
4.	Truck colliding with truck driver	1	5	300	1	5	300	1	5	300
5.	Transporter colliding with transporter	95	5	150	160	5	150	64	5	150
6.	Truck colliding with truck	0	3	15	0	3	15	0	3	15
7.	Transporter striking against object	348	5	200	134	5	200	174	5	200
8.	Load falling from transporter onto worker	3	5	225	4	5	225	4	5	225
9.	Transporter falling off loading dock	348	5	200	348	5	200	348	5	200
10.	Goods fall down due to improper stacking	174	5	225	67	5	225	87	5	225
				1835			1835			1895

Table 6.5: The results of the number of trucks that arrive in peak hour, the required number of pre-staging areas, loading points and transporters, and the average pre-staging time, loading time and truck service time for the three picking processes in the case of a medium brewery (6 million hL/year).

	Directly from warehouse	Using cross-docking	Using pre-staging
Number of trucks	8	8	8
Number of pre-staging areas	-	-	8
Number of loading points	8	8	8
Number of transporters	4	4	-
Number of transporter to pre-staging	-	-	6
Number of transporters from pre-staging	-	-	4
Average pre-staging time [min]	-	-	18
Average truck loading time [min]	35	22	22
Average truck service time [min]	56	36	45

Table 6.6: The results for the potential number of times that a hazard can occur (#), the resulting frequency score (f) and the risk level for the large brewery (11 million hL/year), considering the three picking processes.

	Hazard	Directly from warehouse			Using cross-docking			Using pre-staging		
		#	f	Risk	#	f	Risk	#	f	Risk
1.	Injuries due to manual loading of goods	0	0	0	0	0	0	0	0	0
2.	Transporter colliding with worker	5	5	400	3	5	400	4	5	400
3.	Truck colliding with worker	0	3	180	0	3	180	0	3	180
4.	Truck colliding with truck driver	1	5	300	2	5	300	2	5	300
5.	Transporter colliding with transporter	281	5	150	290	5	150	169	5	150
6.	Truck colliding with truck	0	3	15	0	3	15	1	5	25
7.	Transporter striking against object	560	5	200	244	5	200	280	5	200
8.	Load falling from transporter onto worker	5	5	225	3	5	225	4	5	225
9.	Transporter falling off loading dock	560	5	200	560	5	200	560	5	200
10.	Goods fall down due to improper stacking	280	5	225	122	5	225	140	5	225
				1835			1835			1905

Table 6.7: The results of the number of trucks that arrive in peak hour, the required number of pre-staging areas, loading points and transporters, and the average pre-staging time, loading time and truck service time for the three picking processes in the case of a large brewery (11 million hL/year).

	Directly from warehouse	Using cross-docking	Using pre-staging
Number of trucks	14	14	14
Number of pre-staging areas	-	-	13
Number of loading points	13	13	12
Number of transporters	9	5	-
Number of transporter to pre-staging	-	-	8
Number of transporters from pre-staging	-	-	5
Average pre-staging time [min]	-	-	19
Average truck loading time [min]	39	26	22
Average truck service time [min]	69	52	46

6.3.2. Results level of automation

As said before in Section 6.2.2, the level of automation is evaluated using the pre-staging process as within this type of process most equipment combinations can be established. To clearly see the impact the level of automation (LoA) has on the risk level of both the transportation task and the loading task, these will first be evaluated separately. Subsequently, the overall risk level of the scenarios is determined. The impact of an accident remains the same for the different types of equipment. However, the probability that an accident occurs, changes for the different equipment types. An overview of the impact and probabilities was given in Table 4.2.

Influence of level of automation on the transportation task

The three hazards that are influenced by the type of equipment, as described in Section 6.2.2, are evaluated for both the FLT and the LGV. Additionally, the level of automation and the number of transporters that is needed to pre-stage the goods in time are provided. The results are presented in Table 6.8.

It can be seen that the total risk in the scenario where an LGV is used is much lower than in the scenario where an FLT is used, whereas the number of crossings is almost the same. This lower risk level is mainly due to the (much) lower probability (see Table 4.2). Because the LGV is not dependent on human handling but on sensors, the chance of a collision is much smaller. Therefore, the risk is much lower.

Table 6.8: The results for the level of automation (LoA), the number of transporters needed, the number of times that the hazard can occur, the frequency score and the risk level for the two types of equipment in the transportation part of the pre-staging picking process.

Equipment	LoA	Number of transporters	Hazard	Number of times hazard can occur	Frequency score	Risk level
FLT (double fork)	4	6	FLT colliding with other FLT	49	5	150
			FLT colliding with an object	174	5	200
			Goods falling down on FLT	87	5	225
						575
LGV (double fork)	7	8	LGV colliding with other LGV	40	5	5
			LGV colliding with an object	174	5	5
			Goods falling down on LGV	87	5	225
						235

Influence of level of automation on the loading task

In Table 6.9, the hazards are presented which can occur in the loading area when using a specific loading method. From every method the level of automation, the number of transporters that are required, and the corresponding number of crossings, the frequency score and the risk level are evaluated.

With respect to the loading task it can be seen that, except for the use of FLTs, the risk level generally decreases with an increase in the level of automation. Especially when an ATLS is used, the risk level is extremely low. This is due to the fact that none of the ten hazards occurs when considering the hazards that can occur in the loading part. The reason that the risk level in the scenario where FLTs are used is high is mainly because the interaction between FLTs and pedestrians is particularly high.

Table 6.9: The results for the level of automation (LoA), the number of transporters needed, the number of times that the hazard can occur, the frequency score and the risk level for the two types of equipment in the transportation part of the pre-staging picking process.

Equipment	LoA	Number of transporters	Hazard	Number of times hazard can occur	Frequency score	Risk level
Manual loading	2	4	Injured due to manual loading	174	5	200
			Worker falling off loading dock	348	5	200
						400
FLT (single fork)	4	4	FLT colliding with worker	4	5	400
			FLT colliding with other FLT	8	5	150
			Load falling off FLT onto worker	4	5	225
			FLT falling off loading dock	348	5	200
						975
LGV (single fork)	7	5	LGV colliding with worker	3	5	10
			LGV colliding with other LGV	8	5	5
			Load falling off FLT onto worker	3	5	7.5
			LGV falling off loading dock	348	5	200
						222.5
ATLS	7	8				0
						0

Influence of level of automation on the overall risk level

To show the influence of the level of automation on the overall risk level of both the transportation and loading task, the results are combined in Table 6.10, in which the results are sorted in descending order from highest to lowest risk level. As sometimes different equipment types are used, the level of automation is taken as an average number of the two types of equipment. In case this results in a number with decimals, the level of automation is rounded down to an even number.

The results show that the combinations with the highest level of automation have the lowest risk level. When considering the top four combinations with the highest risk, it can be seen that the FLT is included in all of them. Only the combination in which the FLT is combined with the ATLS results in a relatively low risk, but this is mainly because the ATLS has a very low risk. In principle, it can be said that the level of automation decreases the risk level, except for the scenario in which FLTs are involved. It is therefore good to critically consider the use of FLTs at all, as they are always a big danger in the area.

Table 6.10: The combined results for the transportation part and the loading part in the pre-staging picking process considering the level of automation (LoA).

Transportation equipment	Loading equipment	Level of automation	Risk level transportation part	Risk level loading part	Overall risk level
FLT (double fork)	FLT (single fork)	4	575	975	1550
LGV (double fork)	FLT (single fork)	5	235	975	1210
FLT (double fork)	Manual loading	3	575	400	975
FLT (double fork)	LGV (single fork)	5	575	222.5	797.5
LGV (double fork)	Manual loading	4	235	400	635
FLT (double fork)	ATLS	5	575	0	575
LGV (double fork)	LGV (single fork)	7	235	222.5	457.5
LGV (double fork)	ATLS	7	235	0	235

6.3.3. Influence of the number of aisles on the risk level

In Table 6.11, the results of the scenarios in which the number of aisles is varied are presented for the case that there are 11 aisles (when the shape factor is 2:1), 5 aisles and 22 aisles. Similar to the results found for the picking processes, the frequency score and the risk level are identical in all scenarios whereas the number of crossings do differ. The highest number of crossings appears to occur in the most efficient layout, so the one with 11 aisles.

When looking at the number of transporters that is required to guarantee the truck service time of 30 minutes, it is interesting to see that four transporters are needed in the 11 aisle and 22 aisle configurations, whereas five transporters are needed in the 5 aisle configuration. However, although there is one transporter more in the 5 aisle configuration, the number of crossings is almost similar to that of the 22 aisle configuration.

By looking more closely at the location where the crossings occur, it follows that most crossings occur in the area where transporters drive in and out of the truck. It is therefore not strange that most crossings happen in the scenario with the most efficient layout as in this scenario the transporters load the pallets in the shortest time. This results in the most frequent movements in this area, which again increases the chance of a crossing. Because of the location where most of the potential crossings occur, it follows that changing the number of aisles alone does not have a big influence on the number of crossings. Therefore, the number of aisles is evaluated in combination with equally distributing the doors over the width of the warehouse in the next section, to see whether a combination of them has an influence on the risk level.

Table 6.11: The results on the number of crossings that occur between transporters within the warehouse and the number of transporters that are needed when varying the number of aisles.

Number of aisles	Number of transporters	Number of times crossings can occur	Frequency score	Risk level
11 aisles	4	107	5	150
5 aisles	5	83	5	150
22 aisles	4	82	5	150

6.3.4. Results distance between loading points

In this section, the three scenarios as described in the previous section are compared to the case of equally distributed dock doors along the side of the warehouse. The results are presented in Table 6.12. It can be seen that the number of possible path crossings has increased in the case of 11 aisles, is approximately similar for 5 aisles and has decreased for 22 aisles. This indicates that a wider layout is beneficial when the loading points are evenly distributed over the width.

In the case of 11 aisles one might also expect a decrease in number of crossings as there are more aisles than loading points in the 11 aisle configuration. It should therefore be possible to (partly) separate the transporters. In the 5 aisle scenario this is more difficult as there are more loading points than aisles and therefore the chance is higher that transporters need to retrieve goods from the same aisle and cross each others paths. In the brewery in Den Bosch they load trucks that arrive at the far left loading point as much as possible with goods from the left side of the warehouse. If a similar chance would be inserted in the model, the number of crossings can be reduced a lot for, in particular, the 11 aisle and 22 aisle configurations. More on this will be described in the discussion of this research, in Chapter 8.

Table 6.12: The results on the number of crossings that occur between transporters within the warehouse and the number of transporters that are needed when varying distance between loading points.

Number of aisles	Distribution of the doors	Number of transporters	Number of times crossings can occur	Frequency score	Risk level
11 aisles	Close to each other	4	107	5	150
	Equally distributed	4	116	5	150
5 aisles	Close to each other	5	83	5	150
	Equally distributed	5	86	5	150
22 aisles	Close to each other	4	82	5	150
	Equally distributed	4	66	5	150

6.3.5. Results crossings on different level

The hazards that are concerned in this scenario involve the hazard in which a transporter collides with a worker and the hazard in which goods can fall off a transporter onto a worker. In the results presented in Section 6.3.1, these risk levels were calculated for the use of FLTs. The risk level corresponding to those two hazards were 400 for an FLT colliding with a worker and 225 for goods falling off an FLT onto a worker in all scenarios. This results in a combined risk of 625. These risk levels were determined for the case that FLTs are used. Therefore, the risk can be reduced by 625 when the crossings between FLTs and pedestrians are separated by implementing a crossing on a different level. This would mean that the total risk is reduced by approximately a third (in the case of using FLTs). When considering the case in which LGVs are used, the combined risk for the two hazards is only 10 (5 for each hazard). The reduced risk would in this case only be reduced by 10.

6.3.6. Overview results

When looking at the results of the five different design choices, it was found that for small breweries the picking process using pre-staging results in the lowest risk, whereas for increasing brewery sizes the other two picking processes, directly from warehouse and using cross-docking, resulted in a lower risk level. Furthermore, it followed that an increase in level of automation generally causes a decrease in risk level. The exception in this case was the use of FLTs, which resulted in a very high risk level, especially when they come in contact with pedestrians. Therefore, the use of FLTs can generally better be avoided. Thirdly, a change in the number of aisles in itself did not necessarily influence the number of crossings that occurred. However, when considering the number of aisles in combination with evenly distributing the loading points over the width of the warehouse, it was found that an increase in aisles reduces the risk level. Especially when certain aisles are dedicated to certain loading points, most crossings are expected to be eliminated. Lastly, by implementing crossings on a different level, and therefore removing the crossings between transporters and workers, the risk can be reduced. Especially when using FLTs, this reduction is significant (by almost a third).

6.4. Discussion on the results

While analysing the results, it often occurred that the frequency score resulted in the maximum score of 5, despite a significant difference in the actual number of times that a hazard could potentially occur, which was also found in Chapter 5. The score of 5 indicates that the hazard occurs ‘several times per shift’. From the results it follows that almost all hazards analysed in this research occur ‘several times per shift’. This is partly due to the fact that the top three most occurring accidents have been analysed, but it does not take away that the current system makes it impossible to distinguish between activities that happen often or very often. As the specific activities that take place in the warehouse loading area typically occur a lot, the current system is not specific enough. Therefore, it is proposed to extend the definition of the frequency score to make it suitable for the warehouse loading area. An alternative, extended method to improve the current frequency scoring system, applicable in areas where hazardous situations arise more regularly, is proposed in the next chapter.

7

Alternative Frequency Scoring System

The frequency scoring system from 1 to 5 currently used by Heineken, has, in the previous chapter, proven to be insufficient with respect to the type of activities that typically occur in the warehouse loading area. Therefore, an extension of the frequency scoring system is proposed in this chapter. An overview of the problem with respect to the current system is shortly explained in Section 7.1. Subsequently, in Section 7.2, the proposed system is described. To evaluate the impact of the alternative system, it is tested in Section 7.3. Finally, a discussion on the proposed system is provided in Section 7.4.

7.1. The problem

For clarity, the system with which the frequency score is currently determined is presented again in Table 7.1, in which the score goes from 1 to 5. Currently, when a hazard is not present in an area, this hazard is not included in the analysis. However, when evaluating different designs, specific hazards might occur in one design which do not occur in other designs. For example, injuries due to manual loading of goods did not occur in all scenarios described in the previous chapter. Currently, this hazard would not have been included in the list of hazards at all. However, when a consistent analysis is desired, it is better to include all hazards and score those that do not occur a zero. In this way, the type of hazards are always similar and a good comparison can be made.

