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DEPARTEMENT BEDRYFS- EN SISTEEMINGENIEURSWESE
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

VOORBLAD VIR INDIVIDUELE WERKOPDRAGTE - 2016
FRONT PAGE FOR INDIVIDUAL ASSIGNMENTS - 2016

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Modulekode **Module Code**	BPJ 410
Werkopdragnommer **Assignment number**	Preliminary Project Report
Onderwerp **Subject**	Final Year Project
Dosent **Lecturer**	Prof. J Joubert
Datum **Date**	2016-05-16

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Final Project Report

Warren M. Gertzen

2016-09-26

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Executive Summary

The aim of this project is to provide a new company, African Beer Importers, with a set of designs for their new warehouse in Silver Lakes, Pretoria. The designs were tested using a simulation model and compared according to several metrics; the most prominent being the Total Handling time, which measures how much time is spent handling the pallets, and the second being the Rack Utilisation, which measures how much the racks are being used. Two solutions excelled, one for each metric, and so both are being presented in order for the company to make a final decision based on whether they prioritise space or time more.

The first design uses a Chevron-Aisle floor pattern, with a 3-Class storage policy. The Chevron aisles minimise the travel distance incurred on the reach trucks, by approximating the Euclidean distance (as the crow flies)from the offloading point to any particular pallet, and minimising the tedious and traditional rectilinear movement pattern. The 3-Class storage policy allocates positions on the shelves based on the popularity of the beers, and puts the most frequently collected beers closest to the loading area, and the least used beers at the back, so that the most common trips are the shortest ones.

The second design uses a Leaf-Aisle floor pattern, with a Random storage policy. The Leaf pattern allows for more storage slots than the Chevron pattern, but has shorter travel distances than the traditional long, horizontal aisle patterns. The Random storage policy is actually pseudo-random, as the beers are simply stored in the first available position. This allows for maximum shelf-space utilisation, but comes at the cost of long material handling times and confusion in finding the correct beers.

The final solutions are shown in the figures 1 and 2 below:

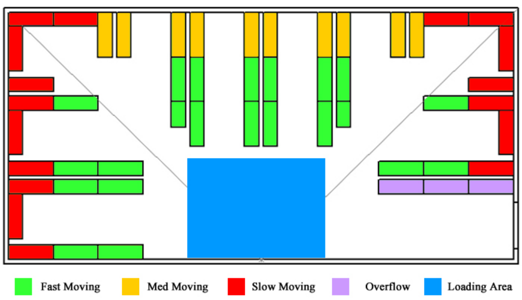

Figure 1: Final Solution A: Chevron Floor Layout with 3-Class Storage Policy

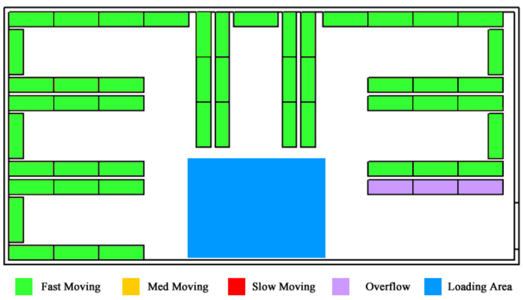

Figure 2: Solution B: Leaf Floor Layout with Random Storage Policy

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Glossary

General Terms

Picking refers to the selection of parts from storage to consolidate for a customer order.

Interleaving is the process of collecting two or more items in a single picking-run, and is sometimes referred to as a dual-address system.

Storage Slot refers to a position in the warehouse which may be filled with a full pallet, a semi-filled pallet, or may be an empty spot where a pallet may be placed. It is distinctly different from an aisle, where no pallet should ever be stored.

Material Handling Equipment refers to equipment which is used to transport products and items around the warehouse, usually from Receiving, to Storage, to Shipping. Examples include forklifts, pallet jacks, and trolleys.

Storage Policy refers to a set of rules that determines where certain items should be stored. The most basic rule is randomised, but alphabetical storage or class-based storage policies are also common.

Single-Command Order Picking refers to the picking of an order where only one part is picked per trip, and then returned to the collection area. In contrast, see Interleaving.

I/O Point refers to a point or area which is considered as a node in the network. The Input/Output point in this report will be the loading area, from where all pallets will be stored, where the forklifts shall live, and where the picked pallets will be brought.

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AnyLogic Terms

Agent refers to an entity within the AnyLogic model that will pass through the logical process. An agent must be created at the start, can be given specific parameters or functions, and will be subject to the instructions and processes that each logic block offers. In this model, the agents are the beer cases, the pallets, and the orders.

Logic Block refers to a block of code (alongside a GUI block) which creates, alters, withholds, moves, copies, or destroys an agent.

Source refers to a logic block which creates a new agent and inserts them into the process.

Enter refers to a logic block which calls a pre-existing agent from a population to enter the logic process. Enter is used to insert specific agents into specific streams of logic, and is especially helpful when there are multiple logical processes, or when the agent itself does not dictate its own flow through a process. In this report, pallets are called to 'enter' the picking process once an order requests them to do so.

Exit refers to a logic block which causes an agent to leave the logic process. The agent is not destroyed, it is simply stored in an external 'waiting area' of sorts, known as a population, where it waits until it is called by an 'Enter' block.

Sink refers to a logic block which terminates an agent, and completely removes it from the simulation.

Delay refers to a logic block which holds an agent for a set period of time, or until it receives a "release" message, and prevents the agent from moving further along in the system.

Batch refers to the logic block which waits for a certain number of components to enter, and then combines those component agents to form a new 'batched' agent. In this report, cases of beer act as the components, and are batched into a single pallet.

selectOutput refers to the logic block which accepts an incoming agent, and then sends the agent to a specific logic process line, depending on some criteria. This criteria may be a random assignment to different paths, or it can be based on a specific parameter or variable either within the model or within the agent itself.

Queue refers to the logic block which holds agents in order of arrival until the next logic block is ready to accept them. The queue can have a set capacity, or an indefinite maximum.

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List of Acronyms

ABE African Beer Emporium

ABI African Beer Importers

AS/RS Automated Storage & Retrieval System

C2 2-Class Storage Assignment

C3 2-Class Storage Assignment

FCFS First Come First Served

MIL Mandatory Interleaving

NIL No Interleaving

RAN Randomised Storage Assignment

SCOR Supply Chain Operations Reference

SKU Stock Keeping Unit

WMS Warehouse Management System

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Chapter 1

Introduction

1.1 Company Profile

African Beer Importers (ABI) is a new distribution company started by the owners of the successful alehouse, Capital Craft. ABI was started as a supporting company for a new alehouse, called African Beer Emporium(ABE), where beers from across Africa are sold to customers in the restaurant.

Goals of the Company Firstly, to consolidate and store large orders of beer from breweries around Africa. Given the logistical nature of Africa, it is necessary to have a large storage space to benefit from economies of scale, and the space requirements cannot be met by ABE alone. This is because of the long lead times caused by long distances, complex border procedures, and lack of infrastructure across the continent. This means that large and infrequent orders are best, but this requires a large storage space, such as a warehouse. Secondly, to expand the distribution capabilities and activities of ABI. Although ABI primarily serves ABE, it has the potential to access markets from across the country provided that it changes its mindset to target retailers not individual consumers.

1.2 Problem Identification

ABI has already purchased a warehouse to store all of the imported beers. They require that the functioning of the warehouse be designed in order to maximise the conflicting characteristics of space utilisation and customer service. The company will need both a physical design of the warehouse, which includes the layout of the storage racks and the types of shelving to use (if any), and a methodology for the allocation of storage space to beers. Space utilisation is important because the amount of storage space available in the warehouse will dictate the amount of inventory that will be ordered, and this has an influence on the volume and variety of the products that can be distributed. It also dictates the value for money achieved by having that amount of space. Customer service is also important, as ensuring good customer relations through correct and timely orders will keep a loyal and consistent customer base. This is dependent on many of the design aspects of the warehouse, such as how quickly an order can be picked, how little stock is lost due to material handling, or how many backorders are created due to inefficient use of space.

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1.3 Research Design

This project utilises simulation models to design and test several alternatives for the warehouse design. Using principles and frameworks from literature, key issues to warehouse design (such as aisle layout and storage policy) are considered and used to formulate 9 different scenarios to be compared. The scenarios are formed as a pairing of storage policies with various floor layouts. The designs are compared using several metrics which measure inter-related and core issues, and following the results, a discussion shows the importance of the results and the high-level processes that they influence. The champion design was then packaged and presented to the company as decision support, where the adoption of the design is ultimately up to company management. The package includes the tested designs, along with the results obtained, as well as an interpretation of the results and a recommendation.

1.4 Research Methodology

Using agent-based simulation, a scale design is used to test several of the concepts. A single-aisle model is used to determine the effects and the validity of the different storage policies in a single dimension (i.e. one line). The different policies are analysed to ensure that the model conforms with results gathered in other models and literature, in order to ensure that the concepts hold true. If the model conforms using a single piece of equipment travelling in one dimension, then multiple pieces of equipment will be tested.

Following this, the model is expanded to a two-dimensional framework, where the floor layout begins to have an effect on the distance travelled by the material handling equipment. Initially, a single piece of equipment is used to determine results on each of the metrics defined in the conceptual design section below. Finally, multiple pieces of equipment are allowed to operate within the various floor layouts, and the results are compiled into several tables for analysis.

Each simulation has a degree of randomness, as introduced by the stochastic customer demands. To compensate for this, each model was run 50 times and the outputs of each metric were averaged out to create a final figure that was used for comparison. Given the randomness of the inputs, there is no need for the weighting of any of the values, and a simple average will be used.

In order to make the models in this report more easily comparable to models from literature, similar assumptions will be used. These assumptions will be stated in full at the presentation of the model's design.

In terms of data collection, ABI will provide insight into the importance of the different metrics after the results have been generated. This allows for models with conflicting performance (i.e. winning at one metric, but losing in another) to be properly compared in line with the requirements of the company. Data regarding the speeds of handling equipment were estimated initially, in order to determine a preliminary set of results. Actual figures for data such as vehicle speed were then obtained at a later stage, during the final runs of the model. The lack of data was not an issue, as all of the models will use the same figures, and thus the results were measured proportionally, rather than as actual values.

Finally, agent-based simulation was chosen over analytical and mathematical modelling methods for several reasons. The first of these is the number of interdependencies between some of the decisions. This meant that the compilation of equations to manage all of the decisions would be complex and time-consuming. Secondly, simulation allows for a certain

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level of stochastic modelling that is difficult to match using analytical methods. Thirdly, simulation is less restrictive in the model's ability to change and adapt. Simulation models allow for small changes to be made without redeveloping large portions of the problem, and this is especially important in the design of a warehouse because of the largely qualitative nature of the initial design steps.

1.5 Document Structure

The second chapter of this document will cover some of the introductory literature to the warehouse design problem. A number of frameworks are reviewed, and then integrated to develop the steps taken in this report. In Chapter 3 will have a conceptual model formulated to identify the key scenarios which will be tested, as well as the creation of scale models to test individual concepts and to validate assumptions. Chapter 4 will consist of the preliminary simulation experiments performed, along with their results. This is then used to validate ideas presented in literature, and to start identifying the sensitivity of factors affecting the main results. Chapter 5 will contain the full-scale simulation model, which will include the results of each experiment and some interpretation of those results. Chapter 6 will conclude the report, and contain interpretations more specific to the business. This will also contain the recommendations for the company, as well as recommendations for duplication and extension of the experiments performed. It will also contain a critical discussion on the validity of simulation as a tool to solve this problem, and how it could potentially be improved in the future.

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Chapter 2

Literature Review

The design of a warehouse is a problem with significant complexity and difficulty, requiring consideration of numerous interrelated factors which have a variety of effects at every level of operation [10]. This literature study is loosely broken up into two sections, where the first will look at the various considerations required for the design of the warehouse, and the latter will briefly look at simulation as the best tool to approach this problem.

2.1 Warehouse Design

There are several problems that are common to the majority of warehouse designs and design scenarios. These problems and decisions all have various relations with each other, and in order to simplify the process, certain decisions are clustered together and solved simultaneously [13]. As such, there has been research into some of the most common and the most influential problems for warehouse design. The following literature review follows the structure of a review article on warehouse planning by Gu et al. [6], which addresses the five major decision groups that need attention in the initial planning phase. These decisions are expanded on by incorporating the framework proposed by Hassan [7] and developing a deeper insight into the practicalities of each decision. Finally, Rouwenhorst et al. [13] provide insight for each decision on strategic, tactical and operational levels, further adding to the robustness of the process. The individual questions relating to the warehouse design are then addressed in detail in specific papers, which will be reviewed below.

It should be noted from the beginning that the majority of these papers focus on large-scale warehouse design, where small improvements to efficiency have a large impact on the workings of the warehouse. Whilst efficiency is a key factor in the design of the ABI warehouse, it is important to note that in most cases, heuristics have been derived from the papers and that the entire model presented in literature is not always used. This is partly due to the time constraints of the project, but in part, also due to the scale and expected operation of the warehouse. The ABI warehouse is fairly small, and is likely to have minimal amounts of equipment, fairly slow-moving goods and infrequent orders. As such, advanced models do not provide significant benefit to the overall productivity of the warehouse, and more useful heuristics are therefore derived by considering the aims of each paper, the logic and methodology of finding and testing a solution, and then the application of an algorithm or model to approximate the same results.

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2.1.1 Warehouse Functions

Rouwenhorst et al. [13] considers the characterisation of the warehouse to be the initial step of warehouse design. The ABI warehouse will be classified as a finished goods, distribution warehouse [15], handling only the final beer products delivered from manufacturing sources. The four main functions (receiving, storing, picking and shipping) will be the main functions for the warehouse, with staging and potentially cross-docking functions added as required. Figure 2.1 shows the basic logical flow of products and orders through a warehouse.

2.1.2 Departments

The warehouse needs to be divided into separate departments in order to better allocate resources and to track problems to their source. Each of these departments should have a specific function and therefore a singular objective.

