Turning nuisance into nutrition

Performance based parametric design of an automated warehouse in an insect rearing system

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by

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Preface

This thesis is written as part of my graduation project for the master mechanical engineering at the Delft university of technology. The project was supported by the company Protifarm. I found that the combination of the mechanical and logistics aspects of automated warehouse design are even more interesting in an insect rearing system, where biological processes play a large role.
I would like to thank Dingena Schott, Wouter Beelaerts van Blokland and Jovana Jovanova for their supervision on behalf of the Delft university. Thanks to Jeroen Blansjaar for the interesting discussions and inspiring guidance on behalf of Protifarm. I would like to thank my partner for her patience and support and thanks to my parents for their continuous belief in me becoming an engineer.

B.C. Wijsman
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Abstract

This thesis project features a design method of an automated warehouse in an insect rearing system, where pallets are transported from storage to a feeding machine and back into storage. From seven material handling equipment concepts, the most promising concepts are selected through a combined expert panel evaluation of 7 criteria and a basic design evaluation of four criteria. Inspired by the automated generation of design paradigm, a performance based parametric design approach is taken, where a parametric description of the warehouse lay-out is coupled to a pallet flow simulation. Iterative simulations are then performed until a lay-out design is obtained that provides the required handling capacity with minimal material handling equipment. Lay-out designs are generated for three operational scenarios with a shuttle and orbiter, and one scenario with an automated forklift.

Summary

In an effort to reduce environmental impact of food production, insects are an upcoming source of high quality nutrients. Industrial scale insect rearing is needed to obtain meaningful quantities of nutrients, and successful automation is critical to the economic and biological success of the rearing process.

This research project focuses on the design of an automated warehouse in an insect rearing system. The design process includes the selection of a suitable material handling equipment concept, and the production of a lay-out design for the automated warehouse. The material handling equipment selection is based on an expert panel concept evaluation, and basic warehouse design evaluation on handling capacity, storage density, cost and climate. Of seven concepts, the automated forklift and shuttle and orbiter type pallet handling concept are best suited to an insect rearing system. In the subsequent lay-out design phase the required number of material handling devices, and the optimal number of warehouse aisles, storage channels and channel depth are determined. Inspired on the paradigm of automated generation of design, a performance based parametric design method is developed and applied to determine these lay-out design parameters for a required storage capacity, handling capacity and expected performance of the material handling equipment. A parametric model of the warehouse lay-out is used as input for a pallet flow simulation, and adapted in an iterative manner until the desired material handling capacity is reached. Lay-out designs are generated for three operational scenarios with a shuttle and orbiter (1: case study, 2: dynamic storage, 3: first-in first-out). For the automated forklift concept separate lay-out designs are generated with single-deep or double-deep storage (4a: single-deep, 4b: double-deep). A case study is performed at an operational insect rearing facility in the Netherlands, with a shuttle and orbiter material handling concept. Measurements were performed to determine the material handling equipment performance and operational experience gained in this facility is included in this research through discussions with employees and the use of an expert panel in the material handling concept evaluation. The important lessons obtained from the case study are the importance of punctual provision of feed and the sensitivity of optical sensors to pollutants present in the rearing environment.

The material handling concept evaluation results in the selection of the shuttle and orbiter concept and the automated forklift concept as most suited to the insect rearing application. From the generated lay-out designs, several interesting conclusions can drawn. Firstly, the simulated case study scenario requires one extra shuttle and orbiter compared to the real case study design. The actual case study design therefore cannot provide sufficient handling capacity. Secondly, the implementation of a dynamic storage strategy significantly increases pallet handling capacity, allowing for a potential increase in pallet storage, or decrease in material handling devices. Lastly, an automated warehouse where material handling is done by an automated forklift achieves a significantly lower storage density, due to wider warehouse aisles and lower storage channel depth. A warehouse area around 60% larger is required to storage an equal amount of pallets.

Scenario 2 is concluded to provide the best design based on cost and handling capacity for the model inputs, at the cost of a punctual feeding process. Further research towards this trade-off between logistics optimization and biological yield maximization is therefore required. An important limitation of this design study is the omission of multi-layered storage, although automated warehouse technology is proven in multi-layered storage systems.

The performance based parametric design model gives a good insight in the solution space, and may be a helpful tool to automated warehouse designers.

Samenvatting

In een poging om the negatieve invloed van voedsel productie op het milue te reduceren, blijken insecten een potentiële bron van hoogwaardige voedingsstoffen. Om bruikbare hoeveelheden van deze voedingsstoffen te kunnen produceren, is de kweek van insecten op industriele schaal een vereiste en succesvolle automatisering wordt een kritiek onderdeel geacht van het economische en biologische succes van het kweekproces.
Dit onderzoeksproject focust op het ontwerp van een geautomatiseerd magazijn in een kweeksysteem voor insecten. Het ontwerpproces omvat de selectie van een geschikt materiaaltransport concept en de oplevering van een lay-out ontwerp voor het geautomatiseerd magazijn. De selectie van het materiaaltransport concept is gebaseerd op de concept-evaluatie van een groep deskundigen en de beoordeling van initiele magazijnontwerpen op basis van transport capaciteit, opslag dichtheid, kosten en klimaatbeheersing. De evaluatie van zeven concepten resulteert in de selectie van de geautomatiseerde vorkheftruck en shuttle en orbiter als meest geschikt voor de toepassing in een insectenkweek systeem. In de hieropvolgende ontwerpfase worden het benodigde aantal materiaaltransport systemen bepaald, alsmede het optimale aantal magazijngangen en opslagkanalen en de diepte van de opslagkanalen. Geïnspireerd op het paradigma *Automated generation of design*, is een prestatiegericht parametrisch ontwerp model ontwikkeld en toegepast om de lay-out ontwerp parameters te bepalen voor een gegeven opslag capaciteit, transport capaciteit en prestaties van de apparatuur voor materiaaltransport. Een parametrische beschrijving van de magazijn lay-out is gekoppeld aan een simulatie model van pallet-bewegingen, en iteratief aangepast tot de vereiste transportcapaciteit is bereikt. Een lay-out ontwerp is opgeleverd voor drie operationele scenarios met de shuttle en orbiter (1: case study, 2: dynamic storage, 3: first-in first-out). Een apart lay-out ontwerp is opgeleverd voor de geautomatiseerde vorkheftruck met enkel-diepe en dubbel-diepe pallet opslag (4a: enkel-diep, 4b: dubbel-diep). Een operationele insectenkweek faciliteit in Nederland met een shuttle en orbiter wordt behandeld als case study. Hier zijn metingen verricht om de prestaties van het materiaaltransport systeem te bepalen en de opgedane operationele ervaring is meegenomen in dit onderzoek door middel van discussies met ervaren medewerkers en het gebruik van een groep experts om de transport concepten te beoordelen. Belangrijke operationele lessen die geleerd zijn in de case study zijn het belang van punctuele voerverstrekking en de gevoeligheid van optische sensoren voor vervuiling in de kweekomgeving.
Het resultaat van de evaluatie van transportconcepten is de selectie van het shuttle en orbiter concept en het geautomatiseerde forkheftruck concept als meest geschikt voor een insectenkweek systeem. Uit de gegenereerde lay-out ontwerpen kunnen meerdere meerdere interessante conclusies getrokken worden. Ten eerste, dat het gesimuleerde case study ontwerp één extra shuttle en orbiter nodig heeft, ten opzichte van het daadwerkelijke case study ontwerp. Het daadwerkelijke ontwerp beschikt dus niet over voldoende transport capaciteit. Ten tweede zorgt de implementatie van een dynamische opslag strategie voor een significante toename van de transport capaciteit, waardoor potentieel het aantal opgeslagen pallets verhoogd kan worden, of het aantal shuttles en orbiters verlaagd kan worden. Als laatste blijkt uit de resultaten dat een geautomatiseerd magazijn waarin een geautomatiseerde vorkheftruck is toegepast, te resulteren in een significant lagere opslag dichtheid, vanwege de bredere gangen en gelimiteerde diepte van de opslagkanalen. De benodigde magazijn oppervlakte is rond de 60% hoger voor een gelijk aantal pallets met een shuttle en orbiter. In conclusie is de prestatie van scenario 2 optimaal op het gebied van kosten en transport capaciteit voor de gebruikte model invoer, ten koste van de punctualiteit van de voergift. Verder onderzoek naar de afweging tussen het logistiek optimum en biologische opbrengst maximalisatie is hier aan te raden. Een belangrijke limitatie van dit onderzoek is het buiten beschouwing laten van pallet opslag over meerdere verdiepingen, terwijl geautomatiseerde magazijntechnologie hier wel toe in staat is.
Het prestatiegericht parametrisch ontwerp model geeft goed inzicht in de oplossingsruimte en kan een nuttig gereedschap zijn in het ontwerp van geautomatiseerde magazijnen.

Contents

1
Introduction

1.1. Introduction to insect rearing

To put this report into perspective, the relevance of insect production for the human diet and the global environment is briefly discussed below. Followed by an overview on the global state of art in insect production, and a resume on the key considerations for the design and operation of an automated insect production system. Then the scope is narrowed to the insect species that is of interest to this study: the lesser mealworm. It's lifecycle and characteristics are discussed in relation to insect production.

1.1.1. The relevance of insect production

The human population is predicted to grow to nine billion by 2050, and the consumption of animal-based protein is expected to increase at a higher rate (Godfray et al. 2018). While these predictions may be disputed (Tomlinson 2013), the fulfilment of future demand without completely depleting earths resources poses a serious challenge, which cannot be ignored. Another driver that increases demand for high-quality animal protein is that new generations expect higher quality protein sources than their parent or grandparents, which will result in a 72% increase in meat production over the next 35 years (Wu, Bazer, and Cross 2014). A worrying prediction, as animal-based food becomes increasingly expensive from both the economic and environmental perspective. In a study on land use in 2011 (Thornton, Herrero, and Ericksen 2011) it was found that animal rearing and animal feed production occupy 24% of the world's surface area, whilst another study concluded that these activities were responsible of 18% of global greenhouse gas emissions (Steinfeld et al. 2006), with 45% of these emissions coming from feed production (Gerber et al. 2013). Another problematic aspect is the origin of soybean meal and fishmeal, the principal sources of protein for animal feed. Soy production being a major contributor to the clearance of Amazonian rainforest, and fishmeal production being partly responsible for the depletion of global fish stocks, with real term prices expected to rise by 90% in the 2010-2030 period (World Bank 2013). Could the inclusion of insects in the global diet help deal with these challenges?

When looking at it from the historical perspective, insects have always been one of many sources of food that humans have relied upon. And although insects remain a popular food today, they have disappeared from the Western diet entirely (Dunkel and Payne 2016). Another interesting point is made by (Rothman et al. 2014), who points out that in heavily plant-based diets, insects provide crucial fats, proteins and micro nutrients. In chapter 1 of the book *Insects as Sustainable Food Ingredients*, the development of innovative technologies to increase access to edible insects is described as a critical aspect of our future success (Dunkel and Payne 2016).

1.1.2. State of art in production techniques

An interesting overview on the state of art in production techniques and important considerations in the production of insects, is found in chapter 6 of the book *Insects as Sustainable Food Ingredients*, which is aptly titled *Insect Mass Production Technologies* (Cortes Ortiz et al. 2016). The book is published in 2016, so it may present a partly outdated perspective on the state of art in insect production, considering the fast development in the automation industry and the insect production industry. However, due to the completeness of the overview this chapter presents, it is considered a valid source.

Production management

According to (Cortes Ortiz et al. 2016), one of the main challenges in large scale insect rearing is to find the correct balance in mechanization, automation, and productivity. Important aspects in insect production like feeding, watering, handling, harvesting, cleaning, processing, packaging and storage can be significantly improved through the addition of technology. It is also stated that current edible-insect productions systems fail in the implementation of high levels of mechanisation, which adversely affects price and consistency in quality. Insect protein as an alternative to meat in the human diet and fishmeal in animal feed, is only feasible when large volumes of high quality biomass can be produced at a competitive price. A mechanization level of at least 80% of the production process is stated to enable competitiveness with animal protein sources (Cortes Ortiz et al. 2016). Opportunities are expected in the integration of monitoring and control systems regarding feeding, mating, oviposition rates, environmental-, microbiological control and life cycle.

Production techniques

It should be noted that the information below is based on studying the production of the yellow mealworm (*T. Molitor*) and this report is concerned with a production system of the lesser mealworm (*A. Diaperinus*). The considerations and findings described here may be entirely true for the lesser mealworm as well, but differences will certainly exists to a lesser or greater extent.

In conventional mealworm rearing systems, the larvae or adults are kept in trays, made from wood, high density polyethylene or fiberglass. The trays are typically arranged in multilevel racks or shelves, while the tray size is chosen for easy handling, with sufficient depth to prevent the larvae or adults from escaping. Although the tray has clear practical advantages in handling, there are several disadvantages as well. Frass continuously accumulates in the trays, which favors mite proliferation. Furthermore, eggs laid in the bottom of the tray cannot be safely recovered, and will therefore remain in the tray, so adults must be separated from the feed and tray for every oviposition period (Cortes Ortiz et al. 2016). The elimination of frass particles from the containers will reduce mite infestations, and allows for increased precision in monitoring of food consumption, which is important to optimize production and detect colony problems as early as possible (Cortes Ortiz et al. 2016).

Feed

T. Molitor has the ability to survive and reproduce feeding solely on wheat bran, significant gains in development time, larval survival, food conversion and fecundity of adults is observed through the addition of food supplements like sliced potato, carrot or cabbage (Cortes Ortiz et al. 2016). The vegetables add important nutrients such as vitamins, essential fatty acids and sterols (Broekhoven et al. 2015). Well balanced nutrient ratios are of great importance to *T. Molitor*. Increased protein content is found to increase survival rate and shorten development time (J. A. Morales-Ramos et al. 2011) (Broekhoven et al. 2015), although increasing the price of feed. Increasing the calorie content of the food increases growth rate and pupal mass (J. A. Morales-Ramos et al. 2011), but high calorie diets reduce larval survival rates (Broekhoven et al. 2015), and even limits the ability of insects to respond to disease ((Krams et al. 2015).

Water

As *T. Molitor* larvae posses the ability to take up water vapor from air, the water requirements for this species are minimal, as relative humidity is kept at a minimum of 75% (Juan A. Morales-Ramos, Guadalupe Rojas, et al. 2012). However, maintaining high levels of relative humidity can be expensive, and the larvae grow faster when they are provided with a direct source of water (Cortes Ortiz et al. 2016). Adult beetles are not capable of taking in atmospheric water, and must be provided with a source of water. Continuous supply of water proves to be difficult in current production systems, because leaks will aggravate fungal and mite growth (Cortes Ortiz et al. 2016). Production systems in the United States provide water by manually dispensing small amounts of water every few days (Cortes Ortiz et al. 2016). The introduction of water saturated polymers into the rearing trays is found to be an alternative in providing water. Long-term impacts of the polymers on the insect colony and the final product are unknown. The development of improved watering systems is a key challenge in the mass production of insects (Cortes Ortiz et al. 2016).

Rearing density

The density with which mealworms are kept is of influence to several physiological factors, and economic factors. Increased rearing density means that the same amount of larvae can be kept in a smaller space, which most likely will reduce costs. But it is not as simple as easily increasing profits by increasing the rearing density. Reduced larval densities are found to improve the food conversion efficiency (Juan A. Morales-Ramos and Rojas 2015) and reduce development time (Savvidou and Bell 1994). In adult populations, high rearing densities may result in reduced oviposition rates, reduced adult longevity and increased egg cannibalism (Juan A. Morales-Ramos, Guadalupe Rojas, et al. 2012). An optimal rearing density should be determined, balancing before stated economic effects against the required rearing area.

Climate
Accurate climate conditioning, to be specific the regulation of temperature, humidity and gas mixture, is extremely important to successful insect rearing for multiple reasons. Firstly, insects are poikilothermic organisms, which means that they are unable to regulate their own body temperature metabolically. Their development speed is positively correlated to the temperature, but when the temperature becomes too high, mortality rates will increase. Secondly, humidity plays an important role in healthy insect growth. High humidity increases the probability of diseases and food spoilage, whilst physiological problems or dried food will present problems when humidity becomes too low. Lastly, air flow plays an important role in climate conditioning. Not only to keep the concentration of carbon dioxide or toxic gasses below critical levels, but also to avoid local areas of air stagnation. Air stagnation increases the probability of disease and food degradation, and negatively affects insect development and health of workers (Cortes Ortiz et al. 2016). Although there is no doubt about the food conversion efficiency of insects, the air conditioning process may require a considerable amount of energy, some of which may be saved through a well designed climate control system. The most important factor in the entire climate control system being uniformity through the entire warehouse over the time of the day (Cortes Ortiz et al. 2016).

1.1.3. Lesser mealworm

The lesser mealworm or *Alphitobius Diaperinus* is said to have originated from sub-Saharan Africa and is well suited to a warm and humid environment. It is considered a general stored products pest, usually found infesting flour, meal or other grain products. *A. Diaperinus* is also found inhabiting poultry droppings, and is considered a significant pest in the poultry industry as well as a vector or reservoir for several poultry pathogens and parasites. It has the ability to damage poultry housing, and is a suspected health risk for humans when they come in close contact to larvae and adults (Dunford and Kaufman 2007).

Description
The adult lesser mealworm is oval in shape, and black or brownish-black in colour, but can vary depending on age or strain. The length of the body is approximately 5.8 to 6.3 mm. It's larvae have a segmented body with three pairs of legs and are approximately 7 to 11 mm in length when in the last instar phase. Immediately after hatching the larvae exhibit a milky colour, turning to a shade of brown after the third instar. The larvae will undergo between 6 to 11 instar phases. The pupae are 6 to 8 mm in length, colour varies between creamy white and tan (Dunford and Kaufman 2007).

Lifecycle
An adult female beetle lays an average of 200 to 400 eggs, with a maximum of over 2000 eggs. The eggs are laid in cracks or crevises at an interval of one to five days. The life expectancy of an adult beetle ranges between three to twelve months. Larvae hatch from the eggs in four to seven days, and reach the adult stage in 40 to 100 days, while the speed of development is influenced by feed quality and temperature (Dunford and Kaufman 2007). The entire cycle from egg to adult is shown in figure 1.1.

1.1.4. Insect rearing in short

Replacement of vertebrae sourced protein in the human diet with insect protein in meaningful quantities, provides an opportunity to drastically reduce farmland and greenhouse gas emissions, whilst still containing critical nutrients. Successful automation and precise climate control are of extreme importance to the economic and biological success of a modern mass production system for insects, whilst diet and rearing technique are also of influence.

1.2. Research Questions

The main research questions is:

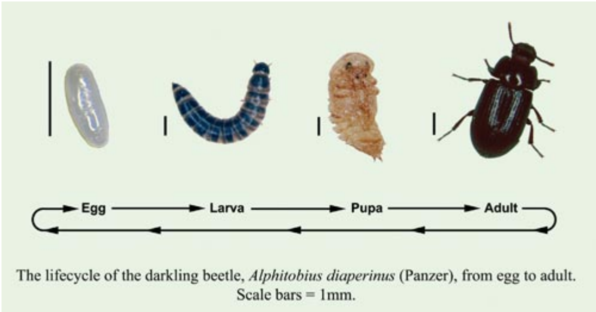


Figure 1.1: The lifecycle of *A. Diaperinus* (Lambkin 2006)

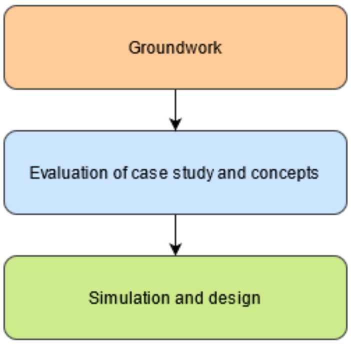


Figure 1.2: Simplification of the present study into three steps

How to design an automated warehouse for an insect rearing system?

The following subquestions are defined:

- How to take an automated generation of design approach to automated warehouse design?
- How does the insect rearing process work in the case study?
- What lessons can be learned from the experiences gained in the case study?
- What are the key performance indicators for an automated warehouse in the insect rearing application?
- What material handling equipment concept is best suited to the insect rearing process?
- What is the optimal lay-out design for an automated warehouse in an insect rearing system?

1.3. Methodology

The aim of this present study is to validate the automated warehouse concept as used in the case study, and to design a near optimal factory lay-out using the case study concept, and the best alternative concept. The near optimal lay-out will be automatically generated within the paradigm of automated generation of design. Throughout the project, theoretical knowledge on the subjects of insect mass production, (automated) warehouse design and automated generation of design is combined with practical knowledge obtained in the operational environment of the case study. To indicate where each method fits in, the project is divided into three parts being groundwork, evaluation of case study and concepts, and simulation and design (figure 1.2). The methods that are used to obtain or generate information are described below, along with where each method fits into the project.

1.3.1. Literature

The literature study forms the groundwork of this study, and is concerned with the subjects of insect mass production, automated warehouse design and automated generation of design. The information aggregated

Search engine	Scopus	Google Scholar
Search terms	Results	
Insect AND rearing	4,412 documents	310,000 documents
Large AND scale AND insect AND rearing	163 documents	148,000 documents
Insect AND production	27,693 documents	2,690,000 documents
large AND scale AND insect AND production	1,118 documents	1,810,000 documents
Insect AND mass AND production	2,472 documents	2,030,000 documents

Table 1.1: Search terms and results on insect rearing literature

here forms a theoretical basis to which can be referred when conclusions are drawn or decisions are made later on in the project. To obtain relevant literature, both the Scopus and Google Scholar search engine are employed. To ensure that only peer review scientific work is included, results from Google Scholar also need to be accessible through Scopus.