Table 7.1: Definition of the score for the frequency of an activity, as used by Heineken.

Score	Frequency of activity
5	Activity performed several times per shift.
4	Activity performed 1 - 3 times per day.
3	Activity performed 1 - 3 times per week.
2	Activity performed 1 - 3 times per month.
1	Activity performed 1 - 3 times per year.

Furthermore, it became clear that the current system has its shortcomings for an area where typically a lot of movements occur. For the warehouse loading area, where this is the case, the frequency score almost always resulted to be 5. However, the actual number of times that a hazard could possibly occur varied from 3 up to 560 times per hour. In the next section, an alternative system is proposed to make it more suitable for areas in which typically a lot of activities occur.

7.2. Proposed system

The proposed system should be able to score the typical activities occurring in the warehouse loading area in a better way, by especially enabling a better distinction in the case that activities occur multiple times per hour. In literature, different classifications can be found to score the likelihood of an accident (which is the combination of frequency and probability) [Ilbahar et al., 2018, Jacinto and Silva, 2010, Lyon et al., 2016, Reniers et al., 2005]. However, a specific method to classify the frequency score has not been found. Besides that, the scoring systems found for the likelihood of an accident are mostly using a subjective scoring system, like accidents happen very rarely, frequently, continuously, etc. However, as the frequency score is directly related to the number of times an activity occurs, it is proposed to use the available numbers, as calculated by the model, to establish a scoring system based on actual data. This is also encouraged in literature, by for example Ilbahar et al. [2018] and Jacinto and Silva [2010]. As there is no risk assessment method appropriate for all business areas, as stated by Gul and Ak [2018], the proposed system will specifically be developed for the warehouse loading area and is based on the collected data in this research.

The calculated number of times that the different hazards could potentially occur showed a big spread. Therefore, a linear distribution to score the frequency is not desired. Instead, an exponential distribution is proposed for the alternative scoring system. In this way, it remains possible to distinguish between activities that have a lower occurrence. For the higher occurrences this will be less precise using the exponential distribution, but it is assumed that the distinction between the activities that occur 500 times or 600 times is less important than the distinction between 2 and 10 times.

The results found for the picking processes, as presented in Tables 6.2, 6.4 and 6.6, give a clear overview of the deviation in the number of times that a hazard can occur, which ranges from 0 up to 560. Based on these numbers, a suitable exponential distribution is chosen. Based on the calculated number of times that a hazard occurs, a suitable value for the base number follows to be 6. By calculating the number of times a hazard can potentially occur per year, using 6^{n-1}, in which n is equal to the frequency score and -1 compensates for the score of 0, a scoring system from 0 to 10 results. In Table 7.2, the frequency scores and corresponding descriptions are presented, by which the descriptions are translated into comprehensible units. The term 'activity performed' is adopted from the current frequency scoring system and represents the number of times that a hazard can potentially occur. The score of 0 represents the case in which the hazard cannot occur. In this way, a comparison of the same hazardous situations can be conducted for different designs without having to change the list of hazards every time. When due to a change in design, the hazard will be present, it can easily be taken into account again as it will have a score for the impact and probability.

Table 7.2: Proposed alternative to score the frequency, as used by Heineken. The term 'activity performed' is adopted from the current frequency scoring system and represents the number of times that a hazard can potentially occur.

Score	Frequency of activity *(6^{n-1} per year, where n = score)*
10	Activity performed up to 1150 times per hour.
9	Activity performed up to 192 times per hour.
8	Activity performed up to 32 times per hour.
7	Activity performed up to 5 times per hour.
6	Activity performed up to 1 time per hour.
5	Activity performed up to 1 time per shift (8 hours).
4	Activity performed up to 1 time per day.
3	Activity performed up to 1 time per week.
2	Activity performed up to 1 time per month.
1	Activity performed up to 1 time per year.
0	Activity cannot occur.

7.3. Test case

To see what the impact of the alternative system is on the resulting risk levels, the system is tested for the scenario in which the three picking processes (directly from warehouse, using cross-docking and using pre-staging) are compared. This is done for all three brewery sizes (small, medium and large). In Tables 7.3, 7.4 and 7.5 the results are presented using the alternative frequency scoring system. An overview of the risk levels using both the current system and the alternative system is provided in Table 7.6.

Table 7.3: The results for the potential number of times that a hazard can occur (#), the resulting frequency score (f) and the risk level for the small brewery (1 million hL/year) using the alternative frequency scoring system, considering the picking processes directly from warehouse, using cross-docking and pre-staging.

	Hazard	Directly from warehouse			Using cross-docking			Using pre-staging		
		#	f	Risk	#	f	Risk	#	f	Risk
1.	Injuries due to manual loading of goods	0	0	0	0	0	0	0	0	0
2.	Transporter colliding with worker	1	6	480	2	7	560	1	6	480
3.	Truck colliding with worker	0	3	180	0	3	180	0	3	180
4.	Truck colliding with truck driver	0	3	180	0	3	180	0	3	180
5.	Transporter colliding with transporter	1	6	180	1	6	180	0	0	0
6.	Truck colliding with truck	0	3	15	0	3	15	0	3	15
7.	Transporter striking against object	84	9	360	84	9	360	42	9	360
8.	Load falling from transporter onto worker	1	6	270	2	7	315	1	6	270
9.	Transporter falling off loading dock	84	9	360	84	9	360	84	9	360
10.	Goods fall down due to improper stacking	42	9	405	13	8	360	21	8	360
				2430			2510			2205

Table 7.4: The results for the potential number of times that a hazard can occur (#), the resulting frequency score (f) and the risk level for the medium brewery (6 million hL/year) using the alternative frequency scoring system, considering the picking processes directly from warehouse, using cross-docking and pre-staging.

	Hazard	Directly from warehouse			Using cross-docking			Using pre-staging		
		#	f	Risk	#	f	Risk	#	f	Risk
1.	Injuries due to manual loading of goods	0	0	0	0	0	0	0	0	0
2.	Transporter colliding with worker	3	7	560	4	7	560	4	7	560
3.	Truck colliding with worker	0	3	180	0	3	180	0	3	180
4.	Truck colliding with truck driver	1	6	360	1	6	360	1	6	360
5.	Transporter colliding with transporter	95	9	270	160	9	270	64	9	270
6.	Truck colliding with truck	0	3	15	0	3	15	0	3	15
7.	Transporter striking against object	348	10	400	134	9	360	174	9	360
8.	Load falling from transporter onto worker	3	7	315	4	7	315	4	7	315
9.	Transporter falling off loading dock	348	10	400	348	10	400	348	10	400
10.	Goods fall down due to improper stacking	174	9	405	67	9	405	87	9	405
				2905			2865			2865

Table 7.5: The results for the potential number of times that a hazard can occur (#), the resulting frequency score (f) and the risk level for the large brewery (11 million hL/year) using the alternative frequency scoring system, considering the picking processes directly from warehouse, using cross-docking and pre-staging.

	Hazard	Directly from warehouse			Using cross-docking			Using pre-staging		
		#	f	Risk	#	f	Risk	#	f	Risk
1.	Injuries due to manual loading of goods	0	0	0	0	0	0	0	0	0
2.	Transporter colliding with worker	5	7	560	3	7	560	4	7	560
3.	Truck colliding with worker	0	3	180	0	3	180	0	3	180
4.	Truck colliding with truck driver	1	6	360	2	7	420	2	7	420
5.	Transporter colliding with transporter	281	10	300	290	10	300	169	9	270
6.	Truck colliding with truck	0	3	15	0	3	15	1	6	30
7.	Transporter striking against object	560	10	400	244	10	400	280	10	400
8.	Load falling from transporter onto worker	5	7	315	3	7	315	4	7	315
9.	Transporter falling off loading dock	560	10	400	560	10	400	560	10	400
10.	Goods fall down due to improper stacking	280	10	450	122	9	405	140	9	405
				2980			2995			2980

Table 7.6: Overview of the results for the risk levels calculated using the current method (old risk level) and using the alternative method (new risk level) for the determination of the frequency score.

Picking process	Old risk level			New risk level		
	Small	Medium	Large	Small	Medium	Large
Directly from warehouse	1715	1835	1835	2430	2905	2980
Using cross-docking	1715	1835	1835	2510	2865	2995
Using pre-staging	1655	1895	1905	2205	2865	2980

Based on the alternative frequency scoring system, it follows that for different brewery sizes a different picking process(es) result(s) in a lowest risk. For small breweries, the pre-staging method results in the lowest risk. When the brewery size reaches the medium size, both the picking process using cross-docking and using pre-staging result in a slightly lower risk than the picking process directly from warehouse. Lastly, for large breweries it is slightly better to use the picking process directly from warehouse or using pre-staging instead of using cross-docking.

7.4. Discussion on the proposed system

Comparing the results of the alternative system with the results of the current system, it can be seen that it is now better possible to distinguish between the type of activities that occur ‘several times per hour’. The frequency scores for activities that occur 5 times per hour or 100 times per hour, which is typical for the warehouse loading area, now get a different score. It follows that the alternative frequency scoring system, based on an exponential distribution, makes the calculation of the risk level more specific. Due to this, a better comparison is made between the different scenarios, as tested for the picking processes. Firstly, it can be seen that the risk levels corresponding to the picking processes directly from warehouse and using cross-docking now deviate, whereas they were similar (for all three brewery sizes) using the current scoring system. Additionally, the change in risk level between breweries of a different size is clearer using the alternative system. Especially the difference between small and medium breweries is bigger when using the alternative system. However, when the brewery size increases, the risk levels converge towards each other. Although an increase can be found between the risk levels of a medium and large brewery when using the alternative system, whereas they were similar using the current system, the risk levels do not deviate a lot. It might therefore be necessary to further extend the scoring system to be able to better distinguish between activities that happen a lot and to more clearly see the difference for breweries with an increasing size.

8 Discussion

In this research, a method has been developed to easily evaluate the impact of different design choices on the level of safety. It has been shown that safety can be quantified by one single value, the risk level, and that in this way various designs can be evaluated and compared. The parametric model has shown to be an effective way to evaluate different designs by changing individual parameters.

The risk level was the result of the possible impact of an accident, the frequency that an activity is performed and the probability that an activity results in an accident. These three parameters were all based on their individual scoring systems. However, it was found that the current frequency scoring system was not adequate to use for the warehouse loading area. The system has therefore been extended to better distinguish between the type of activities that typically occur in the area. By changing these scores, different picking processes resulted in a lower risk than when using the current system. This shows that a change in classification has an impact on the preferred design choices. As the alternative frequency scoring system has only been tested for the picking processes and not for the remaining scenarios, it could be that these would result in a different preferred design choice. This should be taken into account when analysing the results.

Likewise, the frequency scoring has been changed to have a scale from 0 to 10 in the alternative scoring system. However, it was found in Chapter 7 that the risk levels for increasing breweries were still almost similar. It might therefore be necessary to further extend the frequency system to even better distinguish between the number of times that activities occur. What would, for example, happen if this scale would be extended to a scale from 0 to 20? Will other design choices result in a lower risk?

Furthermore, the determination of the scores for the impact and the probability of the various hazards are based on the opinion of a safety expert. As these were determined by a human, there is always a certain level of subjectivity involved. When these scores would be determined by another safety expert, it can be that he/she scores the values (slightly) different, which would subsequently result in a different risk level. Due to this, possibly other choices might result in a lower risk level than found in this research. For example, in the case of determining the score for the probability, the influence of subjectivity can be removed by calculating the probability instead of subjectively determining it. If the number of times that the activity is performed as well as the number of times that this activity actually results in an accident is calculated, the probability can be derived based on real data.

Lastly, the preferred design decisions have only been based on the aspect of safety. However, in the complete design process other aspects, such as efficiency, costs, energy usage, etc., also influence the design. It is therefore important to take these into account as well, in order to have a complete assessment of the design.

9 Conclusion

The goal of this research was to investigate the influence of safety on design choices regarding the warehouse loading area. For this, the impact that different design choices have on the risk level needed to be determined. To easily assess multiple design decisions a parametric model has been developed in which different design concepts could be generated. In this chapter, the final conclusions are presented (in Section 9.1) and recommendations for further research are provided (in Section 9.2).

9.1. Conclusions

Using the parametric model, the risk level resulting from the twelve most occurring hazards in the warehouse loading area of Heineken can be evaluated for different scenarios. This risk level was determined according to the risk assessment methodology developed by the American Society of Safety Professionals. According to their methodology, the risk level was the result of the possible impact of an accident, the frequency that an activity is performed and the probability that an activity results in an accident. For the twelve hazards, the impact and probability were determined with the help of a safety expert. The impact number remained the same in all cases, whereas the probability number of a hazard varied for different types of equipment. The number of times an activity could result in a hazard was determined by the parametric model. From this, the risk level for the hazards was calculated.

Subsequently, different scenarios were evaluated to see what impact a certain decision regarding a layout or equipment choice had on the risk level. Decisions regarding the type of picking process, the level of automation, the number of aisles, the distance between loading points and designing crossings on a different level have been evaluated. Using the frequency scoring system as currently used by Heineken, it was found that for small breweries the picking process using pre-staging results in the lowest risk, whereas for increasing brewery sizes the other two picking processes, directly from warehouse and using cross-docking, resulted in a lower risk level. Furthermore, it followed that an increase in level of automation generally causes a decrease in risk level. The exception in this case was the use of FLTs, which resulted in a very high risk level, especially when they come in contact with pedestrians. Therefore, the use of FLTs can generally better be avoided. Thirdly, a change in the number of aisles in itself did not necessarily influence the number of crossings that occurred. However, when considering the number of aisles in combination with evenly distributing the loading points over the width of the warehouse, it was found that an increase in aisles reduces the risk level. Especially when certain aisles are dedicated to certain loading points, most crossings are expected to be eliminated. Lastly, by implementing crossings on a different level, and therefore removing the crossings between transporters and workers, the risk can be reduces. Especially when using FLTs, this reduction is significant (by almost a third).

