SIMULATION BASED EVALUATION OF PALLET MANAGEMENT STRATEGIES IN THE CONTEXT OF SUSTAINABILITY

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SIMULATION BASED EVALUATION OF PALLET MANAGEMENT STRATEGIES IN THE CONTEXT OF SUSTAINABILITY

BY

NIKLAS THIELE

A MASTER THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SYSTEMS ENGINEERING

UNIVERSITY OF RHODE ISLAND

2021
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OF

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APPROVED:

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                  Brenton DeBoef

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2021
ABSTRACT

Due to the continuous pursuit of increasing the efficiency of logistical operations as well as increasing the sustainability of supply chains, choosing the correct pallet management strategy is essential. With increasing cost pressure as well as growing environmental awareness, it is necessary to utilize all potentials within a supply chain including the operation of pallets. In order to estimate the ecological and economic impacts caused by different pallet management strategies, the use of simulation methods has been utilized in this research.

To predict close-to reality results, it is necessary to create generic models, which offer high adaptability for real world scenarios. This master’s thesis deals with the question, which pallet management strategies offer the greatest potential cost-savings and create the smallest negative environmental impact? Four agent-based models will be created and different scenarios will be simulated. After a subsequent analysis of the results, a critical review concerning the sustainability of each strategy within an agent-based simulation environment will be presented.
ACKNOWLEDGMENTS

I am profoundly grateful to Professor Dr. Valerie Maier-Speredelozzi for supervising this Master Thesis. Her critical input contributed a lot to the outcome of this research.
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<thead>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>MeBr</td>
<td>Methyl Bromide</td>
</tr>
<tr>
<td>HT</td>
<td>Heat Treatment</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene Terephthalate</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Polyethylene</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standardization</td>
</tr>
<tr>
<td>DS</td>
<td>Dynamic Systems</td>
</tr>
<tr>
<td>SD</td>
<td>System Dynamics</td>
</tr>
<tr>
<td>DE</td>
<td>Discrete Event</td>
</tr>
<tr>
<td>AB</td>
<td>Agent-Based</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
</tr>
<tr>
<td>GMA</td>
<td>Grocery Manufacturers Association</td>
</tr>
<tr>
<td>CPT</td>
<td>Cost Pass Through</td>
</tr>
<tr>
<td>PRS</td>
<td>Pallet Rental Service</td>
</tr>
<tr>
<td>PSU</td>
<td>Pallet Single Use</td>
</tr>
<tr>
<td>PDU</td>
<td>Pallet Dual Use</td>
</tr>
<tr>
<td>CPM</td>
<td>Consumer Product Manufacturer</td>
</tr>
<tr>
<td>Dist</td>
<td>Distributor</td>
</tr>
<tr>
<td>Ret</td>
<td>Retailer</td>
</tr>
<tr>
<td>EoL</td>
<td>End of Life</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>SP</td>
<td>Service Provider</td>
</tr>
</tbody>
</table>
1 Motivation

Most operations involved in supply chains, especially those involving transportation of goods or cargo involve the usage of pallets. The majority of all pallets involved in these operations are made out of wood. While these pallets play a significant role in almost every supply chain, they do not come free of charge. There is capital spent for acquiring, producing and disposing them, and there is an impact they generate on the environment. Pallets are very popular, used worldwide and not thought about very much. The usage of pallets comes with significant costs, so it is necessary to economize this part of the supply chain as much as everything else involved. Pallets, comparable to all other factors of the process structures of supply chains, offer potential for increasing the efficiency and along with it, increasing the sustainability of the entire system. As this research focuses on pallets, it is important to explain the concept of pallets in the first place. A pallet is an auxiliary device for transporting goods or cargo. The transportation process is not carried out by the pallet itself, but the pallet acts as a foundation of an efficient and secure transport. Pallets are primarily designed to be carried primarily by forklifts, or forklift-like devices such as pallet-jacks, within the events of loading or unloading trucks, shelving, or other warehouse related hardware.

Along with the advantages of pallets comes the question of sustainability and economic factors. According to Bloomberg, the COVID-19 pandemic has increased the e-commerce and therefore driven up the demand of pallets
worldwide. [1]. Also questions of environmental impacts caused by production, transportation and disposal processes are to be investigated.

Originally, the motivation for this research came from reviewing the article the article *Selection of pallet management strategies from the perspective of a supply chain with Anylogic Software* [2], which offered great potential for further investigation, but also had major deficits in its research. In general, the authors have compared three different pallet management strategies under different circumstances. The major problem with the research is the way the authors have compared those strategies and the pallets involved. They have not established a universal model of a pallet, which is applied to all different strategies equally. Neither have they justified, why the pallets of the different strategies have different characteristics and behavior. Examples for this are the consideration of losing pallets within a pallet rental system, but not in the other systems [2] or a general conclusion that an ownership pallet strategy will generally be more expensive than other strategies. It becomes obvious that comparing strategies and pallets with varying characteristics and behaviors without giving any justification for the differences lead to invalid results and wrong conclusions. The strategies discussed in the article include extensive management of pallets, which is a strategy, where the pallet is returned after using it. Transfer of pallet ownership is a strategy, where the pallet will be passed on to the next instance of the supply chain along with its cost. In the pallet rental strategy, an approach for renting pooling pallets is established. The last two strategies are included in this research as well. The goal
of this research is to create simulation models of four different pallet management strategies that work under equal conditions in order to achieve a comparability. A standardization of pallets and supply chains is included in the design of all models. Besides the Cost Pass Through (CPT) strategy and the Pallet Rental Service Strategy (PRS), the Pallet Single Use and Pallet Dual Use strategies will be presented. The PSU involves cheap softwood one-way pallets, that are disposed after transporting a single product only. The Pallet Dual Use System investigates the question about potentially increasing the sustainability of the supply chain as a system in case single use pallets can be used twice. The entire research investigates the potential of the four different pallet management strategies from an ecological and economical point of view. The CPT strategy involves multiple use hardwood pallets used in a cost pass through system, where the pallet gets passed along the supply chain and returned to the beginning of the supply chain afterwards. The PRS model involves the same multiple use hardwood pallets, working in a similar order, but involving a pallet rental model.

The primary objective of this research is to identify how the different strategies perform from a cost- and environmental perspective under equal conditions. The second objective of this research is to establish generic simulation models that offer the potential of great adaptability to real world scenarios that can function as a basis for further investigations.
2 Background and Literature Review

Within this chapter, the theoretical background of this thesis will be presented. It will cover the topics of pallets including the design, purposes, Life Cycle Assessment (LCA), devices used for transportation, different pallet management strategies and simulation paradigms.

2.1 Pallets

Pallets are the backbone of all kinds of logistical operations, which involve handling of goods and materials. The design of most pallets can be described as flat structures, which can be transported by forklifts or pallet jacks.

Pallets started becoming popular transportation and storage devices in the 1920s, when the forklift was invented. This game changing invention allowed stacking of goods and therefore utilizing storage spaces to their full potential. As forklifts were invented, underslung cranes for stacking pallets including goods and cargo became obsolete. Along with forklifts, the development of pallets and pallet couriers took place as well. An introduction of different types of pallets in different shapes and sizes for matching particular material handling requirements follows. [3], [4]
The high amount of goods and items exchanged between allied countries during the 2\textsuperscript{nd} World War resulted in a great increase in demand for pallets. This incline caused standardized designs of pallets such as the 48” x 48” pallet. The advantages of standardized pallet design were noticed and subsequently, most companies integrated the use of standardized pallets within their business models. [4]

The basic advantages of integrating pallets in logistical operations involve decreasing the risk of damaging the items, cargo or goods transported, as only the pallet are in contact with the transport devices. Due to the entire logistical system being optimized for the use of standardized pallet designs, warehouses, truck beds and all other components involved in the processes can operate more efficiently. [5]

Standardized pallet design allows companies to carry or store the maximum number of pallets possible and provides the possibility of reducing handling times. A standardized European 40-tonnes-truck canvas trailer with a maximum carrying capacity of up to 25 metric tons can be unloaded within less than 20 minutes using pallets and forklifts. A regular semi-trailer with solid non-accessible walls could take days to unload if pallets and a forklift are not involved.

European standardized truck beds have been specifically designed to accommodate 34 Europoolpallets (Europallets). According to [5], a Europallet
measures 1,200 mm x 800 mm leading to 0.96 m$^2$ of space. A standardized 40-ton truck trailer measures 13.6 m x 2.55 m x 4 m leading to a floorspace of 34.68 m$^2$. This design leads to the possibility of putting 2 Europallets next to each other in 17 rows. This results in a usage of 32.64 m$^2$ of the available 34.68 m$^2$ or 94.12%. [6]

Besides truck beds, the shelving inside warehouses is also specifically designed to meet the measurements of the pallets, which are to be stored. There are multiple ways to classify pallets such as by design, by purpose, material, accessibility and so forth. Within this thesis, pallets will be classified by material including four different types of pallets. The most common type of pallet is the wooden pallet, which will be the focus of this research. Besides wood, most common used materials are plastics, metals and paper. [5]

As for wooden pallets, the most common materials used are either hardwood, usually oak, or softwood, usually pine. The advantages of wooden pallets include a high level of customization according to the requirements of the customer. Wooden pallets can be used for both transportation and storage. Lightweight wooden pallets allow good handling, even without a forklift, when not loaded. The possibility of repairing or refurbishing extends the lifespan of wooden pallets. At the end of life there are recycling possibilities or the option of rotting away in a landfill, instead of staying in the system for decades, which makes the wooden pallet a sustainable solution. Disadvantages of the wooden pallet include
deterioration when exposed to the elements, vulnerability to bacteria and chemical contaminations. The wooden pallet can also be damaged by water and moisture, as well as by bug infestations. [5]

To avoid damages caused by animals such as the timber worm, the pallet needs to be treated. This treatment can be carried out through a heat treatment (HT) or via chemicals. The chemical treatment includes dry kilns and Methyl Bromide (MeBr) fumigation. [4]