Scientific literature on the topic of insect mass production is studied in the introduction to paint a picture of the state of art of insect production technologies and to learn about the requirements and limitations of large scale rearing of insects. Through this literature study, an external source of information on insect rearing is included on top of the case study. This information is especially valuable when assessing the automated warehouse concepts later on in the report. The search terms on insect rearing are described in table 1.1 and yielded a lot of results. Relevant results from Scopus were mostly studies focus on one tiny detail in insect production, whilst a general overview was required. The search line *insect AND production* in Google Scholar yielded chapter 6 from the book *Insects as Sustainable Food Ingredients* (Cortes Ortiz et al. 2016) as top result, which is used as the primary source for the introduction to insect rearing in this report, as it provides a wealth of information through proper aggregation of sources.

In chapter 2 the paradigm of *automated generation of design* is studied in relation to automated warehouse design. It is a fairly new field of study, which shows in the relatively meager amount of hits on Scopus. But it also shows in that definitions and applications within the paradigm are still of a diverse nature. One of the goals of this part of the literature review is therefore to find out what exactly defines the paradigm of *automated generation of design*. Furthermore an overview is created on methods and applications of the paradigm, and the advantages and pitfalls of automated design generation are explored.
The search terms as listed in table 1.3 are entered in Scopus and Google Scholar. The results are limited to publications in 2018 or later because of the novelty of the paradigm, and through trial and error is was found that limiting the results to engineering related publications yielded more relevant articles. Automated generation of design was found to be applied to wide range of topics, including heating and ventilation, personal health and drug design. Only publications that are concerned with functional shape generation (especially when related to buildings or production processes) are deemed relevant. Through scanning titles and abstracts, articles that did not meet these requirements were excluded. The thesis work of fellow students concerned with automated generation of design was used as an additional source on this topic.
The topic of automated warehouse design is studied in the second half of chapter 2. General considerations regarding the design of an automated warehouse are discussed, as well as an overview on modelling efforts on automated warehouses, which will provide a point of reference in the simulation part of chapter 5. Furthermore, valuable insights could be obtained through existing studies on the application of automated warehousing technology in insect rearing. In chapter 4 scientific literature is used to construct an overview on established automated warehouse concepts in general, and provide neutral information about the advantages and disadvantages of each technological concept. Lastly, common KPIs used in warehouse design are included.
The search terms used are listed in table 1.2. A useful overview on warehouse technologies (Azadeh, De Koster, and Roy 2019) and modelling was obtained, and is extensively referenced in chapter 4. Another interesting result of this literature study was that only one paper was obtained through the bottom search criteria, describing an automated warehouse applied in silkworm rearing (Ohura 2003).

Search engine	Scopus	Google Scholar
Search terms	Results	
Automated AND warehouse AND design	587 documents	88,700 documents
Automated AND warehouse AND design AND review	28 documents	63,100 documents
Automated AND warehouse AND insect AND rearing	1 document	850 documents
Automated AND warehouse AND insect AND production	1 document	9,990 documents

Table 1.2: Search terms and results on automated warehouse design literature

Search engine	Scopus	Google Scholar
Search terms	Results	
Automated AND generation AND design AND review (limits: >2018)	80 documents	111,000 documents
Automated AND warehouse AND design AND review (limits: engineering, >2018)	29 documents	-
Generative AND design AND review (limits: >2018)	136 documents	30,500 documents
Generative AND design AND review (limits: engineering, >2018)	39 documents	-

Table 1.3: Search terms and results on automated generation of design literature

1.3.2. Case study analysis

The analysis of the case study serves multiple purposes. The first goal being the identification of issues and flaws in the current production system, and the identification of advantages and well functioning aspects of the design. So an evaluation is made, and recommendations will be given on adaptations or improvements on the production system. The employees have gained valuable experience in maintaining, operating, or otherwise being involved with the production system, and can therefore be considered experts. Their experience is used to verify the completeness of the list of system requirements, and to qualitatively assess the expected performance of automated warehousing concepts. The final purpose of this analysis is to obtain sufficient information regarding the production process and equipment interactions to create a simulation model. Information is obtained through interviews and the study of documentation.

1.3.3. Selection of material handling equipment

An overview is made on material handling equipment and pallet storage technologies based on literature research. Several automated warehouse concepts are put together based on the overview. The concepts are subsequently qualitatively evaluated by a team experts. A basic design is made for the preferred concepts, and a quantitative evaluation is then used to select the preferred concepts.

1.3.4. Simulation and design

A parametric description of the automated warehouse is coupled to discrete event simulation model to obtain a performance based parametric design approach, where the warehouse lay-out design is iterated until the desired material handling capacity is reached. Lay-out designs are created for four operational scenarios.

1.4. Terms and Definitions

An explanation of the terms used is included here.

Aisle - Path along which storage and retrieval equipment travels, with storage channels on each side
Storage channel - Channel in which pallets are stored
GS - Generative system
Dual command cycle - Combined storage and retrieval job
Unitload system - Warehouse system using pallets
Miniload system - Warehouse system using totes instead of pallets
Tote - Warehouse handling unit, typically a plastic container
VLM - Vertical lift module
ASRS - Automated storage and retrieval system
RMF system - Robotic mobile fulfilment system

SKU - Stock keeping unit
LP - Linear programming
MIP - Mixed integer programming
OQN - Open queuing network
CQN - Closed queuing network
SOQN - Semi open queuing network
CA - Cellular automata
MAS - Multi-agent system
BIM - Building information model
Robot - Material handling robot

2

Automated generation of warehouse design

This thesis aims to employ the concept of automated generation of design to the task of warehouse lay-out design. In the first half of this chapter an overview is presented on the concept of automated generation of design. The origin of the concept is discussed, a definition is given and typical areas of application are reviewed. The advantages and disadvantages in the application of automated generation of design as they are currently understood will be discussed, and a couple of relevant examples of automated generation of design found in literature, will be covered in further detail, as to give provide a context to the application of the concept in chapter 5 of this report. In the second half of this chapter, warehouse design is discussed from the academic perspective. First, a basic overview on the paradigm of (automated) warehouse design will be given, to understand the basic problems and current trends in industry and research. By discussing the relevance of each of the five warehouse design problems as described by (J. Gu, Goetschalckx, and McGinnis 2010), the finer details of warehouse design will become clear and the scope of the design problem more sharply defined. This is followed by a deeper dive into several relevant subjects to find (partial) answers to the research questions of this study related to warehouse design. The complexity of objective functions and the parameters and constraints of warehouse design optimization studies will be discussed to identify the state of art and serve as a starting point. Studies concerned with the evaluation of transportation concepts in warehouse design will be discussed and relevant efforts in warehouse simulation are discussed. A detailed description and discussion of material handling equipment concepts is not included in this chapter, but can be found in chapter 4. The overarching question that this chapter seeks to answer is as follows: How to apply an automated generation of design approach to the automated warehouse design problem?

2.1. Automated generation of design

The relevance of the automated generation of design concept comes forth from the difficulty of the conceptual design phase. This conceptual design phase is the most crucial task in engineering development, as the impact of early decisions heavily influence the final design, whilst little information is yet available to base decisions on (Wang et al. 2002). An estimated 75% of final product cost is incurred early in the design phase, and key areas like performance, reliability, safety and environmental impact are impacted by these decisions (Hsu and Liu 2000). The relationship of incurred cost over the design phase is further worked out by (Dieter and Schmidt 2009) (figure 2.1), who conclude that early design decisions cost very little, but have a major effect on the cost of the product (Dieter and Schmidt 2009).

Rigid user-interfaces like Computer-Aided Design (CAD), are said to be unsuitable for concept generation, as they negatively affect freedom, intuitiveness and creative idea generation. Another interesting point is made by (C et al. 2003) and (Lim et al. 2004), who find that designers prefer manual design and that a large part of design work is done manually. This manual work comes with the disadvantage that adjustments are not easily made in later phases of the design (Naya, Jorge, and Conesa 2002) (Römer et al. 2001).

To overcome these limitations in the design process between designer and product, generative design emerged and added a new component to the long-lasting binary relationship between the designer and the product,

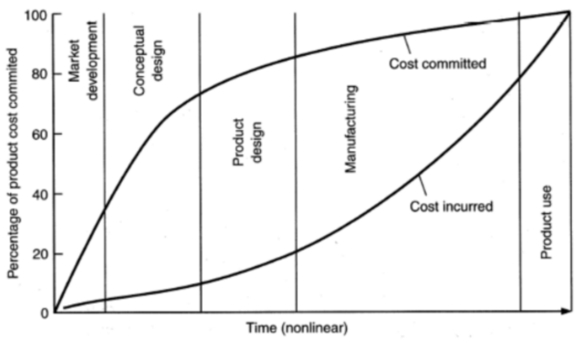


Figure 2.1: The relation between committed costs and incurred costs in different design phases as described by (Dieter and Schmidt 2009) (Dieter and Schmidt 2009).

which transcends into a tertiary relationship between designer, generative system and product (Fischer and Herr 2001). The first generative systems have been developed by mathematicians in an effort to replicate patterns observed in nature (Prusinkiewicz and Lindenmayer 2012), whilst the application of generative systems expanded in the 1970's when architecture, engineering and construction industry researchers began to explore it's possibilities (İlal 2007). This new technology helps make multidisciplinary expertise available to designers, which they could otherwise not rely on (Fischer and Herr 2001) and helps them evaluate designs from a broader perspective. Perhaps the most influential game changer is the fact that generative design brings computing power into the design equation, and enables the evaluation of plenty design variations within a very short time, increasing the chance of finding the (near) optimal design (BuHamdan, Alwisy, and Bouferguene 2020). The complexity of involved disciplines, system interdependencies and stakeholder requirements make the engineering industry (among others) ideal for generative design (BuHamdan, Alwisy, and Bouferguene 2020).

2.1.1. Definition of automated generation of design

Automated generation of design can be seen as an evolution of parametric design (Nagy et al. 2017) and will be discussed from this perspective. Parametric design is an approach to design in which geometric relations are defined through parameters, constraints and equations (Lee, N. Gu, and Williams 2014). Through the description of these relations, not only a final design is described, but the entire system behind this design (Nagy et al. 2017). A broad definition of parametric design is given in (Caetano, Santos, and Leitão 2020), where it is characterised as an approach that describes a design symbolically based on the use of parameters. An important advantage of the parametric design approach is that variations and custom adaptations of the design are easy to generate through variation of the parameters (Nagy et al. 2017).
Automated generation of design, also referred to as generative design, employs algorithmic descriptions that are more autonomous than parametric design (Caetano, Santos, and Leitão 2020). After starting the generative process, the system executes encoded instructions until the stop criterion is satisfied. Performance-based generative design systems are brought up as a good example of the application of a generative design method. In this approach, a designer sets a performance target, and an algorithm is then used to find a design solution that performs accordingly. An important aspect of generative design algorithms, is that the solutions are non-traceable and the results are obtained through probabilistic or non-deterministic search procedures (Caetano, Santos, and Leitão 2020). In (Nagy et al. 2017), generative design is described as an extension of the parametric model, where concrete metrics are defined to evaluate the performance of generated designs, and where a search algorithm controls the input parameters to intelligently tune the parametric model, to obtain high performance designs, as well as complete exploration of the solution space.

2.1.2. Advantages and disadvantages

As parametric design is limited by the abilities of the human designer in the exploration of the design space, however automated generation of design overcomes this limitation through automation of this exploration. Thus variations and custom adaptations of a design are easy to create. When requirements are change in the future, the parametric approach ensures that designs and results can be easily adapted to changing conditions. No new model needs to be built from scratch every time. Arguably, another advantage is that designers are allowed to think in a deeper and more dynamic way compared to traditional design methods (Nagy et al. 2017). A disadvantage of generative design is the tendency of the model to explore the design space without much transparency, thus acting as a black box to the designers (Moussavi 2011). Visualisation of the design generation process may thus be a key area of attention when developing a generative system.

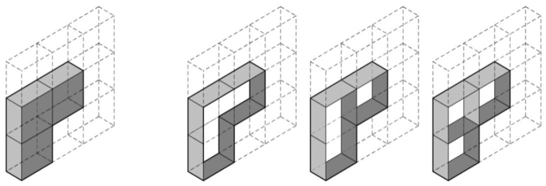
2.1.3. Relevant examples in detail

The automated generation of design concept is often applied in the generation of shapes that posses artistic or perceived qualities, for example in art or architecture. As a key element in the concept is found to be the performance analysis and feedback into the generative design process, one may expect that the real potential lies in the design of systems with objectively measurable performance properties. In a review by (BuHamdan, Alwisy, and Bouferguene 2020), the application of generative systems in the architecture, engineering and construction industry are discussed. Several of these articles are concerned with the generation of a (functional) lay-out and these articles are included in table 2.1. Some general observations on these approaches will be discussed here, as well as interesting outtakes or conclusions drawn by the authors in order to understand the state of art of the automated generation of design concept.

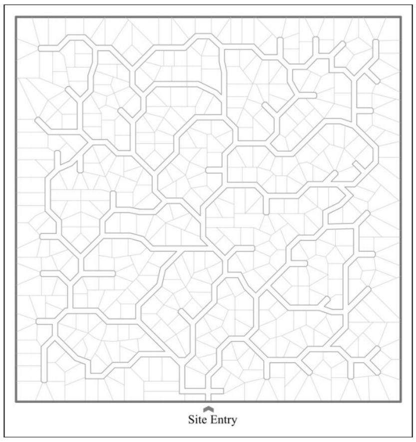
In (Cruz, Karakiewicz, and Kirley 2016) an effort is made to design interesting room lay-outs, cell boundaries are added or removed (figure 2.2a), representing room walls. The results are evaluated through entropy measurement and benchmark comparison, which effectively makes this study an effort to replicate a traditional design through the application of automated generation of design. The performance evaluation lacks any objective criteria, which reflects the objective of creating "interesting spatial organisations".
The generative design method by (Sun and Taplin 2018) is concerned with the generation of a residential area layout where land lots and roads need to be laid (figure 2.2b). The approach optimises for maximal number of lots, and maximal accessibility for pedestrians and cyclists through minimization of the travel distance to certain locations in the network. Through a biology inspired set of evolution rules, a complex form is generated from simple shapes (Sun and Taplin 2018), but the interaction between this evolution process and the optimization of the objective is not clearly described in this paper.
A multi agent system is employed in both (Li et al. 2014) and (Ghaffarian, Fallah, and Jacob 2018), but both studies lack objective criteria upon which the generated designs are evaluated. In (Li et al. 2014), pedestrians are let loose in a previously generated environment. Through the evaluation of repeated visits and unreachable spaces for pedestrians, decisions are made on the removal of walls, and random decisions are made on the placement of walls. In (Ghaffarian, Fallah, and Jacob 2018) the flow patterns of humans through a space with pre-generated obstacles are used to generate organic architectural spaces (figure 2.2d) with "higher efficiency, in a lot of different aspects" (Ghaffarian, Fallah, and Jacob 2018). Whilst there is no doubt about the success in the generation of interesting shapes, no clear performance measurements are mentioned.
In the last paper automated generation of design is applied to customize apartment plans and automatically convert the result into a detailed building information model (BIM) (Veloso, Celani, and Scheeren 2018). Although this paper is heavily focused on the integration of design generation and BIM output generation, it is interesting because it produces a layout that meets legal and economical restrictions from a combination of functional systems. In this case a living room, bedroom, kitchen etc. Variations of the design are created through pre-defined shape grammar rules. Furthermore, the paper is complemented by beautiful visuals that describe the generative process, one of which is included in figure 2.2e.

Author	Goal	Generative technique	Modelling subject	Conclusion
(Cruz, Karakiewicz, and Kirley 2016)	Creation of an interesting spatial organisation for humans	Composite CA	cell boundary or room wall	Strength of generative design may lie in informing the designer rather then generating a completed design
(Sun and Taplin 2018)	Automate design of residential layouts with high density and accessibility	Bottom-up	Cell shape representing roads and residential lots	The technique helped achieve the objective of high density and high accessabily with walkable, coherent communities
(Li et al. 2014)	Generate architectural spaces that support a good spatial experience during walking	MAS, pedestrians directly altering the environment	A pre-made environment	Generative design seems promising in aiding performance oriented design
(Ghaffarian, Fallah, and Jacob 2018)	Create a tool for the generation of organic architectural space	MAS	Crowds walking around obstacles, the movement patterns are transformed into shapes	A shape generation tool is successfully created
(Veloso, Celani, and Scheeren 2018)	Combining algorithmic design generation and integrate detailed BIM model output	Shape grammar rules	House floorplan	The technology might facilitate interactive architectural design where a user applies changes within legal and economic restrictions

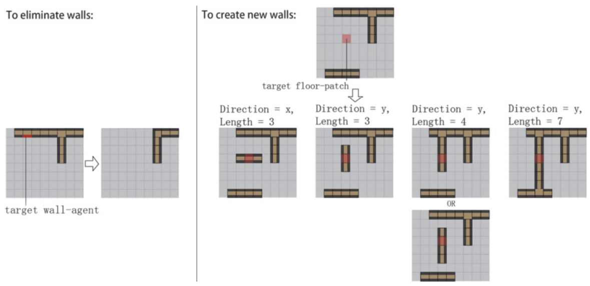
Table 2.1: Relevant studies where automated generation of design concepts are applied



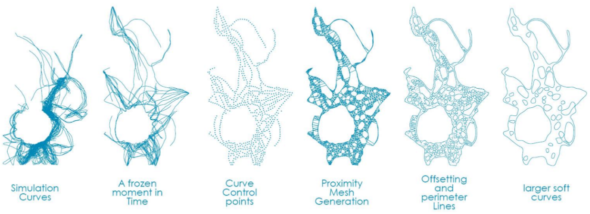
(a) Room wall design process (Cruz, Karakiewicz, and Kirley 2016)



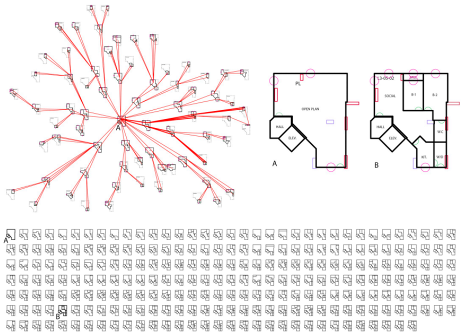
(b) Design result of land plots and roads for a 25 hectare residential site (Sun and Taplin 2018)



(c) Design process for the generation of architectural spaces for walking (Li et al. 2014)



(d) Organic shape design process from walking patterns (Ghaffarian, Fallah, and Jacob 2018)



(e) Appartment floorplan design process (Veloso, Celani, and Scheeren 2018)

Figure 2.2: Examples of applications of automated generation of design

2.2. Warehouse design

2.2.1. Trends

The warehouse operation requires large buildings to store assortments and move stocks. A large space is required to load and unload trailers and containers, and to allow trucks to maneuver or dock (Azadeh, De Koster, and Roy 2019). In these warehouse activities, five main processes can be identified. These are receiving, storage, picking, consolidation and shipping (Rouwenhorst et al. 2000). These processes all take place in and around a warehouse that fulfills the traditional functions of storage and distribution, whilst in the intended application of insect rearing only the storage process takes place. Furthermore, traditional warehouses are built around human operators, who account for more than half of a warehouse's operational cost (Frazelle 2016). The order picking process is not only laborious and expensive, it is also a repetitive job that suffers from poor ergonomics, whilst requiring high-quality employees who are willing to work in shifts, as warehouses have to operate around the clock (Azadeh, De Koster, and Roy 2019). No wonder that one of most important trends in warehouse design it the push for higher levels of automation (Hamberg and Verriet 2012).

During the last decade automated warehouse technology has developed rapidly (Azadeh, De Koster, and Roy 2019), and the industry has taken notice. In the period of 2012 to 2016 in the Netherlands alone, 63 large new warehouses were constructed employing some form of robot technology (Buck Consultants International 2017). Key drivers in this development are autonomous-vehicle based storage and retrieval systems (AVSR), and shuttle based storage and retrieval systems. Automated pallet stacking and destacking is another important technological development. A new generation of automated guided vehicles (AGVs) to support the picking process has recently been introduced, which will eventually result in a fully automated picking process (Azadeh, De Koster, and Roy 2019). In Western Europe about 40 fully automated warehouse are already in operation, and many are under development (Azadeh, De Koster, and Roy 2019). Despite this development, a consultant concluded in 2017 that a majority of warehouse research is still focused on conventional storage and order-picking methods (Buck Consultants International 2017).

2.2.2. Key elements in warehouse design

In an extensive review of research on warehouse design, (J. Gu, Goetschalckx, and McGinnis 2010) identifies five major decisions of warehouse design. The decisions in each level as described in table 2.2 are not presented in a hierarchical order, but are in fact dependent (figure 2.3). This makes warehouse design rather complicated, whilst little integrated design support is available (Rouwenhorst et al. 2000). The design choices influence the cost of construction and maintenance, material handling cost, storage capacity, space utilization and equipment utilization (J. Gu, Goetschalckx, and McGinnis 2010).