As it was found that the current frequency scoring system could not properly distinguish between the activities that typically occur in the warehouse loading area, an alternative system has been proposed. By using an exponential distribution a better distinction could be made. This alternative system was tested by evaluating the three picking processes. Using the proposed scores, it followed that the picking process using pre-staging is best in case the brewery is small, the picking process cross-docking or using pre-staging is best for a medium brewery and although the risk levels are almost similar for large breweries, it is slightly better to use the picking process directly from warehouse or using pre-staging for large breweries.

In conclusion and to answer the main research question: *What is the influence of safety on design decisions regarding the warehouse loading area?*, it is shown that, when taking safety into account, the design is influenced in the direction of:

- Small breweries would be designed to use the picking process using pre-staging;
- Medium breweries would be designed to either use the picking process using cross-docking or using pre-staging;
- Large breweries would be designed to either use the picking process directly from warehouse or using pre-staging;
- Equipment with a higher (combined) level of automation would be used;
- The use of FLTs would be eliminated;
- The loading points would be evenly distributed over the width of the warehouse;
- The number of aisles would be increased;
- All crossings between pedestrians and moving vehicles would be designed on a different level.

9.2. Recommendations

This research has provided a method and tool to quantify and evaluate different designs for the warehouse loading area. In this section, recommendations are proposed to extend the current research.

The first recommendation concerns an extension of the model with respect to the number of layout configurations. In literature, many configurations in which the warehouse area is arranged in the most efficient way have been analysed. Their impact on safety has not yet been evaluated and it is interesting to see what the impact of an increase in efficiency is on the risk level. Additionally, instead of only considering the warehouse loading area, the model can be extended by considering the entire brewery. By defining the parametric relations between them, design concepts can be generated in which all buildings and routes are included. In this way, the resulting risk level of an entire brewery can be easily evaluated.

Secondly, when considering more areas in the model, it is recommended to do further research into the frequency scoring system. As it was found that the current frequency scoring system was not adequate to use for the warehouse loading area, it can be that it is better to adapt the frequency scoring system for other areas as well.

Furthermore, the total risk level of a design has been calculated by taking the sum of the risk levels of each individual hazard in that design. However, it has not been considered that some hazards directly influence other hazards, due to which they should maybe partially be summed instead of fully. This would cause a reduction in risk. As the impact of this partial summation can have a bigger impact in one scenario than in another, it can influence the preferred design choices. This is therefore an interesting aspect to further evaluate.

Another important aspect, that has a significant impact on the number of crossings between transporters inside the warehouse, is that the model did not take into account that trucks positioned at the left side of the warehouse are, as much as possible, being loaded with goods from the left side of the warehouse. In Den Bosch, for example, this was the case. Including this chance will influence the number of crossings between transporters as they will be separated from each other much more than they were now, as they were picking the goods randomly from any location in the warehouse. Especially when considering the number of aisles in the warehouse, this is expected to have a huge impact.

In this research, the risk level was the outcome resulting from the respective layout that was considered. An interesting aspect to evaluate is to see the effect when the risk level is used as input. For this, all design choices should be given a risk level, both individually as well as in certain relations. By changing the risk level, different design configurations will then result based on the allowed risk that is inserted.

Lastly, the possible designs have (only) been evaluated for the twelve hazards which correspond to the top three most occurring accidents in the warehouse loading area. However, to make a final design, other potential hazards should be considered as well as they can have an impact on the risk level too. Similarly, this applies for including other aspects, such as efficiency, costs, energy usage, etc., in the model. In this way, a complete assessment of a design can be conducted.

A

Research Paper

The Quantification and Evaluation of Safety in the Design Process

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***Abstract*— Occupational accidents happen every day and are a major concern across industries, both from a people and financial perspective. An effective design and layout of a workplace can eliminate hazards and contribute to a safer working environment. For this reason, it is important to show the impact of different design choices on safety in an early stage of the design process. The aim of this research is therefore to develop a method which enables the quick generation of design concepts and compare them with respect to safety.**

I. INTRODUCTION

Occupational injuries are a major concern across industries, both from a human suffering as well as a financial point of view [Sun et al., 2006]. The European Agency for Safety and Health at Work has estimated that 4.6 million occupational accidents happen in the EU every year, resulting in 146 million lost working hours [EU OSHA]. In an earlier survey of workplace injury costs in the US, Miller and Galbraith estimated the costs of workplace injuries to be $140 billion annually in the US alone. Preventing occupational accidents is therefore both good for the wellbeing of employees as well as for business [Dorman, 2000].

According to Zakaria et al. [2012], the design is one of the crucial parts in avoiding accidents in the workplace. An effective design and layout of a workplace can eliminate some hazards and help to get a job done safely and properly. When the design and layout of the workplace are done inadequately, this can frequently contribute to accidents by hiding hazards that cause injuries. Additionally, Booth [1979] indicates that the prevention of workplace accidents in the design phase of the workplace is not difficult, but once a dangerous layout is created it is much more difficult to correct. It is therefore imperative that more attention is paid to the design stage within the working environment.

In literature, the conceptual design phase is seen as the most crucial phase. According to Pahl and Beitz [1996], conceptual design determines the principle of a solution. Hsu and Liu [2000] found that decisions made during conceptual design have significant influence on the cost, performance, reliability, safety and environmental impact of a product. They estimated that design decisions account for more than 75% of the final product costs. This is emphasised by Dieter and Schmidt [2009], who looked into the percentage of costs that are committed and incurred in different design phases: "Decisions made in the design process cost very little in terms of the overall product cost but have a major effect on the cost of the product".

According to Wang et al. [2002], conceptual design is perhaps the most crucial task in an engineering development cycle, but it is also very difficult to accomplish. The impact of design decisions is initially very high, but there is not much information available to base decisions on. The impact that one can have declines steeply as the design matures, but the knowledge (or tools) that are available rises, which is shown in Figure 1. In the beginning of a design process there is great opportunity. In subsequent phases, it becomes very difficult to compensate the shortcomings of a poor design concept that has been formulated in an early phase. These findings show that it is important to make good design decisions in an early design phase. Zakaria et al. [2012] and Booth [1979] especially emphasise the importance of a good design to avoid accidents.

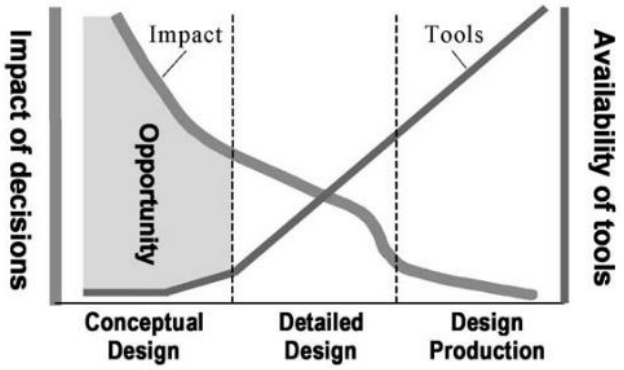

Fig. 1: Relation between the impact of decisions and the availability of tools in different design phases [Wang et al., 2002].

Borg et al. [2003] and Lim et al. [2004] found that designers prefer freehand paper-based sketches during the early design phase, despite the availability of Computer-Aided Design (CAD) technology. A disadvantage of this is that designs are not easily adjustable in a later phase. Additionally, the designs are heavily influenced by ones preference and personal experience, but do not necessarily have to result in the most optimal designs. For example, the person designing might be lacking some of the knowledge due to which a more suitable solution for a specific case is not found. As said by Stone et al. [2002]: "If the designer is experienced or works with experienced engineers, they could draw on their own knowledge or on the experience of others. However, relying only on knowledge gained from one's own past experiences limits the design possibilities and biases the design process".

However, rigid user-interfaces, like CAD, are found to hinder freedom, intuitiveness and creative idea generation, and are therefore not suitable for the generation of various concepts [Naya et al., 2002, Roemer et al., 2001]. According to Balzan et al. [2008], designers need appropriate tools which integrate paper-based sketching with CAD, which would create the possibility to create a form concept which can subsequently be edited to explore form variation. They state that this design collaboration can only be effectively established if the generated model is a parametric model containing the geometric design intent of the designer. In this way, variations can be applied to the model while maintaining the unvaried geometric design intent.

The aim of this research is therefore to develop a parametric model which enables the easy generation of design concepts and to evaluate these designs with respect to their impact on safety. The remainder of this paper consists of 5 sections. In Section II, it is explained how parametric modelling can be used to evaluate designs. In order to compare different designs with respect to safety, a method to quantify safety is provided in Section III. In Section IV, a test case is described in which the evaluation of different designs is tested. Finally, a discussion and conclusion are provided in Sections V and VI, respectively.

II. EVALUATION OF THE DESIGNS

In order to compare and evaluate different designs a parametric model has been developed. Parametric modelling is a design strategy associated with algorithmic scripting, in which geometric relations are represented by using relations between parameters, constraints and equations [Lee et al., 2014]. In parametric design form is shaped by values of parameters and equations are used to describe the relationships between the forms [Milena and Ognen, 2011]. According to Nagy et al. [2017], parametric design allows the designer to not only define a final geometric solution, but to describe the entire system behind how a design is generated. In Figure 2, an example is presented of the relationships that describe a system using a graphical algorithm editor, like Grasshopper. In Figure 3, these relationships are described using a text-based algorithm editor, like Python.

Although it takes more work to describe such a model initially, Nagy et al. mention three main advantages that parametric design offers for the designer. Firstly, once the initial model is defined, the parametric approach makes it easy to create variations and custom adaptations of a design. Instead of manually creating multiple variations, the designer can change critical parameters that drive different variations and automatically generates different versions. A second advantage is that a well-structured parametric model is more adaptable to change in the future. Since it is defined by a series of operations, the design can be easily adapted to changing conditions instead of rebuilding the model from scratch each time. Lastly, it allows designers to think in a deeper and more dynamic way than possible with traditional methods. In the traditional approach, the designer usually studies the design problem, defines the constraints and objectives, and uses their skill and experience to craft a single design solution, or maybe a view at most. Instead of designing a single solution, the designer can generate a variety of solutions using the parametric approach. According to Lee et al. [2013b,a] and Iordanova [2007], parametric design is fundamental to creativity through design exploration during the conceptual design phase, where variations can be generated by alternating design parameters, topological relationships, and rule algorithms.

A limitation of the parametric approach, as mentioned by Nagy et al., is that the exploration of the design space is still limited by the abilities of the human designer. The reason given for this is that the different options must still be investigated by the human designer by manually varying the parameters. Aish and Woodbury [2005] state that the downside of parametric modelling in the conceptual design lays in the fact that "nothing can be created in a parametric system for which a designer has not explicitly externalised". This is emphasised by Moussavi [2011], who state that parametric design cannot advance beyond new ways of shaping matter to produce unexpected spaces.

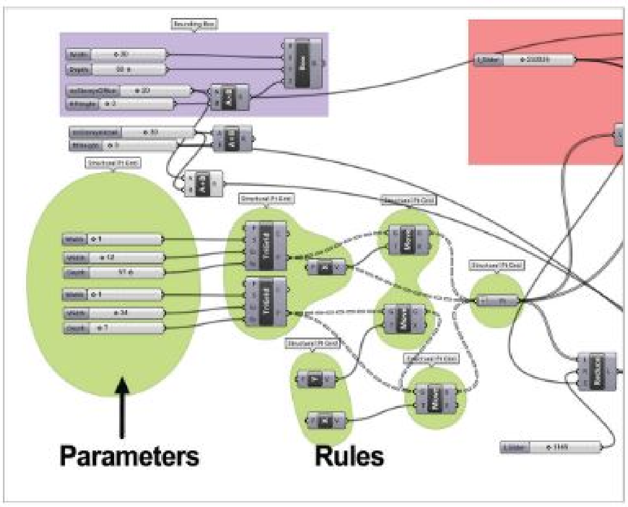

Fig. 2: Examples of parameters and rules in a graphical algorithm editor (Grasshopper), retrieved from [Lee et al., 2014].

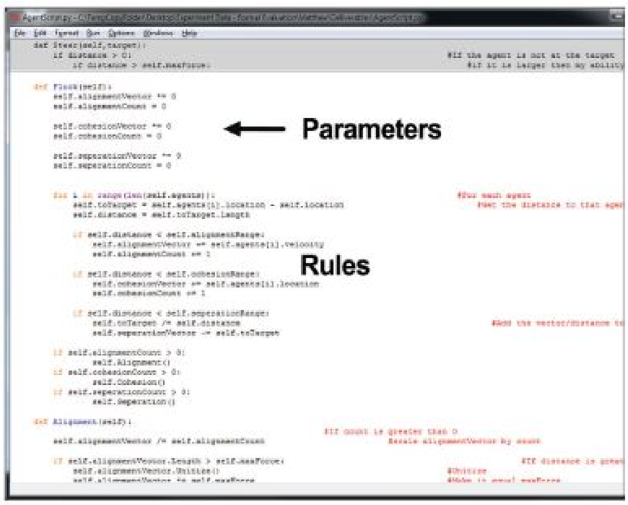

Fig. 3: Examples of parameters and rules in a text-based algorithm editor (Python), retrieved from [Lee et al., 2014].

A possible next step, to account for these limitations, is explored by Nagy et al., which is called generative design. Generative design explores the design space semi-autonomously and therefore allows a much deeper exploration of complex design spaces. Generative design is different from parametric design in that the rough outlines of the model are not known in advance. To go from a basic parametric model to a generative model, the parametric model must be extended in two ways [Nagy et al., 2017]. Firstly, the model must include a concrete metrics by which each design option can be evaluated in order for the computer to determine which designs perform better than others. Secondly, the model needs to be connected to a search algorithm that can control the input parameters of the model, get feedback from the metrics, and intelligently tune the parameters to find high performing designs while also exploring the full possibilities of the design space. A disadvantage of generative design, as stated by Moussavi [2011], is that although implicit low-level rule systems can offer wide design exploration due to their lack of structure, they often act as black boxes to human observers.

The goal of this research is to evaluate the impact of specific design decisions on the safety performance of a design. Because of this reason, it creates more clarity for the designer if the designer can manually change the respective parameter(s) to see the direct impact of this. Within the generative approach it is less clear to the designer what happens, as the model is more like a black box than in the parametric approach. By using the parametric approach instead of the generative approach, the designer is more in control of what happens. In the case of this research, it means that the impact of a design decision can clearly be seen, which is the goal. For this reason, the designs are created using the (basic) parametric approach, without the generative component.