Depending on the requirements and the condition of the wood pallet, prices can vary from about $5 up to $65. Besides soft- and hardwood pallets, alternative wooden materials include presswood and plywood. Presswood pallets are formed through pressing wood waste and wood shavings under higher temperatures into a new structure. Similar to paper pallets, presswood pallets have a very compact shape, which allows an efficient utilization of the available space. Besides this advantage, presswood pallets are also lightweight. Disadvantages of presswood pallets include damage, when exposed to water or moisture as well as a limited carrying capacity. Plywood pallets are designed to accommodate light and medium weight cargo. Due to their design, plywood pallets can be used under rough conditions as they are more resistant to water, moisture and insects. Plywood does not swell, shrink or warp. [5]
Other very common materials for pallets are steel or aluminium. Metal pallets are usually used for heavy duty applications and are ideal for sectors which are processing metal and the automotive industry. They also include numerous advantages such as long-term durability, being fireproof and are easy to sanitize. The last point makes metal pallets very suitable for medical applications as well as for hygienic sensitive products. Due to the material used, metal pallets have considerably stronger structures than wooden pallets. As aluminium is a light metal, using aluminium pallets in air freight has become popular, as they tend to have a lower weight than comparable wooden- or plastic pallets. Metal pallets are not vulnerable to pests and do not have degradation (In case steel is alloyed). As metal pallets can be sanitized easily, they can also be reused or repurposed without extensive effort. Metal pallets can be inside and outside and are popular with food-, tire, battery and paper companies. The disadvantages of metal pallets can include heavy weight due to higher density and difficulties with the repair process, once the pallet is broken. The cost of metal pallets varies from $60 - $120 for new examples and about half the price for recycled and used pallets. [5]

Plastic pallets involve different materials including high-density polyethylene and recycled bottles consisting of Polyethylene Terephthalate (PET). Different procedures, including molding processes are required for the manufacturing process of plastic pallets. Plastic pallets have reinforced, efficiently designed structures and can have high weight capacities while maintaining low weight of the structure. As plastic pallets are not vulnerable to corrosion, rotting and pests, they
are very durable. Depending on the materials involved, plastic pallets can be fire retardant and can be recycled up to 100%. Like the metal pallets, plastic pallets are also easy to clean or sanitize allowing similar applications such as transporting or storing medical products. Due to the material characteristics of plastics, indoor and outdoor usage is possible. Common applications of plastic pallets include transporting and storing biodegradable products, pharmaceutical goods, fresh- and frozen foods and chemicals. A downside of plastic pallets are the costs involved, as new pallet prices vary from $60 - $200 per pallet. Used pallets cost on average between $30 - $45 depending on the size and material of the pallet. Repairing plastic pallets however is problematic. Plastic pallets have proven to offer great performance and efficiency in logistical operations, when compared to other types of pallets. The use of recyclable materials such as PET and HDPE represent an environmentally friendly solution. [5]

The fourth major type of materials used, when it comes to pallets is paper. Paper pallets have proven to be significant due to their super reduced weight, when compared to the other types of pallets. Shapes and structures such as honeycombs integrated in the design allow a stiff structure. The use of paper pallets, however, is strictly limited and the weight capacity is not comparable to plastic or metal pallets for example. As one of the main users of paper pallets, the furniture industry, in particular IKEA, has to be mentioned. The ability of easy customization in design according to the requirements of the particular application, a low-profile design, but most important the reduced costs for storage and shipping
have to be mentioned as the advantages of the paper pallet. Besides these, other advantages are the lack of splinters and nails as well as recyclability and disposability. Especially the disposability and the super light-weight have proven to result in increased cost-effectiveness. The prices of paper pallets can be compared with wooden pallets as they range from $10 - $100 per piece, depending on size and quality. [5]

As this thesis is focused on wooden pallets, the tables 2.1 – 2.3 show the most commonly used pallets including their measurements according to region and purpose.

Table 2.1: Pallets which are designed to fit in ISO containers [5]

<table>
<thead>
<tr>
<th>DIMENSIONS (W x L) inch decimal</th>
<th>DIMENSIONS (W x L) inch fraction</th>
<th>DIMENSIONS (W x L) millimeter</th>
<th>UNUSED FLOOR SPACE in 40' ISO Container</th>
<th>REGION Most Used In</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.00 x 48.00</td>
<td>40 x 48</td>
<td>1016 x 1219</td>
<td>3.7%</td>
<td>North America</td>
</tr>
<tr>
<td>39.37 x 47.24</td>
<td>39 3/8 x 47 1/4</td>
<td>1000 x 1200</td>
<td>6.7%</td>
<td>Europe, Asia (similar to 40&quot; x 4&quot;)</td>
</tr>
<tr>
<td>45.90 x 45.90</td>
<td>45 7/8 x 45 7/8</td>
<td>1165 x 1165</td>
<td>8.1%</td>
<td>Australia</td>
</tr>
<tr>
<td>42.00 x 42.00</td>
<td>42 x 42</td>
<td>1067 x 1067</td>
<td>11.5%</td>
<td>North America, Europe, Asia</td>
</tr>
<tr>
<td>43.30 x 43.30</td>
<td>43 1/4 x 43 1/4</td>
<td>1100 x 1100</td>
<td>14%</td>
<td>Asia</td>
</tr>
<tr>
<td>31.50 x 47.24</td>
<td>31 1/5 x 47 1/4</td>
<td>800 x 1200</td>
<td>15.2%</td>
<td>Europe</td>
</tr>
</tbody>
</table>
Table 2.2: Pallet designs which are commonly used in North America [5]

<table>
<thead>
<tr>
<th>DIMENSIONS (W x L) inch decimal</th>
<th>DIMENSIONS (W x L) inch fraction</th>
<th>DIMENSIONS (W x L) millimeter</th>
<th>PRODUCTION Rank</th>
<th>INDUSTRIES USING Most Used In</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 x 48</td>
<td>40 x 48</td>
<td>1016 x 1219</td>
<td>1</td>
<td>Grocery, many others</td>
</tr>
<tr>
<td>42 x 42</td>
<td>42 x 42</td>
<td>1067 x 1067</td>
<td>2</td>
<td>Telecommunications, Paint</td>
</tr>
<tr>
<td>48 x 48</td>
<td>48 x 48</td>
<td>1219 x 1219</td>
<td>3</td>
<td>Drums</td>
</tr>
<tr>
<td>48 x 40</td>
<td>48 x 40</td>
<td>1219 x 1016</td>
<td>4</td>
<td>Military, Cement</td>
</tr>
<tr>
<td>48 x 42</td>
<td>48 x 42</td>
<td>1219 x 1067</td>
<td>5</td>
<td>Chemical, Beverage</td>
</tr>
<tr>
<td>40 x 40</td>
<td>40 x 40</td>
<td>1016 x 1016</td>
<td>6</td>
<td>Dairy</td>
</tr>
<tr>
<td>48 x 45</td>
<td>48 x 45</td>
<td>1219 x 1143</td>
<td>7</td>
<td>Automotive</td>
</tr>
<tr>
<td>44 x 44</td>
<td>44 x 44</td>
<td>1118 x 1118</td>
<td>8</td>
<td>Drums, Chemical</td>
</tr>
<tr>
<td>36 x 36</td>
<td>36 x 36</td>
<td>914 x 914</td>
<td>9</td>
<td>Beverage</td>
</tr>
<tr>
<td>48 x 36</td>
<td>48 x 36</td>
<td>1219 x 914</td>
<td>10</td>
<td>Beverage, Shingles, Packaged Paper</td>
</tr>
<tr>
<td>35 x 45.50</td>
<td>35 x 45 1/2</td>
<td>889 x 1156</td>
<td>Unknown</td>
<td>Military 1/2 ISO Container, fits 36” Standard Doors</td>
</tr>
<tr>
<td>48 x 20</td>
<td>48 x 20</td>
<td>1219 x 508</td>
<td>Unknown</td>
<td>Retail</td>
</tr>
</tbody>
</table>
Table 2.3: Pallet designs which are commonly used in Europe [5]

<table>
<thead>
<tr>
<th>PALLET TYPE</th>
<th>DIMENSIONS (W x L x D)</th>
<th>DIMENSIONS (W x L x D)</th>
<th>DIMENSIONS (W x L x D)</th>
<th>ISO Pallet Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUR</td>
<td>31.50 x 47.24 x 5.71</td>
<td>31 1/2 x 47 1/4 x 5 3/4</td>
<td>800 x 1200 x 145</td>
<td>ISO, same size as EUR. The pallet weight is 20 -25 kg. Weight of a load: 2490 kg.</td>
</tr>
<tr>
<td>EUR 1</td>
<td>31.50 x 47.24 x 5.71</td>
<td>31 1/2 x 47 1/4 x 5 3/4</td>
<td>800 x 1200 x 145</td>
<td>ISO, 33 kg. Weight of a load: 1470 kg.</td>
</tr>
<tr>
<td>EUR 2</td>
<td>47.24 x 39.37 x 5.67</td>
<td>47 1/4 x 39 3/8 x 5 5/8</td>
<td>1200 x 1000 x 144</td>
<td>The pallet weight is 29 kg. Weight of a load: 1920 kg.</td>
</tr>
<tr>
<td>EUR 3</td>
<td>39.37 x 47.24 x 5.67</td>
<td>39 3/8 x 47 1/4 x 5 5/8</td>
<td>1000 x 1200 x 144</td>
<td>ISO, half size as EUR. The pallet weight is 9.5 kg. Weight of the safe load: 500 kg.</td>
</tr>
<tr>
<td>EUR 6</td>
<td>31.50 x 23.62 x 5.67</td>
<td>31 1/2 x 23 5/8 x 5 5/8</td>
<td>800 x 600 x 144</td>
<td>Quarter the size as EUR.</td>
</tr>
<tr>
<td></td>
<td>23.62 x 15.75</td>
<td>23 5/8 x 15 3/4</td>
<td>600 x 400</td>
<td>One-eighth the size as EUR.</td>
</tr>
<tr>
<td></td>
<td>15.75 x 11.81</td>
<td>15 3/4 x 11 3/4</td>
<td>400 x 300</td>
<td>One-eighth the size as EUR.</td>
</tr>
</tbody>
</table>

Different designs of pallets such as two- or four-way entry are possible. A two-way entry design means that the pallet can be accessed through two sides, a four-way entry design works accordingly. Figure 2.1 gives an overview about different pallet styles. Other design features contain closed decks or open decks.
Depending on the individual requirements of the particular companies using pallets, the most suitable design has to be chosen.