Overall structure	Determines functional areas of a warehouse and defines how orders are assembled
Size and dimension	Identifies the capacities of the warehouse's functional areas
Layout	Defines the physical arrangement of the warehouse areas
Equipment selection	Specifies the material handling equipment to be deployed
Operational strategy	Identifies the high-level operational strategies

Table 2.2: The five major decisions in warehouse design as defined by (J. Gu, Goetschalckx, and McGinnis 2010)

Overall structure

The overall structure is also called the conceptual design. It determines how many storage departments are needed, what technologies will be applied and how orders will be assembled. In this stage of the design, typically just the requirements for storage, throughput and cost minimization are considered. The papers that are discussed by (J. Gu, Goetschalckx, and McGinnis 2010) focus heavily on order picking, and are therefore of limited relevance to this report. Two research contributions are required in this field of study. Firstly a "principle based assessment of appropriate decision aiding for these high level design decisions which are taken with uncertain knowledge of future operating condition" is needed. Secondly, "simple validated models that actually give useful results for guiding overall structural designs" are needed.

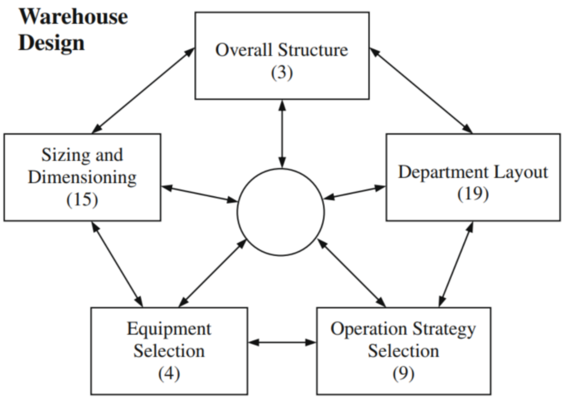


Figure 2.3: The interrelations between the five levels of warehouse design according to (J. Gu, Goetschalckx, and McGinnis 2010).

Size and dimension

Warehouse sizing determines the storage capacity of the warehouse. In the literature discussed by (J. Gu, Goetschalckx, and McGinnis 2010), the most important distinction between models can be made between self controlled inventory levels, or uncontrolled inventory levels. The unanimous assumption made in all models is a single storage department. Dimensioning concerns itself with the translation of the required capacity into floor space to determine construction and operating costs.

Layout

The inputs and outputs of the warehouse layout problem change depending on the warehouse equipment and operational strategy. A three category classification system (table 2.3) of warehouse layout problems as proposed by (J. Gu, Goetschalckx, and McGinnis 2010) is followed and discussed.
The pallet block stacking problem concerns itself with pallet storage directly onto an empty warehouse floor. The number of lanes, storage lane depth, aisle dimensions, stacking height, pallet placement angle and clearance need to be determined to obtain a balanced trade-off between storage density and reachability of stock keeping units (SKUs).
The storage department layout problem is formulated to determine an aisle structure that results in minimal material handling cost and construction cost. Aisle orientation, aisle number, aisle dimensions and door locations are typical design parameters. To evaluate operational costs, assumptions need to be made about storage and picking policies. Commonly, random storage and single-command order picking are assumed. The entire practice of storage department layout optimization is called into question by (Roodbergen and Vis 2006), who argues that it is impossible without knowing the true material handling performance.
The goal of the AS/RS configuration problem is to determine the number of cranes and aisles and the storage rack dimensions for a warehouse in order to minimize the cost of construction, maintenance and operation (and/or to maximize equipment utilization). A typical design optimization model is based upon an empirical expression of cost, using assumptions on the operational policy and known storage and retrieval rates (J. Gu, Goetschalckx, and McGinnis 2010).

Pallet block stacking	Determines pallet placement in a rackless warehouse
Storage department layout	Determines aisle structure
AS/RS configurations	Determines number of cranes, aisles and storage rack dimensions

Table 2.3: Classification of warehouse storage layout problems (J. Gu, Goetschalckx, and McGinnis 2010)

Equipment selection

The equipment selection problem tries to systematically determine the required level of automation and the type of storage and material handling equipment that is needed. These decisions have far reaching consequences on the required investment and subsequent warehouse performance, whilst answers to these questions are far from obvious, and in practice determined based on personal experience of managers and designers. Academic research on this subject is found to be extremely rare, but relevant examples will be discussed in section 2.2.4. Two fundamental issues are yet to be addressed in academic literature. Firstly, how the equipment alternatives that are reasonable for the given storage and retrieval requirement can be identified. Secondly, a significant contribution can be achieved by the development of a method to characterize requirements, and characterize equipment in a way that issues can be addressed in a unified manner (J. Gu, Goetschalckx, and McGinnis 2010).

Operational strategy
The operational strategy is about the choice of a storage strategy and order picking strategy. For example randomized or dedicated storage can be used, or a zone picking strategy can be implemented. These strategies are relevant when demand and inventory vary over time or when orders are picked in a warehouse (J. Gu, Goetschalckx, and McGinnis 2010).

2.2.3. Lay out design

An article by (Rosenblatt, Roll, and Zyser 1993) concerning layout design especially stood out, because of it's iterative approach to design optimization and evaluation approach. This iterative approach forms the basis of automated generation of design. In this paragraph, the goal, method, results and considerations of this approach to layout design of an automated warehouse will be discussed to serve as a guideline in the layout design of an automated warehouse for insect rearing.

Based on the observation that ASRS warehouse design is often studied either from a cost minimizing perspective, or the dynamic system behaviour perspective, (Rosenblatt, Roll, and Zyser 1993) describes an approach that tackles both issues simultaneously through the recursive coupling of an optimization algorithm with a simulation algorithm (figure 2.4). Optimization is done through a non-linear integer model, which minimizes for initial investment and operating costs under several constraints. For the simulation procedure, the performance of an entire warehouse is assessed. Pallets are retrieved from storage and brought to a service station. After service by the operator, pallets are returned to the original storage location. Performance is measured through the determination of average service time (time between order generation and completion) and average service level (proportion of orders completed in the shift they were generated) of the system. The design variables that are determined through optimization for cost are fed into the simulation model, where performance metrics are evaluated. If the requirements are satisfied, the procedure is terminated. Otherwise, relationship functions are determined through a batch of simulations, which are added as additional constraints into the optimization model, and a new set of design parameters is obtained. One of the conclusions drawn from this study is that the assumption of one crane per aisle is often made in ASRS design studies, whilst optimal designs may exist with fewer cranes than aisles. A traversing mechanism for the cranes is necessary in this case. For future research, (Rosenblatt, Roll, and Zyser 1993) recommends that the effects of operating policies on performance figures in simulation should be studied, and that different methods for recursiveness may need to be developed.

2.2.4. Equipment selection

In (J. Gu, Goetschalckx, and McGinnis 2010), several articles and conference proceedings are discussed that are concerned with equipment selection and decision making on the required level of automated. Of these four studies (Cox 1986), (J. White, DeMars, and J. Matson 1981), (J. O. Matson and J. A. White 1981), (Sharp, Vlasta, and Houmas 1994), only one is still available online. The descriptions that follow are based upon the work of (J. Gu, Goetschalckx, and McGinnis 2010). An analytical model is developed in (J. White, DeMars, and J. Matson 1981) to compare block stacking, single-deep, double-deep and deep lane storage and a unit load ASRS to determine a minimum space design. In (J. O. Matson and J. A. White 1981), this approach is extended to a total cost model that incorporates space and material handling costs. In (Sharp, Vlasta, and Houmas 1994) shelving systems, modular drawers, gravity flow racks, carousel systems and mini-load storage and retrieval systems are compared in a warehouse with different dimensions and product sizes. The objective function includes operational costs, floor space costs and equipment costs. Especially the methodology to evaluate different levels of automation through a cost-productivity analysis technique by (Cox 1986) seems worth an in depth review to substantiate the argument for a fully automated warehouse. In a significantly older review publication multiple articles are on equipment selection are mentioned (J. O. Matson and J. A. White 1982). In (Tompkins and Reed 1976), a model described that combines facility lay-out design with the selection of equipment for material handling. A complete list of the equipment types that were included in

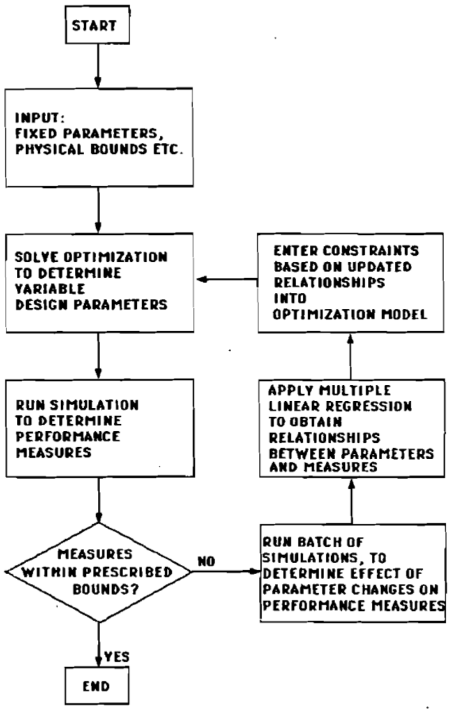


Figure 2.4: The recursive design and simulation procedure by (Rosenblatt, Roll, and Zyser 1993).

this study is not included, but at least an electric platform truck, electric lift truck, manual platform truck and electric tractor were considered.

Some methods for equipment evaluation seem to exist in literature, but the original publications are hard to obtain. The only combined analysis of cost and productivity seems to be done by (Cox 1986), but unfortunately disappeared from Google (Scholar) or Scopus.

2.2.5. Warehouse modelling

Warehouse systems can either be modeled analytically or through simulation. Analytical models provide less accurate solutions than simulations, but also require less time to develop. Therefore, in an early design stage an analytical model may be preferred, whilst a simulation model may be required to provide detailed results (Azadeh, De Koster, and Roy 2019). Decisions revolve around hardware design selection and optimization. The most important objectives being maximized throughput and storage capacity (Azadeh, De Koster, and Roy 2019) or meet storage and throughput requirements while minimizing cost (J. Gu, Goetschalckx, and McGinnis 2010).

LP and MIP

LP or MIP models can be used to optimize many design and operational decisions in automated systems. For example system shape, storage policy and scheduling decisions can be made based on LP or MIP models. The usual application of this technique is a deterministic setting. For stochastic system behaviour, travel time and queuing network models are a preferable solution (Azadeh, De Koster, and Roy 2019). LP models can be solved exactly in polynomial time, but exact solutions of MIP models are generally not tractable. However, near-optimal solutions can be obtained in reasonable solving time through the application of metaheuristic algorithms (Azadeh, De Koster, and Roy 2019).

Travel time

The travel time model is a computationally friendly method that can be used to determine the time needed to store or retrieve a product, or estimate service times. A travel time model is not capable of capturing more complex interactions between multiple resources , parallel processing or queuing. To get these functionalities, a queuing network model is preferred (Azadeh, De Koster, and Roy 2019).

Queuing network
The queuing network model is often used to represent automated picking systems, and has been studied in the variants of an open queuing network (OQN), closed queuing network (CQN) or semiopen queuing network (SOQN). In the OQN, an order enters the system, receives service at different nodes, and will then leave the system. This method is useful to estimate expected order throughput time. When resourced are limited a CQN is preferable. A limited number of resources is paired with incoming orders, and once an order is completed, the resource is used to service another order. This makes the CQN especially useful to estimate maximum throughput capacity of a system. The SOQN is a hybrid version of both models, working with external orders and a limited capacity. This adaptation makes the SOQN capable of capturing external transaction waiting time.

2.2.6. Warehouse KPIs

An overview on automated warehouse KPIs is presented in (Faveto et al. 2021), where commonly used KPIs in research papers are classified in an economic, environmental and social cluster, and the observation is being made that economic KPIs make up 80% of the total. To further structure the economic cluster, five sub-clusters are defined, which are listed below.

- Generic Performance
- Time related Performance
- Cost performance
- Information system performance
- Warehouse Measure

The KPIs in this overview describe all aspects of the warehouse process, thus performance indicators regarding picking, receiving or shipping processes are also included. The most common KPIs of each category are included in table 2.4.

Cluster		KPI
Economic	Generic	Throughput Area occupation Receptivity Capacity Flexibility
	Time Related	Cycle time Picking Time Order Elabor. Time Travel Time
	Cost	Management Cost Storage Cost Retrieval Cost
	Information System	Image Rec. Speed Algorithm Reliability
	Warehouse Measure	Temperature Barometric Pressure Humidity Roof Temperature Pollutant
Environmental		Energy consumption Energy Recovery Pollutant Emission
Social		Human Utilization Human Error

Table 2.4: Common KPIs in automated warehouse related scientific papers (Faveto et al. 2021)

2.3. Conclusion

Automated generation of design can be characterised as an extension of parametric modelling, where concrete performance metrics are defined, and a search algorithm is employed to intelligently tune the design parameters (Nagy et al. 2017). The search procedure is probabilistic or non-deterministic, thus the obtained solutions are not non-traceable (Caetano, Santos, and Leitão 2020). The paradigm combines design generation, performance analysis and evaluation (BuHamdan, Alwisy, and Bouferguene 2020). The main advantages lie in the improved ability to explore the entire design space, and the ease with which designs can be adapted to changing requirements. A remarkable observation comes from the review of recent academic papers, where shapes and layouts are predominantly generated for their artistic or perceived qualities. Whilst performance analysis is a key pillar of the automated generation of design concept, it is only included in (Sun and Taplin 2018), where a residential area design is optimized for plot density and accessibility, and to a lesser extent in (Veloso, Celani, and Scheeren 2018), where an apartment layout design needs to meet economic and legal restrictions. All applications take place in two-dimensional space, with the arguable exception of (Ghaffarian, Fallah, and Jacob 2018), where two-dimensional shapes are stacked into a three-dimensional design. In most papers, the tendency of automated generation of design to function as a black box is taken seriously, and emphasis is laid on the visualisation of the generative methods, especially in (Veloso, Celani, and Scheeren 2018). In warehouse design, cost minimization and dynamic system performance are often studied separately. The required level of automation for automated warehouses and the subsequent systematic evaluation of warehouse equipment are studied in a very limited fashion, and decisions are often made based on the experience of managers or designers (J. Gu, Goetschalckx, and McGinnis 2010). SOQN looks like a promising method to represent an automated warehouse with limited transportation resources. The application of automated generation of design to create a tool that simultaneously evaluates cost and performance could aid experienced automated warehouse designers in making more substantiated design decisions.

3

Key performance indicators

In this section the state-of-art in insect rearing, automated warehouse design and the lessons learned from the case study are combined to select a coherent set of key performance indicators, to find out what the key performance indicators are for an automated warehouse in the insect rearing application.

3.1. Selection of KPIs

From the introduction on insect rearing, it has become clear that from a biological standpoint, on-time provision of sufficiently low rearing densities, a nutritious diet and maintenance of constant climate conditions are critical to the successful rearing of insects. To accurately provide feed to the insects on a daily basis, the proper functioning of the material handling equipment is required. A lesson that is learned the hard way in the case study, where optical sensors lack robustness against the pollution present in the warehouse.
Not all of the automated warehouse KPIs that were included in chapter 2 are relevant for the intended insect rearing application. For example the system will not include a goods receiving or shipping process, or an order picking process as is common in traditional warehouse operations. Of the generic kpis, handling capacity (or throughput), area occupation and storage capacity (or receptivity) are relevant. The time related kpis are relevant when designing an operational planning. This may be relevant for the systems ability to stay within the 24 hour schedule, but this level of detail is not included in this study. Although cost is ofcourse an important KPI, the literature focuses very much on traditional warehouse operations, and a more broad approach towards capital expenditure and operational expenses is required. Information system and warehouse measure KPIs are not often included in automated warehouse studies, but the latter is indeed of importance for insect rearing. Warehouse temperature, humidity and air quality are all important to the survival of the insects. The energy consumption of the automated warehouse solution is relevant from the operational expenses point of view, as well as the environmental footprint of the final product. As the process is intended to be fully automated, social aspects are not relevant.

3.2. Definition of KPIs

- Storage capacity
- Handling capacity
- Climate conditioning
- Cost (CAPEX - OPEX)
- Operability
- Maintainability
- Reliability

- Robustness
- Breeding quality

3.2.1. Storage capacity

The storage capacity of a warehouse will increase when the storage area is increased, or when a more space-efficient storage concept is implemented in the same warehouse. To be able to compare the performance of different storage concepts, the storage capacity relative to the warehouse area is defining, and therefore the total storage capacity of crates is divided over the total warehouse area. This space includes paths, aisles or conveyors over which the crates are transported, but excludes other equipment surrounding the warehouse, like handling or feeding equipment. Whilst the warehousing concept might have implications for the size of this equipment, it is assumed that the same equipment is necessary for every warehouse, and therefore not of any influence.

$$\text{Storage capacity KPI} = \frac{\text{Pallets}}{\text{Total warehouse area}} \left[\frac{1}{m^2}\right]$$

3.2.2. Handling capacity

The handling capacity or throughput of a warehouse characterises the amount of pallets that can be extracted from or inserted in the storage space, withing a certain time-frame. Under the assumption that there are always pallets requested from the warehouse, and pallets ready to be put back in the warehouse, the handling capacity will be measured in the amount of pallets that can be retrieved from *and* returned to storage. So one retrieval move and one storage move will result in a handling capacity of 1 pallet. The pallet handling capacity is measured per 24 hours, as the production cycle is completed in 24 hours.

$$\text{Handling capacity KPI} = \frac{\text{Pallets}}{\text{24 Hours}} \left[\frac{1}{24h}\right]$$

3.2.3. Climate conditioning

A well controlled climate is quite literally of vital importance to any insect rearing facility. Insects development speed is correlated to their body temperature, which they cannot control themselves. The temperature inside the rearing facility needs to be as high as possible to achieve maximum growth, but when temperatures are too high, mortality rates will increase and production yield will be negatively affected (Cortes Ortiz et al. 2016). Humidity also needs to be controlled. Too high humidity will result in increased chances of disease and food spoilage. Low humidity will result in physiological problems, and feed drying out (Cortes Ortiz et al. 2016). Furthermore, it is important to realize that the insects produce carbon dioxide, as well as heat through metabolic and friction processes. Therefore, air flow design is extremely important to keep local fluctuations in climate conditions to a minimum. Temperature differences will increase with warehouse height, unless individual insulated climate zones are made. But then the differential still exists outside these storage compartments, unless large volumes of air are mixed, thus needed expensive and energy hungry air conditioning systems.

3.2.4. Cost

The goal of the insect rearing facility is to produce a raw material at a competitive price. The design choices that are made in the developmental phase of the insect rearing facility may have far reaching consequences on the cost of the final product. As is conventional, the cost is divided into capital expenditure and operational expenses, i.e. the required initial investment and the cost of keeping the facility operational. In this study, a comparison is made between different designs, therefore the difference in cost between these designs is of interest.

Capital expenditure

In this study, a fixed amount of pallets is assumed, therefore the cost of pallets and crates, as well as the equipment required for feeding, harvesting and breeding are equal for all different designs. The difference in capital expenditure is made in the number of required material handling equipment, as well as the cost of different types of pallet racking.

$$\text{Automated warehouse investment} = \text{Cost of material handling equipment} \times \text{Required amount} + \text{Cost of racking} \, [€]$$

Operating expenses
Under operational expenses fall maintenance cost, warehouse rent, energy consumption as well as feed and water and labour cost. As energy requirements for air-conditioning may be dependent on the warehouse size, as a larger building is more prone to lose heat to it's environment, it is also dependent on the type of climate control system in place, and the level of isolation. The cost of feed may also be influenced by the rearing system design, as an ideal rearing system would have a high feed conversion and reduced operational cost, but the exact relations are yet to be determined. Maintenance cost and labour cost are assumed to be equal between different material handling concepts, as this is extremely hard to predict beforehand. The comparison in operational expenses is therefore simplified to rent of warehouse floor space. A concept with lower storage density will require a larger warehouse, and thus increased OpEx.

$$\text{Yearly warehouse rent} = \text{Required warehouse area} \times \text{Warehouse rent} \left[\frac{€}{year}\right]$$

3.2.5. Operability

Operability is interpreted here as the ease with which the system is kept operational. This manifests itself in the complexity of machine interactions and the complexity of the material flows and management software.

$$\text{Operability KPI} = \text{Mean time until system is operational after malfunction} \, [h]$$

3.2.6. Maintainability

The maintainability of the system describes the ease at which failed parts are changed out, and thus the system is fully functioning again. Multiple KPI's may be defined regarding maintainability like total downtime due to maintenance, or total cost of maintenance. Because of the importance of process continuity, the mean time to repair is used as the maintainability KPI. This gives the best indication if maintenance processes can easily be fitted into the production schedule, or if they will severely impact production.

$$\text{Maintainability KPI} = \text{Mean time to repair} \, [h]$$

3.2.7. Reliability

Reliability is interpreted as the amount of time that the factory can work without failure. In the current factory, simple mechanical components like the chain driven conveyors prove extremely reliable. Electrical systems are prone to failure due to mice eating into the wiring harnesses, or insects crawling inside relays. Optical sensor based systems prove susceptible to dirt, although induction based proximity sensors prove to be reliable. To generalise this information: Less complex components tend to be more reliable, and less complex system interactions tend to rely on fewer sensors, and thus be more reliable. What's not there, cannot break.

$$\text{Reliability KPI} = \text{Mean time between failure} \, [d]$$

3.2.8. Robustness

A process which is insensitive to noise variation is called a robust process (Mondal, Ray, and Maiti 2014).
A robust manufacturing process may be defined as a process which maintains its acceptable performance consistently at a desired level, even if there may be significant and substantial changes occurring in the levels of input variables and noise parameters during a given period of time or planning horizon. (Mondal, Ray, and Maiti 2014) The robustness KPI is closely related to the reliability KPI, but with a slightly different definition. While the reliability is measured in time between failure of physical components of the system, robustness is measured in time between system malfunctions where no physical component failure occurs. Causes for this behavior may be software errors, or polluted sensors giving the wrong input. Error removal, physical cleaning or restarting of the management system may be necessary, but no changing of components occurs. Operability describes fixing a "robustness error", maintainability describes fixing a "reliability error".

$$\text{Robustness KPI} = \text{Mean time between malfunction} \, [d]$$

3.2.9. Breeding quality

A warehouse system that is more naturally suitable to the insect rearing process, may be the preferable choice. A system that enables for simple pallet flows, or reduced material handling (e.g. a first-in first-out storage policy) may simplify the design, and perform better.