As parametric modelling is now well established within the computational design community [Harding and Shepherd, 2017], several software packages offer graphical algorithm editors [Milena and Ognen, 2011]. In the evaluated literature, the most mentioned parametric application is Grasshopper [Lee et al., 2014, Milena and Ognen, 2011, Krish, 2011, Harding and Shepherd, 2017, Kensek, 2014], which is a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators [Davidson, S., 2019]. And although with respect to architectural design, Grasshopper is one of the most commonly used generative design editors [Milena and Ognen, 2011].

The concept of Grasshopper can however also be applied for other design problems as the concept of establishing relationships stays the same. The advantage to use Grasshopper for this research is that it is tightly integrated with Rhino, which gives the opportunity to visualise the designs. This again reduces the influence of the black box, which Moussavi [2011] mentioned as possible disadvantage, and gives the chance to clearly show the designers intent. Another advantage is that the programming language Python is embedded within Grasshopper. In this way, the graphical modelling of Grasshopper can be combined with the advantages that scripting modelling provides, like simulation.

III. QUANTIFICATION OF SAFETY

Lowrance [1976] define safety as a measure of the acceptability of risk. As this acceptability is dependent on the type of person, a high level of subjectivity is involved [Sousa et al., 2014]. Where one person feels safe in a specific situation, another might not. However, in order to evaluate different designs with regard to safety, it needs to be possible to compare the respective levels of safety.

The American Society of Safety Professionals have developed a standard which provides specific guidelines for addressing occupational hazards and risks in design and redesign processes, which is the ANSI/ASSE Z590.3-2011 standard. According to the methodology, a risk matrix (of which an example is presented in Figure 4) can be used as tool to show the risk based on the relation between the impact of an accident and the likelihood that a certain accident occurs. In literature, different classifications are used to describe the impact and likelihood of an accident [Marhavilas et al., 2011, Arimbi et al., 2019, Azadeh-Fard et al., 2015], which is adapted to a form that is suitable for them.

In this research, the likelihood is subdivided into two parameters, which are the frequency and the probability. The frequency represents the number of times that an activity is expected to occur and the probability is the chance that this activity actually results in an accident. By multiplying the impact, frequency and probability, a single value to quantify safety is calculated, the risk level [Lyon et al., 2016]:

$$Risk\ level = Impact \cdot Frequency \cdot Probability$$

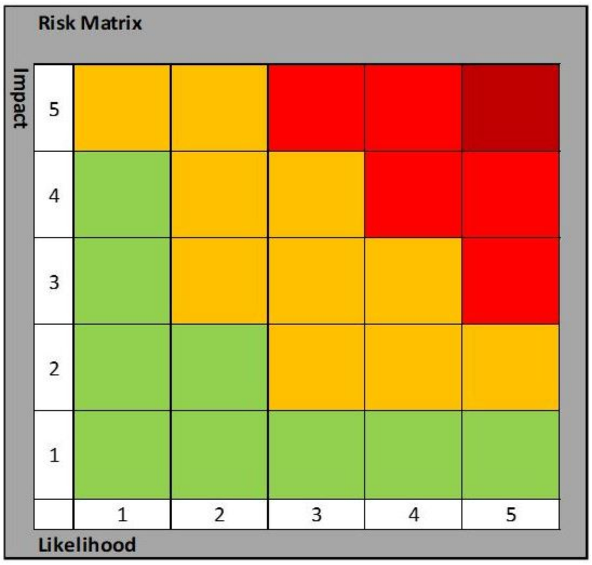

Fig. 4: Example of a risk matrix.

The values of these parameters depend on the type of accident, or hazard, which is defined by Reniers et al. [2005] as “any unsafe condition or potential source of an undesirable event with potential for harm or damage”. When the scoring system from 1 to 5 would be used for those parameters (as shown in the matrix), it could be the case that a hazard with a high impact (5) but a low probability (1) will result in a low risk rating. This is not desired and therefore Lyon et al. [2016] advice a more conservative approach to score the parameters. More on the scoring method that is used is explained in the next section, when describing the test case.

IV. TEST CASE

The quantification and evaluation of the aspect of safety is tested for Heineken breweries. By analysing their accident reporting investigation software database, in which they collect information about the incidents and accidents that happen worldwide, it was found that most accidents occur in the warehouse loading area. In the past years, many studies have been conducted to find the optimal design for the most efficient warehouse layout [Pohl et al., 2009, Gue and Meller, 2009, Oztürkoglu et al., 2014]. These studies have all looked into the optimal layout in terms of efficiency, in which they optimised the layout in order to minimise the travel time that is needed to complete the picking process. The impact on safety on the other hand, is usually neglected Hudock et al. [1998]. Therefore, this is an interesting area to gain more insight in with respect to safety. Using the parametric model various design decisions will be evaluated to see what the actual impact is on the risk level.

First, the way the model is developed is explained in Section IV-A. In Section IV-B, the calculation of the risk level is discussed. An overview of the results that have been found is given in Section IV-C. Subsequently, a discussion on the results is provided in Section IV-D. In the last section, Section IV-E, an alternative frequency scoring system is proposed to better score the type of activities that typically occur in the warehouse loading area.

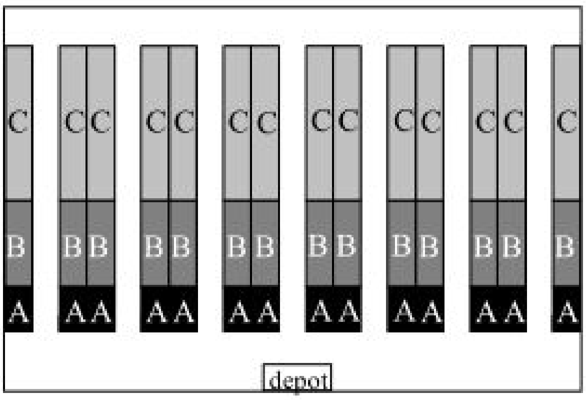

Fig. 5: A common way to implement class-based storage, retrieved from [Koster et al., 2007]. The products with the highest demand, the A-products, are located closest to the loading points. At the moment the truck arrives, these goods can be loaded into the truck quickly.

A. *Model development*

To gain insight in the design decisions regarding the layout of the warehouse loading area, the relatively simple layout configuration as presented in Figure 5 is evaluated. In this layout, the concept of class-based storage is included as well. This means that products can be grouped with respect to their priority so that the products with the highest demand are located closest to the loading point.

In inventory control, a classical way for dividing items into classes based on popularity is the Pareto’s method [Koster et al., 2007]. Pareto Analysis is a statistical technique in decision-making, and the principle is named after the Italian economist Vilfredo Pareto, who observed that 80% of the income in Italy went to 20% of the population [Haughey, D., 2019]. As described by Koster et al. [2007], the idea is to group products into classes in such a way that the fastest moving class contributes to about 80% of the turnover. Each class is then assigned to a dedicated area of the warehouse. The fastest moving items are usually called A-items, the next fastest moving category of products is called B-items, and so on. The number of classes is generally restricted to three. Within Heineken they use a similar approach and the respective percentages of products that usually fall in a specific category are presented in Table I.

TABLE I: Subdivision of products in product classes A, B and C, based on Pareto’s method.

Class	Percentage of products in a class
A	80%
B	15%
C	5%

By inserting the expected sales volume per product type per year, the time a product type is expected to stay in stock and the expected sales in peak month, the expected volume that goes into stock can be determined. From this, the space that is required for the storage area can be derived. Similarly, the throughput of goods in peak hour can be calculated based on the expected sales volume per year, the expected sales volume in peak month and the number of days per year and the number of hours per day a brewery operates. This throughput influences the number of transporters that is required to transport and load all the goods into the truck and the number of trucks that comes to pickup the goods. The number of trucks also depends on the type of truck as the bigger the truck is, the fewer trucks are needed to transport all the pallets. The truck type can vary per country. In some countries it is common to have very big trucks, whereas in other countries smaller trucks are more likely. Therefore, the truck type(s) need to be inserted as input in the model.

Subsequently, a distinction has been made between three types of picking processes which can be chosen in the model. The picking process is the method by which the general operation of transporting and loading goods is executed. The first method that can be chosen is to start picking the goods from the warehouse at the moment the truck arrives, and then load them directly into the truck. In the remainder of this paper, this method is called directly from warehouse. The second option is to use pre-staging, or staged inventory, which is a method in which goods are transferred from the storage area to a location where they are ready to be loaded onto the truck [BusinessDictionary, 2019]. This location can be any random area between the storage area and the loading points, but it can also be an automatic truck loading system. In this way, goods can be picked from the storage area before the actual truck arrives and be temporarily stored in the pre-staging area. Lastly, the third method concerns cross-docking, in which incoming shipments are directly transferred to outgoing vehicles without storing them in between [Van Belle et al., 2012]. In the case of Heineken, this means that goods from the packaging lines are directly transported to the loading area without first being stored in the warehouse storage area.

Besides the choice for the picking process, a choice for the type of equipment that will transport and/or load the goods needs to be made as well. A distinction has been made in equipment types with a different level of automation, which is a measure of the interaction and task division between human and machine [Fasth et al., 2008, Frohm, 2008]. In the model, manual loading, using forklift trucks (FLTs) to transport and/or load the goods, using lifting guided vehicles (LGVs) to transport and/or load the goods, and using an automated truck loading system (ATLS) are included as options.

Based on these choices and the input parameters described before, the layout of the warehouse loading area can be generated. In Figure 6, an example is presented for the case that goods are directly picked from warehouse. The red, orange and green coloured boxes represent the class A, B and C products, respectively. The red squares at the bottom of the figure represent the location of the loading points and the inside space that is required for them. The initial location of the loading points is set to be in the centre of the warehouse. However, an option has been included to change the position of the doors to the left side or the right side of the warehouse when desired. Furthermore, the aisle width between the storage racks and the manoeuvring space needed between the warehouse storage area and the trucks (at the bottom) depend on the type of transporter that is used (e.g. an FLT or LGV). Lastly, the red crosses indicate the locations where transporters can pickup the goods, which are simplified to be one location per class per storage rack.

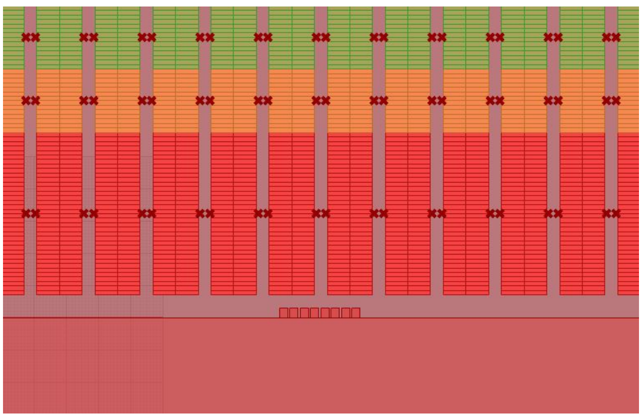

Fig. 6: An example of the generated layout in the case the goods are picked directly from warehouse.

Now that the locations of the storage areas and loading points are known, the different movements can be simulated. These movements include the movements of trucks, truck drivers, transporters and workers. All movements are visualised by dark red lines as shown in Figure 7. In this example, a truck arrival and the movement of a transporter between the warehouse and the truck can be seen.

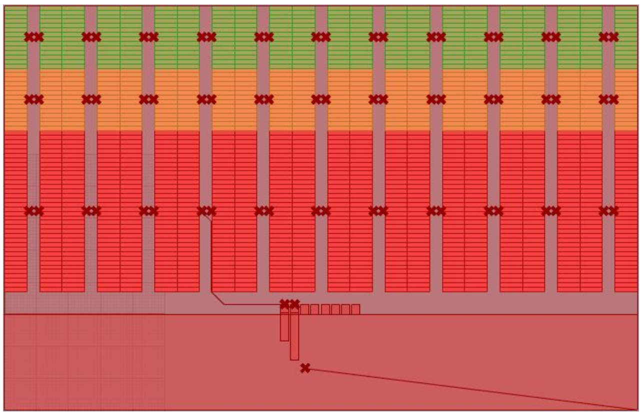

Fig. 7: The movements of trucks, truck drivers, transporters and workers are visualised by a dark red line. In this example, a truck arrival and the movement of a transporter between the warehouse and the truck can be seen.

B. *Calculation of risk level*

In this research, the hazards corresponding to the top three most occurring accidents have been analysed, which concern being injured due to manual loading of goods, being struck by a moving vehicle or striking against object, and being struck by falling object or trapped by overturning material. A total of twelve hazards were identified which could potentially result in one of those three accidents. An example of a hazard is the collision of an FLT and a pedestrian. Each hazard is given a score for the impact, frequency and probability. The scores for the impact and probability for the different hazards and equipment types have been determined with the help of a safety expert, and are based on the definitions as presented in Tables II and III.

The score for the frequency is determined by the model. The model counts the number of times a hazard occurs and determines the corresponding frequency score, based on the definition as presented in Table IV. When the frequency score is determined, the risk level can be calculated by multiplying the scores for the impact, frequency and probability.

TABLE II: Definition of the score for the impact of accidents, as used by Heineken.

Score	Impact of accident
20	(Multiple) fatality, severe permanent effects on blindness, major amputation, paralysis.
15	Severe permanent effects as finger amputation, burn, multiple fractures.
10	Minor or serious but not permanent effects as broken bones, severe cuts.
5	Minor effects as small cuts, minor burns, bruises.
0.1	Negligible effects or no injury at all.

TABLE III: Definition of the score for the probability that an activity can result in an accident, as used by Heineken.

Score	Probability that activity results in an accident
4	Accident happens frequently.
3	Accident happens sometimes.
2	Event happened at least once in the past.
1	We don't know if the event happened in the past, we cannot exclude it.
0.1	It is not possible or hard to believe that this event can happen.

TABLE IV: Definition of the score for the frequency of an activity, as used by Heineken.

Score	Frequency of activity
5	Activity performed several times per shift.
4	Activity performed 1 - 3 times per day.
3	Activity performed 1 - 3 times per week.
2	Activity performed 1 - 3 times per month.
1	Activity performed 1 - 3 times per year.