2.2 Simulation paradigms

According to Borshchev and Filippov, model-based simulation can be broken down into four different simulation paradigms, which are presented within the following section. Namely, these four paradigms include *Dynamic Systems* (DS), *System Dynamics* (SD), *Discrete Event Simulation* (DE) and *Agent-based Simulation* (AB).
Figure 2.2 shows the four simulation paradigms according to their degree of abstraction, level of detail as well as the typical field of application. The horizontal axis shows which paradigms are continuous and which are discrete. [7, p.3]

Dynamic System simulation represents one of the first forms of simulation and includes mainly the virtual reproduction of mechanical, electrical or other technical applications, which are investigated on a micro level. Dynamic System simulation is all about mapping subsystems paying attention to details instead of focusing on whole systems. An example of an application of DS is the simulation of the mode of operation of a single machine instead of an entire factory. Within DS simulation, the level of detail is high to very high, whereas the level of abstraction is low. The
simulation paradigm provides very precise results, but is not flexibly applicable. [7, p.5]

System Dynamic simulation can be seen as the opposite of Dynamic Systems, as the individual machine is abstracted and instead the whole system or factory is simulated. Subsystems are not considered individually within this simulation paradigm. Developing the simulation models is carried out on the basis of realistic integration of global relation of the subsystems. In order to achieve reliable results, precise, respectively accurate sets of data are essential. [7, p.4]

Discrete Event simulation is described as a modelling approach which is based on virtual reproduction of objects. Within this paradigm there is a block structure, also called a statechart, including queues, delays, processing procedures, storing and releasing as well as all sorts of other processes. A statechart resembles a structure including different states, which is, according to fulfilling particular conditions completed discretely. Within Discrete Event simulation, objects are considered passive and can include humans, parts, products, documents, messages, tasks and so forth. The area of application of Discrete Event simulation is diverse and extensive. Applications range from general applications to very specific sample applications. DE is used in areas such as customer service, production and logistics or in other business processes. According to Borshchev and Filippov, DE is defined as a Global Entity Processing algorithm. The authors categorize the level of detail as well as the level abstraction as medium. [7, p.6]
In contrast to Discrete Event simulation, Agent-based simulation uses active objects, which are able to make decisions independently. The large advantage over other simulation paradigms is the wide usability of AB simulation when mapping subsystems as well as whole systems such as the aforementioned machine or factory. The level of detail is dependent on the particular application and can vary from low to very high. Accordingly, the level of abstraction can also vary from a micro- to a macro level. Agent-based simulation is defined as so called *bottom-up modeling*, which focuses on a decentralized, detailed virtual reproduction of subsystems on one side, but allows modelling of entire systems from a holistic perspective as well. [8, p.6]

The perspective of this simulation paradigm is focused on individuals, the so-called *agents*, which have assigned properties and maintain interactions with their particular decentralized surroundings. Dependent on the individual considered mechanisms for adapting the behavior of the particular agent, it is possible to react to (dynamic) changes within the system such as storing- and releasing processes. Dividing the holistic system into individual subsystems allows easier modelling of the subsystems. AB simulation falls into three categories, the agent, the simulation environment and the interactions. The agent represents an active, discrete object, person, etc., which has particular characteristics and reacts to the conditions of its environment including other agents. In general, the agent can only access local
information, which support the decentralized, stochastic structure of an Agent-based simulation model. [8, p.108-110]

Lagemann and Meier investigate a sample application, which is used for modelling different agents and their properties, communication among each other, as well as their interactions with each other. For example, a virtual reproduction of a machine has fundamentally different characteristics (Remote services or predictive maintenance for example), than the agent of a field engineer has (on holiday state, or sick for example). [9]

The interactions or transitions can be triggered through messages or events, which can contain various actions. In the case the machine-agent has a problem due to a failure, a message will be triggered resulting in an action of the field engineer agent (repair the machine for instance). If the field engineer agent is currently not capable of fulfilling the task due to not being available (might be in the holiday state), a follow-up action will be triggered. The level of detail, that can be mapped within this scenario is almost unlimited. [9, p.101-103]

2.3 Development of an Agent-Based Simulation Model

The previous chapter mentioned diverse possible applications of Agent-based simulation, it is only possible to present a generic approach of modeling or extending AB simulation models.
At the beginning of this process is the identification of the problem, as well as an analysis of the status quo. Proposing a problem statement is also essential. Following this step, a concept model will be created and converted into a programming environment. In addition to this, consecutive testing of the model for exposing and eliminating mistakes is required. The next step involves a parametrization and multiple simulation cycles including subsequent plausibility checks of values and conditions.

Figure 2.3: Five stages of developing an Agent-based simulation model [based on 10, p.111]

On the basis of the findings gained through the simulation runs, the characteristics of the agents, the values involved and also the structure of the model and its simulation can be reworked. Once the simulation model has been finalized, the results of additional runs can be analyzed and used for answering the initial problem statement. [11] For allowing further studies or extensions of the simulation model, a detailed documentation of the assumptions of the simulation model, the traceability of the causal connections, as well as the adaptability of the parameters and values involved for matching a particular or new problem statement is essential.
In case the simulation model is required to be used for multiple scenarios including varying conditions, a generic structure needs to be established. In this context, the term *generic simulation* describes a single generation of a simulation environment, that can be applied to multiple, varying scenarios and structures.

### 2.4 Anylogic

*Anylogic* software offers a multimethod modeling environment including Discrete Event, Agent Based and System Dynamics simulation possibilities. Combining different simulation methods offers great potential for achieving the desired level of detail including the appropriate level of abstraction in an efficient way. As most real-world systems are of a complex nature, describing those systems partial using different methods leads to realistic models and therefore realistic results. Accessing different simulation methods with one software leads to an increased convenience and a flexibility for successful solutions to the particular problem. [12]

Furthermore, *Anylogic* software is used widely in industries such as supply chains, manufacturing, transportation, warehouse operations, rail logistics, mining, oil and gas and ports and terminals. [13] The aforementioned orientation of *Anylogic* Software makes it suitable for this research.
3 Research Methodology and Simulation Modeling

Within this chapter, the current research about analyzing the life cycle of pallets throughout the globe is presented. The chapter also lists the most important factors when assessing the life cycles of wooden pallets. Most research approaches follow the principles of ReCiPe 2016, which is explained in further detail in the following section.

Furthermore, the simulation environment, assumptions and models will be presented in detail. All components involved in the model as well as relationships, decision making processes and the general logic applied are described.

3.1 ReCiPe 2016

Most sources of life cycle assessments of pallets presented in this thesis follow the principles of ReCiPe 2016, a harmonized life cycle impact assessment method at mid- and endpoint level of a product, that has been established by the National Institute for Public Health and the Environment of the Netherlands. [14]

The goal of a life cycle assessment (LCA) is to quantify the environmental impacts caused by a product throughout its entire lifespan. As the product is connected to a number of emissions caused by product-related processes such as resource extractions, it is necessary to categorize those emissions in their environmental
relevance. A life cycle impact assessment (LCIA) is carried out in order to help with interpreting the LCA results. Within the LCIA, a number of environmental impact scores are established. Those scores are based on characterization factors, which represent the environmental impact per unit of the stressor. Examples for characterization factors are kilograms of a resource used for the manufacturing process of a product or emissions released related to the production. [14, p. 13]

The characterization factors for the midpoint analysis include particulate matter, anthropogenic tropospheric ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity (cancer), human toxicity (non-cancer), global warming potential, water use, freshwater ecotoxicity, freshwater eutrophication, tropospheric ozone, terrestrial ecotoxicity, terrestrial acidification, land use and/or transformation of land, marine ecotoxicity, fossil resources used and mineral resources used. The midpoint itself is not specified any further than being at some point in the lifespan of a product. According to ReCiPe 2016, the endpoint characterization factors can be summarized as the damage to human health, damage to the ecosystem and damage to the availability of resources. [14, p. 17]

3.2 Assessing the Life Cycle of Wooden Pallets

According to Bengtsson, et al., the life cycle assessment of pallets highly varies on different parameters. In the case of wooden pallets, the environmental impact created is mostly dependent on the area of use and its related distances.
Bengtsson and Logie state that an Australian pallet usually has a worse impact on global warming, than a Chinese pallet. The tables 3.1 and 3.2 show the life cycle impacts for both cases [15, p. 418]. Only in the case of softwood One Way pallets, the impact of the Chinese pallets is above the Australian pallets. The authors justify this higher value due to timber for the Chinese one-way softwood pallet being imported from North America, Australia and New Zealand, whereas the Australian softwood one-way pallet uses domestic timber only [15, p. 416]. According to the authors, single use pallets have a worse environmental impact than pooling pallets, as more single use pallets are required for the same cargo volume. Both tables show a life cycle impact over 1,000 trips, one trip being 50 kilometers or 31 miles on average.

Table 3.1: Life cycle impact results for Australian pallets based on [15, p. 418]

<table>
<thead>
<tr>
<th></th>
<th>Global Warming Potential</th>
<th>Fossil Fuel depletion</th>
<th>ReCiPe endpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg CO₂ e</td>
<td>kg oil equivalent</td>
<td>Pt</td>
</tr>
<tr>
<td>Softwood pallet pooled</td>
<td>599</td>
<td>243</td>
<td>81</td>
</tr>
<tr>
<td>Hardwood pallet pooled</td>
<td>730</td>
<td>297</td>
<td>94</td>
</tr>
<tr>
<td>Softwood Single Use</td>
<td>1,079</td>
<td>520</td>
<td>408</td>
</tr>
</tbody>
</table>
Table 3.2: Life cycle impact results for Chinese pallets based on [15, p. 418]

<table>
<thead>
<tr>
<th></th>
<th>Global Warming Potential</th>
<th>Fossil Fuel depletion</th>
<th>ReCiPe endpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood pallet</td>
<td>437</td>
<td>131</td>
<td>68</td>
</tr>
<tr>
<td>pooled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood pallet</td>
<td>575</td>
<td>166</td>
<td>97</td>
</tr>
<tr>
<td>pooled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Softwood Single Use</td>
<td>1,558</td>
<td>394</td>
<td>414</td>
</tr>
</tbody>
</table>

Koči’s research is focused on energy efficiency of pallets under the standards of ReCiPe 2016. Koči states that a combustion of pallets for energy recovery is a more environmentally friendly solution than putting the particular pallets into landfill. [16, p. 526] Carrano, et al. supports this finding with the following points: An incineration of pallets substitutes the consumption and burning procedures of other fossil fuels. The energy gained from the incineration process of wooden pallet can be utilized for heating, drying or power generation purposes. Recovering the steel from the nails of the pallet results in an environmental credit. Further, the authors state that displacing the combustion of other fuels results in additional environmental credit of the CO₂ equivalent that would have been emitted when burning fossil fuels instead. When put into landfill, pallets will usually be buried and rot under the absence of oxygen. These decomposition processes result in the generation of methane, which is a strong greenhouse gas, that can cause worse impacts on the climate than CO₂. [17, p. 6]
The research of Anil, et al. focuses on a life cycle assessment of wooden- versus plastic pallets in the North American grocery industry. A major point about Anil’s research represents the treatment processes involved in the production of Grocery Manufacturers Association (GMA) pallets. Anil also presents a modeling approach of pallet breakdowns that functions as a major assumption within the simulation model of this thesis [18 p. 877]. Within his research, a transportation sensitivity analysis including roundtrips ranging from 100 to 350 miles involving the manufacturer, distribution centers, clients and retail stores is carried out. Table 3.3 and 3.4 show the results of treated wooden pallets of Anil. [18, p. 877 – 880]