2.1.3 Warehouse Size

In most warehouse design problems, the size of the warehouse is a function of expected demand and therefore the demand forecasting is required to select an appropriate amount of warehouse space. However, ABI have already chosen a warehouse, and as such, the inventory and orders have now become constrained by the given, fixed size of the warehouse. Rao and Rao [11] provide a set of basic formulations which help to determine the size of a warehouse when there is deterministic demand. To counter this, they suggest creating demand profiles for pessimistic, most likely, and optimistic projections. The authors then derive an optimal solution to the warehouse space required using a set of simple linear programs.

2.1.4 Demand Forecasting

As the company is extremely new and the product incredibly unique, there is no guarantee that the product will be successful, and if so, how great the demand will be. Rao and Rao [11]'s equations can be reversed to represent the warehouse size as a constraint and use it to determine limits on demand, even if this is done through trials to outline the boundaries of inventory and demand profiles. In order to create a set of simple and somewhat realistic demand profiles, information about ABEs sister company, Capital Craft, will be used to determine what the pessimistic, most likely, and optimistic demands for different products will be. This will then be consolidated and sorted into the various storage classes to create a simulated profile for the new stock taken in by ABI.

2.1.5 Departmental Layout

Gu et al. [6] discusses the departmental layout in terms of three problems: P1 is the pallet block-stacking pattern, P2 is the storage department layout, and P3 is the Automated Storage & Retrieval System (AS/RS) configuration.

P1 Block-Stacking Problem Pallet block-stacking patterns are essentially a trade-off between the space utilisation of a warehouse and the ease of storage and retrieval. The models that address the aisles look to answer questions regarding orientation, quantity and dimensions of aisles and racks. Warehouses which aim to minimise the handling cost of differ greatly from those who aim to minimise the cost driven by occupied space. The

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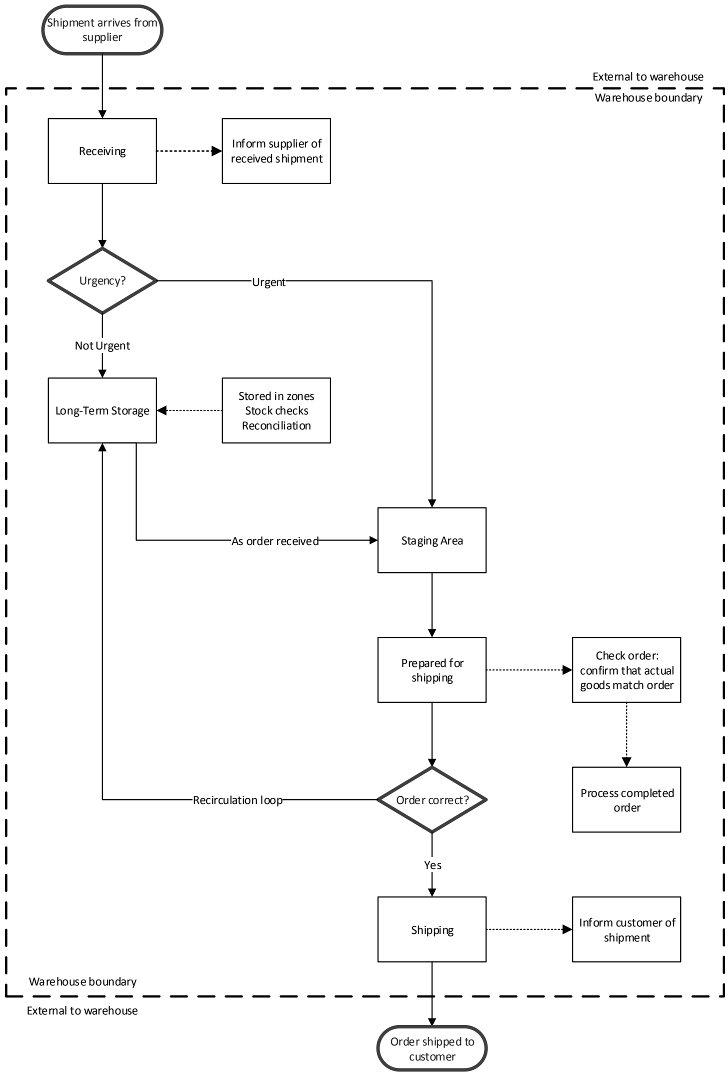

Figure 2.1: Flow chart of the basic warehouse processes

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ABI warehouse is primarily focused on the minimization of the material handling costs, as the warehouse size is predetermined and constant.
This problem is broken down into several smaller decisions, each with their own dedicated papers. One paper was most closely analysed, as it has the clearest perspective on the problem. Berry [2] introduces two simple models used for block-stacking, namely the traditional square-aisle model and then a diagonal aisle model.

He proposes that the diagonal model is more efficient when the number of stock lines is small, and proves to better for both area costs and material handling distance costs. However, these benefits need to be considered alongside the shape of the warehouse. The ABI warehouse is noticeably rectangular, and the optimum square-aisle model tends to be square. This can potentially be incorporated in the warehouse as two square storage systems, with the main loading area in a large aisle in between the two systems. It is worth considering both a diagonal and a square-based aisle model for the final solution in this report, as the approach to a rectangular warehouse is not well documented in the above article.

P2 Storage Department Layout Problem Storage department layout considers the layout of the products, or where each product is assigned within the rack system. The drawback is that the assumptions presented in the articles are usually that the storage is random, and that only single-command order picking occurs. Single-command order picking refers to the selection of one pallet per trip, rather than collecting several products in the same trip before returning to the loading area (a process known as interleaving). Roodbergen and Vis [12] use the metric of route lengths to determine the optimum storage policy given long, parallel aisles. The solutions developed present interesting models for the routing of orders. The two main solutions are the S-shaped model, where the vehicle snakes through the appropriate aisles; and the largest-gap model, which is better suited to two-lane aisles. Both of these concepts will be tested, however, not every goal and assumption applies to the ABI warehouse. These include an assumption of long, parallel aisles, whereas ABI will be testing various layouts; the test of ideal loading location, where ABI has already determined such; and unlimited slot visits per trip, whereas ABI will have certain constraints on the number of parts that can be stored on a single pallet in a single trip.

Whilst interleaving would add an interesting level of complexity and depth to this problem, it is unlikely that ABI will experience orders that are so small that they will need to have specifically prepared for interleaving. It is much more likely that they will receive orders that use pallets or beers as their units.

P3 AS/RS Problem The AS/RS system refers to an automated system of pallet storage and retrieval from a rack system. In large warehouses, these system replace the typical material handling equipment, such as forklifts and trolleys, and rather automate the entire process by using a machine to pick and store pallets, and a conveyor belt system to move the pallets further. These systems are extremely efficient and maximise the amount of space that can be utilised for storage, as there is no need for large aisles for forklifts to turn. These systems also minimise the material handling time, the risk of human error, and the costs of labour.

However, these systems are extremely expensive to install, and work best in the largest of warehouses, where hundreds or thousands of picks and stores are completed each day. That makes this system too expensive to match the benefits gained from being a more

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efficient system.

2.1.6 Equipment Selection

Equipment selection concerns the tactical-level decision of how mechanised a warehouse is. The decision is important because material handling will account for one of the largest costs of the warehouse, including as much as half of all factory space and anything between 15% and 70% of the entire cost to company [14]. The ABI warehouse will not require a full Automated Storage/Retrieval System (AS/RS), at least for this warehouse. The flow volume of products is not significant enough to warrant an expensive system, especially given the young age of the company. However, some automation is required as the pallets of products are simply too heavy and too cumbersome to move by hand. As such, several types of equipment (such as forklifts, trolleys and conveyor systems) will be compared in order to ensure that the business is capable of handling the current volumes and potential future volumes of products, whilst minimising the costs.

Costing of Equipment Park and Webster [10] suggest some simple cost equations to compare differences in equipment types and storage rules. These equations can be used to compare different types of equipment once a selection of equipment types has been identified and the relevant attributes quantified. The first important equation shows that the quantity of material handling equipment is a function of the preferred handling rate (i.e. the number of Stock Keeping Units (SKUs) to be processed per unit time) and the average travel time per pick. The second important equation determines the expected labour costs as a function of cost per operator of the equipment, as well as the expected inflation rates, which are then brought out over a period of n years. Facility, operating and maintenance costs are also considered in the paper. Finally, the total costs are consolidated into a total investment cost, with appropriate tools for depreciation being applied. Thus, the general annual equivalent cost is calculated in Equation (2.1)

$$\begin{aligned} NPV(i) =& C^{\text{inv}} + \sum_{n=1}^{N} \Big[C^{\text{op}}(n) + C^{\text{mnt}}(n) + C^{\text{lab}}(n) \cdot (1-T) \\ & - T \cdot D(n) - S(N) \Big] \times \left(\frac{1}{1+f} \right)^{n} \times \left(\frac{1}{1+i} \right)^{n} \end{aligned} \tag{2.1}$$

Where:

NPV = Net Present Value
C^{inv} = Cost of Total Investment
C^{op} = Cost of Operating
C^{mnt} = Cost of Maintenance
C^{lab} = Cost of Labour
T = Annual Rate of Tax
D = Annual Depreciation
S = Expected Salvage Value
f = Annual Inflation Rate
i = Inflation-free Discount Rate
n = Number of Years

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2.1.7 Storage Policies

Hausman et al. [8] looks at the storage policy of a automated warehouse by analysing the optimal placement for pallets in a single face, long and tall rack. The assumptions used by the team simplify the calculations greatly, and allow for the same logic to be applied to a single-level floor plan, where AS/RS cranes are replaced by forklifts. The papers then analyse three different storage assignment rules:

1. Randomised Storage Assignment (RAN)

   Every item has an equal likelihood to be placed in every position. In practice, this manifests as a closest-position first system

2. Class-based Storage Assignment

   Items are ranked into classes based on their predicted turnover. Areas are specifically designated to certain classes, with the highest turnover classes placed nearest to the I/O point. Items are stored randomly within their class area. The paper considers both a 2-Class Storage Assignment (C2) and a 2-Class Storage Assignment (C3).

3. Full Turnover-based Storage Assignment (FULL)

   Items are placed based on their individual turnover. This is equivalent to a continuous-turnover placement strategy, where each item is considered as an individual class. This is impractical to implement, but serves as a good metric for measuring the optimal theoretical solution.

Graves et al. [5] extends on work done by the same team in Hausman et al. [8] by including interleaving into the process of selecting a storage assignment rule. Interleaving is the process of collecting two items in a single picking-run, and is sometimes referred to as a dual-address system. Interleaving was ignored in the previous paper[8] by applying a No Interleaving (NIL) system, whereby the equipment travels from the I/O point to the item, waits to retrieve the item, and then returns directly to the I/O point. Two interleaving rules are addressed in the paper:

1. Mandatory Interleaving (MIL) with a First Come First Served (FCFS) retrieval policy (MIL/FCFS)

   The picking-order is carried out in sequence whilst forcing interleaving

2. Mandatory Interleaving with selection queue of K retrieves (MIL/K)

   The picking order is carried out whilst forcing interleaving, but the first K number of retrieves need not be in sequential order.

Results are then published for ten different scenarios comprised of combinations of the above storage and interleaving policies, and Table 2.1 provides a summary of the policy rankings.

The limitations on the above work is that the model assumes that only one piece of material handling equipment can operate in any area, which makes sense given that the model was computed with a single AS/RS crane in mind. The simulation created for ABI will expand on this by allowing for multiple, simultaneous and independent pieces of equipment to operate in the same environment, as it is done in practice. The same assumptions as Hausman will be made, and these will be presented during the formulation of the model.

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Table 2.1: Travel times per policy scenario [5]

Rank	Policy	Expected return trip time
1	C3/MIL/K	1.330
2	C2/MIL/K	1.428
3	FULL/MIL/FCFS	1.430
4	C3/MIL/FCFS	1.481
5	C2/MIL/FCFS	1.537
6	RAN/MIL/FCFS	1.800
7	FULL/NIL/FCFS	1.963
8	C3/NIL/FCFS	2.070
9	C2/NIL/FCFS	2.184
10	RAN/NIL/FCFS	2.667

2.1.8 Warehouse Management Systems

Gu et al. [6] describes the function of a Warehouse Management System (WMS) as software to aid the operation of the warehouse by tracking the movements of the items stored within the warehouse. This means that the WMS should track orders, receipts, allocations, and shipments, as well as aiding in the management of human resources, equipment and storage space. The WMS may also help with storage assignment, following algorithms that have been determined by the storage policy. Unfortunately, literature on the WMS tends to focus on the design of said systems, rather than effective metrics that could be used to differentiate between the available options. Given the scale of the ABI warehouse, it is impractical to design a WMS to meet its needs; it is also impractical to spend money on an expensive and advanced system when an open-source, freely available system could do the same job. As such, open-source Enterprise Resource Planning (ERP) programs such as OpenBravo Commerce Suite and Odoo should be considered by the company to perform the function of warehouse management. The inclusion of a WMS is a necessary consideration for ABI, but will fall outside of the scope of this report.

2.2 Simulation

2.2.1 What is Simulation Modelling?

A simulation model is a representation of a real-world process that aims to replicate the most significant parameters and their interactions. By that definition, a simulation will never be a true representation of the real world, but an effective model includes enough of the important contributors of change, and considers all other parameters as negligible, in order to try and predict likely outcomes. One of the key benefits to simulation is the ability to experiment with a number of different alternatives, and to easily analyse the differences between models with small changes.

2.2.2 When should we use Simulation Modelling?

According to Carson [4], simulation is most useful when there is no simple analytical model, most interactions are well defined, assumptions need verification, or if a new system is being designed by someone with little experience in the field. Simulation also works best for

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experimentation with large or expensive changes, situations without strict mathematical formulations, and for solving problems whose solutions need to be presented in a clear and easy to understand manner for non-engineers and non-specialists. Given that the above characteristics almost perfectly align with the description of the ABI warehousing problem, simulation will be used as the main tool for the formulation and validation of a solution. Pure analytical modelling is time consuming and complex, and is usually limiting in the number of ideas that can be tried and tested. Therefore mathematical modelling will be used sparingly, and only when it is considerably better than simulation in solving a particular problem.