C. SCENARIOS AND RESULTS

In this section, critical design choices that are expected to affect the risk level are provided. Firstly, the choice for which picking process (directly from warehouse, using cross-docking or using pre-staging) will be evaluated. Currently, the risk level is hardly an important factor in the choice for a picking process within Heineken. Instead, efficiency and costs are the leading factors. It is therefore interesting to demonstrate which picking process actually results in the lowest (and highest) risk. Heineken has a big variety in brewery sizes and it might be the case that a certain picking process works fine for a small brewery but not for a large brewery. Therefore, the three picking processes are evaluated for small (1 million hL/year), medium (6 million hL/year) and large (11 million hL/year) breweries. This comparison will show whether the size of the brewery has an impact on the risk level and for what size which picking process is best.

Secondly, the type of equipment with which the transportation and/or loading operation is going to be executed will be evaluated. It was found that most hazards that occur are injuries due to manual loading or are a result from an interaction with an FLT. However, these are still the most commonly used methods within Heineken because of their relatively low costs and high flexibility. These two methods have a relatively low level of automation, especially the manual loading. It is therefore interesting to compare those with equipment types with a high(er) level of automation, like an LGV and an ATLS. Does an increase in the level of automation cause a decrease in the risk level? To investigate this impact equipment with different levels of automation will be compared.

The third design decision concerns the number of aisles that are present in the warehouse storage area. In literature, it was found that the shape factor of the warehouse has a big influence on the efficiency of the warehouse [Tutam and White, 2019]. The 2:1 ratio, which means that the length of the warehouse is half the width of the warehouse, is most optimal in terms of efficiency. This rule of thumb is also used by Heineken. However, as the shape factor has an influence on the efficiency, it might also have an influence on the risk level. The wider a warehouse is, the more aisles a warehouse has and the smaller the chance is that two or more transporters need to pick goods from the same aisle, which reduces the chance of a collision. Therefore, it is interesting to evaluate the impact of the number of aisles regarding the risk level of the warehouse.

When looking more closely to the precise location of the collisions, it was found that most collisions occur in the area where the FLTs/LGVs drive in and out of the trucks. The reason for this is that all FLTs/LGVs need to travel to and from the same small area as the loading points are usually positioned next to each other as close as possible. Therefore, the influence that the distance between loading points has on the risk level will be evaluated.

Lastly, the biggest dangers resulted from a collision of a moving vehicle with a pedestrian. The solution of arranging the crossing on a different level will therefore be evaluated to see what the difference in risk level is when this measure would be implemented.

It was found that for small breweries the picking process using pre-staging results in the lowest risk, whereas for increasing brewery sizes the other two picking processes, directly from warehouse and using cross-docking, result in a lower risk level. Furthermore, it followed that an increase in level of automation generally causes a decrease in risk level. The exception in this case was the use of FLTs, which resulted in a very high risk level, especially when they come in contact with pedestrians. Therefore, the use of FLTs can generally better be avoided. Thirdly, a change in the number of aisles in itself did not necessarily influence the number of crossings that occurred. However, when considering the number of aisles in combination with evenly distributing the loading points over the width of the warehouse, it was found that an increase in aisles reduces the risk level. Especially when certain aisles are dedicated to certain loading points, most crossings are expected to be eliminated. Lastly, by implementing crossings on a different level, and therefore removing the crossings between transporters and workers, the risk can be reduced. Especially when using FLTs, this reduction is significant (by almost a third).

D. Discussion on results

While analysing the results, it often occurred that the frequency score resulted in the maximum score of 5, despite a significant difference in the actual number of times that a hazard could potentially occur. The score of 5 indicates that the hazard occurs ‘several times per shift’. It followed that almost all hazards analysed in this research occur ‘several times per shift’. This is partly due to the fact that the top three most occurring accidents have been analysed, but it does not take away that the current system makes it impossible to distinguish between activities that happen often or very often. As the specific activities that take place in the warehouse loading area typically occur a lot, the current system is not specific enough. Therefore, it is proposed to extend the definition of the frequency score to make it suitable for the warehouse loading area. An alternative, extended method to improve the current frequency scoring system, applicable in areas where hazardous situations arise more regularly, is therefore proposed.

E. Alternative frequency scoring system

The proposed system should be able to score the typical activities occurring in the warehouse loading area in a better way, by especially enabling a better distinction in the case that activities occur multiple times per hour. In literature, different classifications can be found to score the likelihood of an accident (which is the combination of frequency and probability) [Ilbahar et al., 2018, Jacinto and Silva, 2010, Reniers et al., 2005, Lyon et al., 2016]. However, a specific method to classify the frequency score has not been found. Besides that, the scoring systems found for the likelihood of an accident are mostly using a subjective scoring system, like accidents happen very rarely, frequently, continuously, etc. However, as the frequency score is directly related to the number of times an activity occurs, it is proposed to use the available numbers, as calculated by the model, to establish a scoring system based on actual data. This is also encouraged in literature, by for example Ilbahar et al. [2018] and Jacinto and Silva [2010]. As there is no risk assessment method appropriate for all business areas, as stated by Gul and Ak [2018], the proposed system will specifically be developed for the warehouse loading area and is based on the collected data in this research.

The calculated number of times that the different hazards could potentially occur showed a big spread. Therefore, a linear distribution to score the frequency is not desired. Instead, an exponential distribution is proposed for the alternative scoring system. In this way, it remains possible to distinguish between activities that have a lower occurrence. For the higher occurrences this will be less precise using the exponential distribution, but it is assumed that the distinction between the activities that occur 500 times or 600 times is less important than the distinction between 2 and 10 times.

The results found for the picking processes showed a deviation in the number of times that a hazard can occur, which ranges from 0 up to 560. Based on these numbers, a suitable exponential distribution is chosen. Based on the calculated number of times that a hazard occurs, a suitable value for the base number follows to be 6. By calculating the number of times a hazard can potentially occur per year, using 6^{n-1}, in which n is equal to the frequency score and -1 compensates for the score of 0, a scoring system from 0 to 10 results. In Table V, the frequency scores and corresponding descriptions are presented, by which the descriptions are translated into comprehensible units. The term ‘activity performed’ is adopted from the current frequency scoring system and represents the number of times that a hazard can potentially occur. The score of 0 represents the case in which the hazard cannot occur. In this way, a comparison of the same hazardous situations can be conducted for different designs without having to change the list of hazards every time. When due to a change in design, the hazard will be present, it can easily be taken into account again as it will have a score for the impact and probability.

TABLE V: Proposed alternative for the definition of the frequency scoring system, as used by Heineken. The term ‘activity performed’ is adopted from the current frequency scoring system and represents the number of times that a hazard can potentially occur.

Score	Frequency of activity *(6^n per year, where n = score)*
10	Activity performed up to 1150 times per hour.
9	Activity performed up to 192 times per hour.
8	Activity performed up to 32 times per hour.
7	Activity performed up to 5 times per hour.
6	Activity performed up to 1 time per hour.
5	Activity performed up to 1 time per shift (8 hours).
4	Activity performed up to 1 time per day.
3	Activity performed up to 1 time per week.
2	Activity performed up to 1 time per month.
1	Activity performed up to 1 time per year.
0	Activity cannot occur.

To see what the impact of the alternative system is on the resulting risk levels, the system is tested for the scenario in which the three picking processes (directly from warehouse, using cross-docking and using pre-staging) are compared. This is done for all three brewery sizes (small, medium and large). It was found that it is best to use the picking process using pre-staging for small breweries (1 million hL/year), to either use the picking process using cross-docking or using pre-staging for medium breweries (6 million hL/year), and to either use the picking process directly from warehouse or using pre-staging for large breweries (11 million hL/year).

V. DISCUSSION

In this research, a method has been developed to easily evaluate the impact of different design choices on the level of safety. It has been shown that safety can be quantified by one single value, the risk level, and that in this way various designs can be evaluated and compared. The parametric model has shown to be an effective way to evaluate different designs by changing individual parameters.

The risk level was the result of the possible impact of an accident, the frequency that an activity is performed and the probability that an activity results in an accident. These three parameters were all based on their individual scoring systems. However, it was found that the current frequency scoring system was not adequate to use for the warehouse loading area. The system has therefore been extended to better distinguish between the type of activities that typically occur in the area. By changing these scores, different picking processes resulted in a lower risk than when using the current system. This shows that a change in classification has an impact on the preferred design choices. As the alternative frequency scoring system has only been tested for the picking processes and not for the remaining scenarios, it could be that these would result in a different preferred design choice. This should be taken into account when analysing the results.

Likewise, the frequency scoring has been changed to have a scale from 0 to 10 in the alternative scoring system. However, it was found that the risk levels for increasing breweries were still almost similar. It might therefore be necessary to further extend the frequency system to even better distinguish between the number of times that activities occur. What would, for example, happen if this scale would be extended to a scale from 0 to 20? Will other design choices result in a lower risk?

Furthermore, the determination of the scores for the impact and the probability of the various hazards are based on the opinion of a safety expert. As these were determined by a human, there is always a certain level of subjectivity involved. When these scores would be determined by another safety expert, it can be that he/she scores the values (slightly) different, which would subsequently result in a different risk level. Due to this, possibly other choices might result in a lower risk level than found in this research. For example, in the case of determining the score for the probability, the influence of subjectivity can be removed by calculating the probability instead of subjectively determining it. If the number of times that the activity is performed as well as the number of times that this activity actually results in an accident is calculated, the probability can be derived based on real data.

Lastly, the preferred design decisions have only been based on the aspect of safety. However, in the complete design process other aspects, such as efficiency, costs, energy usage, etc., also influence the design. It is therefore important to take these into account as well, in order to have a complete assessment of the design.

VI. CONCLUSION

The aim of this research was to develop a parametric model which enables the easy generation of design concepts and to evaluate these designs with respect to their impact on safety, which has been tested for the warehouse loading area. Using the parametric model, the risk level resulting from the twelve most occurring hazards in the warehouse loading area of Heineken can be evaluated for different scenarios. This risk level was determined based on the possible impact of an accident, the frequency that an activity is performed and the probability that an activity results in an accident. For the twelve hazards, the impact and probability were determined with the help of a safety expert. The number of times an activity could result in a hazard was determined by the parametric model. From this, the risk level for the hazards was calculated.

Subsequently, different scenarios were evaluated to see what impact a certain decision regarding a layout or equipment choice had on the risk level. Decisions regarding the type of picking process, the level of automation, the number of aisles, the distance between loading points and designing crossings on a different level have been evaluated. As it was found that the current frequency scoring system could not properly distinguish between the activities that typically occur in the warehouse loading area, an alternative system has been proposed. By using an exponential distribution a better distinction could be made.

In conclusion, it can be said that the parametric model can indeed quickly generate different design concepts, by changing a single or multiple parameters. By simulating the different processes the model can calculate the number of times that an activity occurs, and determine the corresponding frequency score. In this way, the parametric model can be used to evaluate safety in the design phase.

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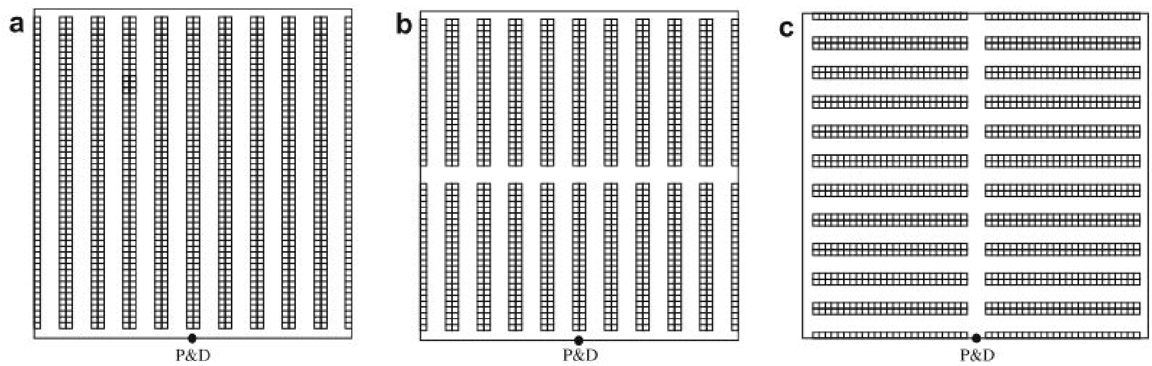
B

Possible Warehouse Configurations

Many studies have been conducted to find the optimal design for the most efficient warehouse layout, mainly with respect to reducing the travel time. In this appendix, various layout configurations are presented together with their advantages and disadvantages. In Section B.1, general layout configurations are described. Different ways to implement class-based storage are provided in Section B.2.

B.1. Design configurations

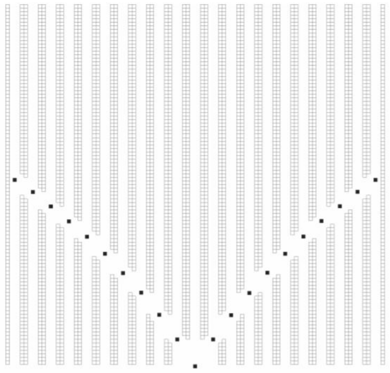
In most studies regarding the design of a warehouse layout the commonly used design configurations that have been evaluated are the once in which the storage blocks are positioned in the horizontal or vertical direction, as shown in the figures below.



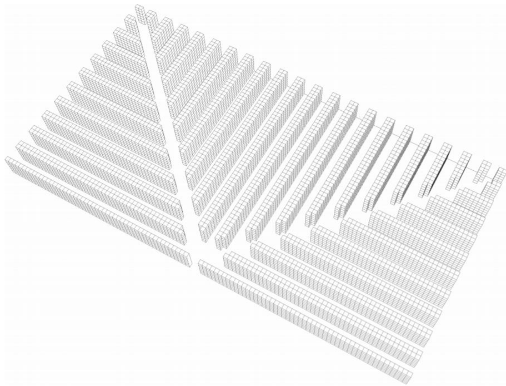
(a) Layout A. (b) Layout B. (c) Layout C.

Figure B.1: Three possible warehouse aisle layouts, retrieved from [Pohl et al., 2009].

Gue and Meller [2009] have considered designs in which the problem of arranging aisles is addressed in new ways to reduce the cost of travel for a single-command cycle within these warehouses. The configurations they designed are presented in Figures B.2a and B.2b, and are called the V-shape and fishbone design, respectively.