Table 3.3: Sensitivity analysis of wooden pallets to compare various lifetimes [18, p. 879]

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>10 Trips</th>
<th>15 Trips</th>
<th>20 Trips</th>
<th>25 Trips</th>
<th>30 Trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>kg C₂H₃Cl eq.</td>
<td>0.585</td>
<td>0.587</td>
<td>0.588</td>
<td>0.590</td>
<td>0.592</td>
</tr>
<tr>
<td>Ozone layer depletion</td>
<td>kg CFC-11 eq.</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Aquatic eco-toxicity</td>
<td>kg TEG water</td>
<td>917.588</td>
<td>1,021.831</td>
<td>1,126.074</td>
<td>1,230.317</td>
<td>1,334.561</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO₂ eq.</td>
<td>0.614</td>
<td>0.758</td>
<td>0.902</td>
<td>1.046</td>
<td>1.190</td>
</tr>
<tr>
<td>Land occupation</td>
<td>m² org.arable</td>
<td>2.624</td>
<td>2.628</td>
<td>2.631</td>
<td>2.634</td>
<td>2.637</td>
</tr>
<tr>
<td>Aquatic acidification</td>
<td>kg SO₂ eq.</td>
<td>0.133</td>
<td>0.156</td>
<td>0.19</td>
<td>0.202</td>
<td>0.224</td>
</tr>
<tr>
<td>Aquatic eutrophication</td>
<td>kg PO₄ P-lim</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO₂ eq</td>
<td>17.193</td>
<td>20.051</td>
<td>22.909</td>
<td>25.768</td>
<td>28.626</td>
</tr>
</tbody>
</table>
Table 3.4: Sensitivity analysis of wooden pallets to compare various transportation distances [18, p. 880]

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>100 Miles</th>
<th>150 Miles</th>
<th>200 Miles</th>
<th>250 Miles</th>
<th>300 Miles</th>
<th>350 Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-renewable energy</td>
<td>MJ primary</td>
<td>166.852</td>
<td>180.130</td>
<td>193.408</td>
<td>206.686</td>
<td>219.964</td>
<td></td>
</tr>
<tr>
<td>Mineral extraction</td>
<td>MJ surplus</td>
<td>0.271</td>
<td>0.272</td>
<td>0.273</td>
<td>0.274</td>
<td>0.275</td>
<td></td>
</tr>
<tr>
<td>Carcinogens</td>
<td>kg C2H2Cl eq.</td>
<td>0.585</td>
<td>0.586</td>
<td>0.587</td>
<td>0.588</td>
<td>0.589</td>
<td>0.590</td>
</tr>
<tr>
<td>Ozone layer depletion</td>
<td>kg CFC-11 eq.</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Aquatic eco-toxicity</td>
<td>kg TEG water</td>
<td>865.447</td>
<td>943.658</td>
<td>1,021.896</td>
<td>1,100.004</td>
<td>1,178.189</td>
<td>1,256.375</td>
</tr>
<tr>
<td>Terrestrial eco-toxicity</td>
<td>kg TEG soil</td>
<td>179.460</td>
<td>190.829</td>
<td>202.203</td>
<td>213.558</td>
<td>224.924</td>
<td>236.290</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq.</td>
<td>0.542</td>
<td>0.650</td>
<td>0.758</td>
<td>0.866</td>
<td>0.974</td>
<td>1.082</td>
</tr>
<tr>
<td>Land occupation</td>
<td>m2org.ara ble</td>
<td>2.632</td>
<td>2.625</td>
<td>2.628</td>
<td>2.630</td>
<td>2.633</td>
<td>2.635</td>
</tr>
<tr>
<td>Aquatic acidification</td>
<td>kg SO2 eq.</td>
<td>0.122</td>
<td>0.139</td>
<td>0.156</td>
<td>0.173</td>
<td>0.190</td>
<td>0.207</td>
</tr>
<tr>
<td>Aquatic eutrophication</td>
<td>kg PO4 P- lim</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>15.763</td>
<td>17.907</td>
<td>20.053</td>
<td>22.194</td>
<td>24.338</td>
<td>26.482</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>MJ primary</td>
<td>160.211</td>
<td>170.173</td>
<td>180.139</td>
<td>190.087</td>
<td>200.046</td>
<td>210.005</td>
</tr>
<tr>
<td>Mineral extraction</td>
<td>MJ surplus</td>
<td>0.271</td>
<td>0.272</td>
<td>0.272</td>
<td>0.273</td>
<td>0.274</td>
<td>0.275</td>
</tr>
</tbody>
</table>

A closer look at the numbers from this research results shows that the relation between increasing miles traveled or increasing number of trips conducted is linear. An average of 11.477 kg CO2 equivalent is emitted for the production and end-of-life of the average pallet according to Anil, et al. In order to guarantee coherent results, the average trip length in Table 3.3 has to be 13.32 miles.
Furthermore, Anil, et al. presents a detailed overview of the emissions related to producing, using and disposing a pallet as shown in Table 3.5. [18, p. 882]

Table 3.5: Impact Assessment of wooden pallets for each impact category per one trip [18, p. 882]

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Production</th>
<th>Transportation</th>
<th>Heat Treatment</th>
<th>End of Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone layer depletion</td>
<td>kg CFC-11 eq.</td>
<td>2.9E-06</td>
<td>2.7E-07</td>
<td>2.7E-08</td>
<td>-1.2E-07</td>
</tr>
<tr>
<td>Respiratory organics</td>
<td>kg C₂H₄ eq.</td>
<td>6.4E-02</td>
<td>8.9E-04</td>
<td>5.5E-04</td>
<td>-8.6E03</td>
</tr>
<tr>
<td>Aquatic eco-toxicity</td>
<td>kg TEG water</td>
<td>484.019</td>
<td>20.836</td>
<td>82.633</td>
<td>158.343</td>
</tr>
<tr>
<td>Terrestrial eco-toxicity</td>
<td>kg TEG soil</td>
<td>111.925</td>
<td>3.029</td>
<td>14.513</td>
<td>28.289</td>
</tr>
<tr>
<td>Land occupation</td>
<td>m2org.arable</td>
<td>2.104</td>
<td>0.001</td>
<td>0.002</td>
<td>0.239</td>
</tr>
<tr>
<td>Aquatic acidification</td>
<td>kg SO₂ eq.</td>
<td>6.7E-02</td>
<td>4.6E-03</td>
<td>7.3E-03</td>
<td>6.5E-03</td>
</tr>
<tr>
<td>Aquatic eutrophication</td>
<td>kg PO₄ P-lim</td>
<td>8.6E-05</td>
<td>9.2E-07</td>
<td>7.7E-06</td>
<td>3.0E-05</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO₂ eq</td>
<td>7.947</td>
<td>0.600</td>
<td>2.200</td>
<td>2.070</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>MJ primary</td>
<td>90.601</td>
<td>2.654</td>
<td>20.489</td>
<td>26.558</td>
</tr>
</tbody>
</table>

3.3 The Basic Concept of the Simulation Model and its Variations

Due to the limitations of the educational software version used in this thesis, the original concept of the model, which is displayed in figure 3.1 had to be scaled down to a reduced version, displayed in figure 3.2. The newer version includes less details than the previous concept. The recycler has been included in the end-of-life states, the pallet manufacturer has been integrated in the consumer product manufacturer, the raw-material and reseller have been discarded. The
maintenance instance as well as the end-of-life state no longer display as independent agents. However, even with a lower number of independent agents, the level of detail is only slightly reduced. The dark blue arrows represent the main product-pallet flow. Purple arrows are related to the end-of-life state. Solid arrows show the main flow of the system, whereas dotted arrows represent secondary flows. Red arrows are related to either maintenance or stocking up pallets in case they are required. Light blue arrows are related to the recycling processes of pallets.

*Figure 3.1: Original simulation model concept of a cost pass through pallet management system*
The new modelling approach in figure 3.2 offers the advantage of a more flexible concept. With only minor changes to the simulation modelling environment, the other pallet management strategies can be adapted. The two faded instances *Maintenance* and *End-of-Life / Recycler* still gather data and are used within the system, but do not work independently. Locations for these instances are not specific. Therefore, it is assumed that every instance repairs pallets themselves in-house.
Figures 3.3 and 3.4 show the basic working principles of the PSU- and PDU-system, using dark blue solid arrows for the main product/pallet flow. Displayed in purple (solid and dotted) are the possibilities for disposing pallets. As this concept is about using pallets only once, there are no further instances or processes involved such as maintenance or returning pallets to the CPM. Within all modelling approaches, the main supply chain always stays untouched. This results in the advantage of creating equal scenarios including equal locations and therefore equal distances traveled for a better comparability of the results. Within the PSU approach, sudden failure of pallets is not considered.
The PDU strategy has all entities of the PSU system, but utilizes the softwood pallets for a second time. After transporting two products to the retailers, the pallets will reach their end of life. Neither maintenance nor sudden failure is considered within this approach.

*Figure 3.5: Actual concept for the simulation*

*Figure 3.5* shows the basic working principle of the Pallet Rental Service system. Similar to the previously mentioned principles of the other simulation models, only the main supply chain has independent agents and the pallet rental service functions as a passive participant. However, at this model, maintenance is carried out by the pallet rental service provider.
3.4 Assumptions, Boundaries and Constraints

Every simulation model and its modeling approach needs assumptions as a foundation. Those assumptions are a combination of information gathered from data sheets such as: size of pallets, carrying capacity of pallets, vehicles, throughput of a factory, lead-times, average speed of vehicles and many more. *Figure 3.6* shows an example of a data sheet for pallets.
Figure 3.6: Data sheet of the World pallet including the measurements and carrying capacity [19]
Previous research within this field also contributes valuable information, such as life expectancy of pallets. Other assumptions are specific to the model being developed, in order to achieve the desired level of detail. In this research, that includes assumptions about wear and tear of the pallets.

In this research, simulation models are produced to represent a mock supply chain, which does not exist in the real world. However, the design of the models is such that adaptability to real world scenarios and specific problems with minor changes to input-data files is possible.

In total, a simplified version of a supply chain including a consumer product manufacturer, three distributors and twelve retailers is modeled. Products will be created by the consumer product manufacturer and then passed along to distributors and then retailers. Attached to each product is a pallet, which in some modeling scenarios will be fed back into the supply chain at the consumer product manufacturers location. Every instance of the supply chain uses trucks for delivering the products and pallets. The logic and organizational structure of the model will be discussed in further detail in the following sections.