3.3. Dependency of KPI's

Some dependencies exist between these KPI's, but all KPI's are at least partly independent. Handling capacity may for example be increased through the addition of material handling equipment, therefore also increasing cost. However, a different operational strategy may also improve handling capacity, whilst not having any direct influence on cost. Another example being a material handling concept that results in very high density storage, but also needs high pallet stacking. Climate conditions may be improved through decreasing the stacking height, but storage density may be improved through a reduction of warehouse aisles.

4

Selection of material handling equipment

In this chapter, an alternative warehouse concept will be chosen, that is currently available on the market. Firstly an extensive overview of existing automated storage and retrieval (ASR) concepts is presented, after which the suitability to the Protifarm case is discussed, the most promising solution is selected for further comparison against the current warehouse solution as delivered by SSI Schäfer.
In the overview, transportation concepts and storage concepts are discussed separately, as multiple combinations of transportation and storage concepts are possible. The considered handling unit is a pallet, therefore automated warehouse technology specialised in order picking applications are not included. This overview is limited to pallet handling ASR systems. A list of relevant automated warehouse concepts is distilled from this overview. Then a panel of experts scores each concept for suitability. In a second step, a basic design of each of the remaining concepts is made, and a definitive concept choice is made, to determine which material handling equipment concept is best suited to the insect rearing process.

4.1. Material handling

This part of the overview is focused on the transportation aspect of the warehousing technology. In the next section the storage concepts are described. The following concepts are included:

- Stacker crane
- Automated forklift
- Aisle based shuttle
- Orbiter
- Gravity rack
- Conveyor
- Grid based shuttle (AGV)

4.1.1. Stacker crane and automated forklift

An automated warehouse operated by a crane or automated forklift most closely resembles a traditional warehouse with racks and aisles. The main difference between the two being that the stacker crane (Figure 4.2b) is aisle captive, and the (high-bay) automated forklift (Figure 4.2a) is aisle roaming.
Storage can be done on multiple levels, with stacker cranes reaching especially high, up to 30 or 40 meters (Azadeh, De Koster, and Roy 2019). Storage depth is single or double-deep, so pallets are relatively reachable, at the cost of the aisles taking up more space. The significant height that can be reached by a stacking crane makes that a high storage density can still be achieved.
Driving and lifting action can be done at the same time, resulting in shorter cycle time.
The storage of loads in double deep racks. The crane can then be equipped with double-deep telescopic

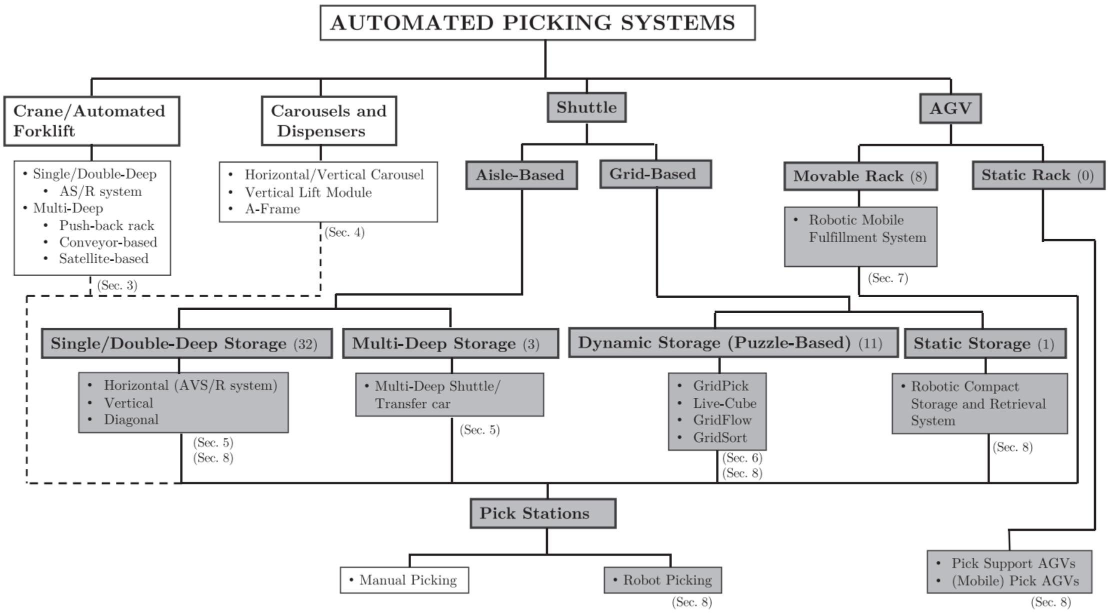
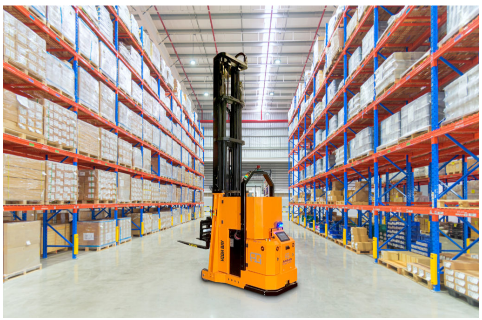


Figure 4.1: Classification of automated picking systems, as used by (Azadeh, De Koster, and Roy 2019) (Azadeh, De Koster, and Roy 2019).



(a) Isle roaming forklift (Demaitre 2020)

(b) Aisle captive stacker crane (chain 2021)

Figure 4.2: Examples of aisle roaming or aisle captive ASR concepts

forks, to provide access to both storage layers (Azadeh, De Koster, and Roy 2019). These systems are particularly popular for storing products when storage space minimization is a primary concern (e.g. fresh produce, cold storage).

4.1.2. Aisle-Based Shuttle Systems

One of the drawbacks of the crane based ASRS system, is the fact that one crane needs to service all vertical levels. To improve throughput, the shuttle-based concept was developed, where multiple shuttles can move in the horizontal plane on each level of the warehouse (Figure 4.3). Furthermore capacity can be increased or decreased by adding or removing shuttles. Either a shuttle can move in both the x and y direction, or the shuttle carries a special vehicle (orbiter or satellite) that moves in the perpendicular direction. By using a lift, the shuttles have the ability to move between different levels. More recently, shuttles have been developed which can move diagonally or vertically without the need of a lift. With this extra functionality, the shuttles are often called robots. The aisle-based shuttle concept is often applied in textiles, automotive spare parts and fresh produce (Azadeh, De Koster, and Roy 2019).

4.1.3. Orbiter

A shuttle travels through the aisle, carrying an orbiter on board. As the shuttle can only perform movements in the x-direction, the orbiter can leave the shuttle to travel into a storage channel. The storage system there-

Figure 4.3: Example of an aisle-based shuttle ASRS (SSI Schäfer 2021)

fore only consists of racks, which makes the storage system cheap to build and low-maintenance. A drawback of the system is that only one pallet can be moved at the same time by the orbiter.

4.1.4. Gravity rack

The basis of this storage principle is a slanted rack, where pallets are stored on rollers. The pallets move by the force of gravity over the rollers, and this force is determined by the incline of the rack minus the friction over the rollers. The basic configuration being either a pushback rack, where pallets roll to the front of the racking, and a new pallet will push the other pallets back into the rack, or a pallet flow rack, where pallets are inserted on one side of the rack, and roll towards the other side of the rack, where the pallets are then extracted. Thus both a FIFO and LIFO storage policy is possible.

4.1.5. Conveyor

A shuttle travels through the aisle, but does not carry an orbiter. Instead, the storage channel is chain driven, resembling a conveyor. All pallets will therefore move at the same time.

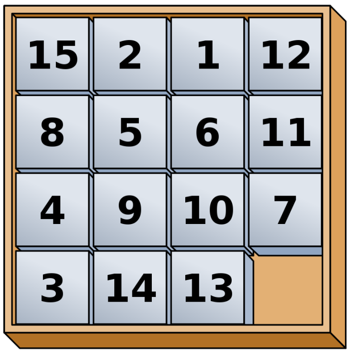
4.1.6. AGV (Grid based shuttle)

The AGV (or grid-based shuttle system) is comparable to the aisle based shuttle system, but here, the shuttle moves over the storage grid, instead of through dedicated aisles. To avoid confusion with the aisle based shuttle, this concept is referred to as AGV. The concept is inspired on the 15 puzzle (Figure4.4), and designed to maximize the storage density. Because a minimum of one grid place needs to be left open to retrieve a loads from the grid, the maximum storage capacity of the grid equals $\frac{n-1}{n}$, where n indicates the grid size (Azadeh, De Koster, and Roy 2019). The loads are stored either directly onto the floor (4.5 or in a storage rack, and an AGV travels through the grid under the loads, and lift the loads to move them. The concept is growing in many fields, especially in automated parking systems (Azadeh, De Koster, and Roy 2019).

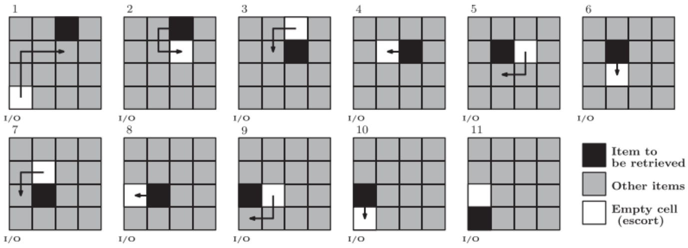
4.2. Pallet storage

The container currently in use by Protifarm is chosen as a given. The container is designed to be stacked on a pallet, and therefore strong and durable. When a carousel type system would be chosen, stacking is no longer necessary, and it would be possible to choose a cheaper and lighter container design. This however, is left out of scope.

- Single-deep storage
- Double-deep storage
- Multi-deep storage



(a) The 15 puzzle, the goal is to shift the pieces until the number are in sorted from low to high in reading order (Wikipedia 2021).

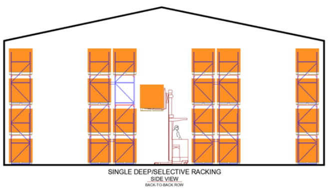


(b) Retrieval process of a grid-stored unit load. (Azadeh, De Koster, and Roy 2019)

Figure 4.4: Grid based storage concept compared to the 15 puzzle.

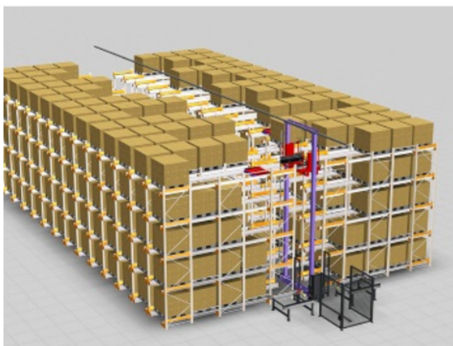
Fig. 4: "GridFlow system with pallets and robots"

Figure 4.5: Gridflow storage concept (Furmans, Nobbe, and Schwab 2011).



(a) Single-deep storage (Granitto 2019)

(b) Double-deep storage (Konstant Complete Storage System Solutions 2021)



(c) Multi-deep storage (Daifuku Logistics Solutions 2021)

Figure 4.6: Examples of a carousel, VLM and automatic dispenser type concepts.

4.2.1. Single-deep storage

If single-deep storage racks (figure 4.6a) are implemented in a warehouse, all stored pallets will be directly accessible from the warehouse aisle. Typically 50-60% of the floor space will be taken up by aisles in such a configuration (Frazelle 2016).

4.2.2. Double-deep storage

A double-deep storage rack (figure 4.6b) will reduce the floor space taken up by aisles by 50% (Frazelle 2016). The pallet racking now features storage channels that can accommodate two pallets each. Thus a higher storage density is achieved, but half of the pallets in the warehouse are stored behind another pallet. If one of these pallets needs to be retrieved from the warehouse, the front pallet needs to be moved out of the way, and a telescopic fork is needed to reach deeper into the storage channel.

4.2.3. Multi-deep storage

In a multi-deep storage (figure 4.6c) rack, the depth of the storage channel is no longer limited to one or two pallets. The fork of a stacker crane or automated forklift is not long enough to reach into these storage channels, therefore a shuttle, gravity rack or conveyor is employed to store or retrieve pallets.

4.3. Concepts to consider

The following material handling concepts are considered:

- Stacker crane
- Automated forklift
- Shuttle and orbiter
- Shuttle and gravity rack
- Shuttle and conveyor
- AGV on ground
- AGV in rack

4.4. Qualitative concept evaluation

The different material handling equipment concepts were presented to a panel of Protifarm employees, who worked with the case-study insect rearing plant for several years, and are therefore considered experts in their field. The material handling concepts were presented to the panel, and each individual concept was then discussed to decide on an unanimous decision. Each concept is graded per criteria as listed in table 4.1.

Grade	Value
Insufficient	0
Neutral	1
Acceptable	2
Good	3
Very good	4
Excellent	5

Table 4.1: Scoring scale

	Concepts						
	Stacker crane	Automated forklift	Shuttle and orbiter	Shuttle and gravity rack	Shuttle and conveyor	AGV on ground	AGV in rack
Storage capacity	Excellent 5	Acceptable 2	Good 3	Good 3	Good 3	Very good 4	Very good 4
Handling capacity	Very good 4	Very good 4	Good 3	Very good 4	Excellent 5	Good 3	Good 3
Climate conditioning	Acceptable 2	Excellent 5	Good 3	Good 3	Good 3	Acceptable 2	Insufficient 0
Cost	Good 3	Very good 4	Very good 4	Very good 4	Acceptable 2	Excellent 5	Very good 4
Operability	Very good 4	Very good 4	Good 3	Good 3	Very good 4	Acceptable 2	Acceptable 2
Maintainability	Good 3	Very good 4	Excellent 5	Acceptable 2	Acceptable 2	Very good 4	Good 3
Reliability	Very Good 4	Good 3	Very good 4	Neutral 1	Very good 4	Insufficient 0	Good 3
Robustness				- -			
Breeding quality	Very good 4	Very good 4	Good 3	Good 3	Excellent 5	Acceptable 2	Acceptable 2
Total score	Stacker crane 29	Automated forklift 30	Shuttle and orbiter 28	Shuttle and gravity rack 23	Shuttle and conveyor 28	AGV on ground 22	AGV in rack 21

Table 4.2: Qualitative material concept evaluation by the case study expert panel

Static capacity	1000	pallet positions
Dynamic capacity	1500	pallets per day

Table 4.3: Requirements for the basic warehouse design

4.4.1. Conclusion

The shuttle and gravity rack and both AGV concepts score significantly lower compared to the other concepts. They are therefore considered not suitable for the intended application, and excluded from the following quantitative evaluation.

4.5. Quantitative concept evaluation

Existing automated warehouse technologies are described in the previous section. As not every ASR concept is relevant, only the concepts listed below are considered. In this section, these concepts are evaluated along the criteria that were presented in chapter 3, in order to make a well founded concept choice.

- Stacker crane
- Automated forklift
- Shuttle and orbiter
- Shuttle and conveyor

To be able to quantify the performance of each warehousing concept, it helps to have a general idea of the lay-out of the warehouse. Therefore the amount of pallet positions needed and the required dynamic capacity need to be determined. Subsequently the amount of storage channels and aisles can be determined to meet the requirements. For this basic lay-out design, the requirements set can be found in Table 4.3, and correspond roughly to the specifications of the existing Protifarm warehouse.
The maximum speed of the transport equipment as stated in spec sheets is used to determine the theoretical throughput of the warehouse as a function of storage-channel depth and aisle length, with an estimated delay added for the pickup and putdown of a pallet. To calculate the general lay-out of the warehouse, the following method is used:

1. Travel speeds for each warehouse concept are obtained from specification sheets and verified through video material if possible
2. Storage depth and stacking height are set
3. Length of the Aisle is calculated for $\textit{dynamic capacity} = 1.5 * \textit{static capacity}$
4. If static capacity is too low, a second aisle is added, lengthening the aisle would lengthen cycle time
5. If static capacity is too high, the aisle length is shortened

4.5.1. Stacker crane

A stacker crane concept with double-deep storage and a height of 20m (or 5 pallets) is considered, which according to (Porras-Amores, Mazarrón, and Cañas 2014) could result in a temperature differential of 6°C in an air-conditioned warehouse. This could probably be brought down a bit by sufficient mixing, or local blowing of conditioned air, but is definitely something that needs dealing with.
From the calculations made, a warehouse layout as described in Table 4.4 is recommended. The dynamic capacity is slightly lower then the requirement. An extra aisle is not added because this would create extremely large overcapacity, while the requirement is almost reached.

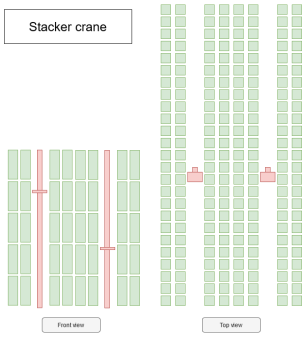


Figure 4.7: Schematic front-view and top-view of the stacker crane concept

Concept	Stacker crane
Static capacity	1000
Dynamic capacity	1344
Aisles	2
Stacking height	5 pallets
Storage channels	25
Channel depth	2
Dimensions (LxWxH)	25x16x20

Table 4.4: Specifications for the basic design of a stacker-crane operated warehouse

4.5.2. Automated forklift

The maximum reachable storage height with an automated forklift is typically around 3 pallets. But an automated forklift can also be used with 2 storage levels, or just 1 storage level. In this case, a 3 level and a 1 level double deep racking system is considered, as shown in figure 4.8. In table 4.5, the specifications for both warehouses are given.

4.5.3. Shuttle and orbiter

With the shuttle and orbiter, depth of the storage channels is no longer limited, because the ability of the orbiter to simply drive into the storage channel. Deeper storage channels makes for increased storage density, but the accessibility of the pallets decreases. Multiple storage levels are also possible, either by a separate pallet or shuttle lift, or through integration of a lift in the shuttle, so it can access multiple levels by itself.
Traditionally a LIFO storage policy is used with this concept, where pallets in the rear of a storage channel are simply locked up by the pallets in front of them. But when storage channels are made accessible from both sides, a FIFO storage policy can be implemented (figure 4.9 As discussed in the previous chapter, this would simplify pallet operations. Because there are many variations possible, no less than six concepts are considered with a shuttle and orbiter: Double-deep storage, multi-deep storage, and FIFO storage. And each of these in either single level or three level storage. The specifications are presented in table 4.6.

Concept	Automated forklift 1 level	Automated forklift 3 levels
Static capacity	1000	1008
Dynamic capacity	1479	1584
Aisles	2	2
Stacking height	1 pallet	3 pallets
Storage channels	125	42
Channel depth	2	2
Dimensions (LxWxH)	125x18,4x4	42x18,4x12

Table 4.5: Specifications for the basic design of two automated forklift operated warehouses

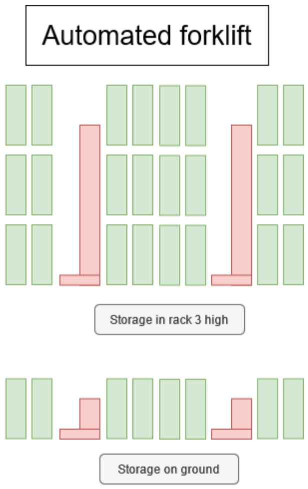


Figure 4.8: Schematic representation of ground storage or 3-high rack storage with an automated forklift

Concept	Double-deep 1 level	Multi-deep 1 level	FIFO 1 level	Double-deep 3 levels	Multi-deep 3 levels	FIFO 3 levels
Static capacity	1040	1000	1000	1008	1020	1020
Dynamic capacity	3091	1416	2107	2472	2266	1702
Aisles	2	1	2	2	2	2
Stacking height	1 pallet	1 pallet	1 pallet	3 pallets	3 pallets	3 pallets
Storage channels	130	100	100	42	17	34
Channel depth	2	5	10	2	5	10
Dimensions (LxWxH)	130x14,8x4	100x15,8x4	100x17,6x4	42x14,8x12	17x31,6x12	34x17,6x12

Table 4.6: Specifications for the basic design of six shuttle and orbiter operated warehouses

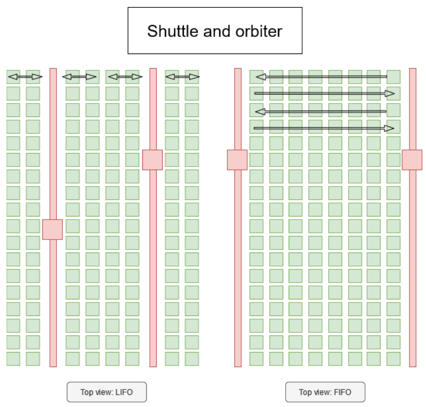


Figure 4.9: Schematic representation of LIFO and FIFO storage policy with a shuttle and orbiter

Concept	Gravity rack 1 level	Gravity rack 3 levels
Static capacity	1050	1080
Dynamic capacity	7276	2743
Aisles	2	2
Stacking height	1 pallet	3 pallets
Storage channels	35	12
Channel depth	30	30
Dimensions (LxWxH)	35x45,6x4	12,45,6x12

Table 4.7: Specifications for the basic design of two gravity rack operated warehouses in pallet flow configuration

Concept	Conveyor rack 1 level	Conveyor rack 3 levels
Static capacity	1050	1080
Dynamic capacity	7276	2743
Aisles	2	2
Stacking height	1 pallet	3 pallets
Storage channels	35	12
Channel depth	30	30
Dimensions (LxWxH)	35x45,6x4	12,45,6x12

Table 4.8: Specifications for the basic design of two conveyor rack operated warehouses

4.5.4. Gravity rack

In the pallet flow configuration, the gravity rack has a clear advantage in simplicity and the possibility to implement a FIFO storage policy. When used in push-back configuration, the moving parts in the racking are just a liability. Therefore, only pallet flow racking will be considered (FIFO in figure 4.9), in both single level and three level storage.