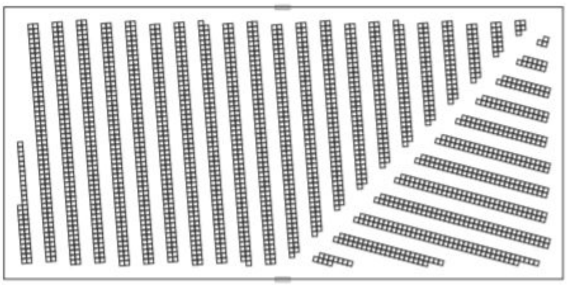
(a) Warehouse design with a flying V-cross.



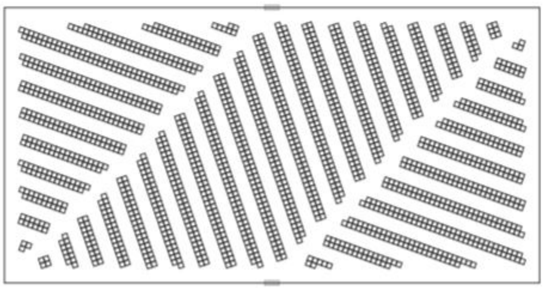
(b) Fishbone design.

Figure B.2: Two warehouse designs with a flying V-cross (a) and a fishbone design (b), retrieved from [Gue and Meller, 2009].

Subsequently, Öztürkoglu et al. [2014] have taken these ideas further to propose new aisle designs for unit-load storage spaces that have multiple access locations, as is the case for Heineken. They have not restricted themselves by only vertical or horizontal configurations of the storage areas, but have allowed all rotations. Their designs are presented in Figures B.3a and B.3b.



(a) Design C1.



(b) Design C2.

Figure B.3: Designs with one (left) and two (right) cross aisles for an I-shaped warehouse where there is one pickup-point at the top and one at the bottom, retrieved from [Öztürkoglu et al., 2014].

B.2. Ways to implement class-based storage

Class-based storage concerns the decision on how the zones of the storage area of the warehouse should be divided (e.g. zones for different product groups). This concept of class-based storage [Koster et al., 2007] was explained in Section 3.3. Products with the highest demand can be located close to the loading point in order to reduce the distance that needs to be travelled, and therewith reduce the picking time [Hassan, 2002]. In Figure B.4, two common ways to implement class-based storage are presented, in which A is the most popular product and C is the least popular product [Koster et al., 2007].

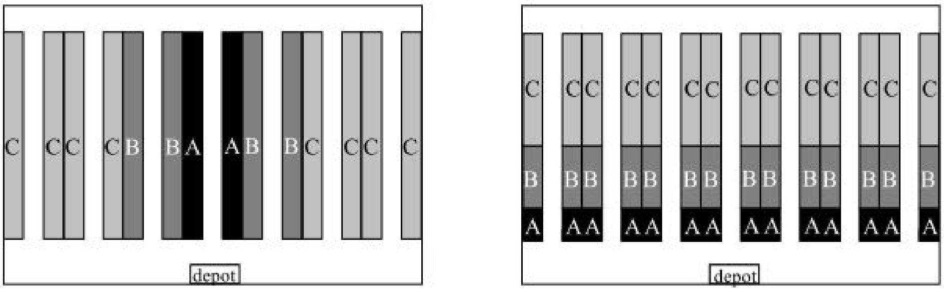


Figure B.4: Two common ways to implement class-based storage (retrieved from [Koster et al., 2007]).

In both cases it has been decided to place the depot point in the middle of the warehouse, as was found by Francis [1967] to be most efficient. However, if for some reasons the depot point needs to be moved to the left or to the right of the building, class-based storage can also have the arrangement as presented in Figure B.5 [Ashayeri et al., 2002].

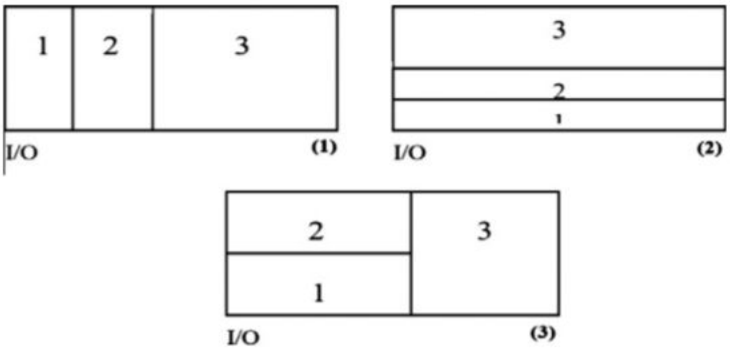


Figure B.5: Three other possible class-based storage layouts, retrieved from [Ashayeri et al., 2002].

C
Layouts Scenarios

In this appendix, all layouts of the different scenarios, that were discussed in Chapter 6, are included. They follow the same order as in Chapter 6. In the different sections, the various layouts corresponding to the following scenarios are provided:

C.1 Layouts scenario picking processes;
C.2 Layouts scenario level of automation;
C.3 Layouts scenario number of aisles;
C.4 Layouts scenario distance between loading points.

The scenario in which the implementation of a crossing on a different level is evaluated is based on the layouts used for the picking processes. These are therefore not presented in this appendix.

C.1. Layouts scenario picking processes

C.1.1. Layouts small breweries

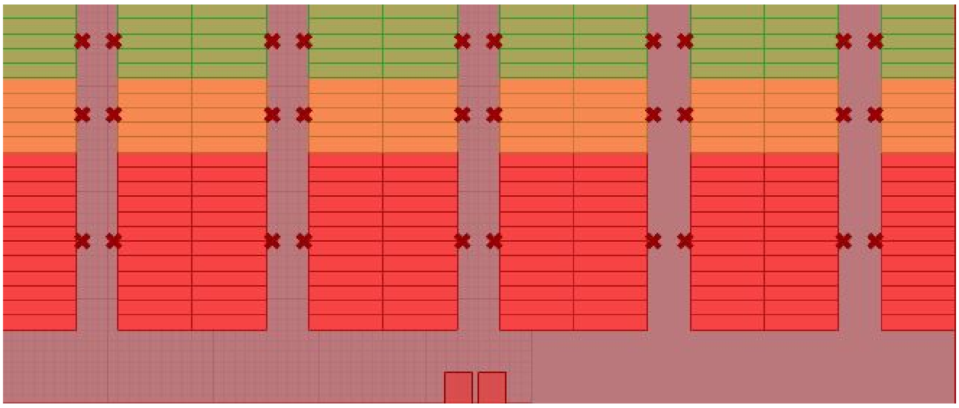


Figure C.1: The generated layout for the scenario "Directly from warehouse - Small brewery (1 million hL/year)".

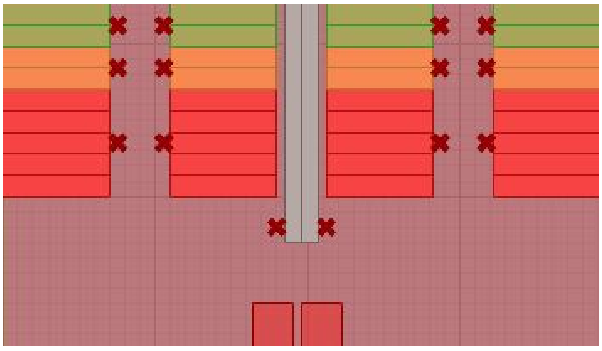


Figure C.2: The generated layout for the scenario "Using cross-docking - Small brewery (1 million hL/year)".

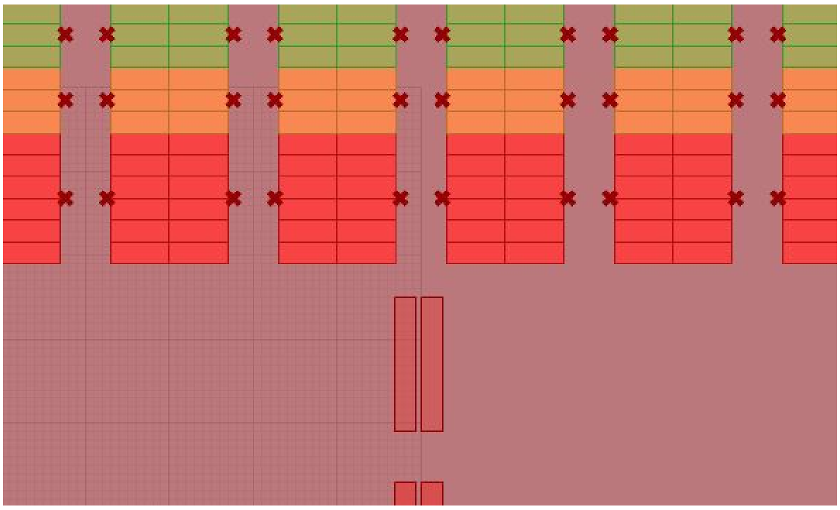


Figure C.3: The generated layout for the scenario "Using pre-staging - Small brewery (1 million hL/year)".

C.1.2. Layouts medium breweries

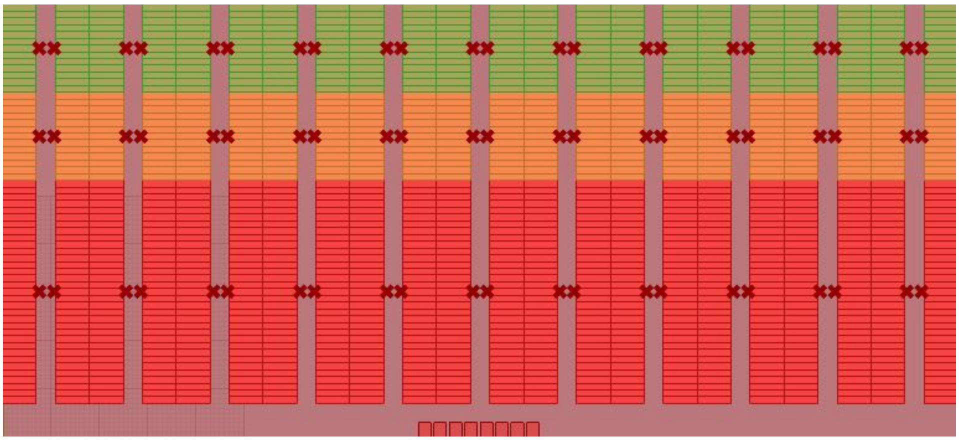


Figure C.4: The generated layout for the scenario ”Directly from warehouse - Medium brewery (6 million hL/year)”.

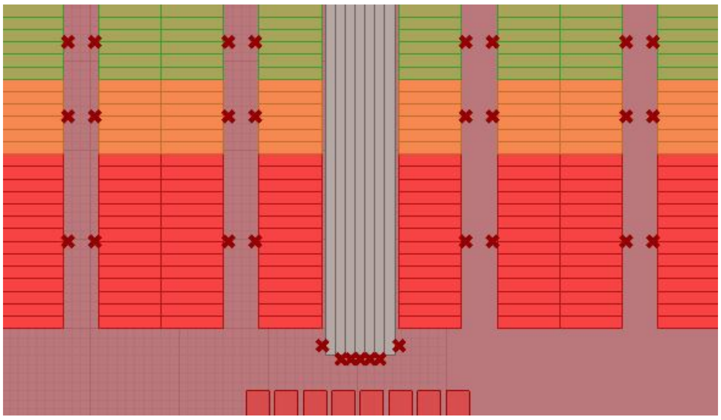


Figure C.5: The generated layout for the scenario ”Using cross-docking - Medium brewery (6 million hL/year)”.

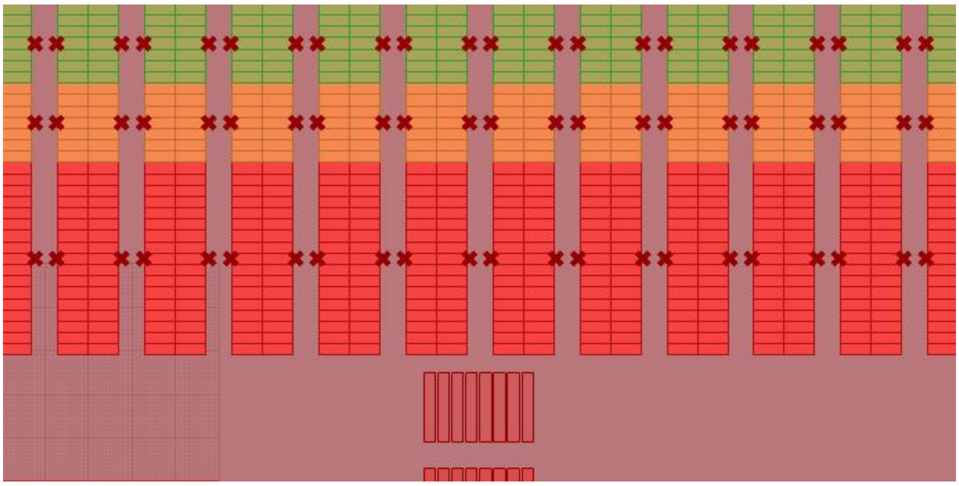


Figure C.6: The generated layout for the scenario ”Using cross-docking - Medium brewery (6 million hL/year)”.

C.1.3. Layouts large breweries

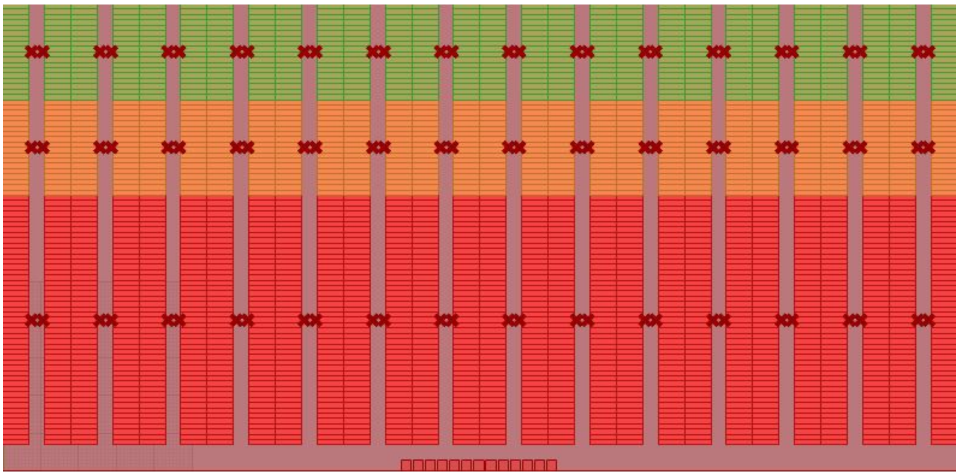


Figure C.7: The generated layout for the scenario "Directly from warehouse - Large brewery (11 million hL/year)".