In total, the four different simulation models include a cost pass through system (CPT), a Pallet Rental Service based system (PRS), a Pallet Single Use system (PSU) and a Pallet Dual Use (PDU) system. Within the Cost Pass Through system, high quality hardwood pallets are passed along all instances of the supply chain,
transferring the ownership of the pallet accordingly. After reaching the retailer, the pallet will be returned to the consumer product manufacturer to repeat the process. The Pallet Rental Service based system works accordingly, but instead of paying the actual price for each pallet, a rental fee is charged. All maintenance related activities, however, are carried out by the pallet rental service. The Pallet Single Use system focuses on One-way softwood pallets, that come at a cheaper price, but can only be used for transferring a single product through the supply chain before being discarded. The Dual Use Pallet system utilizes the same softwood pallets of the Single Use system, but uses them twice before disposal.

The educational version of the agent-based simulation software Anylogic offers only limited features. Those limited features resemble natural constraints for the model-building. The constraints include:

- A maximum lot size of 3965 participants per agent
- A maximum of ten agents
- No program-internal use of databases and spreadsheets

The boundaries of the model are determined to be:

- Limited usability of flow charts
- Limited number of messages used within the model to trigger actions

Assumptions of the simulation-model include:

- All different types of pallet management strategies are based on the same model, but include slightly varying values.
- The scenario is based on 28 locations ranging from the northeast coast of the United States to Lake Michigan. A total of eight participating groups including three different vehicle fleets are created.

- These participating groups include:
  - One Consumer Product Manufacturer (CPM)
  - Three Distributors (Dist)
  - Twelve Retailers (Ret)
  - Seven CPM Trucks
  - 15 Distributor Trucks
  - Twelve Retailer Trucks
  - 3965 Products
  - A variable number of pallets (up to 3965)

- Each truck fleet has varying characteristics including speed, capacity, loading- and unloading times.

- The distributors within the model get assigned different destinations following a sustainability approach. This approach is explained in further detail in section 3.6.

- All locations of the model are randomly picked including 16 out of 28 possible locations (for 1 CPM + 3 Dist + 12 Ret).

- The number of possible combinations can be calculated similarly to a lottery draw, but with multiple cycles without putting the selected locations back into the pool of locations. Therefore, it is defined as the
product of the number of combinations of each participating group without respect to each occurring order:

\[
\text{combinations}_i = \binom{n}{k} = \frac{n!}{k!(n-k)!}
\]

\[
\text{combinations}_R = \binom{28}{12} = \frac{28!}{12!(28-12)!} = 30,421.755
\]

\[
\text{combinations}_D = \binom{16}{3} = \frac{16!}{3!(16-3)!} = 560
\]

\[
\text{combinations}_{CPM} = \binom{13}{1} = 13
\]

\[
\prod \text{combinations}_i = 2.214703764 \times 10^{11}
\]

- The consumer product manufacturer creates its products out of nothing. A supply chain for raw materials or components is not included in the model. Also, pallets spawn directly at the consumer product manufacturer due to the limitations of the model.
- The consumer product manufacturer does not fabricate faulty products.
- Trucks and other vehicles do not break down or fail
- Varying emissions caused by varying traffic conditions such as those created by traffic jams or rush hours are not considered.
- Different end of life (EoL) states such as recycling or incineration are not separately simulated. Once a pallet has reached the end of its life, it will simply be added to an end-of-life list.
- The randomly chosen locations are clustered in different regions including West, Mid and East.

- Pallets have a designated expected lifespan and market value. Pallets depreciate and wear out, but cannot suddenly break. Depending on a decision based on probabilities (see section 3.7.7), a pallet can be repaired and or sent to EoL states. The lifespan of pallets is randomly picked from the x values of four different normal distributions, one per life stage. Therefore, the total number of life stages is limited to four before being disposed. The model of pallets including the distributions will be explained in further detail in section 3.7.7.

- Pallets that have reached the end of life will be disposed locally within a range of ten miles.

- In order to distribute products and pallets randomly, probability-based decisions for routing are carried out by the products. The decision-making procedures of routing will be explained in further detail in section 3.7.2.

### 3.5 The GIS Map

GIS map stands for Geographical Information System map. The principle of a GIS map-based simulation includes accessing information from a database through the internet. As the name already states, this information is of a geographical nature. The simulation software makes it possible to model locations through GIS points on the map. These GIS points can either be defined through setting latitude- and
longitude coordinates or through searching the address through the search engine of Anylogic. After the GIS points are defined, it is not necessary to model any distances between them as all required information is provided by the database. However, it is possible to set a specific route, if desired.

Realtime data about traffic situations and dynamic driving profiles of the particular transport vehicles involved are not accessed. An average speed of the particular transport vehicle is set by the user (see section 3.7.4). The vehicle itself will pick a matching route based on actual roads instead of straight lines.

The GIS maps in these scenarios represent a key aspect of the simulation model. The entire supply chain, the relationships and transport vehicles will be included in the map. Pallets and products are included as well, but will not be displayed.

3.6 The Excel Databases

As it is desired to adapt the simulation model to a specific environment of particular supply chain networks in the real world, the design of the simulation model is generic. To create a generic model, it is necessary to model the dependencies and properties of each instance involved in the supply chain in a variable manner. In order to achieve this, the information required for setting up a specific model is to be stored in multiple external Microsoft Excel files instead of within the simulation model environment itself. Within the model, only variables such as ‘location’ will be
stored and then assigned a specific value or string through reading the particular cell from the Excel sheet.

Achieving a randomized scenario involves a pre-defined catalogue of data, that will be selected at the start of each simulation run, or scenario. Generally, randomizing the data can either be carried out through Anylogic or Microsoft Excel. For the sake of simplicity as well as user-friendliness, this modelling approach focuses setting all required parameters through Microsoft Excel. For example, each location is linked to a random number. Through the reload function of Excel, the random numbers can be re-created with varying values. Then, the user can sort these random numbers either in ascending or descending order, sorting the locations accordingly, and creating a new scenario.

For all models, the first 16 cells in Excel define the locations of the participating groups. Following the assumption that disposing waste is a non-value adding activity, costs and therefore distances traveled related to this activity have to be kept as low as possible. For the modeling approach, this means that whenever a pallet has reached its end of life, it will be disposed by the current owner locally including a standardized distance of ten miles. Each instance involved in the supply chain gets assigned a regional end of life location, which are not specified in further detail. The data read from the Excel files include locations of each participant, market shares, number of trucks per participant and destinations, which are assigned to particular other participants.
As no organizational structure is created, problems such as which distributor is responsible for which retailers occur. The goal is to establish a decision algorithm, which determines that every single retailer gets product deliveries by one distributor only. A retailer shall not be supplied by two or zero distributors. As there are a total of three distributors, all possible retailer locations have been split into three different sectors, East, Mid and West. According to the locations of the distributors, these sectors will be operated by the particular distributor. This means that a distributor which is located in Boston will deliver products to all retailers located in the sector East. If located in New York City, the distributor will supply all Mid-retailers with products and if located in Detroit, the West-sector will be supplied.

However, the randomness of the generic structure of the Excel file also causes problems such as all three distributors being located in the East, leading to all three distributors supplying only the East sector with products, but none to Mid and West. In order to solve this conflict, an algorithm for changing the catchment areas of the required number of distributors has been created. Table 3.6 gives an overview of some possible conflict scenarios and their step-by-step solutions. This algorithm follows an approach, that is focused on sustainability. One of the basic principles is to change as few catchment areas as possible. If Distributor 1 and 2 are located in the East and three is located in the center, Distributor 2 will change its catchment
area to West, instead of shifting Distributor 2 and 3. A total of all possible 27 scenarios is considered in the solution finding algorithm.

Table 3.6: Overview on particular conflict scenarios and their solutions

<table>
<thead>
<tr>
<th></th>
<th>Distributor 1</th>
<th>Distributor 2</th>
<th>Distributor 3</th>
<th>Distributor changes value to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Problem</td>
<td>East</td>
<td>East</td>
<td>East</td>
<td>Dist 1 = Mid</td>
</tr>
<tr>
<td>1st Iteration</td>
<td>Mid</td>
<td>East</td>
<td>East</td>
<td>Dist 3 = West</td>
</tr>
<tr>
<td>2nd Iteration</td>
<td>Mid</td>
<td>East</td>
<td>West</td>
<td>Solved</td>
</tr>
<tr>
<td>Initial Problem</td>
<td>East</td>
<td>Mid</td>
<td>East</td>
<td>Dist 3 = West</td>
</tr>
<tr>
<td>1st Iteration</td>
<td>East</td>
<td>Mid</td>
<td>West</td>
<td>Solved</td>
</tr>
<tr>
<td>Initial Problem</td>
<td>East</td>
<td>East</td>
<td>West</td>
<td>Dist 2 = West</td>
</tr>
<tr>
<td>1st Iteration</td>
<td>East</td>
<td>West</td>
<td>Mid</td>
<td>Solved</td>
</tr>
<tr>
<td>Initial Problem</td>
<td>West</td>
<td>West</td>
<td>West</td>
<td>Dist 1 = East</td>
</tr>
<tr>
<td>1st Iteration</td>
<td>East</td>
<td>West</td>
<td>West</td>
<td>Dist 3 = Mid</td>
</tr>
<tr>
<td>2nd Iteration</td>
<td>East</td>
<td>West</td>
<td>Mid</td>
<td>Solved</td>
</tr>
<tr>
<td>Initial Problem</td>
<td>Mid</td>
<td>Mid</td>
<td>Mid</td>
<td>Dist 1 = West</td>
</tr>
<tr>
<td>1st Iteration</td>
<td>West</td>
<td>Mid</td>
<td>Mid</td>
<td>Dist 3 = East</td>
</tr>
<tr>
<td>2nd Iteration</td>
<td>West</td>
<td>Mid</td>
<td>East</td>
<td>Solved</td>
</tr>
</tbody>
</table>

3.7 The Agents

The following section gives a detailed overview of all agents involved in the models, their relationships, decision making procedures and input- and output data including the particular variables and parameters.
3.7.1 The Main

The main of each model resembles the central point of the simulation program. At the beginning of the simulation, the input data is read, populations of agents are created and randomized numbers and probability distributions are calculated within the main. Upon model start, different functions for carrying out these tasks are started. The main functions as the central communication interface of all participating agents. Whenever an agent wants to interact with another agent, information will be transferred through the main. Figure 3.7 and 3.8 show the user interface of the agent main.