2.2.3 Simulation software

It was decided to use the Anylogic 7.3 Personal Learning Edition to design the simulation models. This is because of the broad nature of AnyLogic's capabilities, along with the author's familiarity with the program. AnyLogic has been used to present many other simulation papers, and a quick browsing of the Winter Conference papers will easily show this. AnyLogic provides both the graphical interface and technical code-heavy functionality to allow for complex agent-based models to be developed. The 3D presentation suite in AnyLogic is also sufficient for the needs of the project.

Given the above, AnyLogic meets the requirements for the software, and suits the needs of the report.

2.3 Summary of Literature

In the above review, we can see that there are a number of design steps that need to be taken in order to develop a warehouse model. Some of those steps occur simultaneously, and it is likely that several iterations of these are required in order to balance the considerations of each.

The main questions fall into two main categories: How do we design the floor layout, and how do we arrange products within that layout. These overarching ideas then provide a structure for which all other questions of equipment, timing, capacity, and utilisation can be organised and answered.

The next step is to begin to arrange the most important principles and primary ideas together to develop an initial design, which can the be critiqued and improved upon iteratively throughout the report.

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Chapter 3

Warehouse Design

3.1 Overarching Design Considerations

The design of a warehouse is a mixture of science and art. Whilst there are several guidelines for the creation of efficient warehouses and storage, the amount of variety in warehousing design decisions make it difficult to apply strict principles to every situation. Thus, instead of using a well-defined formulation for the design, we shall set several qualitative goals for the warehouse, which each iteration of the design must conform to. These goals include:

Flexibility ensuring that multiple types of SKUs can be handled by the warehouse, an important characteristic for a new and growing company

Efficient movement of SKUs, personnel and material handling equipment able to respond to incoming orders quickly and accurately

Recirculation loops to allow for easy solution to errors or misreads when picking orders

Employee empowerment ensuring that sufficient training and interaction with employees occurs to motivate and include employees

3.2 Overarching Design Decisions

The design of a warehouse consists of five major decisions, according to Gu et al. [6]. These can be further broken down into a set of questions that need to be answered by fitting the framework proposed by Hassan [7] to the framework, thereby expanding the level of detail and providing a strengthened guideline for the inexperienced designer. The following sections are a summary of the decisions made in each of the steps, where the decision was based on logical thinking and then validated by the company. It should be noted that to keep this section concise, not every option is described in detail, although all considered options are mentioned.

3.2.1 Overall Warehouse Structure

Warehouse Functions The main role of the warehouse is primarily storage of beers imported from African countries to be distributed by ABI to restaurants such as ABE. However, the business owners believe that the space should also be used for several other support functions for their companies. In order to achieve this, the warehouse is divided

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into several functional departments. The main department will be the storage of imported beers, and will be divided into the following sub-departments:

1. Shipping/receiving area
2. Staging area
3. Long-term storage area
4. Micro-brewery space allocation
5. Mobile brewery space allocation

The first three functional areas are within the scope of the project, and will be described in detail. The last two departments are space allocations for future developments and will be considered as black boxes during the initial warehouse design.

The first step is to determine some of the key attributes that the warehouse should have. This helps to guide the decisions made in later steps. This warehouse will be classified as a finished goods field warehouse [15], handling only the final beer products delivered from manufacturing sources. As the company is not currently manufacturing any beer, nor is the warehouse shared with other companies, it is neither a manufacturing nor public warehouse. The main objective of the warehouse is consolidate a variety of different beers into a single storage space, and then to ship orders in reasonable batch sizes to the restaurant and other clients. Whilst providing beer to African Beer Emporium is the main objective of the warehouse, it is expected to expand and to serve customers in other provinces of South Africa by the end of the year, thereby fulfilling its goals as a distributor.

Functional Departments There are several functional departments in the warehouse. Firstly, we have the loading area. Here is where the truck pulls into the warehouse and the goods are either loaded or offloaded. The loading area will serve the functions of both receiving and shipping. This is a necessary constraint, given that there is a single door to the warehouse. The loading area will extend slightly into the warehouse to prevent rain damage during loading and also to allow for additional tools to be installed, such as a loading platform. However, this area will need to be kept as small as possible to ensure maximum utilisation of space.

We then have the main storage department. This will house the majority of the incoming beer, and will act as the standard long-term storage (where long-term implies the foreseeable future until an order determines otherwise). The received shipments will be delivered straight to their respective zones within the storage area. The main storage department will be able to house several different SKUs, including cases of cans, cases of bottles, and kegs.

Finally, we have a certain allocation of empty space. ABI and the owners require space to expand some of their unrelated operations (such as brewing, mobile sales, etc), and so a certain area will be deemed unusable in terms of future expansion.

3.2.2 Sizing and Dimensioning

In a general sense, sizing has huge implications on the costs of a warehouse, from initial costs during construction through to inventory- and material handling. In the case of ABI, the warehouse was selected before the start of the project. This is because the owners of ABI would prefer to have the warehouse dictate the order quantities of the inventory, rather than the traditional method. The scope of the inventory, both in terms of scale

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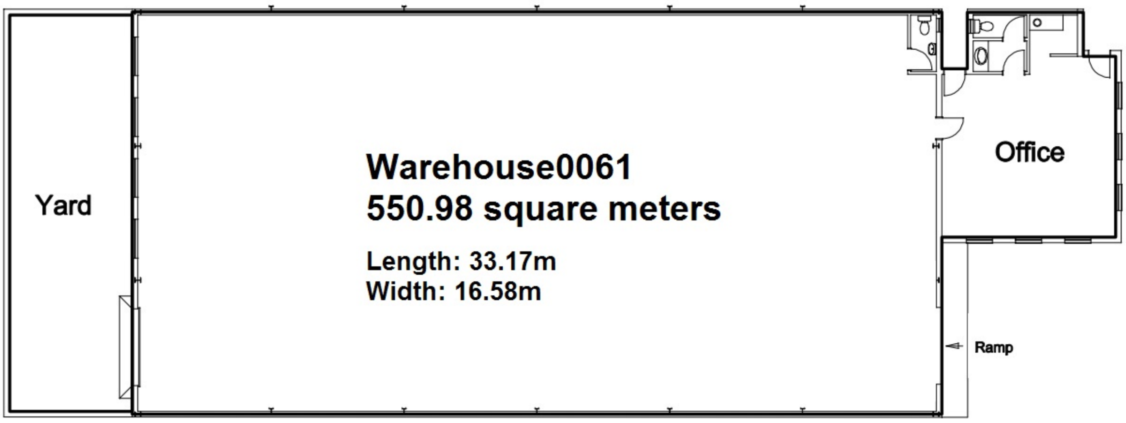

Figure 3.1: Basic aerial view of warehouse, as supplied by ABE

and variety, have not been fully developed yet and the limitations of the warehouse will act as a constraint for this.

In contrast to the flexible size warehouses discussed by Lowe et al. and Hung & Fisk, the ABI warehouse has already been selected, and its sized is assumed fixed. Figure 3.1 shows the floor plan for the warehouse, as supplied to ABE by the warehouse owners. Figure 3.2 shows the location of the warehouse, which is in Silver Lakes, Pretoria.

3.3 Development of Metrics

3.3.1 SCOR Metrics

Supply Chain Operations Reference (SCOR) is a set of metrics developed by the Supply Chain Council to measure certain lines of performance in supply chains. SCOR metrics were considered for the design phase of the warehouse. However, after an analysis on Leproi et al. [9] and on Bolstorff and Rosenbaum [3], it becomes apparent that the metrics are not particularly suitable for the initial design of the warehouse. The SCOR metrics tend to focus on monetary values, or throughput based on customer demands, neither of which ABI have a firm grasp of as yet. As such, SCOR may be used in the future to determine and improve the operations of the warehouse, but will be excluded for the design.

3.3.2 Additional Metrics

The following metrics were developed specifically for the model. They represent criteria that the company will find particularly useful and interesting, based on discussions with the project owners. The metrics are either directly important (ie, total number of storage slots) or indirectly important based on another factor that they influence (ie, total travel distance, which influences costs of material handling).

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Figure 3.2: Basic map view of warehouse, as supplied by Google Maps, 2016

Number of Storage Slots (SS) is a straightforward metric measuring the number of available storage slots in the current design. This metric follows a "the higher the better" standard. The number of storage slots can then be used to calculate concepts such as space utilisation, but is unnecessary here as the same shelving and the same floor space is used for each design.

Average Machine Travel Distance (AMTD) is a measurement of the distance travelled by a single piece of material handling equipment over a certain time period, divided by the number of storage slots visited.

$$\frac{Distance\ travelled\ per\ time\ period\ [m]}{Number\ of\ slots\ visited}$$

This metric follows a "the lower the better" standard.

Number of Orders Processed simply quantifies how many orders could be fulfilled in the given amount of time. Since each of the models will be subjected to the same orders for each seeded run, the model which can fulfil the most orders will be objectively better. This metric follows a "the higher the better" standard.

Machine Utilisation measures the percentage of working hours where the material handling equipment is being used.

$$\frac{Hours\ in\ use}{Total\ available\ working\ hours}$$

This metric follows a "the lower the better" standard, with a range of $[0; 1]$.

Rack Utilisation measures the average usage of the rack system over the time of the model. In other words, it how full the model is at every point in time, averaged over the entire runtime of the model.

Table 3.1: Summary of Metrics.

Metric	Name	Objective
SS	Number of Storage Slots	MAX
AMTD	Average Machine Travel Distance	MIN
OP	Number of Orders Processed	MAX
MU	Machine Utilisation	MIN
RU	Rack Utilisation	MAX
TTH	Total Time Handled	MIN
MQL	Maximum Queue Length	MIN
MO	Maximum Overflow	MIN

$$\frac{\sum Percentage\ of\ slots\ filled}{Time}$$

This metric follows a "the higher the better" standard, with a range of $[0; 1]$.

Total Time Handled measures the amount of time that is experienced by a pallet for any and all material handling operations. This will include any time spent moving, as well as any time spent in temporary storage positions, such as waiting in the loading area to be stored. This metric follows a "the lower the better" standard.

Maximum Queue Length refers to the length of the queue of pallets waiting to be stored. These are pallets that are in the loading area, but have not yet been transferred to the storage racks yet. The length of this queue is determined by the speed at which the forklifts can store the pallets that are ready.

Maximum Overflow Size refers to the number of pallets which have been delivered to restock the inventory, but there is currently no space available in their section. These pallets then move into an area without any organisation, where they will wait for a slot in their section to open up. The metric will measure what is the largest size that this overflow area will need to be, given the maximum number of pallets that are in the overflow area.

Table 3.1 provides a quick summary of the above-stated metrics.

3.4 Development of Scenarios

The problem of designing a warehouse is multi-dimensional, given the number of inter-related decisions that are made. As such, several different scenarios will be tested, in order to try and measure the individual effect of each. The results from each scenario will then be compared in order to select the champion combination of decisions.

Facility Layout Three layouts will be tested here. These are the deep vertical aisle model (known as Flat), the Mixed-Orthogonal model (known as Leaf)and finally, the diagonal aisle model (known as Chevron). Figure 3.3 indicates the Flat aisle layout, whilst Figure 3.4 shows the Leaf aisle layout, and finally Figure 3.5 shows the concept of having a Chevron design with diagonal aisles.

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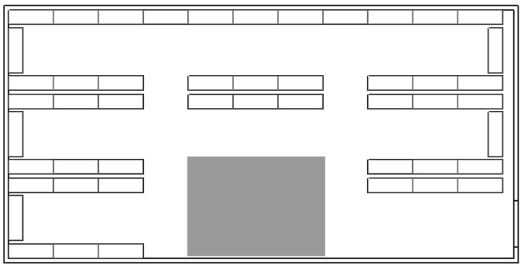

Figure 3.3: Flat Floor Layout

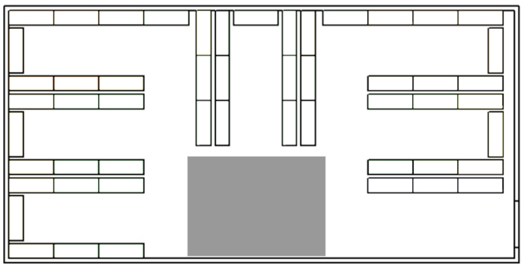

Figure 3.4: Leaf Floor Layout

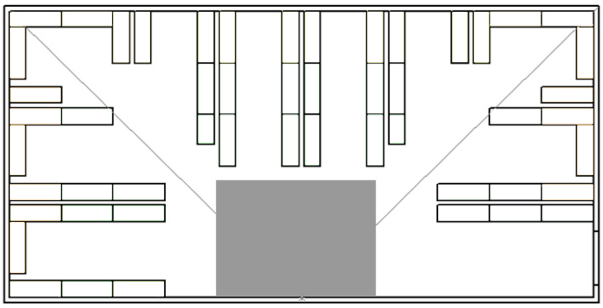

Figure 3.5: Chevron Floor Layout

Storage Policy Three storage policies will be evaluated in the model. These are the Random-based storage (in practise, first-available slot storage), 2-Class storage, and 3-Class storage. The storage policies have already been discussed in detail in the Literature Review section, Storage Policies.

Scenarios As such, the 9 scenarios presented in Table 3.2 will be tested according the given criteria in the initial modelling phase. The results will be captured and presented to the company for feedback, in order to determine the weighting of each of the metrics, which will be used to guide the remainder of the project.

Table 3.2: Summary of scenarios specific scenario numbers.

Facility layout	**Storage policy**		
	Random	2-Class	3-Class
Flat	1	2	3
Leaf	4	5	6
Chevron	7	8	9

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Chapter 4

Preliminary Simulation Experiment

4.1 Single-Dimension Model

Before building the final model, a preliminary scale model was designed and created. The model would serve three purposes:

1. To ensure that the warehouse could be modelled to reasonably match the real world.

2. To ensure that a model could produce results which mirror those found in literature.

3. To identify and address any unexpected issues with logic before committing to build the final models.

This scale model is useful in providing a simplistic platform for explaining the core concepts of the models' designs. The model is broken down into two sections: Receiving & Storage, and then Orders & Retrieval.