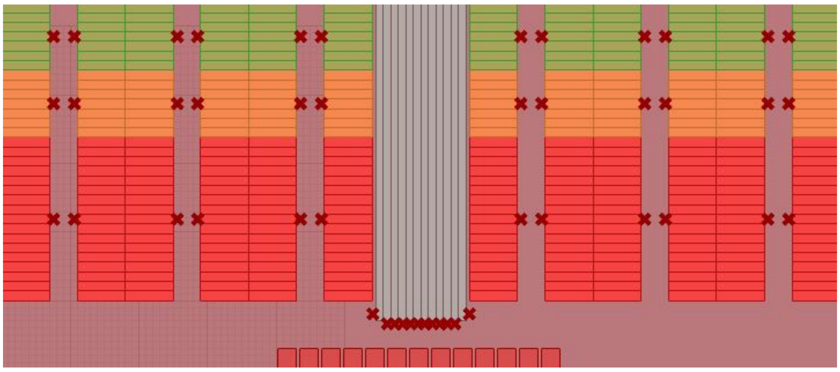


Figure C.8: The generated layout for the scenario "Using cross-docking - Large brewery (11 million hL/year)".

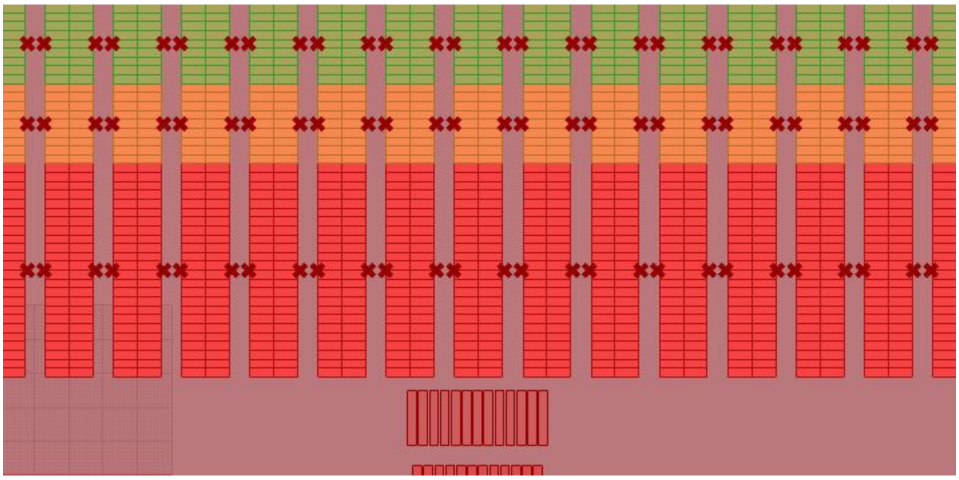


Figure C.9: The generated layout for the scenario "Using pre-staging - Large brewery (11 million hL/year)".

C.2. Layouts scenario level of automation

C.2.1. Layouts in which double FLTs are used for the transportation part

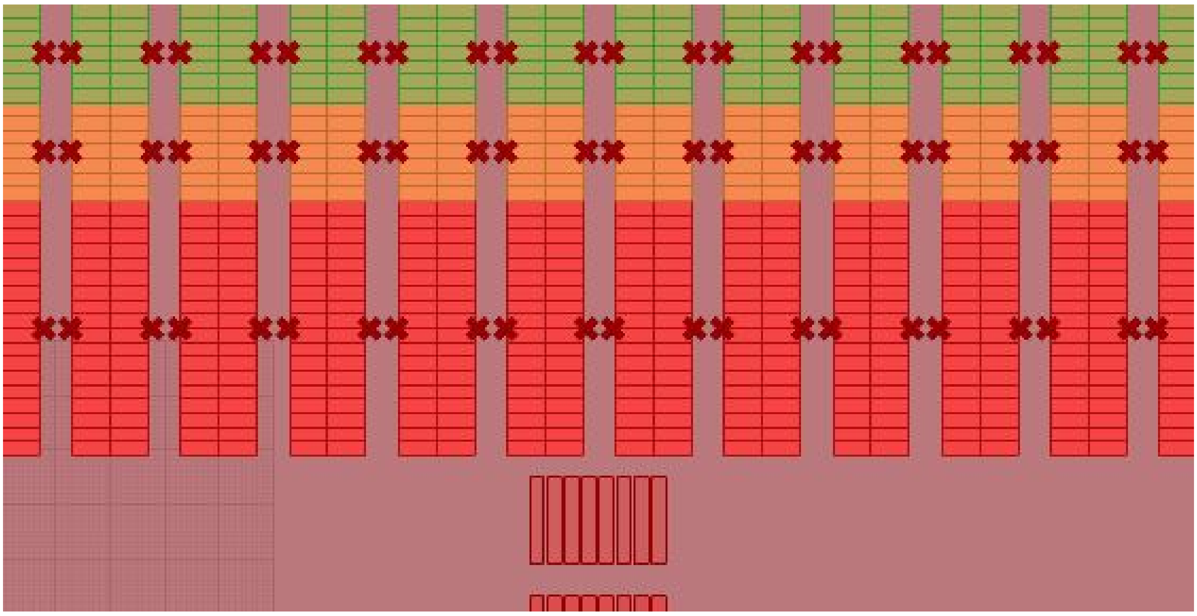


Figure C.10: The generated layout for the scenario "Using double fork FLTs for the transportation task and manual loading for the loading task".

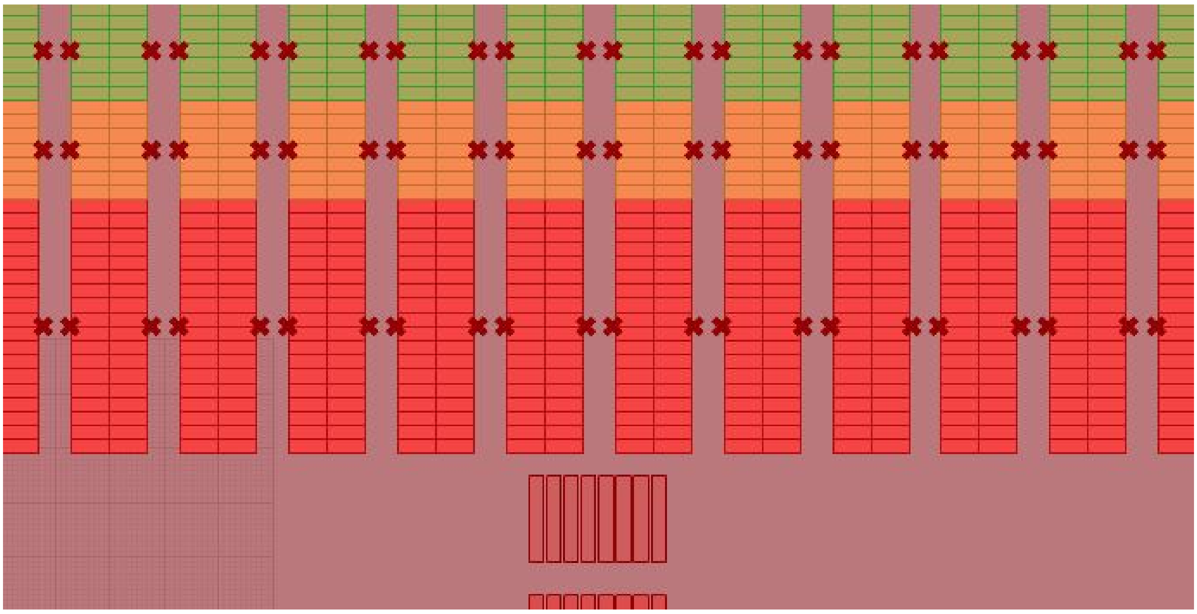


Figure C.11: The generated layout for the scenario "Using double fork FLTs for the transportation task and single FLTs for the loading task".

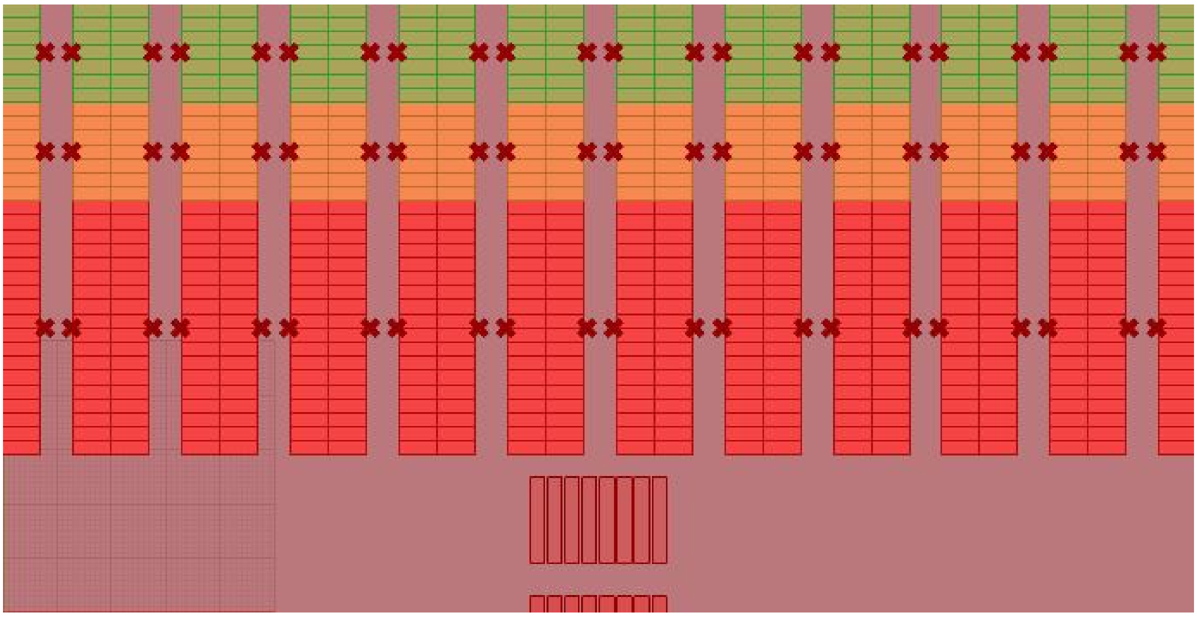


Figure C.12: The generated layout for the scenario ”Using double fork FLTs for the transportation task and single LGVs for the loading task”.

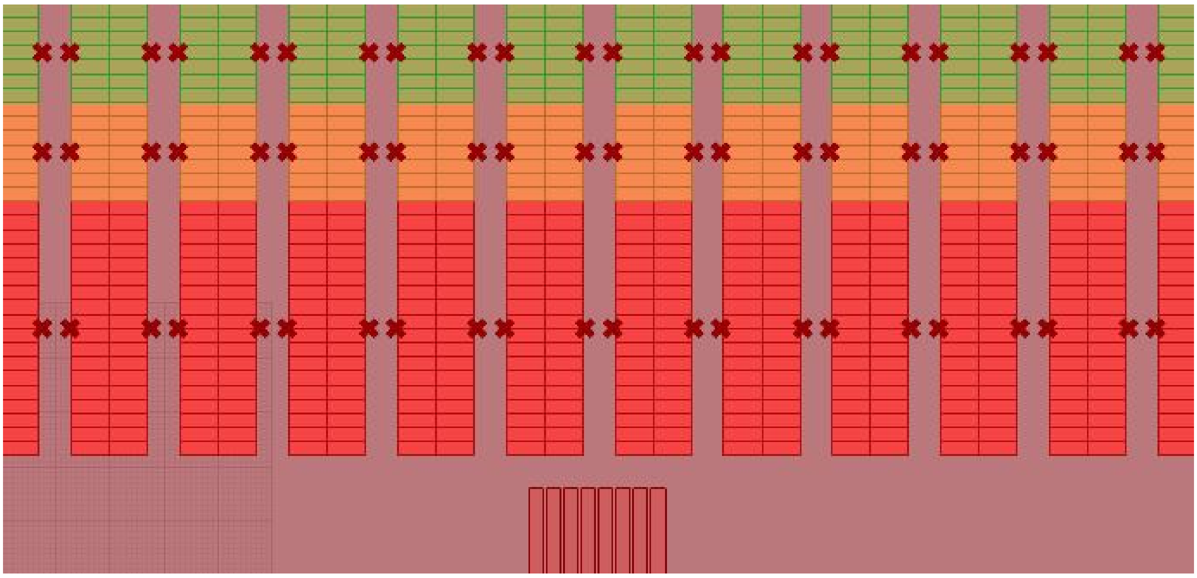


Figure C.13: The generated layout for the scenario ”Using double fork FLTs for the transportation task and an ATLS for the loading task”.

C.2.2. Layouts in which double LGVs are used for the transportation part

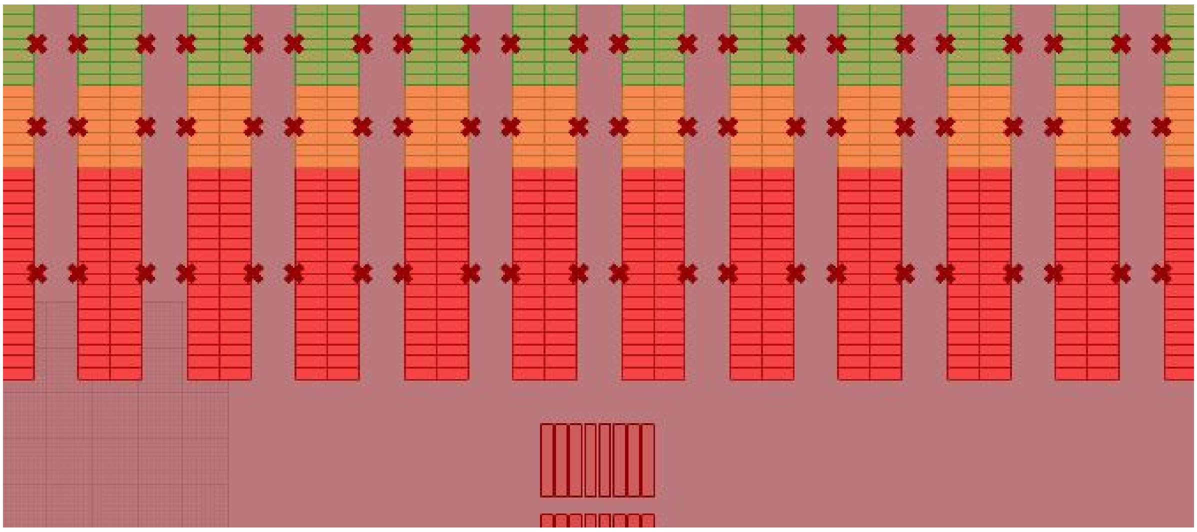


Figure C.14: The generated layout for the scenario "Using double fork LGVs for the transportation task and manual loading for the loading task".