Figure 3.7: Overview of all agents, parameters, input- and output files, functions and distributions of the main

The parameters Amounts list the total number of each agent population. The amounts of each population are mainly required as a counting measurement for
loops in order to create or assign characteristics. The product- and pallet distributions will be explained in the particular sections of those agents. Most agents are created through Anylogic automatically, however, some information is not fully assigned automatically. Therefore, the function read_Information adds the missing data for the consumer product manufacturer, the distributors, the retailers and the pallets. The function create_Trucks establishes all three truck fleets with their sub-fleets according to the information read from the Excel file trucks. This Excel file however, only includes the following four parameters for each truck: capacity, loading time, unloading time and average speed. The information of the initial location as well as the sub-population of every truck sub-fleet is read from the locations Excel file. For example, there are a total of 15 trucks for three distributors. Each distributor has a sub-fleet of five trucks at its initial location, therefore it is necessary to distinguish between each case. Assign_Destinations represents the counter part of a decision algorithm established in the locations.xlsx Excel file. This decision algorithm will be described in section 3.7.5. Basically, this function assigns a retailer to its matching distributor. The function read_Market_Shares transfers the information about market shares of distributors and retailers to the particular participant. The market shares play a central role for routing the product. Each distributor’s market share is proportional to the number of retailers assigned to the particular distributor. Therefore, the market share of each distributor is defined as:

\[ market\ Share\ Dist = k \times \frac{1}{n} \]
with \( k = \text{number of retailers of particular distributor} \)

and \( n = \text{total number of retailers} \)

For the market share of each retailer, the retailers are clustered into three subgroups including retailers east, mid and west. The market share of each sub-group-retailer is defined through the fraction of a random number, divided by the sum of all random numbers of that sub-group multiplied with the market share of the matching distributor. Therefore, it is defined as:

\[
\text{market Share Ret} = \text{market Share Dist} \times \left( \frac{r}{\sum r_i} \right)
\]

with \( r = \text{random number assigned to retailers} \)

The function \textit{route_Product} will be explained in further detail in section 3.7.2. \textit{Adding_Product_Information} sets the spawn point of each product depending on an arrival rate based on the \textit{arrival_Rate_CPM_distribution}.
Figure 3.8: Presentation of the GIS map including the agents Consumer Product Manufacturer, Distributor, Retailer and particular trucks

Figure 3.8 shows the animations of every agent type included in the model except for pallets and products. Within the simulation process itself, every agent population will be displayed in its correct number at its correct location. The red factory is the consumer product manufacturer, the yellow warehouse resembles the distributor and the green store is the retailer. The red semi-truck belongs to the CPM, the blue truck to the distributor and the yellow truck to the retailer. The consumer product manufacturer involves 15 pallet handlings in its processes, the distributor uses 10 handlings and the retailer 9 handlings, leading to a total number of 34 pallet handlings per delivered product.
3.7.2 The Product

The mode of operation of the product differs from a real-world application. Other than having a demand created by a customer and communicated to a retailer and then to the manufacturer, the product within this model gets pushed into the market. As the goal of this simulation is not about modeling a close-to-reality market behavior, the product chooses its way itself. Even though a product is a passive object in the real world, in the simulation environment, it is modeled as an independent agent. Therefore, the product can actively make decisions comparable to the supply chain agents or trucks. In order to carry out this behavior, the product is involved in two similar decision-making procedures. Through the product distributions \textit{products\_random\_number\_Dist\_distribution} and \textit{products\_random\_number\_Ret\_distribution}, each single product gets a random number between zero and one based on 100 observations of a normal distribution. The counterpart to this random number is the market share of each distributor and retailer. After comparing the random number of the product with the market share of the other participant, the decision for routing the product is made. In order to be able to distinguish between the participants, it is necessary to sum the different market shares. \textit{Figure 3.9} shows a graphical representation of this process.

\textit{Figure 3.9}: Decision process for choosing the distributor of a particular product
The above-described decision-making process is triggered by the function \textit{route\_Product} in the main. \textit{Figure 3.10} shows product-agent. The parameters of the product include the product number, the random numbers for distributor and retailer described above, the arrival rate and based on the arrival rate the spawn time.
Also, the initial location gets read in as a string from the locations Excel file described in section 4.5.1. The variable initial_Location2 is a conversion of initial_Location, where the data type is changed from string into GIS point. The
variable *corresponding_Pallet* is a link to the particular pallet-agent, which gets attached to this product while being transferred through the supply chain. *Pallet_Solved* is a variable of the type Boolean, which is used by the corresponding distributor-agent in order to check the status of the attached/corresponding pallet.

Every single agent of this model has an initializing-state with an attached transition triggered by a timeout of one minute to allow all required information to be read in and set up. As the original idea of using flow charts within the model does not allow the possibility of a one-minute delay before working, flow charts have led to problems caused by missing information. Therefore, flow charts have been abandoned and the entire model has been based on state charts instead.

The *Order_Income* state is reached after initializing and left once the spawn time of the particular product is reached. Once the product is at the consumer product manufacturer, it sends out a message to the CPM calling for a pallet to be attached to the product. After the pallet is attached, the CPM responds with a message releasing the product with the attached pallet for shipping. The product will only be shipped once the corresponding waiting queue size matches the capacity of the CPM truck. When the truck reaches the particular distributor, the product will be unloaded from the truck, dispatched by the distributor and released for shipping to the retailer. It will be sent out to the matching retailer once a condition according to the previous shipping condition is met. The distributor truck will leave the distributor when the waiting queue is transferred to the truck bed. Once the truck
reaches the retailer and the product gets unloaded, it receives a message from the truck triggering the *At_Retailer* state. At the retailer, the product gets separated from the attached corresponding pallet and disposed to a sink. The product is considered sold at this point, but will be saved on a list at the retailer-agent for writing results.

### 3.7.3 The Consumer Product Manufacturer

The consumer product manufacturer represents a major part within the simulation environment. It functions not only as the spawn point for products and pallets, but also *stores* used pallets for all other agents due to simplifications made in the coding structure. *Figure 3.11* gives an overview of the consumer product manufacturer of the cost pass through model.
The CPM has different parameters, which represent read in data from the Excel file. These parameters include `no_Of_Trucks`, `pallet_Handlings_CPM` and the `location`. Also, the CPM has different counters such as the `reuse_Pallet.Counter`, the `out_Of_Use.Counter`, the `new_Product_Number` or the `new_Pallet_Number`. The `reuse_Pallet.Counter` for example counts every single time, a used pallet gets fed into the supply chain again. The `out_Of_Use.Counter` determines how often pallets reach the end of a life-stage and need either repairing or disposal. The two

**Figure 3.11**: Parameters, variables, collections, events and the state chart of the consumer product manufacturer agent
variables new_Product_Number and new_Pallet_Number are, the newest product and pallet currently processed and also a counter for the sum of all new products and pallets that are fed into the system. All of these counters are of the type integer. The variables actual_Product, available_Truck, Distributor_1 – 3, load_Product and acutal_Truck are all linked agents involved in different actions. The remaining parameters, variables, events and collections will be explained in the context of the state chart.

At the beginning of the simulation, the event Setting_Dist_Destinations will link all three distributors of this simulation to the variables Distributor_1 – 3. These variables function as destinations for all products. After initializing, the CPM remains idling until it receives a message by the product agent for attaching a pallet. Once it receives this message, the pallet demand of the consumer product manufacturer will be increased by one and the inventory control state will be entered. Within the inventory control, the decision for choosing a matching pallet is made. Also, the pallet handlings of the CPM are carried out within this state. Used pallets, if available in the pallet pool, are prioritized against new pallets in order to follow a sustainability approach for reusing already existing resources. The used pallet, however can have a smaller number of pallet handlings left in its lifespan than required by the CPM. In this case, the current pallet will receive a message triggering an out-of-use-state of the pallet. The out_Of_Use_Counter will be increased by one. The CPM will then re-decide which pallet is most suitable. It will re-consider used pallets until either a suitable pallet is found or until there are
no used pallets left in the pallet pool. In the second case, a new pallet will be chosen and the new pallet counter will be increased by one. The attaching process of the pallet includes linking a particular pallet-agent to the matching product. From this point on, the pallet itself will not be addressed directly, but always through the corresponding product agent in order to always guarantee the correct pallet is used. The variable pallet Demand 2, which functions as a reproduction of the variable pallet Demand, will be decreased by one. Duplicating the original pallet demand in the first place is required to allow a comparison-based condition for ending the decision loop of attaching the correct pallet. Besides choosing and attaching a suitable pallet, the budget of the CPM spent on pallets will be adjusted according to the current market value of the particular pallet. In the case of a pallet breakdown, the pallet Sales CPM will be increased by $5 always within the CPT system. In the case of the PRS, this calculation does not apply. Also if a softwood pallet, used in the PSU and PDU system break, they will be disposed without any sales. Once the CPM is done with the required actions of this state, it will send itself a message to continue with the dispatch of the product/pallet. Also, another message will be sent to the product triggering the transition to the state Shipping To Distributor (section 3.7.2).

When entering the dispatch state, the CPM decides which distributor will receive the particular product-pallet-combination. Therefore, three different product queues have been established resembling badges of products and pallets for shipment. The reoccurring event checking Truck Availability, that takes place
every 180 minutes, determines if there are any free trucks at the consumer product manufacturer. If required, this is achieved through accessing every single truck-agent of the corresponding fleet and checking the status. The status of the particular truck can either be set to busy or available. The status of the truck will only be available if the truck is empty and stationed at the location of the CPM. When the first truck is busy, the second truck will be accessed and checked, following the third if busy, and so on.

After leaving the dispatch state, a branch will be entered. Following different conditions, the next state will be chosen. If none of the number of entries of each product queue matches the available truck bed capacity, the CPM will return to the idling state. If a product queue size is equal to the matching truck bed capacity, the particular truck will be loaded. The information of the truck agent will also be duplicated as actual_Truck. This back up is required to avoid following communication problems between the CPM and the truck, when leaving the CPM. The same principle applies for the variable loading_Product, which is a duplication of the variable actual_Product. Once the truck is loaded, the status of the truck is changed to busy. After entering and leaving the Shipping state, the truck leaves the CPM and the CPM returns to the branch and then to the idling state.

The pallet pool collection has been split into three different pallet pools, one for each instance of the supply chain. When more than one agent tries to access a single pallet pool collection simultaneously, hierarchy problems occur. As the
simulation program has no strategy for deciding who can access a list with high priority, establishing a hierarchy is required. Creating a hierarchy would have caused significant additional effort, leading to a different solution for this problem. According to possible real-world solutions, three different pallet pools have been established. Each individual agent population can only access their own list or pallet pool, leading to a less efficient, but arguably more realistic solution. Once a pallet has reached its end of life, it will be added to the collection _pallet_End_Of_Life_. At 520.000 minutes (day 361), the event _writing_Results is triggered and will save all important gathered data to the Excel file _results.xlsx_. Theoretically it should be possible to write all results within the last minute of the simulation (525.600 min). However, a point at 520.000 minutes has been chosen as time stamp in order to allow all agents involved in the simulation to have enough time for writing the results without any errors. At this point in the simulation, all 3965 products will have traveled through the system and the simulation remains idling throughout all scenarios and all models.