4.5.5. Conveyor

A conveyor based system is largely comparable to the gravity rack concept. There is no travel time into the storage channels, as the conveyor brings pallets forward towards the shuttle, thereby reducing the cycle time, and allowing for deeper storage channels. As can be seen in table 4.8, the storage channels have a depth of 30 pallets, which is extremely deep in comparison to the other basic design. Although it could be argued that a more shallow storage depth is preferable to increase accessibility. As the main advantage of a conveyor racking system would be the implementation of a FIFO storage policy, no other policies are considered.

4.5.6. AGV

AGV technologies exist both in combination with racking, and without racking systems. The only difference for a racked AGV being the added cost for a racking system, and the advantage of being elevated above the ground. The same lay-out for both possibilities is presented in table 4.9.

Concept	AGV
Static capacity	1000
Dynamic capacity	1658
Aisles	2
Stacking height	1 pallet
Storage channels	100
Channel depth	10
Dimensions (LxWxH)	100x17,4x4

Table 4.9: Specifications for the basic design of a AGV operated warehouses

4.5.7. Cost and Climate

The values used for the price and climate comparison of the automated warehouse concepts are listed in table 4.10, along with their respective sources.

Equipment	Price	Unit	Source
Stacker crane	€150,000	Per aisle	(Made-in-China.com 2021)
Automated forklift	€80,000	Per vehicle	(AGVnetwork.com 2021)
Shuttle and orbiter	€135,000	Per aisle	Estimate
Shuttle	€67,500	Per aisle	Estimate
AGV	€35,000	Per vehicle	(AGVnetwork.com 2021)
Standard racking	€100	Per pallet position	(Conner and Arif 2020)
Gravity racking	€280	Per pallet position	(Conner and Arif 2020)
Conveyor racking	€2,000	Per pallet position	(Bastian Solutions 2021) (Cisco-Eagle 2021)
Temperature differential	0.3 °C	Per meter height	(Porras-Amores, Mazarrón, and Cañas 2014)

Table 4.10: Numbers and sources

4.5.8. Concepts compared

The material handling equipment concepts are compared in table 4.11.

	Concepts						
	Stacker crane	Automated forklift		Shuttle and orbiter		Shuttle and conveyor	
Stacking height [pallets]	5	1	3	1	3	1	3
Static capacity [pallets]	1000	1000	1008	1040	1008	1020	1080
Storage density [pallets/m^2]	2.5	0.4	1.3	0.5	1.6	0.6	1.7
Dynamic capacity [pallets per day]	1344	1479	1584	3091	2472	7353	2743
Temperature differential [°C]	6	1,2	3,6	1,2	3,6	1,2	3,6
Cost (CapEx)	€400,000	€160,000	€260,800	€374,000	€370,800	€2,175,000	€2,295,000

Table 4.11: Basic concept evaluation

4.6. Conclusion

A total of seven automated warehouse concepts are considered in this chapter. The gravity rack and AGV based concepts were excluded based on low scores from the panel of experts. In the subsequent evaluation step, storage density, material handling capacity, climate condition and cost were estimated for the remaining for concepts. The analysis of the stacker crane showed that temperature control becomes a problem when employing the full stacking height of up to 40 meters. To mitigate this temperature differential problem, stacking height will need to be reduced but at 20 meters, the expected magnitude of the temperature differential is still 6 °C. Thus even longer aisles are needed to accommodate the required amount of pallets. Storage density will go down, and pallet handling capacity will go down. Due to the climate requirements, the full potential of the stacker crane cannot be employed. Although the conveyor based concept is promising from a handling capacity standpoint, it is estimated to cost almost 6 times as much as the shuttle and orbiter concept. The conveyor is therefore considered a cost prohibitive solution. The preferred material handling equipment concepts are therefore the shuttle and orbiter and the automated forklift.

5
Simulation and Design

This chapter describes the application of discrete event simulation to obtain the optimal automated warehouse lay-out for four different operational scenarios. In three of the scenarios shuttle and orbiter type material handling equipment is proposed, in one scenario automated forklift material handling equipment is proposed. The model is implemented in Python and uses the Salabim (Ham 2021) library for discrete event simulation. The model inputs are the required pallet storage capacity, the required pallet storage and retrieval actions in 24 hours and the velocity and acceleration figures of the material handling equipment. The model outputs are the number of aisles, aisle length and channel depth of the warehouse. The output is obtained through the simulation of the pallet flows for warehouse lay-outs, where the material handling equipment is increased by one unit with each iteration, until a satisfactory solution is obtained.
In section 5.1 a detailed explanation is given on the methodology, followed by a description of the model in section 5.2. For each of the four scenario's, a description is given, a separate sensitivity analysis is performed and results are presented and discussed (section **??**, section **??**, section **??**, section **??**). A comparison between the different scenarios is made in section 5.3 and finally a conclusion is drawn up in section 5.4, to determine what the optimal lay-out design is for an automated warehouse in an insect rearing application.

Definitions recap
Storage capacity - Amount of pallets that can be stored in the automated warehouse
Handling capacity - Amount of pallets that can be processed within a one day cycle of 24 hours
Handling capacity factor - Ratio between handling capacity and storage capacity
Feeding process time - Time required to finish the feeding process for all pallets in the warehouse
Pallet feeding time - Time required to finish the feeding process for one single pallet

5.1. Methodology

The goal of this part of the research is to determine the minimal amount of material handlers, and the best performing lay-out design for an automated warehouse in the insect rearing application. In other words, the number of warehouse aisles, storage channels, and channel depth need to be determined, that performs according to the requirements for the insect rearing process regarding storage capacity and handling capacity of pallets. These requirements are based upon the case study and travel time measurements are performed to accurately represent the material handling equipment in the model. As shown in (Srinivasan, Bozer, and Cho 1994), the throughput analysis can be done through an analytical approach. However, a simulation approach is taken to allow for an extension of the model scope towards the inclusion of stochastic processes like short stoppages or breakdowns.

5.1.1. Approach

To find an answer to this question, a simulation model is built that simulates a simplified version of the pallet flow process that is required in one 24 hour cycle of the factory operation. The warehouse model includes pallet storage in pallet positions, storage and retrieval by material handling equipment (either the shuttle and orbiter or the automated forklift) and the feeding process.

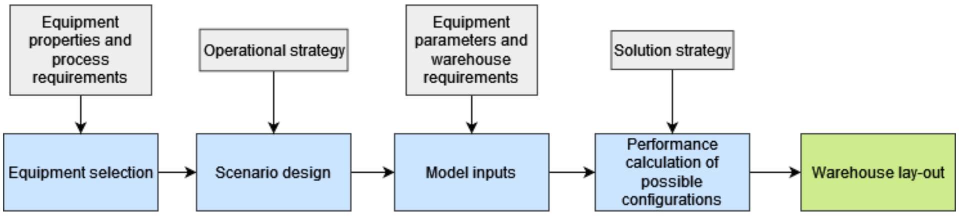


Figure 5.1: A modified version of the design framework used by (Vijlbrief 2018)

	Scenario name	Equipment	Description
Scenario 1	Case study	Shuttle and orbiter	Operational strategy according to the case study
Scenario 2	Dynamic storage	Shuttle and orbiter	Dedicated buffer channel replaced for dynamic storage policy
Scenario 3	First-in first-out	Shuttle and orbiter	Pallets are inserted in front and extracted at the end of the storage channel
Scenario 4	Modular design	Automated forklift	Aisle roaming equipment

Table 5.1: Scenarios and operational strategy

Depending on the type of material handling equipment used, multiple operational strategies are possible. The way the material handling equipment and storage capability are employed influences lay-out, capacity and performance. Therefore, four scenarios are drawn up (table 5.1) to explore each operational strategy independently and to be able to make a comparison.

The goal of the simulation model is to find out what the optimal lay-out design is, based on knowledge of the applied material handling equipment and the production process. The inputs and outputs for the simulation model are defined in figure 5.2.

Extra outputs
A. Increased storage capacity
The handling capacity can be increased by adding an aisle, and thus an extra shuttle and orbiter. It is therefore possible that the minimum amount of material handling robots can handle more pallets than required. What is the maximum amount of pallets for the determined minimum aisles?

B. Increased material handling equipment performance
If new material handling equipment can be designed according to new speed and acceleration requirements, what requirements are needed to reduce the amount of aisles (and thus shuttle and orbiters) by one?

C. Loosened constraint: Aisle roaming shuttle and orbiter
When a shuttle and orbiter combination could traverse to a second aisle when finished with the first aisle, the total travel time will significantly reduce, as the shuttle and orbiter need to travel a shorter total distance. With the first extra aisle, the travel distance is effectively halved. Would this added functionality be an effective way to improve performance?

Solution strategy
From the model inputs, a vast quantity of warehouse lay-out designs can be generated and evaluated. The solution strategy determines which lay-outs are evaluated, and which lay-outs are not evaluated. A two-step iterative approach is taken (figure 5.3) that ensures that the optimal design is found. In step 1 the number of aisles is determined, which starts at one. In step 2, the channel depth is determined, which also starts

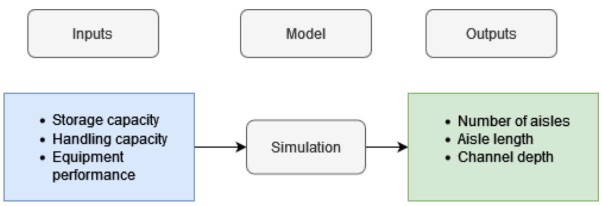


Figure 5.2: The inputs and outputs of the simulation model

Input	Parameter	Unit	Description
Storage capacity		pallets	Pallet storage positions in the warehouse
Handling capacity		pallets	Amount of pallets that can be stored and retrieved within 24 hours
Equipment performance	*velocity*	$m\,s^{-1}$	Maximum velocity
	acceleration	$m\,s^{-2}$	Maximum acceleration

Table 5.2: Model inputs

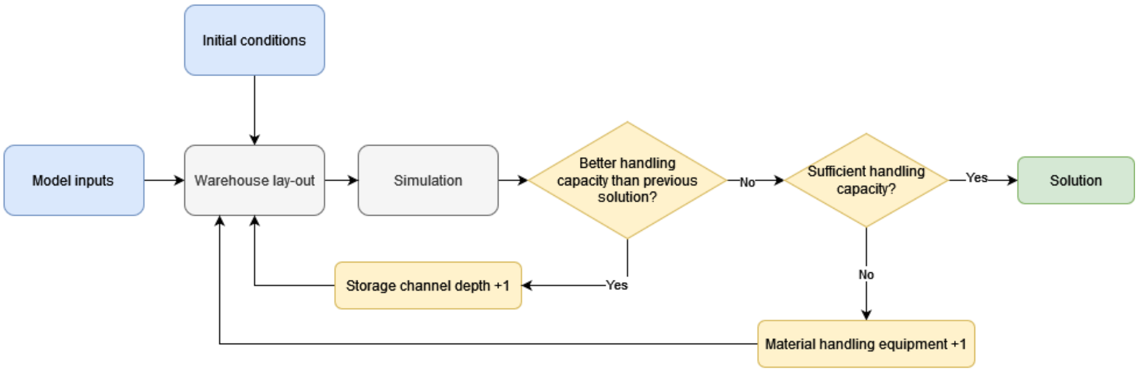


Figure 5.3: Schematic representation of the two-step solution strategy

at one. The aisle length can then be determined from the storage capacity input and the number of aisles and channel depth. When all are determined, the determined properties can be used to generate the first iteration of the pallet flow simulation. The first warehouse design that goes through the pallet flow simulation thus consists of one aisle, a channel depth of one pallet. The channel depth is then increased by one pallet, until the result of the latest simulation is a worse performance than the previous simulation and thus the optimal ratio between aisle length and channel depth is found. Step 2 is now terminated, and the process returns to step 1. The resulting throughput capacity is compared to the required throughput capacity. If the performance is insufficient, one aisle (thus one extra shuttle and orbiter) is added, and step 2 is repeated. This iterative process is continued until a design is obtained that produces at least the required performance.
To determine output A, step 1 of the two step method is adapted, but instead of one extra aisle, the amount of pallets is increased by 100 until the simulated handling time is greater than the required handling time. Then the iterative process is repeated, but now the amount of pallets is decreased by 10 until the simulated handling time is smaller than the required handling time. The maximum amount of pallets is thus determined to an accuracy of 10 pallets.
To determine output B, the predetermined number of aisles is reduced by 1, and again a modified version of the two-step iterative method is applied. But now the acceleration and maximum velocity of the shuttle and orbiter are increased by a fixed value of (v + 0.5, a + 0.1). The material handling equipment performance is increased until the simulated handling time fulfills the handling time requirement.
To determine output C, the two-step method is modified to a three-step method. In step 0, the amount of aisles serviced by one shuttle is determined, starting by 2 and limited to 5. Effectively, the amount of pallets is divided by the amount of aisles serviced by one shuttle, and after the simulation, the simulated handling time is multiplied by the before-mentioned amount of aisles. The unavoidable travel time of the shuttle orbiter combination between aisles is not considered here.

5.1.2. Data collection and analysis

Pallet position dimensions

The dimensions of a pallet position in the warehouse are needed to translate the warehouse distances to meters. A pallet position is 1.5m wide and 1.2m deep, as indicated in figure 5.4. The distances are measured from a technical drawing of the case-study warehouse.

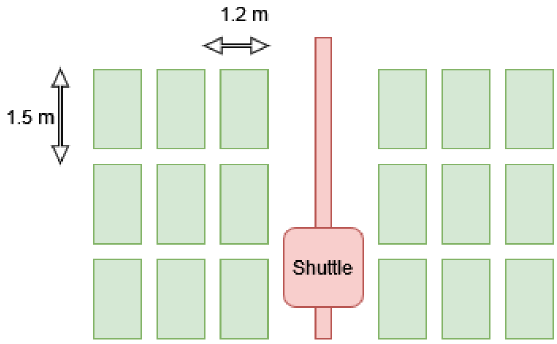


Figure 5.4: Dimensions of a pallet position in the warehouse

Travel time shuttle and orbiter
Travel time for the shuttle and orbiter as a function of the aisle length and channel depth were measured on the case-study warehouse. Each measurement was repeated three times and then averaged. The resulting measurements are listed in table 5.3 (shuttle) and table 5.3 (orbiter). These measurements are used to validate the travel time model for the shuttle and orbiter as described in paragraph 5.2.2. The travel time model is initially based on the assumption that the shuttle or orbiter always travel under maximum acceleration or maximum velocity, but the measurements clearly show a large difference. To compensate for this deviation, either (shuttle) or two terms (orbiter) are added to fit the model to the measurements. The fitted travel time model is plotted with the measurements in figure 5.5. The values of the added terms and a description is given in table 5.6 and the accompanying formulas.

Aisle length in pallets	Distance	Travel time
1	1.5 m	7.4 s
10	15 m	11.1 s
20	30 m	15.2 s
30	45 m	19.3 s

Table 5.3: Measurement of shuttle travel time as a function of aisle length

Channel depth in pallets	Distance	Travel time
1	1.2 m	16.5 s
5	6 m	18.4 s

Table 5.4: Measurement of orbiter travel time as a function of channel depth

5.2. Model

The pallet flow simulation model translates basic warehouse properties (storage capacity, handling capacity, number of aisles, aisle length, channel depth) into a digital warehouse that performs an entire feeding cycle, and returns a simulated handling time value. This section provides an in depth description of the way physical warehouse processes and properties are represented in the simulation model, and how the simulated handling time is determined.

5.2.1. Warehouse model

The warehouse consists of pallet positions for storage, material handling equipment to transport pallets, and a combination of subsystems to perform the feeding process.

Storage channel
The storage channels in the warehouse are represented in the model as Salabim queue's. The pallet capacity of each storage channel is limited to a certain amount of pallets, and this limit is referred to as the *depth* of

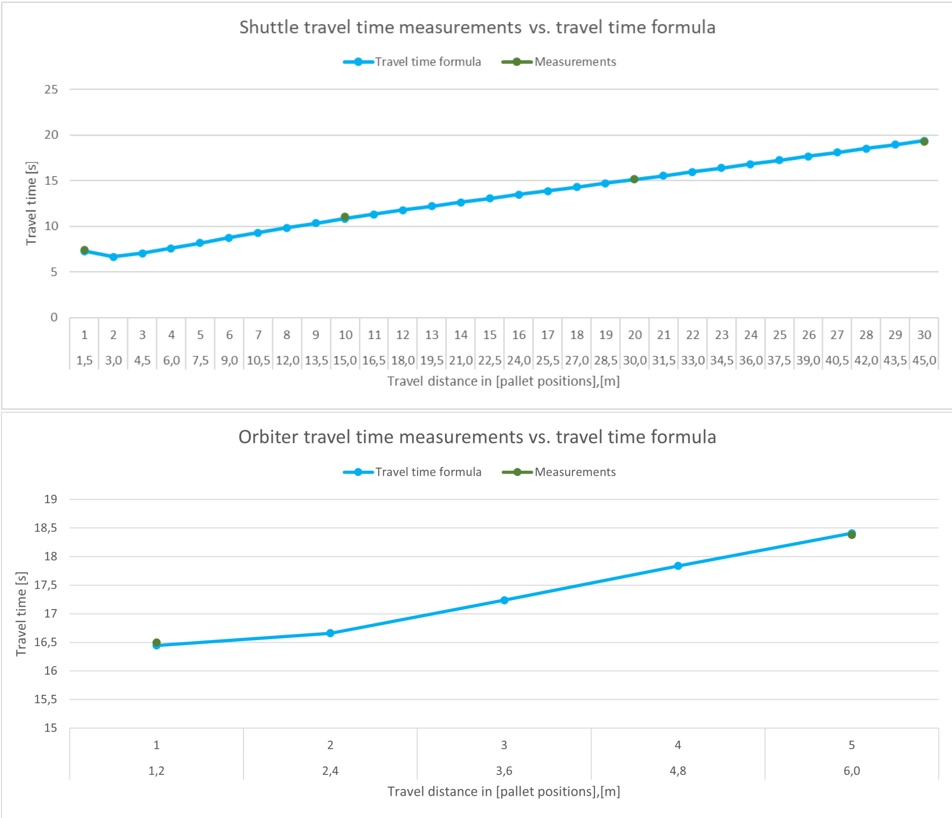


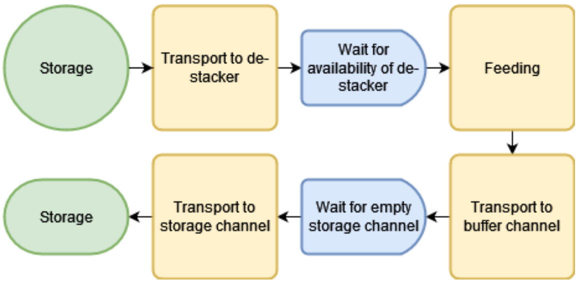
Figure 5.5: Measurements vs travel time formula

the storage channel. E.g. a storage channel with a depth of three can contain up to three pallets. Each storage channel is also given a position in x- and y-coordinates in the warehouse, so distances in the warehouse can be determined.

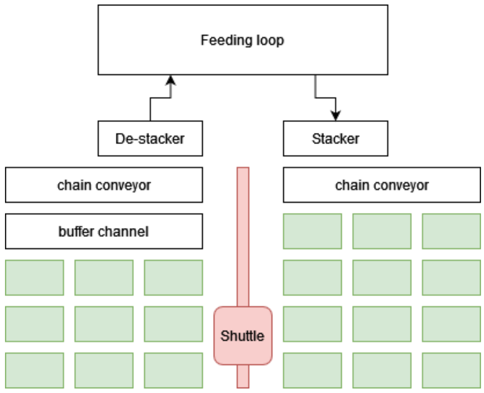
Pallet
Each pallet is modelled as a separate instance (or object when following Python conventions) of a Salabim class. The information on which storage channel to use, and when to request the material handling equipment is all defined within each instance of the pallet class. All equipment is therefore reactive to the requests from pallet instances.

Shuttle and orbiter
The shuttle and orbiter combination is modeled as a Salabim resource with a capacity of one pallet. When a pallet requests transportation, the shuttle and orbiter combination travels to the location of the pallet, and takes the pallet to the desired location. The pallet then releases the resource, and the shuttle and orbiter are ready to transport the next pallet. After each movement, the location of the shuttle and orbiter are updated. The travel time of the shuttle is dependent on the distance between itself and the target storage channel, whilst the travel time of the shuttle is dependent on the distance that needs to be traveled inside the storage channel. The travel time is thus dependent on the distance between two warehouse coordinates, and the amount of pallets in the target storage channel queue. They are calculated in two separate functions which are described in paragraph 5.2.2.