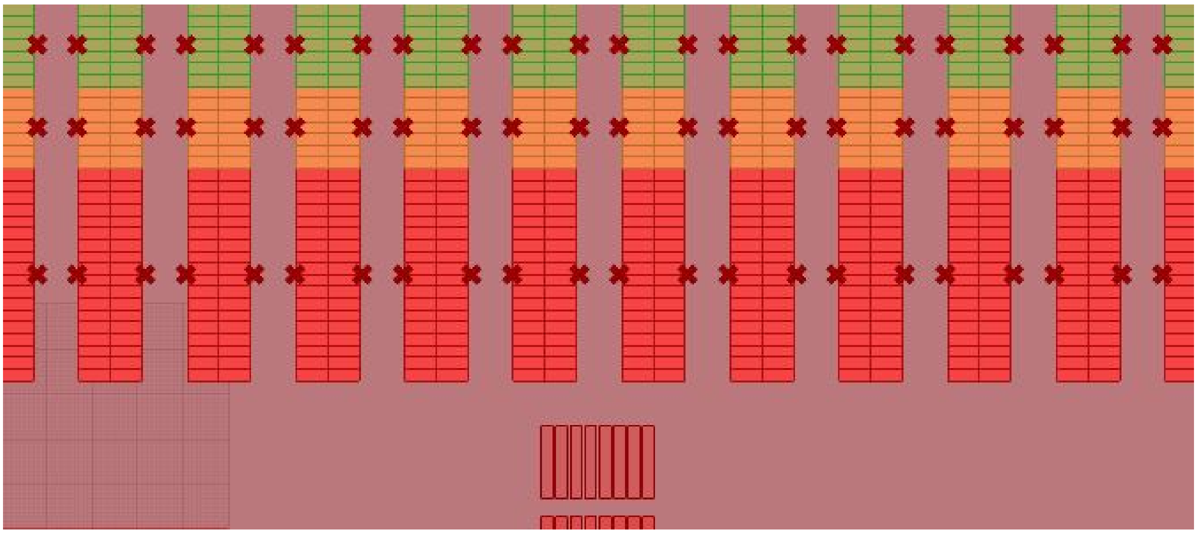


Figure C.15: The generated layout for the scenario "Using double fork LGVs for the transportation task and single FLTs for the loading task".

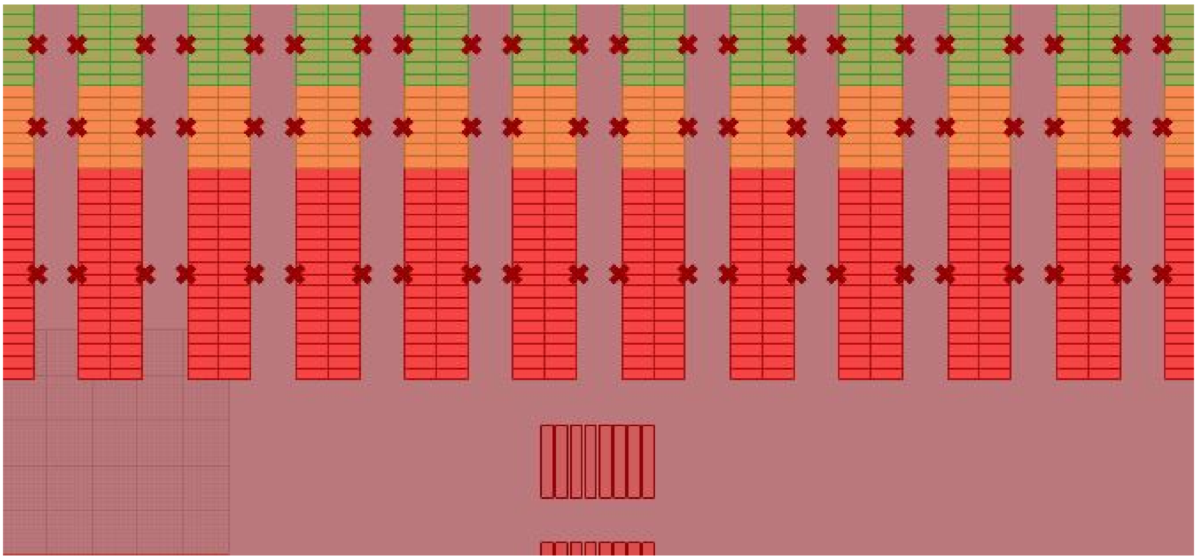


Figure C.16: The generated layout for the scenario ”Using double fork LGVs for the transportation task and single LGVs for the loading task”.

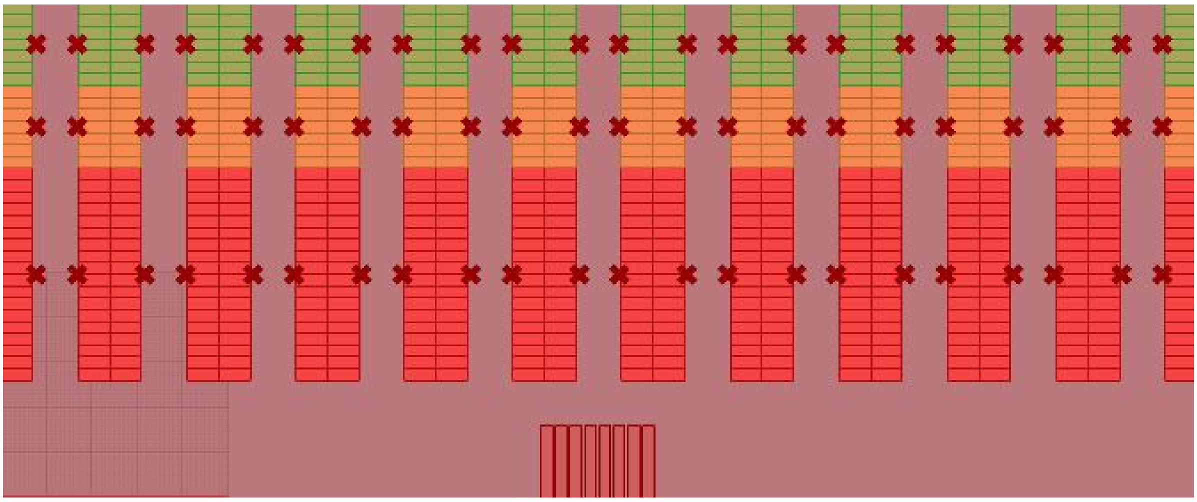


Figure C.17: The generated layout for the scenario ”Using double fork LGVs for the transportation task and an ATLS for the loading task”.

C.3. Layouts scenario number of aisles

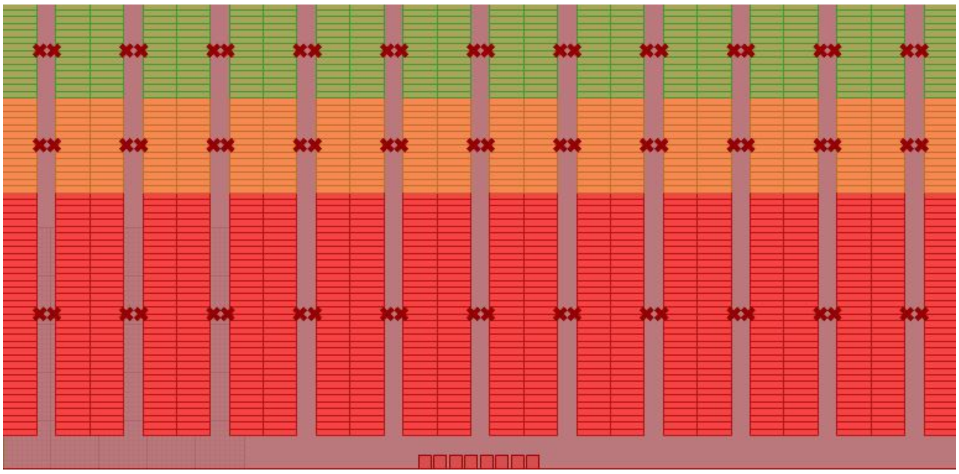


Figure C.18: The generated layout for the scenario ”Number of aisles is 11”.

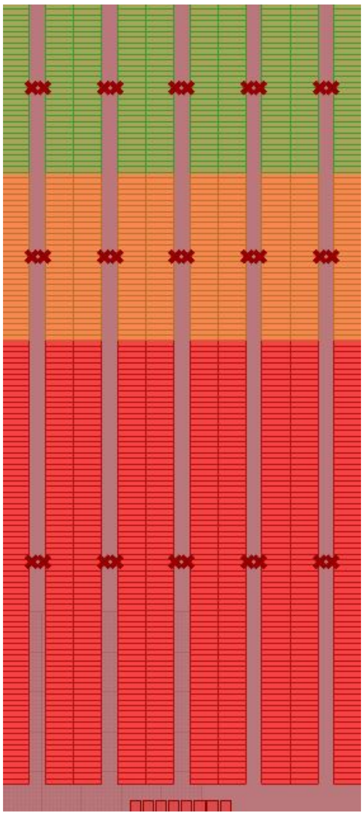


Figure C.19: The generated layout for the scenario ”Number of aisles is 5”.

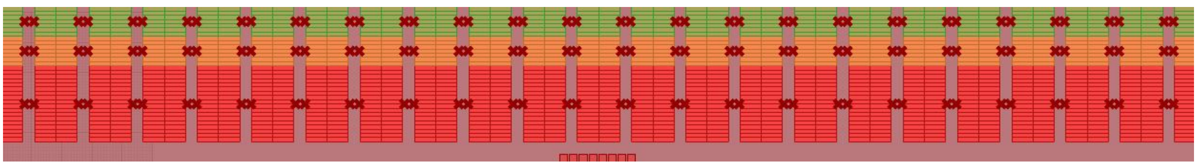


Figure C.20: The generated layout for the scenario ”Number of aisles is 22”.

C.4. Layouts scenario distance between loading points

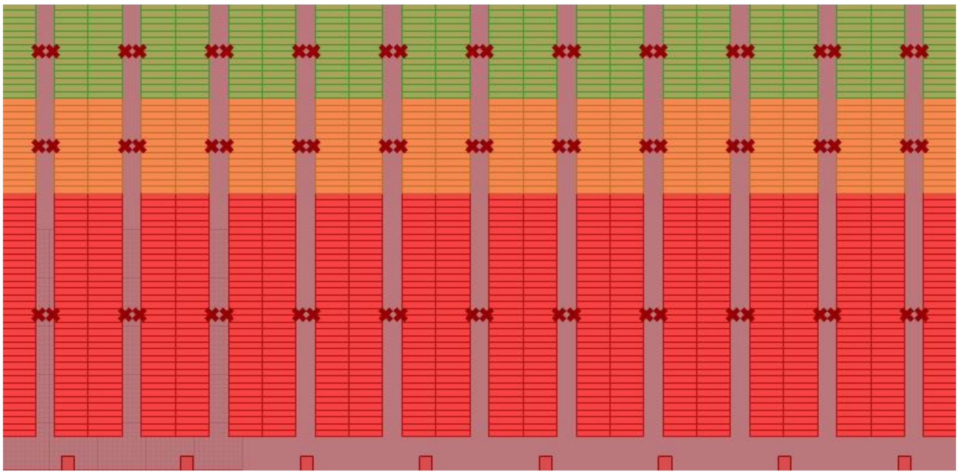


Figure C.21: The generated layout for the scenario "Equally distributed doors over the width of the warehouse when the number of aisles is 11".

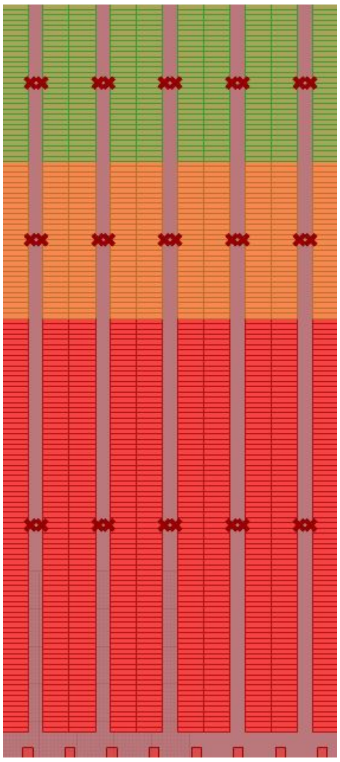


Figure C.22: The generated layout for the scenario "Equally distributed doors over the width of the warehouse when the number of aisles is 5".

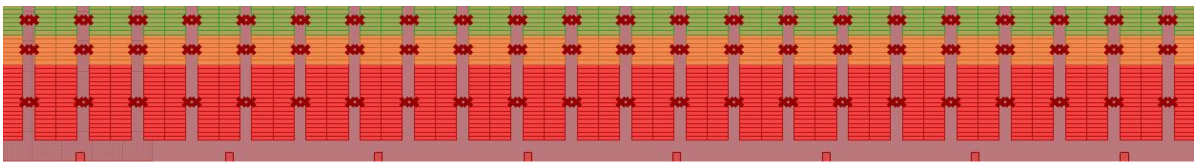


Figure C.23: The generated layout for the scenario "Equally distributed doors over the width of the warehouse when the number of aisles is 22".

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