Figure 4.1 shows a snapshot from the model, indicating the various storage racks according to their stock, the overflow area on the far right, and the loading area labelled as "Waiting for Storage".

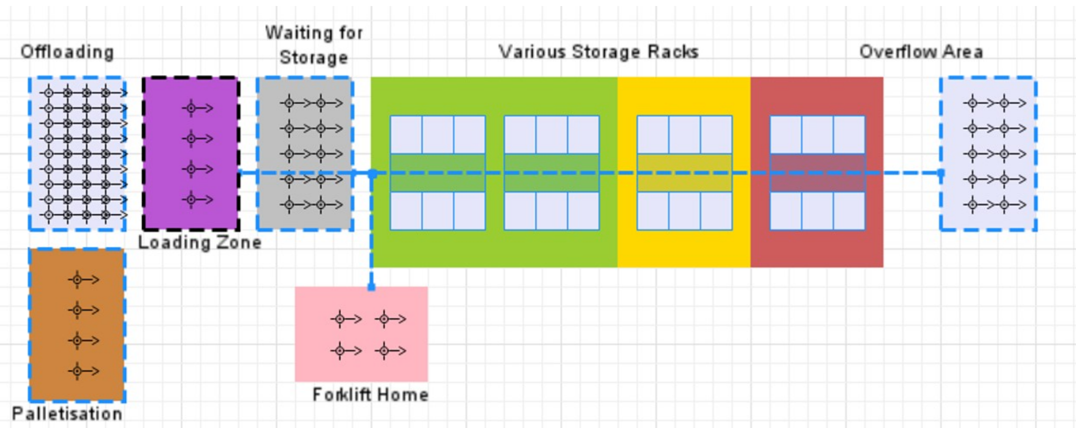

Figure 4.1: One dimensional Floor Layout

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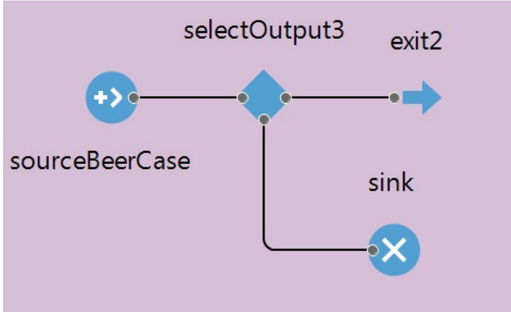

Figure 4.2: Beer creation logic

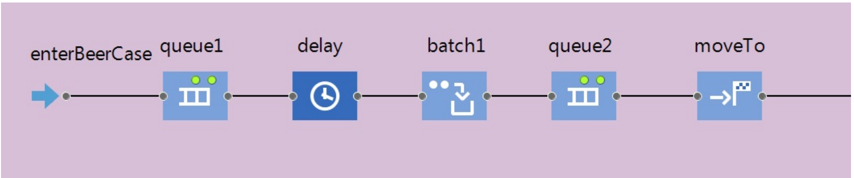

Figure 4.3: Beer batching

4.1.1 Receiving & Storage

There are four main steps to this portion of the model:

1. Beers are created

   A source creates individual cases of beer and assigns them characteristics which represents the spread of the various brands and types of beer. The selectOutput component is a simplified mechanism which represents the concept of "good management", where it checks to see whether there is space in the warehouse to house a new shipment of stock, and removes the request for new stock if there is not. The exit component simply ends the current line of logic. This is represented in Figure 4.2.

2. Beers arrive and are batched.

   Individual beer cases are then sorted according to brand, and are batched together to represent palletisation. Palletisation is done by hand, and only the stocked pallets are handled by the forklifts. This is represented in Figure 4.3.

3. Beers are assigned a position.

   If there is an open position on the racks for the pallet, then the position and the pallet are paired. If there is not space for the pallet, it is assigned to the overflow area, where it will wait until a position becomes available. This is represented in Figure 4.4.

4. Beers are stored.

   The pallets call for a forklift to store them at their respective positions on the correct rack. The forklift then returns to the waiting area. This is represented in Figure 4.5.

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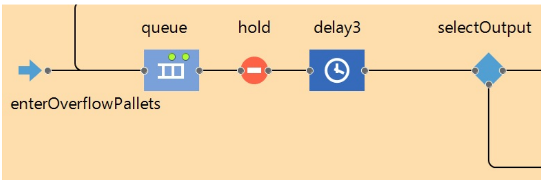

Figure 4.4: Beer position assignment

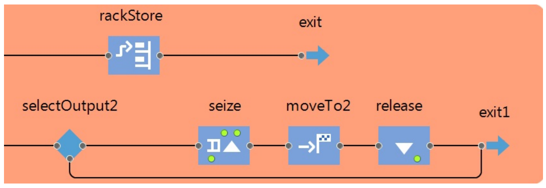

Figure 4.5: Beer storage

4.1.2 Orders & Retrieval

There are four main steps to this portion of the model as well:

1. Orders for beer are received

   Orders are created using pseudo-random sources, which creates orders for fast-moving beers more often than for slow-moving beers. The delay component ensures that only one order is processed at a time. This is important because the variables which update the available stock are only updated once the order has been fully processed. If multiple orders are allowed to be processed simultaneously, two different orders might reserve the same pallet of beer and cause the model to crash. This is represented in Figure 4.6.

2. Orders check stock availability

   The order then checks whether there is enough stock of the required brand to fulfil the order completely. If the order cannot be filled, it is sunk immediately. Initially, the unfilled orders were allowed to recirculate back into the logic, and could be fulfilled at a later stage, but that unfortunately disrupts the balance of fast-moving to slow-moving beers and clogs the system with orders.

3. Matching beer pallets are retrieved

   If there is stock to fulfil an order, then agents called splitOrders are created. There is one splitOrder for each pallet of beer that is requested. The splitOrder then finds the oldest of the requested beer, and calls the forklift to retrieve that pallet from the shelf and bring it to the loading area. This is represented in Figure 4.7.

4. Orders and beers combine and are shipped out.

   Once in the loading area, the pallet is sunk to represent collection of the placed order. The order is also sunk (in a different sink to the unfulfilled orders) to represent its fulfilment.

4.1.3 Control Parameters

In the context of the models, control parameter refers to a value which must be decided upon and kept constant in all scenarios, but do not have a fixed or set value. For example, the number of forklifts used in the model is considered a control parameter, but the forklift speed is not (since it can be determined from specifications). Determination of the control parameters was primarily performed using trial and error methods, where the resultant value simply appeared to best facilitate the running of the model. It should be pointed out that the actual values of these parameters are less important than their consistency throughout every model. This means that even if one of the parameters is not entirely in line with the real-world version, the same 'handicap' is experienced by every model. The

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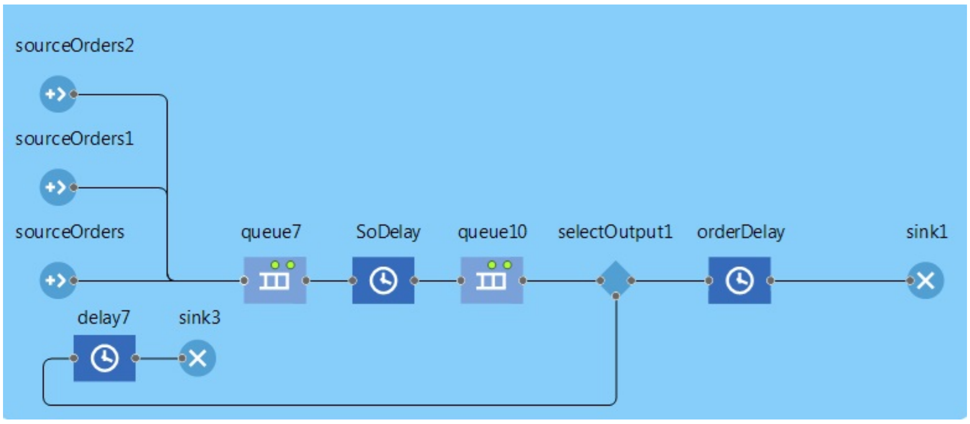

Figure 4.6: Beer batching

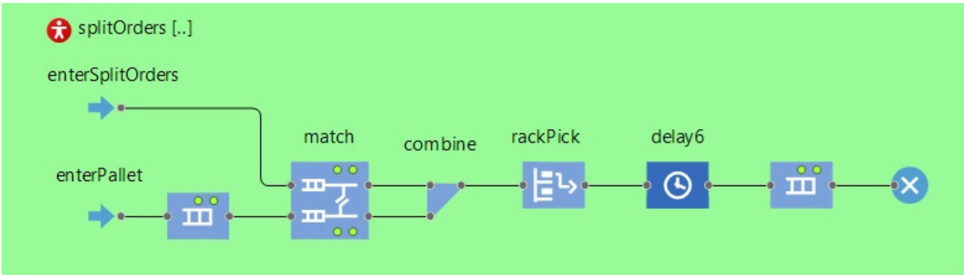

Figure 4.7: Beer batching

values of the model were selected to ensure that each storage policy model was strained, but did not break.

1. Minimum and maximum values for BeerCase arrival

   Min: 100, Max: 200, Distribution: Uniform.

   These values determine the size of each restocking event. The ordering of stock is considered stochastic, as a deterministic arrival schedule is an unnecessary level of detail for this model, especially given the number of runs and scenarios faced. A uniform distribution was chosen over a normal distribution because a uniform distribution better represents the yearly restock distribution. The actual distribution is seasonal (considerably more beer is sold in summer), and a uniform distribution is the simplest representation of the annual demand for the beers. Figure 4.8 shows the results of the various runs.

2. Number of forklifts: 4

   The number of forklifts was chosen in order to best facilitate the working of the model. This was determined by comparing the number of forklifts against two measures: the maximum size of the queue which holds pallets waiting to be stored, and the overall forklift utilisation including start up. At four forklifts, the maximum queue length becomes a realistic quantity for all storage policies, and forklift utilisation drops to just under 90%, indicating that the forklifts are in use for the majority of the time without being overworked.

3. Known issues

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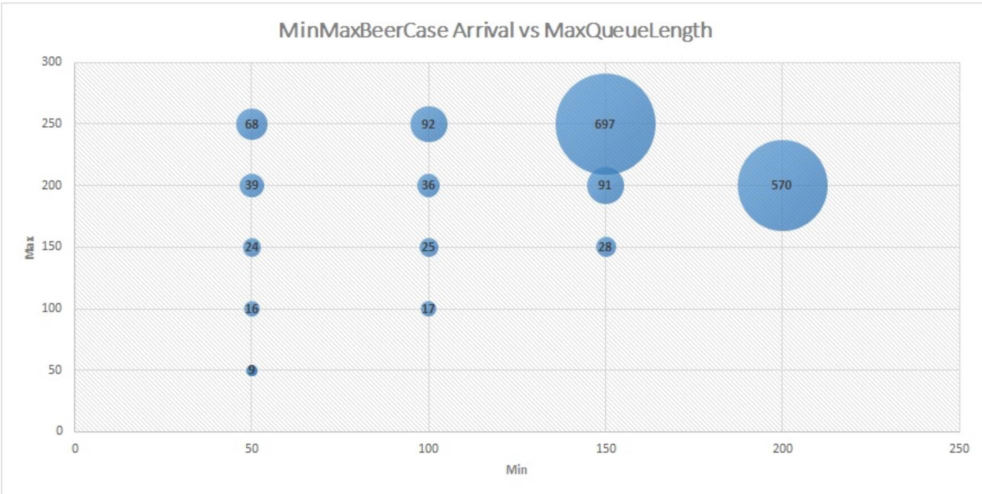

Figure 4.8: Beer Arrival Parameters against Maximum Queue Length Experienced

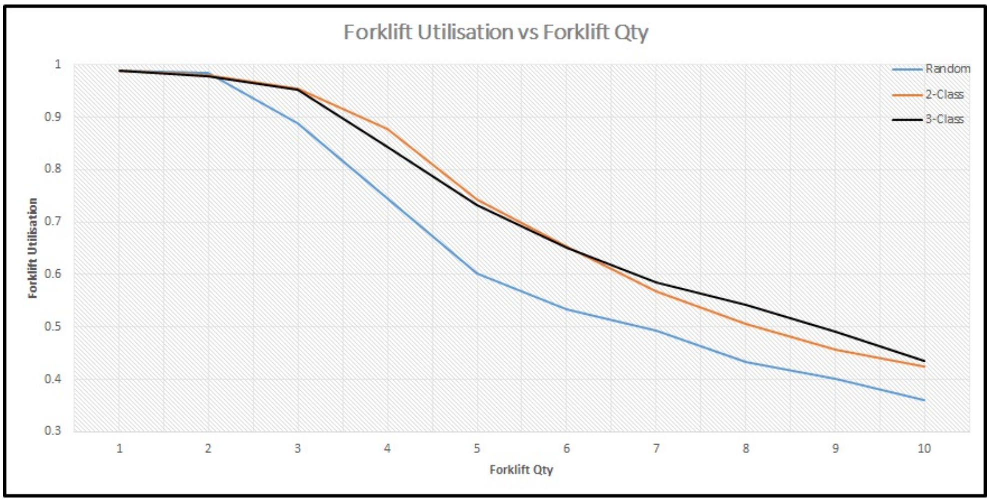

Figure 4.9: Number of Forklifts vs Forklift Utilisation

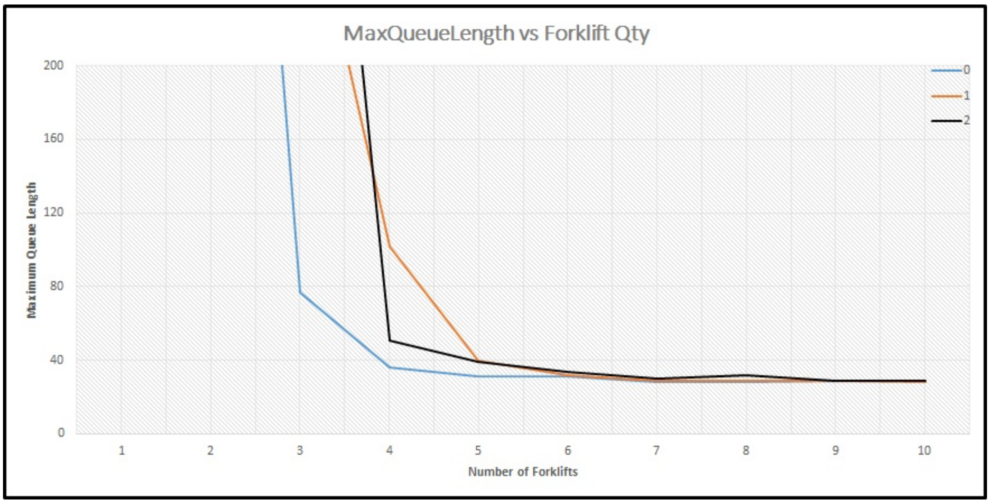

Figure 4.10: Number of Forklifts vs Maximum Queue Length

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Not every one of the parameters (control or otherwise) are entirely reflective of the actual happenings within a real warehouse. There are several parameters which seem problematic on first inspection. These issues include the pseudo-random arrival rate (rather than the pre-planned and reactive rates), the quantities and distribution of the different beer brands (and therefore the exact spread of the classes), and the number of beer cases per pallet (and whether this changes between beers). However, these issues do not have a large effect on the model (which is comparative rather than absolute). As long as these parameters remain constant throughout the various experiments, the results should hold true, as each scenario will experience the same 'flaws'.