### 3.7.4 The Trucks of the Simulation Model

As mentioned in section 3.3 each part of the supply chain has its own fleet of trucks. However, all three truck agents only show minor differences to one another. This is the reason why they are described in this section for the example of the CPM truck.
After every truck is created following the principles explained in section 3.7.1, every sub fleet of trucks spawns at the particular location. This means seven trucks are available at the consumer product manufacturer, five trucks at each distributor and one truck at every retailer. The truck-agents differ from one another in size, shape, average speed, loading- and unloading times, locations and destinations. A population of a particular truck type, the CPM trucks for example, do not vary in their characteristics. Figure 4.11 shows the working principles of the truck agent at the example of the CPM truck.

Figure 3.12: Parameters, variables, collections and the state chart of the consumer product manufacturer agent
Every type of truck is only capable of addressing a single type of agent for delivering products and pallets (only products in the case of the retailer truck) and will return to its home location afterwards. Milk runs have been tested, but have proven to be inefficient in their logic. Milk runs will be discussed in further detail in section 3.7.5.

The parameters `capacity, loading_Time, unloading_Time` and `speed` are read in through the `create_Trucks` function in the main (see section 3.7.1). The initial location of each truck will be assigned according to the matching distributor. The variable `initial_Location2` utilizes the string from `initial_Location` and converts it into a GIS point for spawning the particular truck. The status of each truck is set to `available` by default and will be changed to `busy` once the truck gets loaded. This parameter is required for evaluating which truck can currently be used for the next transport. The `distributors` collection is the sum of all distributors, whereas the destinations are a limited number of destinations chosen from the `distributors` collection. As every CPM truck addresses every distributor, `destinations` and `distributors` have the same entries listed. The `product_Queue_Dist` collection is a collection of products, which resembles the cargo transported by the truck. The variable `unload_Product` is a variable for deleting the last product from `product_Queue_Dist` and adding it to the next collection `product_Delivery_Dist` of the distributor agent. `Actual_Truck` represents the actual number of the particular truck and is used for counting purposes. The variable `where_To` of type distributor (agent) determines the next product delivery destination of the truck.
After the initializing process, the truck will remain at the CPM, before being loaded. Triggered by a timeout of the loading time, the truck will leave the CPM, once it receives a message to do so. At this point, the truck will enter the $Moving\_To\_Distributor$ state until it reaches its destination. At the destination, the unloading process will be carried until the truck is empty. After another delay of the length of the unloading time, the truck will return to the CPM. Once reaching the CPM, the status will be reset to $available$, where $To$ and $unload\_Product$ will be set to null in order to avoid double use of entities. In the case, $unload\_Product$ would not be reset, it can happen that a product, which has already been loaded, transported and unloaded will falsely repeat this process. This leads to doubling an agent and also leads to additional problems when this agent is involved in further processes. The figures 3.13 and 3.14 show the truck agents for the distributor and retailer.
Figure 3.13: Parameters, variables, collections and the state chart of the distributor agent

Figure 3.14: Parameters, variables, collections and the state chart of the retailer agent
Table 3.7 gives an overview about the entities of the trucks involved in all simulation models.

Table 3.7: Data sheet of all truck types involved in the simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>Total number of trucks</th>
<th>capacity [pallets / products]</th>
<th>speed [mph]</th>
<th>loading time [min]</th>
<th>unloading time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPM Truck</td>
<td>7</td>
<td>21</td>
<td>35</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Distributor Truck</td>
<td>15</td>
<td>21</td>
<td>35</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Retailer Truck</td>
<td>12</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

The differences in loading and unloading times have been chosen in order to evaluate, if these differences affect the rest of the supply chain operations. The assumption behind the varying capacities is due to different truck sizes. It is assumed, that for transporting the combination of products and pallets, large semi-trailer trucks are required. When returning the pallets, this can be carried out by smaller trucks, that can carry more pallets, as they do not transport any products. Also, it is assumed, that the smaller trucks have a slightly increased average speed due to a better maneuverability. As none of the trucks involved in the simulation only uses interstates, a more conservative, slower average speed is assumed.
3.7.5 The Distributor

The distributor agent includes tasks such as receiving products and sending them further down the supply chain to the particular retailer. After receiving products and pallets, the following dispatch includes checking if the attached pallet is still in working condition. Also, in case the pallet needs exchanging, the distributor will swap the pallet for another used pallet in case pallet\_Pool\_Dist (section 3.7.3) has suitable entries left. The decision process of choosing a suitable exchange pallet is similar to the decision process of the CPM (see section 3.7.3). In case there are no suitable pallets left in the pallet pool, the distributor will choose a new pallet. The distributor will also carry out their pallet handlings and reduce the lifespan of the corresponding pallet by this number.

In an earlier modeling approach, milk runs have been included in the model structure. A milk run represents a delivery with more than one destination along the route. An example of a desired layout of a milk run is shown in Figure 3.15. However, finding a way of designing this layout has led to major problems. As there have not been functions available for determining distances between each agent, an intelligent design for a generic scenario has not been achieved.
Through a sorting algorithm, all products, which are routed to the same retailer are deleted from the truck bed at the matching location, whereas the next remaining product entry determines the next destination. Once the truck is empty, it will return to its home location. This algorithm has led to the possibility of addressing multiple retailers within one trip, but also caused an unintelligent design as shown in figure 3.16. Besides major impracticalities of this design, problems such as doubling listed product agents and wrong routing have occurred. This behavior can be compared to the previously in section 3.7.5 (p. 56) described behavior. Therefore, a simpler solution that only addresses a single retailer per trip has been established in the modeling structure.
Figure 3.16: Actual layout of milk runs included in the simulation model carried out by distributor trucks.

Figure 3.17 gives an overview about the entities of the distributor agent. The variable current_Retailer is required for the event setting_Ret_Destinations, which sets up the retailer destinations of the particular distributor agent, once the simulation is started. This event also needs the collection retailers for the set up. The re-occurring event checking_Truck_Availability determines which truck is available for transporting goods. This event utilizes the same principles as the equivalent event of the CPM agent, see section 4.5.3. Other equalities are found in the parameters, variables and events location, no_Of_Trucks, market_Share, pallet_Demand_Dist, pallet_Budget_Dist, pallet_Sales_Dist, available_Truck_Dist, actual_Product_Dist, actual_Truck_Dist and wiritng_Results, which all work
accordingly to the equivalent entities of the CPM agent.

Figure 3.17: Parameters, variables, events, collections and the state chart of the distributor agent

The parameter number, however, resembles the catchment area of each distributor, which is described in section 3.3. Within the code of the model, the strings *East*, *Mid* and *West* are translated to the numbers 1, 2 and 3. The parameter *matching_Number* is a counting variable, which is used in other decision-making loops.

The distributor agent will leave the idling state once a delivery arrives. This is achieved when the collection *product_Delivery_Dist* has more than zero entries. Within the *Reviewing_Delivery* state, the distributor checks the attached pallets for suitability, carries out their pallet handlings, increases the cost spent on pallets and
adds the reviewed products to the collection \textit{product\_Delivery\_reviewed}. Similar to the CPM, the distributor will prioritize used pallets for exchanging the current pallet, when required. Only if no used pallets are available, the distributor will order a new pallet. Once these actions are finished, the distributor will enter the \textit{Dispatch} state and add the reviewed delivery items to the particular retailer destinations. Every \textit{product\_Queue\_Ret} resembles a list of products that will be ready for shipping, once the size of a queue reaches the capacity of the available truck bed. After leaving the \textit{Dispatch} state, the distributor enters a branch, where it decides to either send out a shipment or return to idling. The condition for choosing the return to idle option is fulfilled if no product queue has a matching size of the truck capacity. Within the transition to the \textit{Shipping} state, the loading process of the distributor truck is carried out and the \textit{pallet\_Sales\_Dist} will be increased according to the market value of the particular pallet. Once the loading process is completed, the variable \textit{actual\_Truck\_Dist} will save the information of the current truck and the shipment will be triggered.
3.7.6 The Retailer

The retailer agent represents the last part of the supply chain. The retailer is responsible for selling the product and returning the pallets to the start of the supply chain, the consumer product manufacturer. In some parts of the basic principles of functioning, the retailer agent is similar to the distributor agent. Figure 3.18 gives an overview about the entities of the retailer agent. At the start of the simulation, the function `setting_CPM_Destination` determines the consumer product manufacturer destinations based on the collection `destinations`. Technically, it can be more than one CPM, but all models used in this research have one CPM agent only.
Figure 3.18: Parameters, variables, events, collections and the state chart of the retailer agent

At the point where the retailer agent receives a delivery, the idling state is left. Also, products and pallets are separated within the Reviewing_Delivery state. The product will be added to the product_Delivery_Ret collection. After reviewing the entries, the product will be disposed and stored in the sink collection. The corresponding pallet agent that arrives with the products will be separated from the product, reviewed and then added to the return_Pallets collection. The pallet handlings are carried out and the pallet lifespan will be reduced by the number of
handlings. As in the previous cases, the pallet will be substituted by a used or new pallet, if necessary. Within this state, also the Budget spent on pallets will be adjusted according to the current market value of the particular pallet. After leaving the Reviewing_Delivery state, the Dispatch state is entered and left immediately again. In the case of the retailer, the dispatch state is a place holder for further details that may be added. Following the dispatch state is another branch, that works according to the branches discussed in the previous agents. In case the return_Pallets collection size matches the capacity of the retailer-truck bed, a shipment will be triggered. Otherwise, the retailer will return to idling, waiting for the next delivery. All other variables including actual_Pallet_Ret, load_Pallet, available_Truck_Ret, destination and actual_Product_Ret work in the same way as previously discussed equivalent variables of the other agents.

3.7.7 The Pallet

The pallet is the last agent involved in this simulation model. Figure 3.19 shows the pallet agent including all its entities and state chart. In total, a pallet can have up to four different stages before reaching its end of life. It is not guaranteed, however, that the pallet will last that long.
As with all other agents, a total population of agents will be created at the startup of the simulation. The total number of pallet agents created is equal to the total number of product agents created. The status of each pallet, however, will determine whether the particular pallet has been used within the system or not. Unused pallets will not be considered within the results. Once a pallet gets activated through an incoming order, the particular pallet will open the results Excel file and document its status and different lifespans. The lifespans are defined by the normal distributions within the main agent (see section 3.7.1). In total, there are four different normal distributions including four different mean values and also
different variances for the different stages of life also called lifespans. Table 3.8 gives an overview about the different distributions.