Destacker buffer
Before entering the destacker and starting with the feeding process, the pallet is transferred from the shuttle to a conveyor. On this conveyor, a pallet can be held until the destacker is finished with the previous pallet. The conveyor therefore functions as a buffer in the pallet flow, where a pallet can wait until entering the destacker and commencing the feeding process. In the simulation model the destacker buffer is modeled as a Salabim resource with a capacity of one pallet.



(a) Flowchart of pallet flow



(b) Schematic top view of storage, transportation and feeding equipment

Figure 5.6: Top view and pallet flow schematic

Equipment	Maximum velocity	Maximum acceleration
Shuttle	$3.5\,\mathrm{m\,s^{-1}}$	$0.55\,\mathrm{m\,s^{-2}}$
Orbiter	$2.5\,\mathrm{m\,s^{-1}}$	$0.6\,\mathrm{m\,s^{-2}}$

Table 5.5: Acceleration and velocity of shuttle and orbiter

Stacker buffer

When the feeding process is finished, the crates are stacked back upon the pallet by the stacker. When the stacking process is finished, the pallet exits the stacker onto a conveyor, which again fulfills a buffer position for the pallet when it awaits handling by the shuttle. The stacker buffer is also modelled as a Salabim resource with a capacity of one pallet.

Storage buffer channel

When a pallet has finished the feeding process, it cannot return to the storage channel until all pallets have been retrieved from that storage channel. Because when a pallet that just received feed is immediately put back into it's storage channel, it will lock up other pallets behind it that still need to receive feed. Therefore a normal storage channel is used as dedicated buffer channel (also called overflow channel), where pallets are stored temporary until they can return to the storage position. The buffer channel has the same capacity limit as the normal storage channel, and is modelled as Salabim queue.

5.2.2. Shuttle and orbiter model

The shuttle and orbiter combination travels along the warehouse aisle, and stops at the desired storage channel to retrieve a pallet. The orbiter then leaves the shuttle and travels into the storage channel to lift the pallet and bring it back to the shuttle. Only one pallet can be transported at once. The travel time needed to get to a new location is determined from the distance to travel, and the acceleration and top speed of the shuttle and orbiter. Is is assumed that the shuttle or orbiter either accelerate or decelerate at a constant rate, or travel at a constant velocity. If the distance is too short to reach top speed, the movement will only consist of constant acceleration and constant deceleration. If the distance is longer, the shuttle or orbiter will accelerate until the maximum velocity is reached. This maximum velocity will be maintained until the destination is almost reached, and constant deceleration starts. The magnitude of deceleration is assumed equal to the magnitude of the acceleration.

Travel time formulae shuttle

For $s \leq 2 * s_{accelshuttle}$

$$t_{shuttle} = 2 * \sqrt{\frac{s}{a_{shuttle}}} + \frac{c_{shuttle}}{s}$$

For $s > 2 * s_{accelshuttle}$

$$t_{shuttle} = 2 * \sqrt{\frac{2 * s_{accelshuttle}}{a_{shuttle}}} + \frac{s - 2 * s_{accelshuttle}}{v_{shuttle}} + \frac{c_{shuttle}}{s}$$

Travel time formulae orbiter

For $s \leq 2 * s_{accelorbiter}$

$$t_{orbiter} = 2 * \sqrt{\frac{s}{a_{orbiter}}} + \frac{c_{orbiter}}{s} + d_{orbiter}$$

For $s > 2 * s_{accelorbiter}$

$$t_{orbiter} = 2 * \sqrt{\frac{s_{accelorbiter}}{a_{orbiter}}} + \frac{s - 2 * s_{accelorbiter}}{v_{orbiter}} + \frac{c_{orbiter}}{s} + d_{orbiter}$$

Equipment	Constant	Value	Description
Shuttle	$v_{shuttle}$	3.5 $m s^{-1}$	Maximum velocity
	$a_{shuttle}$	0.55 $m s^{-2}$	Maximum acceleration
	$s_{accelshuttle}$	11.1 m	Distance needed to accelerate to maximum velocity
	$c_{shuttle}$	6	Constant to fit measurements
Orbiter	$v_{orbiter}$	2.5 $m s^{-1}$	Maximum velocity
	$a_{orbiter}$	0.6 $m s^{-2}$	Maximum acceleration
	$s_{accelorbiter}$	5.2 m	Distance needed to accelerate to maximum velocity
	$c_{orbiter}$	2.3	Constant to fit measurements
	$d_{orbiter}$	11.7	Constant to fit measurements

Table 5.6: Values of constants in travel time formulae of the shuttle and orbiter

5.2.3. Automated forklift model

The automated forklift differs from the shuttle and orbiter in the ability to freely roam the aisles of the warehouse, where the shuttle is restricted to one aisle. Furthermore, the storage depth is limited to two pallet positions. The automated forklift therefore travels in two dimensions. The movement consists of traveling in x-direction to the correct aisle, and then travelling into the aisle to the requested pallet position, after which the pallet is picked up by the fork. Therefore the travel time for the automated forklift needs to be determined, and the time needed to pick up a pallet with the fork.
As no measurements could be done on the travel time for an automated forklift system, an estimation of the travel time is done through employing the travel time model for the shuttle and orbiter, and plugging in the information that we have available (table 5.7). The movement in x- and y-direction through the warehouse are assumed to be a separate movement in x-direction and y-direction, where the automated forklift is in standstill at the beginning and end of each separate movement.

Equipment	Parameter	Value	Obtained from
Automated forklift	Maximum velocity	2.2 $m s^{-1}$	Specsheet (Forklifts 2021)
	Maximum acceleration	0.55 $m s^{-2}$	Assumption
	Pickup time single deep pallet	20 s	Time measurement from video (Forklifts 2021)
	Pickup time double deep pallet	30 s	Time measurement from video (Forklifts 2021)

Table 5.7: Acceleration, velocity and pickup time for an automated forklift

Travel time formulae automated forklift

For $s \leq 2 * s_{accelforklift}$

$$t_{forklift} = 2 * \sqrt{\frac{s}{a_{forklift}}} + \frac{c_{forklift}}{s}$$

For $s > 2 * s_{accelforklift}$

$$t_{forklift} = 2 * \sqrt{\frac{2 * s_{accelforklift}}{a_{forklift}}} + \frac{s - 2 * s_{accelforklift}}{v_{forklift}} + \frac{c_{forklift}}{s}$$

Pickup time formulae automated forklift

For single deep pallet

$$t_{pickup} = 20s$$

For double deep pallet

$$t_{pickup} = 30s$$

Equipment	Constant	Value	Description
Forklift	$v_{forklift}$	$2.2\ \mathrm{m\,s^{-1}}$	Maximum velocity
	$a_{forklift}$	$0.55\ \mathrm{m\,s^{-2}}$	Maximum acceleration
	$s_{accelforklift}$	4.4 m	Distance needed to accelerate to maximum velocity
	$c_{forklift}$	6	Constant assumed similar to shuttle

Table 5.8: Values of constants in travel time formulae of the automated forklift

5.2.4. Feeding process model

A pallet enters the feeding process from the destacker buffer, and leaves the feeding process towards the stacker buffer. When the feeding process for one pallet is finished, it immediately leaves the process and enters the stacker buffer. If a new pallet is already present in the destacker buffer, this pallet enters the feeding process. If no pallet is present, the feeding process will wait until a pallet appears in the destacker buffer, where it awaits transportation by the shuttle. The feeding process is factually modelled as a delay between the destacker and stacker and is taken sufficiently low to optimally use the transportation capacity of the shuttle and orbiter. The value of the delay in the model is given in table 5.9.

Feeding process time per pallet	5 s

Table 5.9: Duration of the feeding process per pallet

5.2.5. Pallet model

Each pallet is modelled as an instance of a Salabim class. The pallet flow process is generated within each instance of the class. This process describes in which storage channel the pallet is inserted, and in which order the pallet will request resources or enter queues. When the pallet is generated, it will enter its designated storage channel and immediately request a place in the destacker buffer queue. When a place is available, the pallet will request transportation from the shuttle and travel to the destacker buffer. When the pallet has arrived in the destacker buffer, it will request the feeding process, and eventually enter the stacker buffer. From here, further transportation to the buffer channel or storage position is then requested. When the pallet has returned to storage, it will signal that it completed the entire process. When all pallets have completed the feeding process, the simulation is terminated.

5.2.6. Constraints

The shuttle and orbiter can transport only one pallet at once. And Only one shuttle and orbiter combination can travel on an aisle. Each additional aisle will therefore need an extra shuttle and orbiter. The buffer in front of the destacker can contain only one pallet. Lastly, pallets have to wait until the entire storage channel is empty, before returning to the designated storage position.

5.2.7. Assumptions

Simplification of pallet types
In the actual factory, multiple types of pallets exist. For example with adult beetles and with larvae. In this simulation it is assumed that there exist only pallets with larvae.

Simplification of pallet flows
In the simulation model, only the feeding process is considered. In the actual production process of the case study, a combination of pallet movements is carried out on top of the feeding schedule to harvest the larvae and beetles at the end of the production cycle, to support the population of larvae and adults or to relocate batches to a different storage area. It is therefore acknowledged that the demand for dynamic capacity of the entire production system is higher than just the dynamic capacity needed to support the feeding process. To incorporate the extra demand in the calculations, a safety factor is used. The requirement for the daily dynamic capacity of the warehouse is set at 1.5 times the static capacity. In other words, the pallet transportation system should be able to retrieve and store 1.5 times the amount of pallets present in the warehouse every day.

Travel time of shuttle and orbiter
To obtain a relation between the travel time of the shuttle and orbiter combination, the length of the aisle and the depth of the storage channel, measurement were done on the actual travel time. The length of the aisle and depth of the storage channel are limited however, so no measurements could be performed outside this range. The relationship that is established based on the measurements is therefore assumed to be valid when extrapolating to longer aisles or deeper storage channels.

No influence of feeding process
A slow feeding process combined with a quick pallet transportation process would result in idle time of the shuttle and orbiter. Thus the total system performance would be negatively impacted, whilst not necessarily providing information about the quality of the warehouse lay-out. The time taken by the feeding process, thus the time before the pallet re-enters the warehouse is taken sufficiently low to prevent it from negatively impacting the system performance.

No optimization in pallet transport
No optimization exists in the pallet transportation process. The shuttle and orbiter transport pallets in a first-come first-serve style, which means that no intelligent dual cycle combinations are being made, and storage channels are serviced in sequence, starting with lower left storage channel.

5.3. Comparison of scenario's

The lay-out designs that were produced by the simulation model for the different scenarios are compared in this section. Due to the discrete number of material handlers, and the material handling capacity being a set input for the model, varying levels of redundant handling capacity may be present for the different scenarios. To properly exhibit this characteristic, two separate comparisons will be made in this chapter. The first comparison being the design result for a warehouse lay-out with a storage capacity of 1000 pallets. The second comparison will discuss the lay-out design for the maximum pallet storage capacity. The advantages and disadvantages of each scenario will be discussed in a qualitative manner, and the lay-out designs will be compared quantitatively from a cost perspective and material handling performance perspective.

5.3.1. Storage capacity

The storage KPI measures the amount of pallets stored per square meter. The calculated storage density for each scenario is listed in table 5.10, the area calculations are included under the cost paragraph of this chapter. Scenario 1 and 2 provide the highest storage densities and scenario 3 proves to be slightly worse in this respect. The wide aisles and limited storage channel depth of scenario 4b result in a 38% lower storage density compared to scenario 1.

Scenario	Pallets	Area	Storage density
Scenario 1	1000	1962 m^2	0.51 $\frac{pallets}{m^2}$
Scenario 2	1000	2010 m^2	0.50 $\frac{pallets}{m^2}$
Scenario 3	1000	2166 m^2	0.46 $\frac{pallets}{m^2}$
Scenario 4b	1000	3175 m^2	0.31 $\frac{pallets}{m^2}$

Table 5.10: Storage density per scenario

5.3.2. Handling capacity

The design procedure sets a minimum handling capacity of 1500 pallets in 24 hours. However, the handling capacity increases in discrete steps through the addition of material handling equipment, so each resulting design results in a different pallet handling capacity. The handling capacity for each design is included in table 5.11. Scenario 2 provides almost the same handling capacity as scenario 1, although employing two instead of three shuttles. Scenario 3 provides a pallet handling capacity that is more than 100% greater than the required 1500 pallets per 24 hours, but also needs four shuttles and orbiters. The resulting handling capacity for scenario 4b is to the requirement.

Scenario	Handling capacity
Scenario 1	2084 $\frac{pallets}{24\ hours}$
Scenario 2	1995 $\frac{pallets}{24\ hours}$
Scenario 3	3026 $\frac{pallets}{24\ hours}$
Scenario 4b	1739 $\frac{pallets}{24\ hours}$

Table 5.11: Handling capacity per scenario

5.3.3. Climate conditioning

From the literature and case study, it became clear that the climate conditions are important for the larvae. The correct temperature, humidity and gas concentrations should be maintained at all times. The automated warehouse system may influence these conditions in several ways. Very dense storage of the pallets may reduce airflow and thus allow for local variations in temperature and gas concentrations. The stacking height of pallets also influences the magnitude of the temperature differential in the warehouse, but this is not relevant for this comparison, as no multi-layer storage system is considered in the scenarios. The overall storage density of pallets affects the size of the warehouse, which also has consequences for the climate conditioning. Scenario 4 with the automated forklift requires a significantly larger warehouse area is needed, resulting in a larger volume of air that needs to be conditioned, but most like also in a larger surface area on the outside of the warehouse. This results in an increased influx of heat in the summer, when the sun heats the warehouse roof, and increased outflux in winter times, when the external temperature is lower than the warehouse temperature. Lastly the heat generated by friction and drivetrain losses of the material handling equipment may cause an increase in temperature. This may differ between the scenarios with a shuttle and orbiter, and the automated forklift scenario.

5.3.4. Cost

The choices in material handling equipment type, and the way this material handling equipment is employed to perform the pallet transportation have consequences for the amount of material handlers needed, the amount of aisles and storage channels and subsequently for the overall space required to store the pallets. If more aisles are needed, the pallet storage density decreases and overall a larger warehouse is required for the same amount of pallets. An efficient operational strategy will require less material handling equipment and cost less. It is assumed that capital and operational expenditure (e.g. building energy consumption, additional warehouse space and office space, maintenance cost, required personnel) are equal for all four scenarios, and the only difference lies in required warehouse space and material handling equipment cost. Further more it is assumed that the material handling equipment is bought and falls under capital expenditure, and the warehouse space is rented, thus it falls under operational expenditure.

Capital expenditure

The capital expenditure for each scenario is calculated by multiplying the amount of material handlers required with the price listed in table 5.12.

Equipment	Price	Unit	Source
Shuttle and orbiter	€135,000	Per aisle	Estimate
Automated forklift	€80,000	Per vehicle	(AGVnetwork.com 2021)

Table 5.12: Cost of material handling equipment

Operating expenses

The operating expenses for each scenario is determined from the calculated warehouse area and the yearly rent cost. The dimensions of pallet storage positions and aisle width that were used to calculate the warehouse area are listed in table 5.13 The warehouse primary rent cost in the Netherlands ranged between 52-68 euro per square meter in the fourth quarter of 2020 (Statista 2021), depending on the location. 52 euro per square meter is used in the calculation. As an example, the optimal lay-out for scenario 1 as determined by the model, is a warehouse with three aisles with a length of 17 pallets and a storage channel depth of 10 pallets. The warehouse length is equal to the length of the aisle:

$$Warehouse\ length = 17\ pallets \times 1.5\ m = 25.5\ m$$

The width of the warehouse is the sum of the width of the warehouse aisles and the pallet positions. The lay-out for scenario 1 has three aisles with 10 pallets on each side of the aisle. The width of the warehouse thus equals:

$$Warehouse\ width = 3\ aisles \times (1.65\ m + 2 \times 10\ pallets \times 1.2\ m) = 76.95\ m$$

The resulting warehouse area equals:

$$Area\ scenario\ 1 = Warehouse\ length \times Warehouse\ width = 25.5\ m \times 76.95\ m \approx 1962\ m^2$$

Operational reserve

The operational reserve is the time left after the retrieval and storage of 1500 pallets and is determined for each scenario. This indicates how close to the limit the system operates under normal circumstances. The operational reserve could be used to perform small maintenance jobs or offset system downtime.

Aisle width for shuttle and orbiter	1.65m
Aisle width for automated forklift	3.6m
Pallet position width	1.2m
Pallet position length	1.5m

Table 5.13: Dimensions of aisle and pallet position

Scenario	Material handlers	CapEx	Area	OpEx	Operational time	Operational reserve
Scenario 1	3	€405,000	1962 m^2	€102,024	17:16	06:44
Scenario 2	2	€270,000	2010 m^2	€104,520	18:03	05:57
Scenario 3	4	€540,000	2166 m^2	€112,632	11:54	12:06
Scenario 4b	3	€320,000	3175 m^2	€165,110	20:42	03:18

Table 5.14: Cost and operational reserve for standard model inputs

Standard comparison

The results that are discussed here are listen in table 5.14. The warehouse design for scenario 1 features three aisles and three material handlers, with a significant operational reserve of over six hours. The simplified operational process of scenario 2 leads to two aisle design and a 33% reduction in capital expenditure whilst providing an operational reserve of almost six hours. Operational expenses are comparable to scenario 1. A significant drawback of the operational process is the reversal of the pallets in the storage channel after each (feeding) cycle. Whilst providing significant gains in material handling capability, the production yield will suffer from increased variability of the feeding process, especially for the front and rear pallet. Minimal variability in the feeding process and a simple pallet flow process are the main advantages of the FIFO storage policy in scenario 3. Although this comes at a price. A two aisle design would only be able to serve 910 pallets within the set operational time, so four aisles and material handlers are required to serve 1000 pallets. Regarding capital expenditure is scenario 3 the most expensive scenario with four material handlers and an operational reserve of more than 12 hours. Furthermore, the pallet flow process in scenario 3 is dependent on the simultaneous operation of two material handlers, seriously limiting robustness in comparison to the other scenarios. Scenario 4 with three automated forklifts and double-deep storage racks would make for a flexible operation due to the aisle roaming capability of the automated forklift. The automated forklift is competitive CapEx wise, but still 18% more expensive than scenario 2. The shallow storage channel depth and wide aisles needed for manouvering of the automated forklift make that a large space is required. The estimated operational expenses are 58% higher than scenario 2. The automated forklift employs optical sensors in its navigational system, which may pose a significant threat in the dusty rearing environment. Scenario 4 also has the lowest operational reserve at 3 hours and 18 minutes.

Maximum pallet comparison

Operational reserve could potentially be used to operate a production system with more than 1000 pallets. This opportunity is explored in table 5.15. Scenario 2 proves again to be the most economical scenario, although the variance in the feeding time still poses a threat. As could be expected, scenario 3 becomes a lot more competitive, as the same capital expenditure can be divided over 1820 pallets, or an increase of 82% in pallets.

Scenario	Pallets	Material handlers	CapEx		Area	OpEx	
			Total	Per pallet		Total	Per pallet
Scenario 1	1360	3	€405,000	€298	2603 m^2	€135,381	€100
Scenario 2	1290	2	€270,000	€209	2562 m^2	€133,240	€103
Scenario 3	1820	4	€540,000	€297	3756 m^2	€195,296	€107
Scenario 4b	1150	3	€320,000	€278	3704 m^2	€192,629	€168

Table 5.15: Cost and operational reserve for standard model inputs

5.3.5. Operability

The operability is determined by the complexity of the machine and the interactions with the environment. The complexity of the interactions between the material handling system and the human operator is partly determined by the machine complexity, and partly by the human interface. The interface may differ between the shuttle and orbiter concept and the automated forklift concept, but may also differ between suppliers, and is therefore relevant in a later stage of the design process. The machine complexity does differ between scenarios. In scenario 1 and 2, one shuttle is responsible for both storage and retrieval. When operating on peak capacity, an optimization algorithm may be applied to increase the amount of double cycles, and thus increase handling capacity. In scenario 3, the pallet flows are so simple that such added complexity is not necessary. The automated forklift possesses the ability to move in two dimensions, compared to the combined one dimensional movements of the shuttle and orbiter. Thus, complexity in movement is added, but there are no longer two separate pieces of equipment required. An irrefutable advantage of the automated forklift over the shuttle and orbiter is the fact that when a breakdown occurs, a reserve forklift could immediately be put into action, whilst the shuttle and orbiter would require more work to replace or repair.

5.3.6. Maintainability

The maintainability is entirely dependent on the difference between material handling equipment. This may again differ between equipment suppliers. The fact that the orbiter can be easily replaced when malfunctions occur, and the more complex navigational systems required in an automated forklift, make that the shuttle and orbiter likely provide superior maintainability.

5.3.7. Reliability

As the humid, warm and dusty conditions of an insect rearing warehouse differ significantly from traditional warehouse conditions, reliability predictions are difficult to make for the automated forklift. The shuttle and orbiter used in the case study provide good mechanical reliability.

5.3.8. Robustness

As learned from the case study, system robustness is greatly dependent on the proper functioning of sensors in the rearing environment. The optical sensors in the shuttle and orbiter concept proved to be susceptible to dust and spider webs, so robustness may be considered relatively poor. The robustness for the FIFO system in scenario 3 is worse than 1 or 2, as the two shuttles are required to operate at the same time to keep processes going. Estimating from the increased sensor complexity due to two-dimensional navigation present in the automated forklift, it may provide lower robustness than the shuttle and orbiter type concept. Although the application of sensors that are less susceptible to dust, or mitigating the presence of spider webs or dust may improve on this problem.