Single-Dimension Validation Each of the three storage policies was given 30 runs to collect results. These results were captured in an excel spreadsheet, where simple statistical analysis was performed. It is important to note that the pallets, as an agent, had the following states:

1. Waiting for Storage

   The time spent waiting to be stored on the shelf. This time begins once the beer is palletised and waiting in the loading area, and stops as soon as the forklift picks the pallet up.

2. On Shelf

   The time spent stored on the shelf, when no order has called for the pallet yet.

3. Waiting for Picking

   The time spent waiting for a pallet to pick it up from the shelf. This time begins when an order calls for that specific pallet, and ends once the pallet has been picked up off the shelf by the forklift.

4. Moving

   This is the amount of time that the pallet spends moving, or being handled by the forklift. This state was divided into two components, based on the destination of the moving pallet.

Table 4.1 shows the average time spent in each state by a single pallet. It also notes the maximum length of queue of pallets waiting to be stored, as well as the utilisation of the four forklifts.

Table 4.2 shows the results for the same criteria as Table 4.1, but splits the results to show the difference in values between the Fast and Medium Movers, whilst showing the average values for the entire model as well.

Table 4.3 does the same as Table 4.2, but with all three classes.

Table 4.4 is a summary of the average amount of time taken to fulfil a single order from each one of the storage policies. This is further broken down into the time per order for the various classes where applicable.

4.1.4 Interpretation of Pallet Results

The results for the average pallet times across the board seem to be acceptable, with a minimal amount of outliers in the data. The 'Fast' class tends to move considerably more

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Table 4.1: Average Time per Pallet for Random Storage Policy

Average time per Pallet	**Random Time [seconds]**
Wait for Storage	31.33
Moving to Storage	1.24
On Shelf	34.10
Waiting for Picking	2.09
Moving from Picking	2.11
Max Queue Length	38.6 pallets
Forklift Utilisation	70.89%

Table 4.2: Average Time per Pallet for 2-Class Storage Policy

Average time per Pallet	**2-Class**		
	All	Fast	Medium
Wait for Store	40.96	41.04	40.84
Moving to Store	1.48	1.00	2.33
On Shelf	34.19	24.21	51.85
Waiting for Pick	2.70	2.24	3.50
Moving from Pick	2.33	1.87	3.15
Max Queue Length	50.63 pallets		
Forklift Utilisation	78.46%		

quickly than the 'Medium' and 'Slow' classes, and this effect is only dampened by the closeness of the various pallet racks in the model (i.e. if one were to place the 'Slow' rack considerably further from the 'Fast' rack than it already is, the difference in results would be amplified).

The only anomaly that is present in the Pallet data is that the average time waiting for picking (i.e. the time between the placement of the order and the collection of the pallet) is best overall in the Random storage policy. This means that whilst the Random policy may not help any particular pallet reach the I/O point faster, there is a faster throughput for all of the warehouse stock. This may be caused by the degree to which the pallet racks are filled. In general, the pallet racks appear spend the majority of the time half-filled, and then ebb and flow between 1/4 and 3/4 full, depending on the timing of pallets received and orders. Because the racks are stacked in a pseudo-random manner, the portion of shelves closest to the I/O point are always full, with those furthest rarely full. When compared to the class-based storage systems, medium- and slow-movers are always stored some distance away from the I/O, and will always take slightly longer to store and to pick. For future runs, it would be valuable to put the model under more stress and to try to keep the entire rack system full for as much of the time as possible, and to see whether this has an effect on the results.

Interpretation of Order Results The results obtained from the average time per order measure the amount of time taken for the warehouse to locate, pick, and place the

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Table 4.3: Average Time per Pallet for 3-Class Storage Policy

Average time per Pallet	**3-Class**			
	All	Fast	Medium	Slow
Wait for Store	40.05	40.09	40.01	39.79
Moving to Store	1.49	1.01	2.27	2.94
On Shelf	34.62	24.38	36.07	187.97
Waiting for Pick	2.69	2.25	3.35	4.42
Moving from Pick	2.33	1.87	3.07	3.80
Max Queue Length	46.63 pallets			
Forklift Utilisation	78.97%			

Table 4.4: Average Time per Order for all Storage Policies

Average time per Order	**Storage Policy**		
	Random	2-Class	3-Class
Total	1.687	1.914	1.925
Fast	-	1.598	1.589
Med	-	2.471	2.464
Slow	-	-	2.929

desired amount of pallets in the shipping area. This timer only begins once the order has begun processing (i.e. once it has been confirmed that the requirements for the order to be fulfilled can be met by the warehouse in it's current state). The actual values of the times were troublesome, as they seemed to suggest that an order of 3-5 pallets can be fully processed in a manner of seconds. However, the ratios between the various storage policies conform to expectations and follow a similar trend to those in the Pallets results, such that the 'Fast' orders tend to be resolved much more quickly than the 'Slow' orders. Again the anomaly of the Random class comes into play when the racks are typically filled halfway to capacity, where the overall average time per order is lower than the average time per order of class-based storage. Once again, this will be linked the nature of class-based storage, which places 'Slow' movers at a considerable distance away from the I/O point.

Model Validation Having considered the above results, it is fair to say that the model conforms to expectation, and can be extended to test the aisle layouts following a couple of small fixes. The order measurements needed to be checked to ensure that the order time is better related to expected real-time values, and the racks remain at a higher filled rate for the duration of the experiment, in order to reduce the biases towards the Random model. These were considered and adjusted before creation of the final model.

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Chapter 5

Full-Scale Model

5.1 Equipment Selected

Just as the scale model required the selection of control parameters, the full-scale model requires the selection of equipment so that the final designs are consistent with real-world principles, limitations and regulations. The model is built in such a way that the final design can be implemented as is, without the need to redesign and reconfigure ideas to fit reality.

5.1.1 Pallets

The selection of pallets is the first step to the final design, as every other design consideration is affected by this. Two specialist companies were consulted to determine the size of the pallets required, and both companies gave the same answer: It depends. The weight of the pallet was estimated using an extremely simple calculation:

$$24\ beers \times \frac{350\ g}{beer} = \frac{8.4\ kg}{case}$$

$$\frac{8.4\ kg}{case} \times \frac{12\ cases}{level} = \frac{100.8\ kg}{level}$$

$$\frac{100.8\ kg}{level} \times 7\ levels = \frac{705.6\ kg}{pallet}\ excluding\ the\ negligible\ weight\ of\ the\ pallet$$

As such, a warehousing catalogue was consulted, and a liquor distribution centre was visited, and both recommended the same pallet; hence the final selection.

The final pallet will be a 1200 x 1000mm pallet, with fork entry at 1200. The pallet can be either wooden or plastic, as the pallet will not being crossing international borders (all pallets will be sourced by ABE, as beers arrive un-palleted). The pallets should have a perimeter bottom, as well as stringers to ensure that the pallet is strong enough to hold the loads required.

5.1.2 Forklifts

The selecting of the forklift is very important in this model, as the forklift would need to meet the requirements of handling the beers in this warehouse, but would also dictate the required aisle widths. Two companies were consulted in the selection process, and both provided different and valuable advice. It was decided to choose a reach truck over a forklift, based on the extended height requirements and on the dimensions of the forklifts

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Figure 5.1: Toyota 9BRU18 Reach Truck [Toy]

and reach trucks. The reach truck is considerably smaller, with smaller minimum aisle requirements but extended lifting heights. The actual model chosen is the Toyota 9BRU18, which has a load capacity of 1580kg and a maximum speed of 10.5km/h. This model is electric, and a maximum fork height of 4902mm. The minimum aisle width for this reach truck, with the above pallets in use, is 2384mm. 305mm of clearance is recommended for easy manoeuvring, and each of the layouts has aisles which meet this requirement.

5.1.3 Racks

The selection of racks comes from a single warehouse catalogue, where the racks used there are also used in the liquor distribution centre and certain mass retailers. The racks meet the requirements of the pallet loads, and are delivered in ready-to-assemble packs. The choice of a commercial set of racks over a hand-made set of racks is based on many considerations, including ease of assembly, minimal calculation required, fair cost, accountability of manufacturer, and pre-designed structures.

The warehouse will use Linvar Pallet Racking. The warehouse will be made up of a combination of single-deep and double-deep bays, each of which are 3658mm tall. The two beams for each level will be either 1524mm for single racks or 2743mm for double racks, each of which can hold the weights of the pallets easily. There will be three levels per bay (made up of all positions between frames), with a maximum of 6 loaded pallets per bay. Each bay can support a maximum load of 8000kg, which is well below the expected weight of a fully loaded bay. Sundry components such as frame spacers, wedge anchors, spring locks, and levelling plates should be purchased as per recommendation of the racking retailer.

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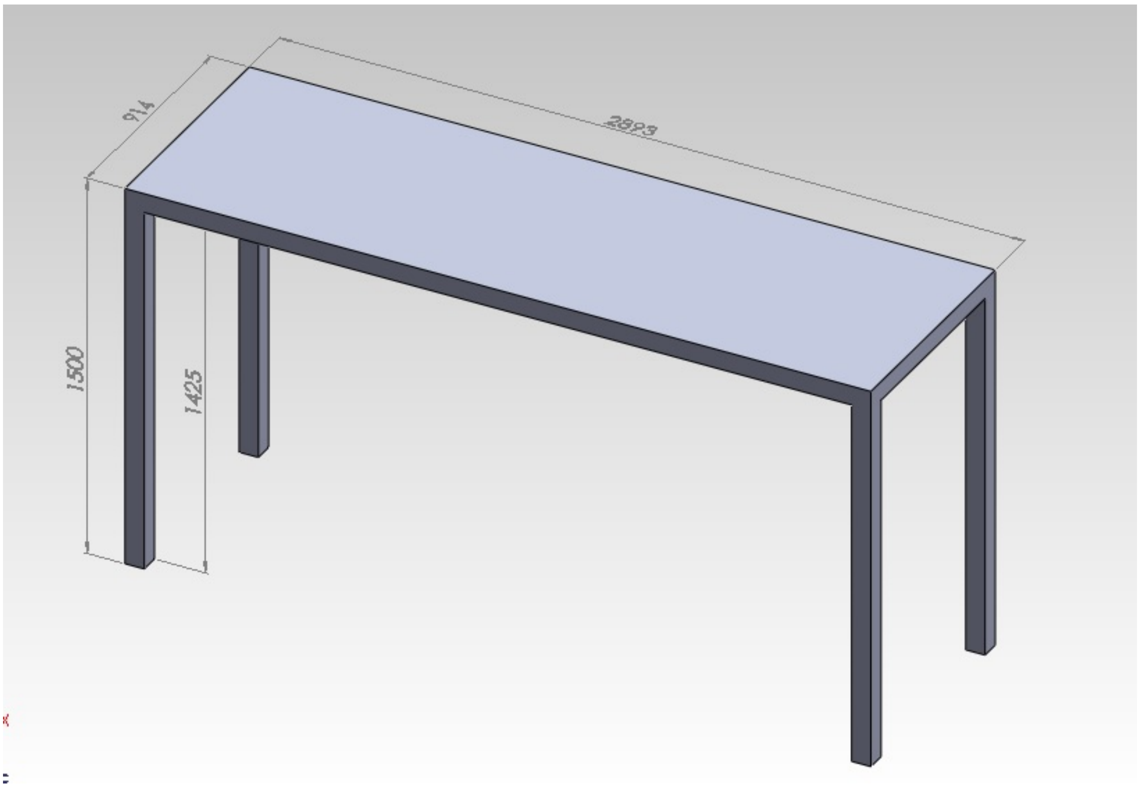

Figure 5.2: Design of Storage Rack, according to specifications of selected rack, which will be stacked two-racks high to allow for three levels of shelf space

5.2 Floor Layouts

Three floor layouts were selected during the literature study and the principles of each were used to design the actual floor layouts in the warehouse. Some adaptation of the principles were required, as the small rectangular shape of the ABI warehouse is not extensively covered in the literature. The final layouts can be found directly below, where the small white blocks represent the storage racks, the large grey block represents the loading area, and the entrance to the warehouse is in the bottom right corner.

5.2.1 Flat Aisle Layout

The Flat Aisle Layout refers to the single, horizontal direction of all of the aisles. This layout has typically been used in large warehouses, and suits the usual rectangular shape of most warehouses quite well, as the shelves line up well with the walls. This traditional layout will serve as the benchmark layout, as it is simplest to apply and most commonly used. This is represented in Figure 5.3.

5.2.2 Leaf Aisle Layout

The Leaf Aisle Layout is similar to the Flat Aisle Layout in its boundary aisles, but differs in upper centre of the warehouse, where the aisles have been rotated 90 degrees. This rotation allows for quicker access to the aisles from the pallet handling area, as the forklift can move more directly to the end aisles than can be achieved in the Flat Aisle Layout. This is represented in Figure 5.4.

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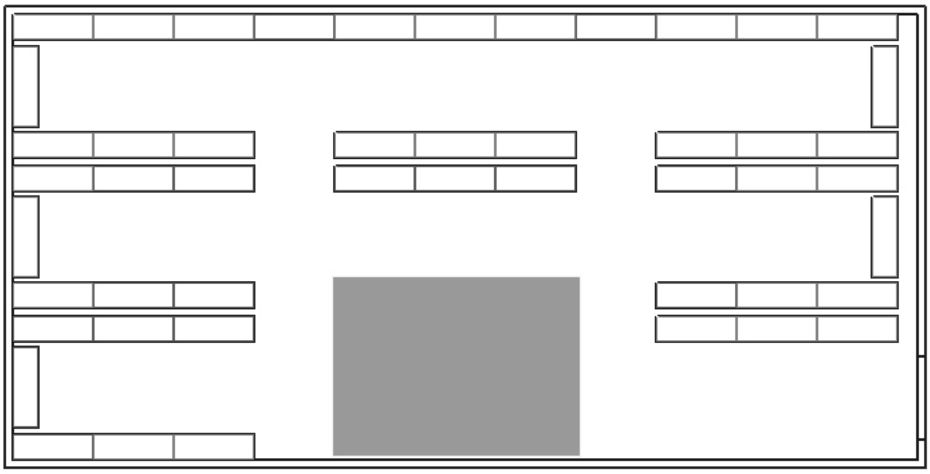

Figure 5.3: Flat Aisle Floor Layout final design

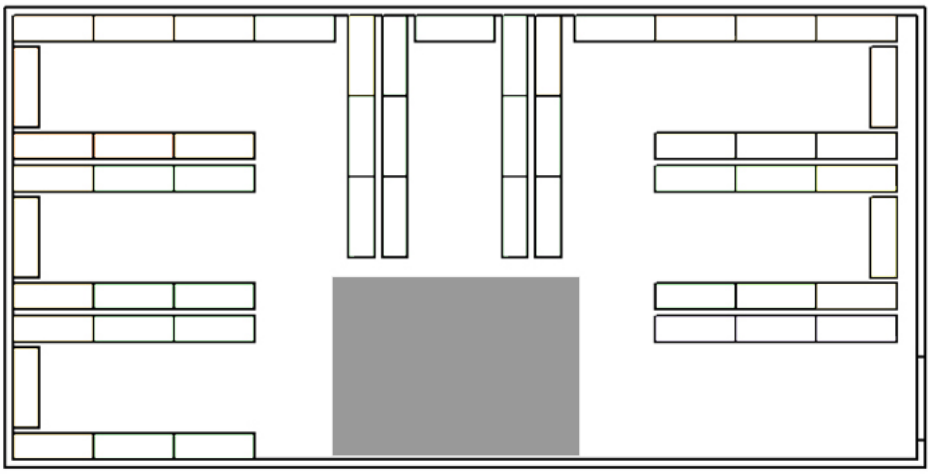

Figure 5.4: Leaf Aisle Floor Layout final design

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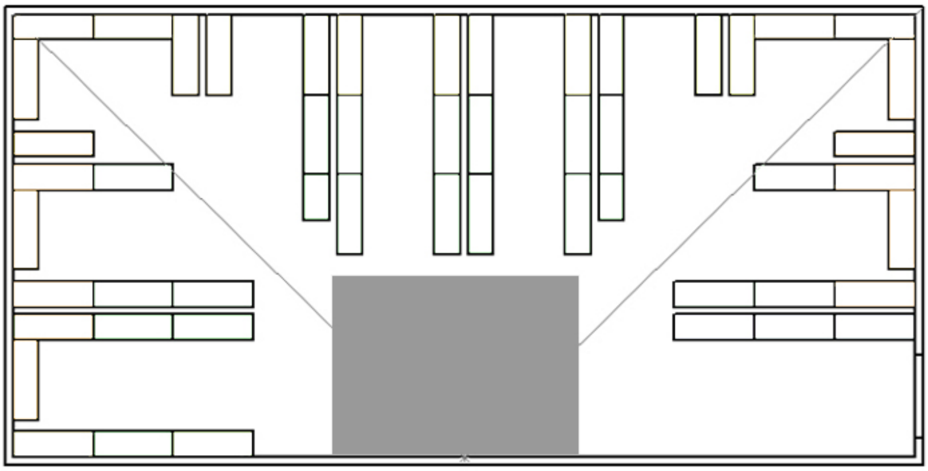

Figure 5.5: Chevron Aisle Floor Layout final design

5.2.3 Chevron Aisle Layout

The Chevron Aisle Layout is the most complex of the layouts, as it adds diagonal movement to the rectilinear movement that was available in the previous layouts. The diagonal aisles are there so as to minimise the distance travelled by the forklift to reach any given spot, and to bring the forklift's path of motion as close to the Euclidean (as the crow flies) distance as possible. This is represented in Figure 5.5.

5.2.4 Comparison of Layouts

Table 5.1: Comparison of the three different floor layouts

Property	**Floor Layout**			
	Unit	Flat	Leaf	Chevron
Number of Positions		276	300	288
Minimum Aisle Width	mm	2893	3314	2615
Size of Offloading Area	m^2	139.54	105.61	110.99

5.3 Storage Policies

The three storage policies chosen for testing in the final model were the Random, 2-Class, and 3-Class Based Storage policies. These were chosen for the ease of which to implement the various storage policies. Given the small nature of the warehouse, the low likelihood of having a complex warehouse management system, and the sheer difficulty involved in tracking more rigorous storage methods, these three provided an adequate spread of policies.

The model does work off of the assumption of perfect knowledge of storage. This means that when an order for a certain beer comes in, the system will identify the beer required and send a forklift to the oldest pallet containing that beer. The system will not make

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mistakes in selecting pallets, nor will it expedite any pallets before they are due, nor will it send the forklift to the wrong location.

5.3.1 Random Based Storage

It is important to note that this is a pseudo-random layout and not random in the conventional programming sense. In this policy, the beers are stored in the first available slot, regardless of their type. This means that an overview of the filled warehouse would not have any particular pattern to it, according to beer types, hence the name. It should be noted that this system will, by the nature of the model, be more effective in the model's world than in reality. This is because of the assumption of perfect knowledge of storage in the model; in reality, the ability to keep track of stock sorted by date is a fairly challenging one. However, the concept is not completely fictitious, as a small warehouse may be able to overcome this issue through a talented workforce who are diligent in their tracking of beer pallets and their placements.

5.3.2 2-Class Based Storage

In this policy, beers are sorted and placed according the the amount of time they are expected to spend on the shelf. Beers which are typically ordered and restocked frequently will have a smaller turnaround time, will spend less time on shelf, and will be classified as Fast Movers. Beers which are typically ordered and restocked infrequently will spend more time on the shelf, will be ordered less often, and will be classified as Slow Movers. The idea behind the 2-Class Based Storage is to place the Fast Movers closer to the I/O point, where they can be accessed more quickly and with less travel distance for the forklifts than the Slow Movers, who will be placed further away. Since the forklifts will interact with the Slow Movers less often, they will be travelling the longest distances least frequently.

5.3.3 3-Class Based Storage

This policy furthers the principle of class-based storage by adding a third grouping of beers, with a turnaround time in between the Fast- and Slow Movers. The 3-Class Based Storage adds Medium Movers, and uses the shelf positions that are neither nearest to the I/O point, nor furthest from it.

Class-based storage could have any number of classes in it, up to the point where each beer would be considered to have a class of it's own. This is known as Full Turnover-based storage. However, the implementation of such a policy is incredibly difficult, not only to keep track of the positioning and quantities of beers currently in the warehouse, but also from a design perspective, as the correct number of slots must be assigned to each beer type to avoid wasting space or having a large overflow section. Full Turnover-based Storage is theoretically the most efficient version of class-based storage, but is best suited to warehouses which have an incredibly consistent and predictable inventory. Any variation requires a redesign and reallocation of slots, and so this policy is nonsensical for both the size of ABE and for the nature of their order and restocking policies (both of which are not yet mature and are still highly variable).

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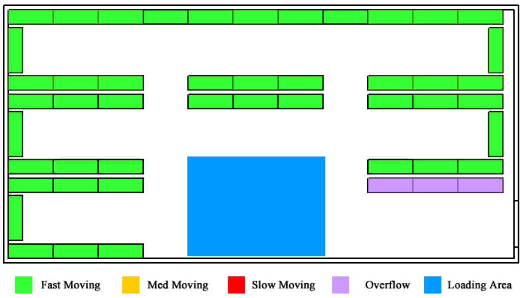

Figure 5.6: Flat with Random

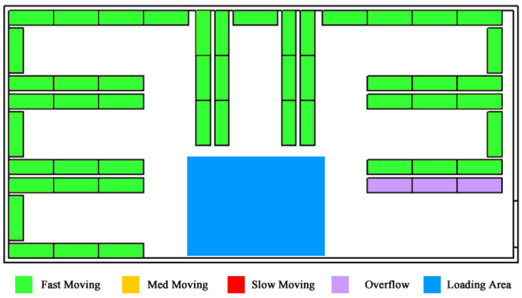

Figure 5.7: Leaf with Random

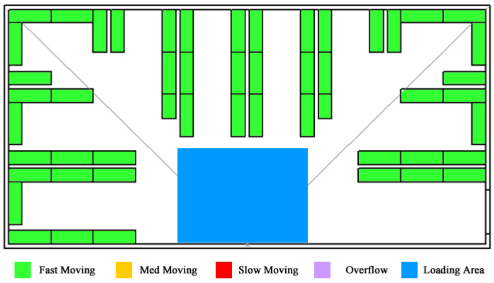

Figure 5.8: Chevron with Random

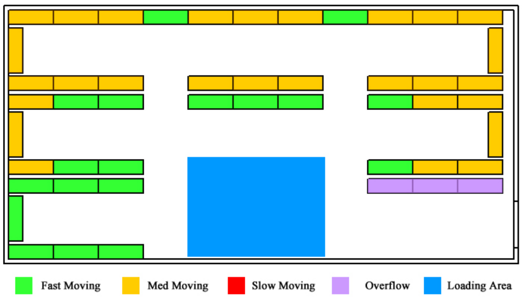

Figure 5.9: Flat with 2-Class

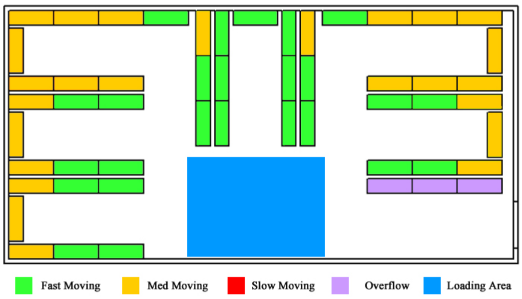

Figure 5.10: leaf with 2-Class

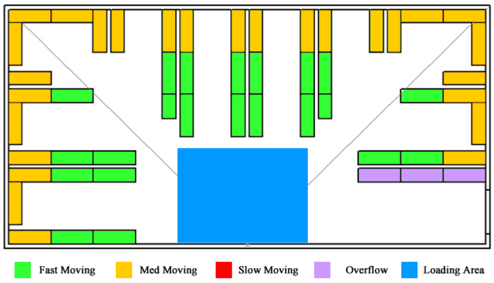

Figure 5.11: Chevron with 2-Class

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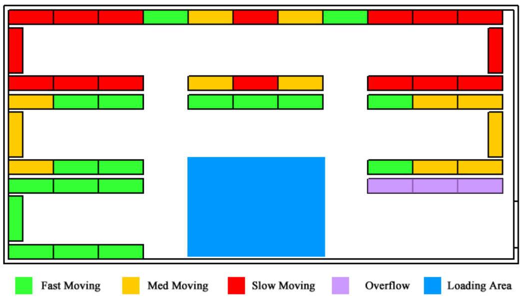

Figure 5.12: Flat with 3-Class

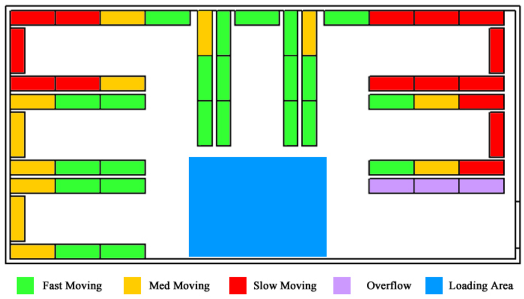

Figure 5.13: leaf with 3-Class

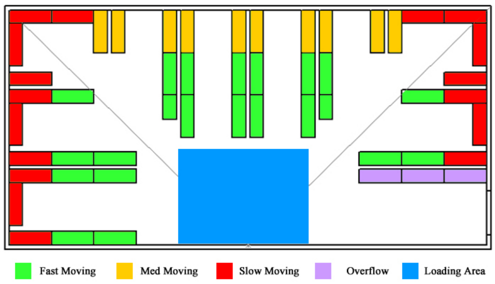

Figure 5.14: Chevron with 3-Class

5.4 Experiment Design

Each floor layout had its own model, where the models only differed in their arrangement of the racks and the various assignments of racks to the different classes where necessary. Each model was then run for a total of 30 000 seconds each, where the first 10 000 seconds was usually the start up phase, and the final 20 000 seconds was the steady-state or equilibrium phase. The start up phase had the warehouse filling up with beers, where the restocking process was aggressive. The equilibrium phase had the restocking logic carefully check how full the warehouse was, and make a re-order decision in order to keep the warehouse full, without overfilling. This entire process is known as a single run.

Each scenario (made up of a floor layout and storage policy pair) was run 50 times, giving a total of 450 runs of data. At the end of each run, the program would write the final values for 80 different variables into an excel spreadsheet. The runs used a fixed seed for reproducible results. The seed was based on the date, and the values were between 2016092001 and 2016092050.