5.3.9. Breeding quality

The quality of the rearing process is partly determined by the ability of the material handling equipment to support a punctual feeding process. In scenario 1 and 4, a punctual feeding schedule could be set up. In scenario 2, the reversal of the order of pallets after feeding creates an inherent delay or advance in the timing of feed provision. The FIFO storage policy in scenario 3 is best suited to the rearing process, as it fits best to the feeding schedule.

5.4. Conclusion

The case-study design consists of only two aisles,whilst simulation of scenario 1 proves that three aisles are needed to reach the desired material handling capacity. It can be concluded that the existing design lacks in material handling capacity.

From a biology and yield-per-pallet standpoint, a FIFO storage policy is preferable. The intuitive pallet flow of scenario 3 is also very elegant, but the decreased system robustness and need for four shuttles and orbiter to obtain enough handling capacity make that scenario 3 is not the best scenario.

The automated forklift has advantages in flexibility and double-deep storage poses a reduced risk in operational delay when an unusable pallet suddenly needs to taken out of the rearing process. The below-average handling performance, reduced storage density and the risk of relying on high resolution sensors for navigation in the dusty rearing environment make scenario 4 too risky to be attractive.

A shuttle and orbiter with the dynamic storage policy of scenario 2 is the most economical and best performing option. Although it would be advisable to consider the influence of the storage channel depth on the variation in feeding time between days. A warehouse lay-out that partly trades off the operational reserve for decreased storage channel depth is therefore advised.

6 Discussion

In section 6.1, the results of this study are discussed. The validity of the method as well as the limitations of the approach are explained here. Suggestions on interesting topics for further research are done in section 6.2.

6.1. Discussion

In this section a brief summary is given on the material handling equipment choice and the warehouse lay-out design through the simulation model. The relation of the simulation approach to the paradigm of automated generation of design is reflected upon. The interpretation of these results is then given, and the implications for the design of an automated warehouse system are discussed. Finally, the limitations of the approach taken are described, to give insight in the weaknesses of this thesis.

The two advisable material handling concepts for an automated warehouse in the insect rearing application are a shuttle and orbiter or an automated forklift. In chapter 5 a parametric model of a warehouse lay-out is explored in an iterative manner until the stop criterion for pallet handling capacity is satisfied. However, no probabilistic or non-deterministic search procedure is employed, that intelligently tunes the parameters. Therefore this approach partly bridges the gap between a parametric and a generative design method and could best be described as performance based parametric design (Oxman 2006).

The lay-out designs are generated for scenarios 1-3 for a shuttle and orbiter with different operational strategies, and for scenario 4 with an automated forklift. When optimizing for material handling capacity, the resulting design for scenario 1 is a three-aisle warehouse with a storage channel depth of 10 pallets. Scenario 2 features a dynamic storage policy, and results in a two-aisle warehouse with a storage channel depth of 12 pallets with a material handling capacity close to scenario 1. In scenario 3, a FIFO storage policy is studied, and the resulting warehouse features four aisles and 18 pallet-deep storage channels. Scenario 4 considers an automated forklift, and the optimal lay-out design obtained from the model features three automated forklifts and 7 aisles. This design would furthermore result in a significantly larger required warehouse area, and thus a lower storage density.

Relatively deep storage channels (up to 12 pallets in scenario 2) result in the maximal material handling capacity and storage density. Deeper storage channels naturally result in a shorter aisle length for a given number of pallets, thus decreasing the overall distance to travel for the shuttle. An important observation comes from the comparison between scenario 1 and scenario 2, where a three aisle warehouse design in scenario 1 performs only marginally better than the two aisle warehouse design obtained from scenario 2. It becomes clear that an operational strategy without the use of a buffer channel leads to significant gains in equipment handling capacity. The FIFO storage policy of scenario 3 is implemented through operating one shuttle for storage, and another shuttle for retrieval. This means that the amount of shuttles is chosen in multiples of two, and as a two-aisle system is just not able to provide sufficient handling capacity, a four-aisle solution is needed. The wide aisles needed for an automated forklift (scenario 4) to manoeuvre, and the storage depth being limited to two pallets result in a larger required warehouse area, which will increase operating expenses through higher rent.

Whilst also being dependent on the depth of storage channels and the length of the aisles, the material handling capacity of the entire system is at large determined by the amount of material handlers. And when the amount of pallets in the system increases, there will be a tipping point, where an extra shuttle or automated forklift is needed. This tipping point is at 910 pallets for scenario 3. In this case, it would make sense to design a warehouse with only 910 pallets, as it would halve the amount of shuttles and orbiters, whilst the amount of pallets is only reduced by 9%. This exemplifies the broader implication, that the material handling capacity is very much dependent on the equipment specification, and the amount of material handlers, and it would make sense to adapt the amount of pallets in the system to the material handling capacity. This would result in an optimal warehouse lay-out and optimal use of the material handing equipment, although it should not be forgotten that this equipment interacts with other processes like feeding, harvesting and redistribution of larvae, whose process speed influences the pallet demand. As one of the goals of this thesis is the validation of the case-study design, the results from the simulation model are very clear for scenario 1, i.e. three shuttles are needed, and the case study design does not provide sufficient material handling capacity for the amount of pallets.

To put these results from this study into context, the limitations of the approach need to be clarified. In the material handling equipment choice, a panel of experts is relied on to score different transportation concepts. Although this panel has a lot of expertise in the specifics of the insect rearing process, and the operation of a shuttle and orbiter material handling concept, their experience and knowledge on other material handling equipment concepts is limited. Their expertise is essentially extrapolated on other concept, and it is assumed that the panel assessments are valid.
The simulation model is only employed to study the influence of operational strategy and warehouse lay-out on the material handling capacity, whilst this can also be determined through an analytical approach. However, the simulation model opens up the possibility of including scenarios of short stops or breakdowns, and improving the lay-out designs based on robustness criteria.
Whenever simulation methods are used to better understand system mechanics, a choice needs to be made on the level of detail of the model. A more detailed model will yield more accurate results, but will also be more complicated and time consuming to build. In this simulation model, two important simplifications are done. The first one being the simplification of the pallet flows. The feeding process is the only process that is being modeled, and other pallet handling demand is included in a pallet handling capacity factor. Secondly, no interactions between the material handling equipment subsystem and other subsystems of the insect rearing system are modelled. The duration of the the redistribution, harvesting or feeding process definitely impacts the demand on the material handling equipment, but the assumption is made that 100% of the handling capacity is being used.
To go into further detail, the travel time model for the shuttle and orbiter is based on measurements on the case study equipment, so aisle length and storage depth were limited. The simulation does consider longer warehouse aisles and deeper storage channels, and the measurements are therefore extrapolated. The travel time model for the automated forklift is an adaption of this travel time model, with a different acceleration and velocity plugged in, whilst the travel time of the material handling equipment when determining the number of automated forklifts, or the warehouse lay-out.
A critical limitation of the lay-out design model is that only a single layer storage rack is considered. The addition of a third dimension would multiply the lay-out design possibilities, and would most likely result in denser storage.

6.2. Recommendations for further research

In this section, the recommendations for further research are done. In the first paragraph, general recommendations are done that would improve or complement this thesis in general. In the second paragraph, recommendations are done that would improve the simulation based design approach and finally a research possibility in the advancement of the automated generation of design concept is presented.

The simulation model does not consider any stochastic processes, whilst the case study clearly showed that short stops and breakdowns seriously impact the production process. The inclusion of these scenarios into the simulation allows for quantitative analysis of the risk of downtime, and a trade-off can be made between

the cost and benefit of possible built in redundancy.
One of the characteristics of the dynamic storage policy as proposed in scenario 2, is the reversal of the order of the pallets in the storage channel every feeding cycle. Due to this characteristic, a pallet that receives feed the first of its row, will be last in next feeding process creating a variation for individual pallets in the duration of the interval between feeding processes. The magnitude of this variation is dependent on the depth of the storage channels, but deeper storage channels improve the total handling capacity of the system. A trade-off therefore needs to be made between pallet handling capacity, and the magnitude of the variation of the feeding interval. It is understood that the yield of larvae decreases when feed is provided irregularly, but further research should be done on the magnitude of this reduction, and at which interval variation this process occurs. Based on this information, a proper trade-off could be made, and the optimal channel depth can be determined.
As the current approach focuses heavily on optimal performance from the material handling perspective, without considering the entire system. In reality, when two processes take place at the same time, it could occur that the two subsystems request a pallet handling action at the same time. If one pallet is delivered too late, the total system could be delayed, if no proper buffers are designed into the system. A successive study should zoom out to the system level, and design a lay-out considering all relevant subsystems and interactions.
The entire approach of this thesis is based on the assumption that it is impossible to service the pallets on location, therefore necessitating pallet handling equipment to bring the pallets to a location where this service is possible. Further research on the possibility to partly or entirely service the pallets *in situ* is recommended. As most of the handling capacity is currently needed to provide feed to the larvae, the required handling capacity would be reduced dramatically if this process could be performed without moving the pallets.
Another interesting direction for future research should concern the susceptibility of (navigational) sensors in material handling equipment to the dust and dirt present in the insect rearing environment. Such a study could produce a set of air quality requirements to allow a certain type of sensors to perform in, or the other way around, a set of requirements to which new sensors could be sourced or developed, to allow for operation in the current rearing environment.

An improved version of the simulation and design model would consider multi-layer storage. As previously discussed, multi-layered storage significantly reduces the required warehouse area and most likely also the travel time for the material handling equipment. The current method is therefore only valid if a single storage layer is needed. Furthermore, no pallet transport optimization is used. The material handling equipment services pallets on a first-come first-serve principle. An optimization method could improve the material handling capacity through increased dual cycle operations.
To make a more complete assessment of the FIFO storage policy in scenario 3, a variation with a reverse flow storage policy should be evaluated.
When considering the automated forklift in this application, further research on the lay-out design should include measurements on the actual travel time. This would be the most important improvement to scenario 4 of this study.

To bridge the gap between the current performance based parametric design approach and the paradigm of automated generation of design, the iterative increase of parameters should be replaced by a more autonomous algorithm that intelligently tunes the lay-out design. To broaden the automated generation of design paradigm, an interesting research direction would be to employ artificial intelligence to the lay-out design of an automated warehouse. The results of the simulation model employed in this study could be used to teach a self learning algorithm about the dependencies between aisle length, channel depth and material handling capacity and eventually predict new configurations without the need for exhaustive performance simulation of many possible configurations.

7
Conclusion

An automated generation of design approach is an extension of parametric design, and combines design generation, performance analysis and design evaluation. Through a probabilistic or non-deterministic search procedure, intelligent exploration of the solution space should be achieved and the resulting design should be easily adaptable when the requirements have changed. A model that simultaneously evaluates of cost and performance can aid experienced warehouse designers in the decision making process.

The case-study insect rearing process functions as an automated warehouse. The mealworms are kept in crates, stacked on pallets. The pallets are stored in multi-deep lanes and the pallet handling is performed by a shuttle and orbiter. When a process needs to be performed on the insects, the pallets are retrieved from the warehouse. Before a pallet returns to its original storage position, it is temporarily stored in a buffer channel, to await the retrieval of the other pallets in the storage channel. The automated warehouse technology proves to be well maintainable, but optical sensors prove to be sensitive to dust and spider webs, and are a regular cause of downtime.

For the design of an automated warehouse for insect rearing, nine relevant criteria are identified. Respectively: storage capacity, handling capacity, climate conditioning, cost, operability, maintainability, reliability, robustness and breeding quality. These criteria were used to evaluate seven material handling equipment concepts. The automated forklift concept and shuttle and orbiter concept are concluded to be suited best to the insect rearing application.

Inspired by the paradigm of automated generation of design, a performance based parametric design approach is taken to generate lay-out designs for three scenarios with a shuttle and orbiter concept and one scenario with an automated forklift. The lay-out design generated for the case-study scenario required three aisles, whereas the actual case-study design only features two aisles, and thus does not possess the required pallet handling capacity. The dynamic storage scenario (scenario 2) delivers almost the same pallet handling capacity, with only a two aisle design, proving that the operational strategy can significantly impact the overall pallet handling capacity of an automated warehouse design. The lay-out design that was generated for a FIFO storage policy (scenario 3) required four aisles, and therefore requires the largest investment in material handling equipment. The design does provide the largest spare handling capacity, indicating that the storage capacity of the automated warehouse should be adjusted to the handling capacity of the equipment to make optimal use of the available pallet handling capacity. The lay-out design with the automated forklift (scenario 4) requires a significantly larger warehouse area, due to the limited depth of storage channels and wider warehouse aisles. The lay-out design with a dynamic storage policy, two aisles and a storage depth of 12 pallets comes out of the comparison as the most preferable, featuring the lowest cost and significant spare handling capacity.

The performance based parametric design approach does make it easy to generate a new lay-out design when the input parameters need to be adjusted, and provides insight in the solution space. This could help a warehouse designer better understand the consequences of design choices on the pallet handling capacity of the system. Furthermore, the model could be used as a tool to come up with equipment requirements, which could serve as basis for discussion with material handling equipment suppliers to accelerate improvements and innovation.

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A

Research paper

Performance based parametric design of warehouse lay-outs for an insect rearing system

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***Abstract*— This paper considers an automated warehouse in an insect rearing application. Pallets are transported by shuttle and orbiter type material handling equipment from storage to a feeding machine, and back into storage. As the punctual timing of feed provision in an insect rearing system is of large influence on the final production yield, the performance of the material handling equipment is extremely important to the success of the production system. Inspired on the paradigm of automated generation of design, a performance based parametric design approach is taken to design the optimal warehouse lay-out for storage and handling requirements as dictated by the production process and material handling equipment performance. A comparison is then made between the optimal lay-out designs for three different operation scenarios.**

I. Introduction

Replacement of vertebrae sourced protein in the human diet with insect protein in meaningful quantities, provides an opportunity to drastically reduce global farmland and greenhouse gas emissions, whilst still providing critical nutrients. Successful automation and precise climate control are of extreme importance to the economic and biological success of a modern mass production system for insects, whilst diet and rearing technique also influence the yield [1]. The insect species that is considered in this work is the lesser mealworm, which is the larval stage of the litter beetle or *alphitobius diaperinus* (figure 1).

During the last decade automated warehouse technology has developed rapidly [3], and the industry has taken notice. In the period between 2012 and 2016 in the Netherlands alone, 63 large new warehouses were constructed employing some form of robot technology [4]. Despite this development, the majority of warehouse research is still focused on conventional storage- and order-picking methods [4].

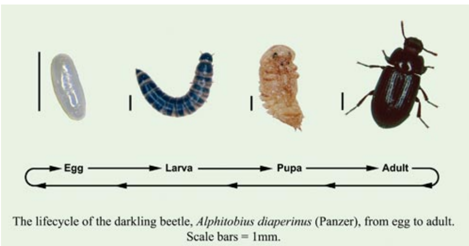

Fig. 1. The lifecycle of the *Alphitobius Diaperinus* [2]

In warehouse design, cost minimization and dynamic system performance are often studied separately [5]. The required level of automation for automated warehouses and the subsequent systematic evaluation of warehouse equipment are studied in a very limited fashion, and decisions are often made based on the experience of managers or designers [6]. Whilst warehouse design is rather complicated, little integrated design support is available [7].

The conceptual design phase is the most crucial task in engineering development, as the initial decisions heavily influence the final design, whilst little information is yet available to substantiate the decisions [8]. An estimated 75% of final product cost is incurred early on in the design phase, and key areas like performance, reliability, safety and environmental impact are impacted by these decisions [9]. The relationship of incurred cost over the design phase is further worked out in figure 2, concluding that early design decisions already heavily influence the incurred cost [10].

In this phase of conceptual warehouse design, the concept of automated generation of design may have the potential to fulfill a key role. The approach is characterised by the merging of the design process, performance analysis and evaluation [11]. In contrast to traditional design processes, the design is immediately evaluated and performance driven improvements are implemented in a feedback-loop towards the optimal design 3. This also means that concrete metrics are needed to automatically evaluate generated designs [12]. The main advantages lie in the improved ability to explore the entire solution space and the ease with which designs can be adapted to changing requirements.

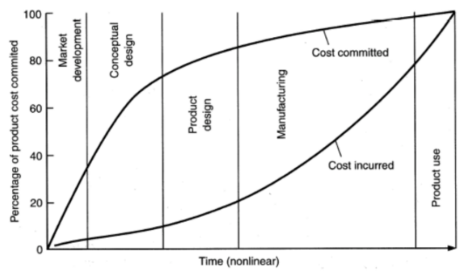

Fig. 2. The relation between committed costs and incurred costs in different design phases [10]

As the advanced in automated warehouse technology provide opportunities in the automation of insect rearing systems, this paper seeks to apply the automated generation of design approach to produce a performance driven lay-out design for an insect rearing system, where pallets are transported by a shuttle and orbiter type material handling equipment. Through a two-step iterative generation and

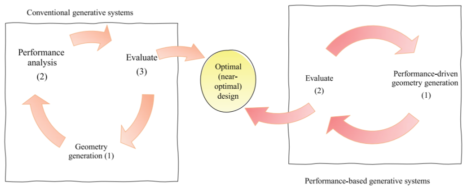

Fig. 3. Comparison between traditional generative methods and performance based generative design [11]

simulation method, inspired on [5], the number of warehouse aisles, aisle length and channel depth are determined for given storage capacity, handling capacity and material handling equipment performance. For three operational scenarios, a warehouse lay-out design is produced with a minimum number of shuttles, and maximum material handling capacity, using an automated generation of design approach. The aim of this work is to determine:

What is the optimal lay-out design for an automated warehouse with shuttle and orbiter type material handling equipment in an insect rearing application?

II. Theory

According to Fischer2001, the emergence of generative systems added a new component to the long-lasting binary relationship between the designer and the product, which transcended into a tertiary relationship between designer, generative system and product [13]. The first generative systems have been developed by mathematicians in an effort to replicate patterns observed in nature [14], whilst the application of generative systems expanded in the 1970's when architecture, engineering and construction industry researchers began to explore it's possibilities [15]. This new technology helps make multidisciplinary expertise available to designers, which they could otherwise not rely on [13] and helps them evaluate designs from a broader perspective. Perhaps the most influential gamechanger is the fact that generative design brings computing power into the design equation, and enables the evaluation of plenty design variations within a very short time, increasing the change of finding the (near) optimal design [11]. The complexity of involved disciplines, system interdependencies and stakeholder requirements make the engineering industry (among others) ideal for generative design [11].

As parametric design is limited by the abilities of the human designer in the exploration of the design space, however automated generation of design overcomes this limitation through automation of this exploration. Thus variations and custom adaptations of a design are easy to create. When requirements are change in the future, the parametric approach ensures that designs and results can be easily adapted to changing conditions. No new model needs to be built from scratch every time. Arguably, another advantage is that designers are allowed to think in a deeper and more dynamic way

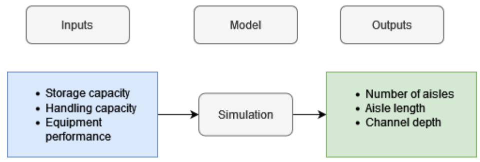

Fig. 4. The inputs and outputs of the simulation model

compared to traditional design methods [12]. A disadvantage of generative design is the tendency of the model to explore the design space without much transparency, thus acting as a black box to the designers [16]. Visualisation of the design generation process may thus be a key area of attention when developing a generative system.

In [5], an iterative design approach is proposed which combines optimization and evaluation of a warehouse lay-out design. In this paper both a cost minimization and dynamic system behaviour are studied, through the coupling of a non-linear integer model that minimizes initial investment and operating expense and a simulation model that considers the performance of the entire warehouse system. If the design parameters created through cost minimization do not fulfill the performance requirements in simulation, a new set of design parameters is generated. If the performance requirements are fulfilled, the iterative process is terminated. Further research on the influence of operating policies on warehouse performance is one of the recommendations.

III. Method

To determine the optimal warehouse lay-out for given requirements in storage capacity and handling capacity, a performance based parametric model is proposed that minimizes required material handling equipment and maximizes material handling capacity. A closed queuing network model is implemented in Python using the Salabim discrete event simulation library [17] that simulates a simplified version of the pallet flow process that is required in one 24 hour cycle of the factory operation. The warehouse model includes pallet storage in pallet positions, storage and retrieval by material handling equipment, and a feeding process. The inputs and outputs of the model are defined in figure 4

From the model inputs, a vast quantity of warehouse lay-out designs can be generated and evaluated. The solution strategy determines which lay-outs are evaluated, and which lay-outs are not evaluated. A two-step iterative approach is taken that ensures that the optimal design is found. In step 1 the number of aisles is determined, which starts at one. In step 2, the channel depth is determined, which also starts at one. The aisle length can then be determined from the storage capacity input and the number of aisles and channel depth. When all are determined, the determined properties can be used to generate the first iteration of the pallet flow simulation. The first warehouse design that goes through the pallet flow simulation thus consists of one aisle, a channel depth of one pallet. The channel depth is then increased by one pallet, until the result of the latest simulation is a worse performance than the previous simulation and thus the optimal ratio between aisle length and channel depth is found. Step 2 is now terminated, and the process returns to step 1. The resulting throughput capacity is compared to the required throughput capacity. If the performance is insufficient, one aisle (thus one extra shuttle and orbiter) is added, and step 2 is repeated. This iterative process is continued until a design is obtained that produces at least the required performance.

IV. Model

The pallet flow simulation model translates basic warehouse properties (storage capacity, handling capacity, number of aisles, aisle length, channel depth) into a simulated warehouse that performs an entire feeding cycle, and returns a handling time value. This section provides an in depth description of the way physical warehouse processes and properties are represented in the simulation model, and how the simulated handling time is determined.

A. Warehouse model

The warehouse consists of pallet positions for storage, material handling equipment to transport pallets, and a combination of subsystems to perform the feeding process.
The storage channels in the warehouse are represented in the model as Salabim queue's. The pallet capacity of each storage channel is limited to a certain amount of pallets, and this limit is referred to as the *depth* of the storage channel. E.g. a storage channel with a depth of three can contain up to three pallets.
Each pallet is modelled as a separate instance (or object when following Python conventions) of a Salabim class. The information on which storage channel to use, and when to request the material handling equipment is all defined within each instance of the pallet class. All equipment is therefore reactive to the requests from pallet instances.
The shuttle and orbiter combination is modeled as a Salabim resource with a capacity of one pallet. When a pallet requests transportation, the shuttle and orbiter combination travels to the location of the pallet, and takes the pallet to the desired location. The pallet then releases the resource, and the shuttle and orbiter are ready to transport the next pallet. After each movement, the location of the shuttle and orbiter are updated. The travel time of the shuttle is dependent on the distance between itself and the target storage channel, whilst the travel time of the shuttle is dependent on the distance that needs to be traveled inside the storage channel. The travel time is thus dependent on the distance between two warehouse coordinates, and the amount of pallets in the target storage channel queue. The travel-time model is described in the following paragraph.
Before entering the destacker and starting with the feeding process, the pallet is transferred from the shuttle to a conveyor. On this conveyor, a pallet can be held until the destacker is finished with the previous pallet. The conveyor therefore functions as a buffer in the pallet flow, where a pallet can wait until entering the destacker and commencing the feeding process. In the simulation model the destacker buffer is modeled as a Salabim resource with a capacity of one pallet.
When the feeding process is finished, the crates are stacked back upon the pallet by the stacker. When the stacking process is finished, the pallet exits the stacker onto a conveyor, which again fulfills a buffer position for the pallet when it awaits handling by the shuttle. The stacker buffer is also modelled as a Salabim resource with a capacity of one pallet.
When a pallet has finished the feeding process, it cannot return to the storage channel until all pallets have been retrieved from that storage channel. Because when a pallet that just received feed is immediately put back into it's storage channel, it will lock up other pallets behind it that still need to receive feed. Therefore a normal storage channel is used as dedicated buffer channel (also called overflow channel), where pallets are stored temporary until they can return to the storage position. The buffer channel has the same capacity limit as the normal storage channel, and is modelled as Salabim queue.

Equipment	Maximum velocity	Maximum acceleration
Shuttle	3.5 $\mathrm{m\,s^{-1}}$	0.55 $\mathrm{m\,s^{-2}}$
Orbiter	2.5 $\mathrm{m\,s^{-1}}$	0.6 $\mathrm{m\,s^{-2}}$

TABLE I
ACCELERATION AND VELOCITY OF SHUTTLE AND ORBITER

B. Shuttle and orbiter model

The shuttle and orbiter combination travels along the warehouse aisle, and stops at the desired storage channel to retrieve a pallet. The orbiter then leaves the shuttle and travels into the storage channel to lift the pallet and bring it back to the shuttle. Only one pallet can be transported at once. The travel time needed to get to a new location is determined from the distance to travel, and the acceleration and top speed of the shuttle and orbiter. Is is assumed that the shuttle or orbiter either accelerate or decelerate at a constant rate, or travel at a constant velocity. If the distance is too short to reach top speed, the movement will only consist of constant acceleration and constant deceleration. If the distance is longer, the shuttle or orbiter will accelerate until the maximum velocity is reached. This maximum velocity will be maintained until the destination is almost reached, and constant deceleration starts. The magnitude of deceleration is assumed equal to the magnitude of the acceleration.

Travel time formulae shuttle
For $s \leq 2 * s_{accelshuttle}$:
$$t_{shuttle} = 2 * \sqrt{\frac{s}{a_{shuttle}}} + \frac{c_{shuttle}}{s}$$
For $s > 2 * s_{accelshuttle}$:

$$t_{shuttle} = 2 * \sqrt{\frac{2 * s_{accelshuttle}}{a_{shuttle}}} + \frac{s - 2 * s_{accelshuttle}}{v_{shuttle}} + \frac{c_{shuttle}}{s}$$

Travel time formulae orbiter

For $s \leq 2 * s_{accelorbiter}$:

$$t_{orbiter} = 2 * \sqrt{\frac{s}{a_{orbiter}}} + \frac{c_{orbiter}}{s} + d_{orbiter}$$

For $s > 2 * s_{accelorbiter}$:

$$t_{orbiter} = 2 * \sqrt{\frac{s_{accelorbiter}}{a_{orbiter}}} + \frac{s - 2 * s_{accelorbiter}}{v_{orbiter}} + \frac{c_{orbiter}}{s} + d_{orbiter}$$

	Constant	Value
Shuttle	$v_{shuttle}$	3.5 $\mathrm{m\,s^{-1}}$
	$a_{shuttle}$	0.55 $\mathrm{m\,s^{-2}}$
	$s_{accelshuttle}$	11.1 m
	$c_{shuttle}$	6
Orbiter	$v_{orbiter}$	2.5 $\mathrm{m\,s^{-1}}$
	$a_{orbiter}$	0.6 $\mathrm{m\,s^{-2}}$
	$s_{accelorbiter}$	5.2 m
	$c_{orbiter}$	2.3
	$d_{orbiter}$	11.7

TABLE II

VALUES OF CONSTANTS IN TRAVEL TIME FORMULAE OF THE SHUTTLE AND ORBITER

V. SCENARIOS

A. Scenario 1

Scenario 1 mimics the warehouse process as performed in the case study. Key element in comparison to the other scenarios is the buffer channel, where pallets are stored temporarily until they can return to the empty storage channel.

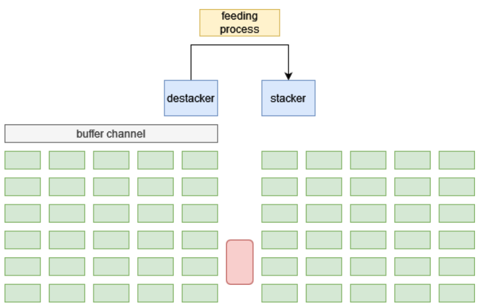

Fig. 5. Schematic top view of the warehouse in scenario 1

B. Scenario 2

In this scenario, pallets do not have a fixed storage position. One channel is always kept empty, so that pallets that return from the feeding process (or any process) can be returned to a new storage position immediately, without waiting in a temporary buffer channel. The original storage channel will be empty when the last pallet is taken to the feeding process. This new channel will then directly receive pallets from the feeding process. As pallets will not return to their original storage position, this system requires robust bookkeeping of storage locations. A drawback of this system is the fact that the pallet that enters the feeding process first, will be returned first, and will be entering the feeding process last in the next feeding cycle. The accuracy of the feeding process will thus be negatively affected, and the time difference will increase with increased storage depth.

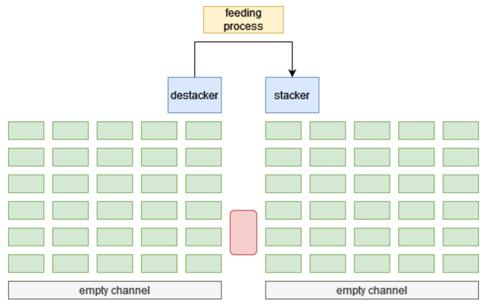

Fig. 6. Schematic top view of the warehouse in scenario 2

C. Scenario 3

Scenario 3 employs the shuttle and orbiter material handling equipment to perform a first-in first-out storage policy. A double aisle with storage channels in between is used, where pallets are retrieved towards the feeding process from one side, whilst storage operation is done through the shuttle and orbiter on the other side of the storage channels (figure 7). This storage policy features a simple pallet flow and optimal feeding accuracy, at the cost of reduced overall throughput due to increased travel distance for the orbiter and the absence of dual cycle operations.

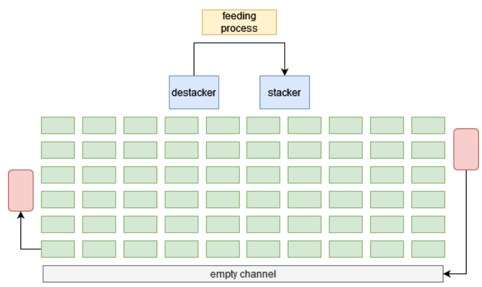

Fig. 7. Schematic top view of the warehouse in scenario 1

VI. RESULTS

The results of each scenario are generated for the model inputs listed in table III.

A. Scenario 1

In table IV the resulting lay-out designs are presented. The optimal design features minimal feeding process time, thus providing the greatest overcapacity in case of downtime or delays. The second lay-out design provides the minimal channel depth, whilst still completing the feeding process within the requirements. In figure 8 the simulated feeding

Input	Value
Storage capacity	1000 pallets
Handling capacity	1500 pallets
$v_{shuttle}$	$3.5\ \mathrm{m\,s^{-1}}$
$a_{shuttle}$	$0.55\ \mathrm{m\,s^{-2}}$
$v_{orbiter}$	$2.5\ \mathrm{m\,s^{-1}}$
$a_{orbiter}$	$0.6\ \mathrm{m\,s^{-2}}$

TABLE III
MODEL INPUTS

Design	Pallets	Aisles	Aisle length	Channel depth
Optimal	1000	3	17	10
Min channel depth	1000	3	84	2

TABLE IV
SCENARIO 1: LAY-OUT DESIGN RESULTS

process time is plotted for a warehouse with one aisle, two aisles and three aisles. A warehouse with three aisles is needed to reach a sufficiently low feeding process time. The optimal design has a channel depth of 10 pallets, but due to overcapacity of the three aisle design, the channel depth can be decreased in depth down to 2 pallets whilst still performing below the maximum feeding process time. Furthermore, it becomes clear from the figure that a warehouse with two aisles almost reaches the desired performance level.

B. Scenario 2

The results that are presented in this paragraph are obtained from simulation scenario 2 for the same input parameters as scenario 1 (table III). In figure 9 the simulated feeding

Design	Pallets	Aisles	Aisle length	Channel depth
Optimal	1000	2	22	12
Min channel depth	1000	2	85	3

TABLE V
SCENARIO 2: LAY-OUT DESIGN RESULTS

process time is plotted for a warehouse with one aisle and two aisles. A warehouse with two aisles is needed to reach a sufficiently low feeding process time. The optimal design has a channel depth of 12 pallets, but due to overcapacity of the two aisle design, the channel depth can be decreased in depth down to three pallets whilst still completing the feeding process within the maximum feeding process time.

C. Scenario 3

The results that are discussed in this paragraph are obtained from simulation scenario 3 for the same input parameters as scenario 1 (table III). The set of simulations done is also identical to scenario 1. In figure 10 the simulated feeding process time is plotted for a warehouse with one double aisle and two double aisles. A warehouse with two double aisles is needed to reach a sufficiently low feeding process time. The optimal design has a channel depth of 18 pallets (table VI, but due to overcapacity of the two double aisles design, the channel depth can be decreased in depth down to three pallets whilst still completing the feeding process within the maximum feeding process time.

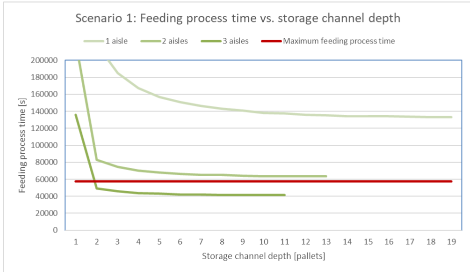

Fig. 8. Visualisation of required number of aisles

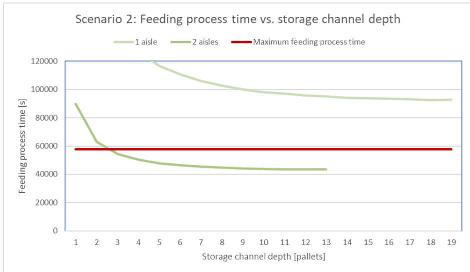

Fig. 9. Visualisation of required number of aisles

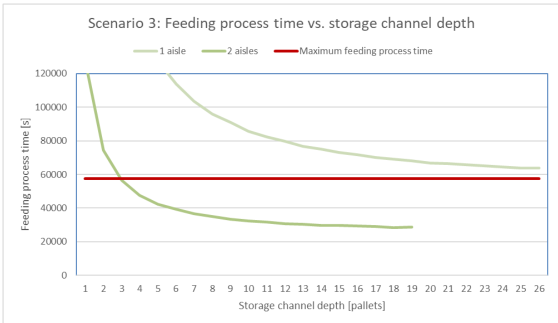

Fig. 10. Visualisation of required number of aisles

D. Comparison

The results that are discussed here are listen in table VII. The warehouse design for scenario 1 features three aisles and three material handlers, with a significant operational reserve of over six hours. The simplified operational process of scenario 2 leads to two aisle design and a 33% reduction in capital expenditure whilst providing an operational reserve of almost six hours. Operational expenses are comparable to scenario 1. A significant drawback of the operational process is the reversal of the pallets in the storage channel after each (feeding) cycle. Whilst providing significant gains in material handling capability, the production yield will suffer from increased variability of the feeding process, especially

Design	Pallets	Aisles	Aisle length	Channel depth
Optimal	1000	2*2	29	18
Min channel depth	1000	2*2	168	3

TABLE VI

LAY-OUT DESIGN RESULTS FOR SCENARIO 3

Scenario	Aisles	Operational time	Operational reserve
Scenario 1	3	17:16	06:44
Scenario 2	2	18:03	05:57
Scenario 3	4	11:54	12:06

TABLE VII

COST AND OPERATIONAL RESERVE FOR STANDARD MODEL INPUTS

for the front and rear pallet. Minimal variability in the feeding process and a simple pallet flow process are the main advantages of the FIFO storage policy in scenario 3. Although this comes at a price. A two aisle design would only be able to serve 910 pallets within the set operational time, so four aisles and material handlers are required to serve 1000 pallets. Regarding capital expenditure is scenario 3 the most expensive scenario with four material handlers and an operational reserve of more than 12 hours. Furthermore, the pallet flow process in scenario 3 is dependent on the simultaneous operation of two material handlers, seriously limiting robustness in comparison to the other scenarios.

VII. DISCUSSION

In this section a brief summary is given on the warehouse lay-out design through the performance based parametric design model. The interpretation of these results is then given, and the implications for the design of an automated warehouse system are discussed. Finally, the limitations of the approach taken are described, to give insight in its weaknesses.

Optimal lay-out designs are generated for scenarios 1-3 for a shuttle and orbiter with different operational strategies. When optimizing for material handling capacity, the resulting design for scenario 1 is a three-aisle warehouse with a storage channel depth of 10 pallets. Scenario 2 features a dynamic storage policy, and results in a two-aisle warehouse with a storage channel depth of 12 pallets with a material handling capacity close to scenario 1. In scenario 3, a FIFO storage policy is studied, and the resulting warehouse features four aisles and 18 pallet-deep storage channels.

Relatively deep storage channels (up to 12 pallets in scenario 2) result in the maximal material handling capacity and storage density. Deeper storage channels naturally result in a shorter aisle length for a given number of pallets, thus decreasing the overall distance to travel for the shuttle. An important observation comes from the comparison between scenario 1 and scenario 2, where a three aisle warehouse design in scenario 1 performs only marginally better than the two aisle warehouse design obtained from scenario 2. It becomes clear that an operational strategy without the use of a buffer channel leads to significant gains in equipment handling capacity. The FIFO storage policy of scenario 3 is implemented through operating one shuttle for storage, and another shuttle for retrieval. This means that the amount of shuttles is chosen in multiples of two, and as a two-aisle system is almost able to provide sufficient handling capacity, a four-aisle solution is needed.

Whilst also being dependent on the depth of storage channels and the length of the aisles, the material handling capacity of the entire system is at large determined by the amount of material handlers. And when the amount of pallets in the system increases, there will be a tipping point, where an extra shuttle or automated forklift is needed. This tipping point is at 910 pallets for scenario 3. In this case, it would make sense to design a warehouse with only 910 pallets, as it would halve the amount of necessary shuttles and orbiters, whilst the amount of pallets is only reduced by 9%. This exemplifies the broader implication, that the material handling capacity is very much dependent on the equipment specification, and the amount of material handlers, and it would make sense to adapt the amount of pallets in the system to the material handling capacity. This would result in an optimal warehouse lay-out and optimal use of the material handing equipment, although it should not be forgotten that this equipment interacts with other processes like feeding, harvesting and redistribution of larvae, whose process speed influences the pallet demand. As one of the aims of this work is the validation of the case-study design, the results from the simulation model are very clear for scenario 1, i.e. three shuttles are needed, and the case study design does not provide sufficient material handling capacity for the amount of pallets.

To put these results from this study into context, the limitations of the approach need to be clarified. Whenever simulation methods are used to better understand system mechanics, a choice needs to be made on the level of detail of the model. A more detailed model will yield more accurate results, but will also be more complicated and time consuming to build. In this simulation model, two important simplifications are done. The first one being the simplification of the pallet flows. The feeding process is the only process that is being modeled, and other pallet handling demand is included in a pallet handling capacity factor. Secondly, no interactions between the material handling equipment subsystem and other subsystems of the insect rearing system are modelled. The duration of the the redistribution, harvesting or feeding process definitely impacts the demand on the material handling equipment, but the assumption is made that 100% of the handling capacity is being used.

To go into further detail, the travel time model for the shuttle and orbiter is based on measurements on the case study equipment, so aisle length and storage depth were limited. The simulation does consider longer warehouse aisles and deeper storage channels, and the measurements are therefore extrapolated.

A critical limitation of the lay-out design model is that only a single layer storage rack is considered. The addition of a third dimension would multiply the lay-out design possibilities, and would most likely result in denser storage.

VIII. Conclusion

This work combines the traditional field of warehouse design with the novel practice of industrial insect rearing, through taking an approach inspired by the concept of automated generation of design to create a lay-out design of an automated warehouse in the insect rearing application. An automated generation of design approach is implemented in Python, employing the Salabim discrete event simulation library. For the following inputs; (storage capacity in number of pallets, material handling capacity in number of pallets per 24 hours, material handling equipment specifications), the model will return a lay-out design that maximizes material handling capacity and minimizes the required material handling equipment, thus minimizing cost.
The approach does make it very easy to generate a new lay-out design when the input parameters need to be adjusted, and clearly shows the impact of different operational strategies on the material handling capabilities of the system. Furthermore, the results from simulation give an interesting insight in the solution space, and could help a warehouse designer better understand the consequences of design choices on the pallet handling capacity of the system. The model could be used as a tool to come up with equipment requirements, which could serve as basis for discussion with material handling equipment suppliers to accelerate improvements and innovation. For the given model inputs, a dynamic pallet storage policy should be implemented, for which a two-aisle lay-out design with a minimal channel depth of three pallets and an optimal channel depth of 12 pallets.

IX. Recommendations

In this section, the recommendations for further research are done. An important direction is the interaction between the biological requirements of insects and the material handling equipment.
One of the characteristics of the dynamic storage policy as proposed in scenario 2, is the reversal of the order of the pallets in the storage channel every feeding cycle. Due to this characteristic, a pallet that receives feed the first of its row, will be last in next feeding process creating a variation for individual pallets in the duration of the interval between feeding processes. The magnitude of this variation is dependent on the depth of the storage channels, but deeper storage channels improve the total handling capacity of the system. A trade-off therefore needs to be made between pallet handling capacity, and the magnitude of the variation of the feeding interval. It is understood that the yield of larvae decreases when feed is provided irregularly, but further research should be done on the magnitude of this reduction, and at which interval variation this process occurs. Based on this information, a proper trade-off could be made, and the optimal channel depth can be determined.
As the current approach focuses heavily on optimal performance from the material handling perspective, without considering the entire system. In reality, when two processes take place at the same time, it could occur that the two subsystems request a pallet handling action at the same time. If one pallet is delivered too late, the total system could be delayed, if no proper buffers are designed into the system. A successive study should zoom out to the system level, and design a lay-out considering all relevant subsystems and interactions.
The entire approach is based on the assumption that it is impossible to service the pallets on location, therefore necessitating pallet handling equipment to bring the pallets to a location where this service is possible. Further research on the possibility to partly or entirely service the pallets *in situ* is recommended. As most of the handling capacity is currently needed to provide feed to the larvae, the required handling capacity would be reduced dramatically if this process could be performed without moving the pallets.
Another interesting direction for future research should concern the susceptibility of (navigational) sensors in material handling equipment to the dust and dirt present in the insect rearing environment. Such a study could produce a set of air quality requirements to allow a certain type of sensors to perform in, or the other way around, a set of requirements to which new sensors could be sourced or developed, to allow for operation in the current rearing environment.
An improved version of the simulation and design model would consider multi-layer storage. As previously discussed, multi-layered storage significantly reduces the required warehouse area and most likely also the travel time for the material handling equipment. The current method is therefore only valid if a single storage layer is needed. Furthermore, no pallet transport optimization is used. The material handling equipment services pallets on a first-come first-serve principle. An optimization method could improve the material handling capacity through increased dual cycle operations.
To make a more complete assessment of the FIFO storage policy in scenario 3, a variation with a reverse flow storage policy should be evaluated.
To broaden the automated generation of design paradigm, an interesting research direction would be to employ artificial intelligence to the lay-out design of an automated warehouse. The results of the simulation model employed in this study could be used to teach a self learning algorithm about the dependencies between aisle length, channel depth and material handling capacity and eventually predict new configurations without the need for exhaustive performance simulation of many possible configurations.

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