Figures 5.15 and 5.16 both show 3D views from inside of the simulation model. Both figures show different angles of the Chevron floor layout with the Random storage policy, both captured at different times during the simulation.

5.5 Results

Once all of the data was collected, it was analysed in a Microsoft Excel spreadsheet, in order to find trends, relationships and outliers. The average, range, and standard deviation was determined for each variable in every scenario, using the 50 data points per scenario. These were then consolidated onto a single sheet which summarised the relationships. Overall, it appears that different scenarios favour different metrics, and so

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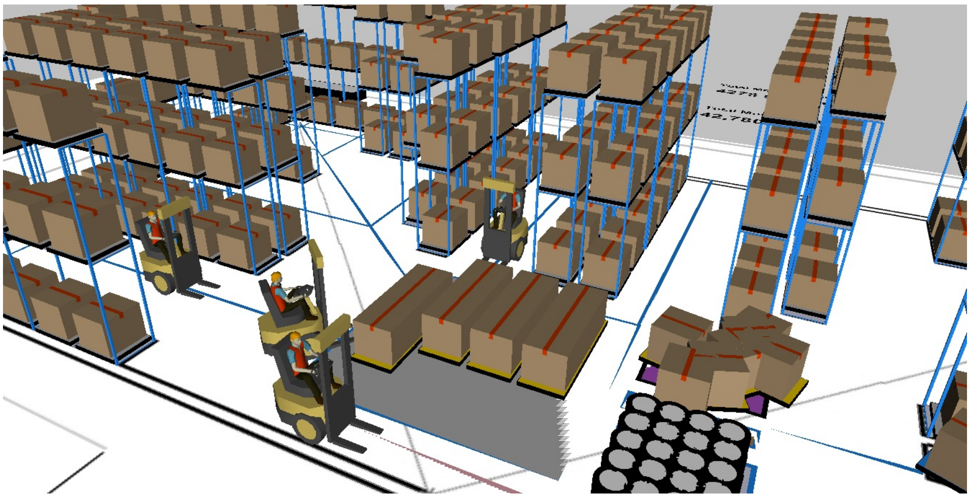

Figure 5.15: 3D view of the Chevron-Random Model running

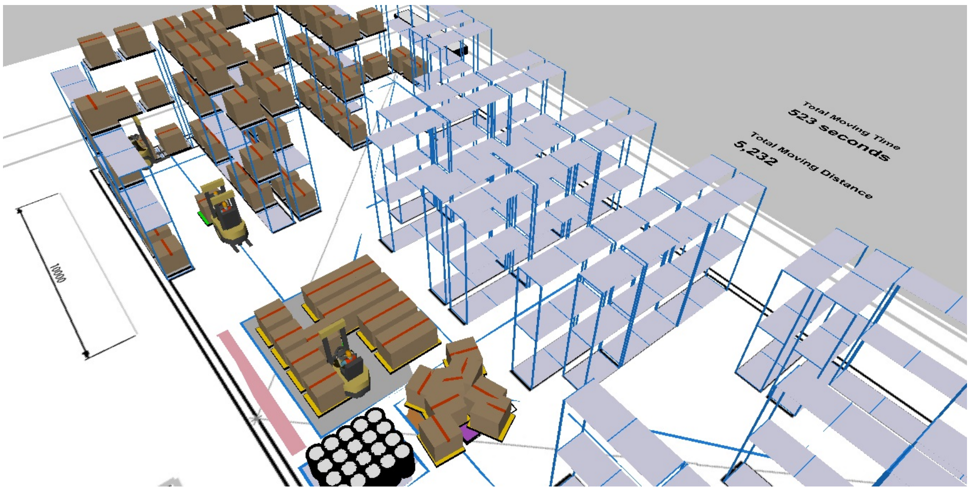

Figure 5.16: Another 3D view of the Chevron-Random Model running

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the prioritisation of the metrics by the company will likely affect the definition of the "best" scenario.

5.5.1 Orders

The following variables were recorded for the tracking of orders: Orders Created, Orders Processed, Orders Unfulfilled, and then Number of Fast, Medium and Slow Orders. The spread of the fast, medium and slow orders was consistent throughout, as each had their own source and so were created almost identically in each run. Table 5.2 shows the average number of orders filled for each scenario, whilst Table 5.3 shows the average number of orders unfulfilled.

The reason for the Flat-Random being considerably stronger than the Chevron-3Class scenario is probably linked to the Rack Utilisation variable, whereby an emptier warehouse is less likely to have the stock required and is more likely to send an order away.

Table 5.2: Orders Processed

Orders Processed Storage Policy	**Floor Layout**		
	Flat	Leaf	Chevron
Random	**1113**	1011	1009
2-Class	1087	987	981
3-Class	1030	942	**923**

Table 5.3: Orders Unfulfilled

Orders Unfulfilled Storage Policy	**Floor Layout**		
	Flat	Leaf	Chevron
Random	**123**	170	172
2-Class	148	194	200
3-Class	205	240	**258**

5.5.2 Utilisation of Equipment

The following variables were recorded to track the utilisation data: Forklift Utilisation, and Rack Utilisation. Table 5.4 shows the average forklift utilisation of each scenario. The forklift utilisation is a measure of the amount of time that the forklift is active compared to the total time of the simulation. A forklift is considered active if it is moving with a pallet, moving without a pallet, or moving a pallet up or down a level.

Note that the winner seems counter-intuitive, as the lowest utilisation wins. This is because of the large number of forklifts in the model. If the utilisation is lower, it means that similar efficiency of the system can be achieved with fewer forklifts, and it means that the system performs with the greatest efficiency. In terms of equipment purchase, the aim is to maximise the machine utilisation. In the model, this is the opposite.

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Table 5.5 shows the total time that was spent travelling by the forklifts. In the model, the speed of the forklift is constant, and so this may also be seen as an indication of the distance travelled. These figures also directly correspond to the results in the previous table.

Table 5.6 follows intuitive measures, whereby the higher the utilisation, the better. This is because the more space used for storage, the more efficient the storage method. It is worth noting that the Random storage policy is considerably better than the other 2 methods. This is because the Random policy uses each space systematically, and every slot can be used at any moment. With the 2-Class and 3-Class storage policies, a new pallet will have to wait for an open slot in it's section, even if the other sections are completely empty. This reduces the utilisation efficiency of the entire warehouse.

Table 5.4: Forklift Utilisation

Forklift Utilisation	**Floor Layout**		
Storage Policy	Flat	Leaf	Chevron
Random	**55.8%**	45.5%	40.7%
2-Class	46.9%	36.1%	32.6%
3-Class	41.4%	32.2%	**27.5%**

Table 5.5: Forklift Travel Time

Forklift Travel Time	**Floor Layout**		
Storage Policy	Flat	Leaf	Chevron
Random	**36817**	29392	26718
2-Class	30390	22580	20979
20979 3-Class	26523	20000	**17410**

5.5.3 Pallet Times

The final set of variables tracked the average amount of time that each pallet spent in each of its 4 states:

1. Waiting for Storage

   The time spent waiting to be stored on the shelf. This time begins once the beer is palletised and waiting in the loading area, and stops as soon as the forklift picks the pallet up.

2. On Shelf

   The time spent stored on the shelf, when no order has called for the pallet yet.

3. Waiting for Picking

   The time spent waiting for a pallet to pick it up from the shelf. This time begins when an order calls for that specific pallet, and ends once the pallet has been picked up off the shelf by the forklift.

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Table 5.6: Rack Utilisation

Rack Utilisation Storage Policy	**Floor Layout** Flat	Leaf	Chevron
Random	93.2%	93.5%	**93.8%**
2-Class Fast	71.1%	67.6%	71.0%
2-Class Medium	86.7%	90.0%	89.3%
2-Class Average	79.0%	78.8%	80.1%
3-Class Fast	52.2%	52.9%	47.2%
3-Class Medium	94.7%	95.2%	95.5%
3-Class Slow	26.1%	23.1%	19.0%
3-Class Average	57.7%	57.1%	**53.9%**

4. Moving

   This is the amount of time that the pallet spends moving, or being handled by the forklift.

Table 5.7 shows the average time per pallet in each of the states. This is the average for every pallet in that scenario, regardless of class. Note that the last two columns show the total times, where Total Time Handled is the sum of all times excluding the time on shelf, whilst the Total Time in System includes all time values.

Table 5.7: Total Time per Pallet

Total Time per Pallet	**Pallet State**					**Totals**	
Storage Policy	Floor Layout	Waiting for Storage	On Shelf	Waiting for Picking	Moving	Total Time Handled	Total Time in System
Random	Flat	**33.5**	1570.9	**3.2**	2.8	**39.5**	1610.4
	Leaf	33.9	**1882.2**	2.6	**2.9**	39.4	**1921.6**
	Chevron	27.7	1817.3	2.3	2.4	32.4	1849.7
2-Class	Flat	25.1	1408.3	2.7	2.5	30.3	1438.6
	Leaf	23.0	1669.3	2.2	2.4	27.7	1696.9
	Chevron	19.1	1647.0	2.0	2.1	23.1	1670.1
3-Class	Flat	20.9	**980.6**	2.6	2.3	25.8	**1006.4**
	Leaf	20.2	1207.2	2.1	2.3	24.6	1231.8
	Chevron	**15.4**	1038.5	**1.8**	**1.9**	**19.1**	1057.6

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5.5.4 Miscellaneous Results

There are a few other variables which provide some interesting results. Table 5.8 shows the maximum queue length of pallets waiting in the loading area to be stored. Table 5.9 refers to the maximum amount of pallets which are stored in the overflow section of the warehouse. A pallet is moved to the overflow section if it has been ordered, but there is no space available on the shelves for it to be packed. It should be noted that a Fast Mover will be placed in the overflow section if there are no spaces available in the assigned Fast Moving section of the warehouse, even if all of the Medium- or Slow Moving slots are open.

Table 5.8: Maximum Queue Length

Maximum Queue Length	**Floor Layout**		
Storage Policy	Flat	Leaf	Chevron
Random	54.5	54.2	**54.7**
2-Class	49.8	50.3	48.8
3-Class	47.5	47.5	**45.1**

Table 5.9: Maximum Overflow

Maximum Overflow	**Floor Layout**		
Storage Policy	Flat	Leaf	Chevron
Random	50.0	49.9	**51.4**
2-Class	43.9	41.5	44.9
3-Class	38.5	**37.7**	37.5

5.6 Interpretation

The results above show a number of mixed conclusions. Table 5.10 shows a summary of the best and second-best scenario for each of the metrics tested. Whilst there is no overwhelming winner, the Chevron-3Class scenario has the most wins, with three wins and two second-bests. The Leaf-3Class scenario is second overall, with two wins and two second-bests. This guides, but does not dictate the final conclusion, as the two leading scenarios are very similar in both their nature and in their strong categories. Both of these scenarios use the 3-Class storage policy, and perform excellently at both overall efficiency of the warehouse (as seen by the low forklift utilisation) and the short total handling times. However, both share the same drawbacks, in the sense of rack utilisation and number of orders processed. The random scenarios tend to perform in the exact opposite manner, processing more orders and having a greater rack utilisation but at the cost of long material handling times, long queues, and a large overflow.

With the systems competing and excelling in vastly different areas, the final solution chosen will be dictated by the company's own prioritisation of metrics. However, as is

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presented in the final chapter, there are a number of considerations to be taken into account when making the final decision.

Table 5.10: Winner's Table

Category	**Scenario**			
	Winner	Value	First Runner Up	Value
Number of Storage Slots	Leaf	300	Chevron	288
Number of Orders Processed	Flat-R	1113	Flat-2	1087
Forklift Utilisation	Chev-3	27.5%	Leaf-3	32.2%
Rack Utilisation	Chev-R	93.8%	Leaf-R	93.5%
Total Time Handled	Chev-3	19.1 seconds	Chev-2	23.1 seconds
Maximum Queue Length	Chev-3	45.1	Leaf-3	47.5
Maximum Overflow	Leaf-3	37.7	Chev-3	37.5

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Chapter 6

Conclusion

The aim of this report is to provide decision support to ABE on the design of their warehouse and their storage policies. After creation of the models which would test the three different storage policies across each of the three different floor layouts, the simulations were run so as to produce conclusive data to support the decision for one of the nine scenarios. However, instead of reaching a single solution, the selection of the best scenario for the business will depend on the metrics that the business itself prioritises. However, the business should still be well-informed before they make a final decision, and so there are certain criteria and certain observations that the company should be made aware of. These are contained in the sections below.

6.1 Metrics

It is important to note the effect of each metric on the business, as well as taking note of some other considerations which have not been analysed in this report.

The number of storage slots available dictates the maximum number of beers that the warehouse can store. If the warehouse has no intention to be filled to the brim, at least not yet, then this number should be given less consideration than if the warehouse expects large amounts of growth. The number of slots should also consider the rack utilisation statistics. If the utilisation is low, then the number of slots needs to be higher in order to maintain certain levels of beer availability. If the utilisation is high, then more slots will be filled (on average) and so there is less need for a larger warehouse.

The handling time is the next biggest metric to consider. There is almost always a trade-off between material handling and space utilisation. As less space is left for the handling equipment, the users of the equipment need to be more careful in their operations, which not only takes more time to handle each pallet of beer, but also leaves the operators more prone to mistakes. Minimising the handling time minimises the exposure of each pallet to human error and potential for incident. In terms of the warehouse design, minimising forklift utilisation means that the warehouse performs more efficiently, which is contradictory to intuition that wants to maximise utilisation. Minimising forklift utilisation means that the shelves were stocked and the orders were picked and processed using less material handling time and effort. It comes down to the idea that doing the job (whether that be storing pallets or picking orders) should be done with as little effort as possible, and so the smaller utilisation of the forklifts is key to achieving that here. It

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also allows for the orders of customers to be matched considerably more quickly, which reduces the lead time for the customer and ultimately works in favour of ABE.

Finally, it is important to realise what the scope of this project does not cover, and yet should still be considered by the business. The first issue is costs. Whilst costs generally form the basis of the decision-making in most companies, this project chose to ignore costs in favour of an optimal solution. That being said, the solutions should not vary tremendously in cost, as they all use the same equipment, just different quantities of each. The second issue not considered is the initial set-up of the warehouse. This includes the time and money spent to arrange the purchasing and set-up of equipment, nor does offer particular insight into the procedure of the set-up nor the first few months of business. The models do measure a start-up scenario, but this may not be directly in line with the actual beginnings of the business. The third issue is maintenance and repair of the warehouse. This was not a major consideration when selecting equipment, nor was it of major concern in the design of the warehouse. Finally, the model helps to gain some idea of what will happen in the real world, and is by no means a guarantee of what will happen. The world is more stochastic than any model, and this is simply there as a guide to what will likely happen.
The company needs to bear these considerations in mind, and use them in conjunction with the results obtained in this report in order to make an informed decision.

6.2 Solution A: Time-focused

Having reviewed the results of the models, the primary recommendation for ABE is the use of the Chevron floor layout, with the 3-Class storage policy. Figure 6.1 gives a graphical representation of the final solution. The Chev-3 scenario performs best at the forklift utilisation, total time handled, and maximum queue length criteria, and comes in at a close second on number of storage slots and maximum overflow. Chev-3 will be the most complicated to set up initially, but not exponentially more so than the set-up of the others.

Prioritising the time component over the space component is most logical for ABE for several reasons. Since the warehouse is brand new, and the customer base for ABE is not vast nor mature, it makes sense to prioritise a faster response time over sheer storage quantity. If you only have a few customers, they are unlikely to make orders that require a full warehouse, and are more likely to have smaller, more frequent orders. This means that the ability to fill an order and send it with expediency is more important than having larger quantities of each product readily available. More than that, the company will not have to change their policy once the business becomes more popular and throughput increases. The Random storage policy is likely to reach a critical point of confusion, where the entire warehouse will have to be shut down in order to rearrange all of the stock in the warehouse into some sort of manageable configuration. The 3-class system is unlikely to face this issue, especially given that each class zone is smaller than the entire warehouse. That means that even if the warehouse needed a rearrangement to fix issues with the randomness within the class, it can do so without interrupting the operation of the other classes.

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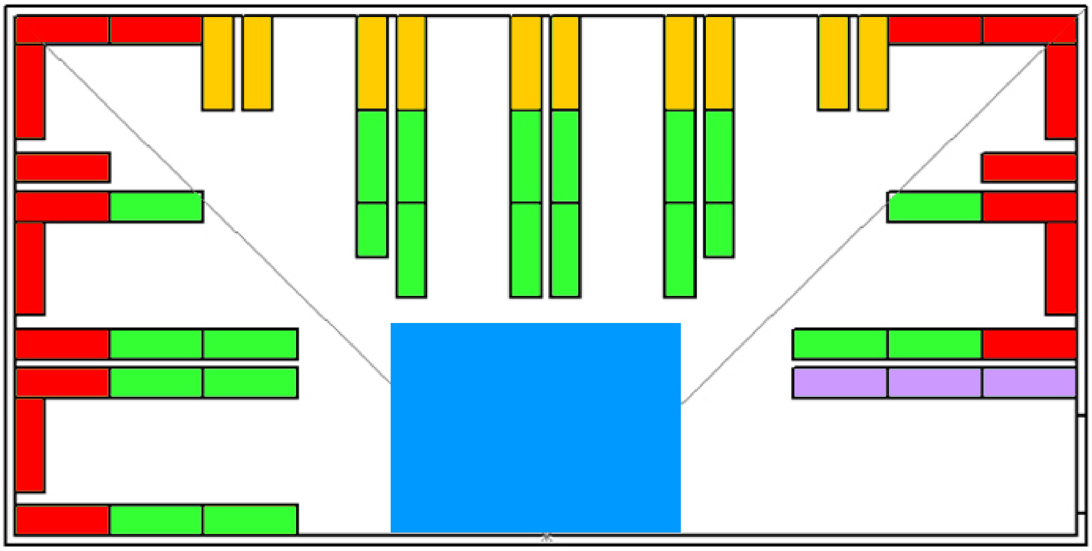

Figure 6.1: Final Solution A - Chevron Aisle Floor Layout with 3-Class Storage Policy

6.3 Solution B: Space-focused

Should the company prioritise the utilisation of space over the time spent handling the products, then the recommendation would be for ABE to use the Leaf floor layout with the Random storage policy. Figure 6.2 gives a graphical representation of the final solution. This scenario would maximise the amount of space used in the warehouse for storage, even if that comes at the cost of a smaller loading area. It would also maximise the utilisation of the shelf space in the warehouse, and allow for more orders to be processed through greater availability of products. However, it should be noted that the Random storage policy is unlikely to perform as well as the model describes without an advanced warehouse management system to keep track of where the beer pallets are and where the operators should collect the orders from.

The prioritisation of space should be considered more important in only two scenarios: one where it takes a considerable amount of time to perform sundry activities regarding orders (such that the picking and storing time becomes negligible anyway), and a scenario where the company orders products in such large and infrequent batches that the arrangement of the products is considerably less important than anything else in the warehousing process. In both scenarios, the maximisation of space utilisation makes sense, and so the Flat-R policy is most effective.

6.4 Final Comments

The selection of a design for a warehouse and the storage policy to match it a complicated and a difficult decision to make. It is challenging to find a quantitative approach to achieve the optimal version of a warehouse, but through the tools available to us, such as simulation, it becomes possible to make more informed decisions and adopt better solutions. Whilst certain principles are easy to apply, others are contradictory and require

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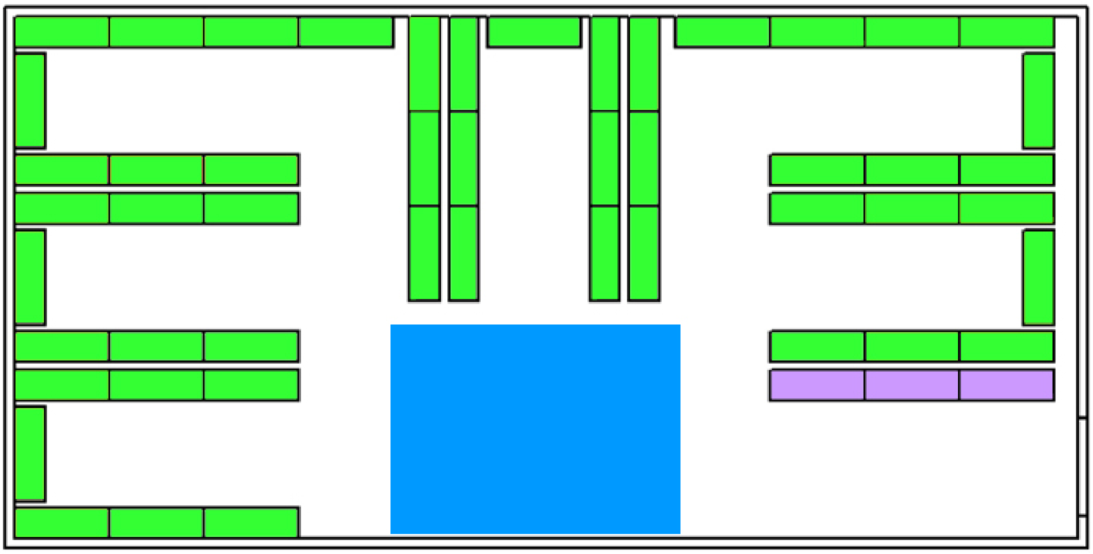

Figure 6.2: Final Solution B - Leaf Aisle Floor Layout with Random Storage Policy

a certain level-headedness in applying the trade-off. This is where the results of a well-fashioned model that truly represents the key aspects of reality have their greatest worth, and where the core quantitative side of scientific principles can take over from the oft critiqued qualitative decisions that engineers are entrusted to make.

This report aimed to create the best set of recommendations to provide ABE, so that they can run the best company possible. I truly believe in the ideas that their company are introducing to our country, and I am happy to have helped them in achieving their goals.

6.5 Recommendations for Future Study

One of the key additions that could be made to future studies is the inclusion of an area-based storage policy. Such a policy would assign entire areas to certain types of beers, rather than allowing a mix-match of all beers of a certain class to exist within a certain area. Another addition to the model would be the inclusion of human error, or at least the creation of a system where perfect knowledge of the beer availability and position is not known. In such a model, the operators would be sent to a certain area, where they would have to inspect each and every pallet on the shelf in that area to find the one they were looking for. Furthermore, the model could improve the relationship it has with Orders. This includes allowing back orders, adding safety stock, using economic order quantities to develop restocking plans, and finally to restock the shelves according to what the demand is and what the warehouse contains, rather than the random entry of beers in the current model.

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Chapter 7

Appendices

7.1 Appendix A: Industry Sponsorship Form

Department of Industrial & Systems Engineering
Final Year Projects
Identification and Responsibility of Project Sponsors

Final Year Projects may be published by the University of Pretoria on *UPSpace* and may thus be freely available on the Internet. These publications portray the quality of education at the University, but they have the potential of exposing sensitive company information. It is important that both students and company representatives or sponsors are aware of such implications.

Key responsibilities of Project Sponsors:

A project sponsor is the key contact person within the company. This person should thus be able to provide guidance to the student throughout the project. The sponsor is also very likely to gain from the success of the project. The project sponsor has the following important responsibilities:

1. Confirm his/her role as project sponsor, duly authorised by the company. Multiple sponsors can be appointed, but this is not advised. The duly completed form will considered as acceptance of sponsor role.
2. Review and approve the Project Proposal, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable from the company's perspective.
3. Review the Final Project Report (delivered during the second semester), ensuring that information is accurate and that the solution addresses the problems and/or design requirements of the defined project.
4. Acknowledges the intended publication of the Project Report on UP Space.
5. Ensures that any sensitive, confidential information or intellectual property of the company is not disclosed in the Final Project Report.

Project Sponsor Details:

Company:	African Beer Importers
Project Description:	Design of a Warehouse for Imported Beer
Student Name:	Warren M. Gertzen
Student number:	12020657
Student Signature:	
Sponsor Name:	Willem van der Schyf
Designation:	Company Owner
E-mail:	willemvanderschyf@gmail.com
Tel No:	012 424 8601
Cell No:	084 317 0384
Fax No:	086 719 7662
Sponsor Signature:	

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7.2 Appendix B: Reflection on Learning

There are several skills that were obtained during this project. Some of the skills are tangible and quantifiable (such as new-found coding skills) whereas others are considered soft skills and difficult to readily attribute to any specific task (such as interviewing skills).

LaTeX is the first and probably one of the best skills that I have learnt over the course of the project. LaTeX is a typesetting language that allows for the easy compilation of advanced and professional-looking scientific documentation. Unlike other word-processing applications such as Microsoft Word or LibreOffice, LaTeX is run from any one of numerous environments (programmes which help display and then compile code). The compilation aspect also means that you do not get to see the final document until you run the code and it compiles, unlike "what you see is what you get" applications like the ones mentioned above. This has numerous advantages, most importantly, the ability to write large amounts of text without worrying about the look of the document. This allows you to focus on the content, rather than the design, of the article. Another benefit to LaTeX is the ability to produce neat and professional mathematical equations with much greater ease than you could in Word. The last, and potentially one of the greatest aspects of writing in LaTeX, is that the control of items such as tables and pictures is handled by the environment itself, and as such, text does not constantly jump around as you try to move a picture into the perfect position in your document.

GitLab is an online repository and version-control system that allows users to upload documents, code and static files (jpegs, pdfs, etc), and tracks various versions of the files to allow for easy backtracking to various points in history. This tool is especially helpful for the following reasons:

1. Cloud storage

   The ability to reliably store documents off-site has been a tremendous relief and has promoted some good practices, such as saving documents often, committing and pushing frequently, and assigning messages to indicate changes in a document.

2. Version-tracking

   As of now, version-tracking has not been especially helpful as a tool, as the only deliverables produced have been documents and not anything code-based. However, given that the project is based on simulation, the ability to store various versions of simulations will become key to the success of the project, as it allows for more freedom when attempting changes within a simulation program.

3. Shared access

   Given that this project is mostly driven by self-discipline (as was the agreement with my supervisor), the ability to see the progress of other students has been extremely motivating. It is also fairly useful in that it holds me accountable on a public space, whilst at the same time allowing me to check the work of others to compare the standards of their projects against my own.

Discipline One of the biggest challenges for me this semester has been maintaining discipline with the BPJ project. I have an otherwise relaxed semester (module-wise) and this has generally garnered a care-free approach to the work done. However, through working

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with the project, and the constant reminder of work from friends and fellow students has really helped to encourage me to work hard and hopefully achieve a memorable result. The prospect of a good mark is always encouraging, but the amount of effort required can often be demotivating. Knowing when to work and when to take a break has been something that has required a certain amount of personal development (moreso for the former than the latter), and it's the first step on a long road to being a better person and an extraordinary engineer.

Java An unexpected tool that I have learnt in the last few months has been the ability to perform basic Java coding. This was absolutely necessary in order to make the AnyLogic model sufficiently complex so as to represent the 'real-world' with the required level of detail. It has been one of the most challenging aspects of the project, especially since there is a considerable gap between coding in raw java (i.e. creation of programs using environments such as Eclipse) and using java to change the functionality of AnyLogic (which also uses Eclipse, albeit a lite version thereof). However, once the initial challenge had been overcome, and more and more experience in the coding was achieved, I was able to quickly move through otherwise difficult scenarios, and to achieve things that would never have been possible without it.

Engineering It is a strange moment when you realise that you will be spending less than 5% of your time actually making good engineering decisions. The rest of your time is spent building models or making calculations, and even that part is 90% scratching your head and wondering why code won't compile, or why your answer is a good 5 orders of magnitude from what it should be. It is a frustrating time in my engineering career, where I am knowledgeable enough to know what can be done, but struggle to actually do those things well and quickly. This is amplified when I (admittedly, foolishly so) compare the complexity of the work I've spent 6 months on to the work a supervisor can do in a week.

However, with practice, I am sure that the hard, grunt work work will come more naturally and happen much faster, and that I will be able to contribute more with good decisions soon.

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