Table 3.8: Normal distributions for all different lifespans of a wooden pallet for scenario 1 of the CPT model

<table>
<thead>
<tr>
<th>Lifespan</th>
<th>Mean $\mu$</th>
<th>Variances $\sigma^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lifespan 1</td>
<td>153</td>
<td>12</td>
</tr>
<tr>
<td>lifespan 2</td>
<td>122</td>
<td>12</td>
</tr>
<tr>
<td>lifespan 3</td>
<td>97</td>
<td>7</td>
</tr>
<tr>
<td>lifespan 4</td>
<td>67</td>
<td>22</td>
</tr>
</tbody>
</table>

The idea behind this model of wear and tear is to establish decrease the maximum possible lifespan of every pallet every time it gets repaired. It is assumed that a refurbished pallet will not be of the same quality as a new pallet. It is also assumed, that used pallets are taken apart for parts. The quality of these parts is comparable to car parts from a junkyard: They remain in working condition, but is uncertain for how long. Therefore, the variance of the third repair is higher than in previous repairs. The pallet is now idling and will leave the idling state after being attached to a product. As not all pallets will have reached the end-of-life state, when the simulation is completed, it is necessary to document the required information at the end. The original goal was to document the current remaining lifespan, the status, current location, no_Of_Transports and no_Of_Repairs at the end of the simulation run. This, however, has led to a problem when executing this order, as
in all scenarios at least 1,300 agents will try to access the Excel file at once. Theoretically, this should not be an issue, in reality it leads to not executing the writing of results order and therefore to a lack of results. Subsequently, another solution to solve this problem had to be found. Therefore, every single pallet agent will return to idling every 50,000 minutes and then return to the *In_Use* state afterwards, documenting the aforementioned variables within the moment of re-reaching the *In_Use* state. This offers the advantage, that every pallet agent will access the Excel file at individual points and will not cause a failure of executing the writing results. As all pallets will be activated and entering the supply chain on different times, the time step chosen for writing results cannot be too big, as some pallets would write no longer up to date values to the Excel file. Depending on the point when a pallet gets activated for the first time, this means that the pallet will overwrite its current variables up to 10 times in the Excel file. For the results, the variables of the particular pallet are only required at the end of the simulation once.

A negative side effect of accessing and writing any Excel file through *Anylogic* is increasing the simulation runtime as a delay is caused. In order to not increase the simulation runtime too drastically, an increment of 50,000 minutes has iteratively proven to be best solution.

The current location is required for analyzing the location of a potential breakdown. The number of transports is defined as the total number of truck transportations between the participants of the supply chain. The number of repairs is determined by a counting variable, which reaches in some cases the `max_no_Of_Repairs`. 
The maximum number of repairs represents a stop criterion and is always limited to three repairs per pallet. Once a pallet has reached the end of a lifespan, it receives a message, stating that the particular pallet is out of use. Now this pallet enters the branch on the left (figure 3.19), leading to three options. These options include:

- Reaching the end-of-life state
- False Failure
- Maintenance

Similar to the product routing decisions, each pallet gets assigned random values for decision making. Depending on the different stages of life of each pallet, the decision percentages vary. This means that a pallet with two repairs has a lower chance of being repaired a third time, than a pallet with zero repairs. The entire model of wear and tear will be explained in the section 5.2.

The criteria for a false failure are defined as a varying decision probability with a low percentage (10% at maximum, [18, p. 874]), the number of repairs and also whether the pallet already has had a false failure within this state of life. A false failure can only occur once per pallet stage of life. The number of repairs defines the stage of life. In case of a false failure, a low number of pallet handlings will be added to the remaining lifespan, the parameter false_Failure of type Boolean will be changed from true to false and the occurrence of the false failure will be
documented in the results.xlsx. With changing the false_Failure to false, another false failure is not possible for the particular pallet.

The criteria for entering the Maintenance state is defined such that no_Of_Repair has to be less than maximum_no_Of_Repairs and the decision probability value of the pallet has to be within the range of probabilities for repairing. Once a pallet gets repaired, a decision between three different cases is made. This decision is based on the actual number of repairs. When a pallet is repaired a third time, the lifespan will be lower than after the first repair. It is assumed that a pallet wears out and cannot be restored to the quality of a new pallet. When the repair is completed, the number of repairs will be increased by one, the market value will be lowered according to the depreciation model of the pallet (see section 4.2 for more details). The parameter lifespan will be assigned the new lifespan_1 – 3 depending on the stage of life. The Boolean false_Failure will be reset to true in order to potentially allow the pallet a scenario of a false failure for this stage of life. The number of repairs and the current location will be documented in results.xlsx. The particular pallet will be added to the pallet pool collection of the consumer product manufacturer.

The criteria for entering the End_Of_Life state are defined by the number of repairs and the matching decision probability value of the particular pallet. Once this value is in the range of the probabilities of the end-of-life state, the pallet will be broken. The status of the pallet will be changed to end of life and the remaining lifespan,
status, current_Location, no_Of_Transactions and no_Of_Repairs will be documented. The end-of-life pallet will also be added to the pallet_End_Of_Life collection of the consumer product manufacturer.

The simulation models represent a basic approach in designing a supply chain including the highest possible level of detail within the educational version of Anylogic. Besides limiting factors established by the developers of Anylogic, other side effects such as not executing orders, when requested by too many agents have been overcome. The entire logic, decision algorithms and other processes have been created from scratch and follow a sustainability approach. In total, all simulation models consist of nine different agent types including three different truck agents, the main, the product, the pallet, the CPM, the distributor and the retailer. With a small number of changes, it is possible to adapt all simulation models to real world scenarios.
4. Running the Simulation

The following chapter gives an overview about the simulation scenarios, the locations assigned to the agents and the differences between each simulation model. In total, 40 simulation runs, 10 of each scenario, have been carried out. Four different simulation models have been established. These models include the cost-pass-through (CPT) system, Pallet Rental Services (PRS), a Pallet Single Use System (PSU) and a Pallet Dual Use System (PDU) (see section 3.3).

4.1 The Locations

*Table 4.1* gives an overview about the locations included in all simulation models of the first execution. The locations for the following nine simulation executions can be found in appendix 1.

*Table 4.1: First scenario including all distances involved in the simulation*

<table>
<thead>
<tr>
<th>From Instance</th>
<th>Location</th>
<th>To Instance</th>
<th>Location</th>
<th>Distance [mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPM</td>
<td>Hartford, CT</td>
<td>Distributor 0</td>
<td>Rochester, NY</td>
<td>335</td>
</tr>
<tr>
<td>CPM</td>
<td>Hartford, CT</td>
<td>Distributor 1</td>
<td>Pittsfield, NY</td>
<td>69.4</td>
</tr>
<tr>
<td>CPM</td>
<td>Hartford, CT</td>
<td>Distributor 2</td>
<td>Cleveland, OH</td>
<td>566</td>
</tr>
<tr>
<td>Distributor 0</td>
<td>Rochester, NY</td>
<td>Retailer 0</td>
<td>New York City, NY</td>
<td>333</td>
</tr>
<tr>
<td>Distributor 0</td>
<td>Rochester, NY</td>
<td>Retailer 2</td>
<td>Buffalo, NY</td>
<td>73.9</td>
</tr>
<tr>
<td>Distributor 1</td>
<td>Pittsfield, MA</td>
<td>Retailer 1</td>
<td>Waterbury, CT</td>
<td>72.7</td>
</tr>
<tr>
<td>Distributor 1</td>
<td>Pittsfield, MA</td>
<td>Retailer 3</td>
<td>New London, CT</td>
<td>131</td>
</tr>
<tr>
<td>Distributor 1</td>
<td>Pittsfield, MA</td>
<td>Retailer 4</td>
<td>Manchester, NH</td>
<td>153</td>
</tr>
<tr>
<td>Distributor 1</td>
<td>Pittsfield, MA</td>
<td>Retailer 6</td>
<td>Boston, MA</td>
<td>138</td>
</tr>
<tr>
<td>Distributor 1</td>
<td>Pittsfield, MA</td>
<td>Retailer 7</td>
<td>New Haven, CT</td>
<td>95.1</td>
</tr>
</tbody>
</table>
### Distribution and Retailer Locations

<table>
<thead>
<tr>
<th>Distributor 1</th>
<th>Pittsfield, MA</th>
<th>Retailer 11</th>
<th>Springfield, MA</th>
<th>55.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributor 2</td>
<td>Cleveland, OH</td>
<td>Retailer 5</td>
<td>Baltimore, MD</td>
<td>376</td>
</tr>
<tr>
<td>Distributor 2</td>
<td>Cleveland, OH</td>
<td>Retailer 8</td>
<td>Scranton, PA</td>
<td>376</td>
</tr>
<tr>
<td>Distributor 2</td>
<td>Cleveland, OH</td>
<td>Retailer 9</td>
<td>Philadelphia, PA</td>
<td>432</td>
</tr>
<tr>
<td>Distributor 2</td>
<td>Cleveland, OH</td>
<td>Retailer 10</td>
<td>Detroit, MI</td>
<td>169</td>
</tr>
<tr>
<td>Retailer 0</td>
<td>New York City, NY</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>116</td>
</tr>
<tr>
<td>Retailer 1</td>
<td>Waterbury, CT</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>30.7</td>
</tr>
<tr>
<td>Retailer 2</td>
<td>Buffalo, NY</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>401</td>
</tr>
<tr>
<td>Retailer 3</td>
<td>New London, CT</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>49.8</td>
</tr>
<tr>
<td>Retailer 4</td>
<td>Manchester, NH</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>140</td>
</tr>
<tr>
<td>Retailer 5</td>
<td>Baltimore, MD</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>313</td>
</tr>
<tr>
<td>Retailer 6</td>
<td>Boston, MA</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>101</td>
</tr>
<tr>
<td>Retailer 7</td>
<td>New Haven, CT</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>38.8</td>
</tr>
<tr>
<td>Retailer 8</td>
<td>Scranton, PA</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>223</td>
</tr>
<tr>
<td>Retailer 9</td>
<td>Philadelphia, PA</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>216</td>
</tr>
<tr>
<td>Retailer 10</td>
<td>Detroit, MI</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>716</td>
</tr>
<tr>
<td>Retailer 11</td>
<td>Springfield, MA</td>
<td>CPM</td>
<td>Hartford, CT</td>
<td>26</td>
</tr>
</tbody>
</table>

### 4.2 The Differences between each Pallet Management Strategy

The differences between each simulation model are determined by the different characteristics of the pallets. For the CPT and PRS models, high quality, reusable pallets made out of hardwood are utilized. The pallets included in these models...
have a market value of $60 per new unit [5]. Within both strategies, a wear and tear model for the pallets has been established. According to the stage of life of the pallet, its market value depreciates. Table 4.2 and 4.3 show the properties of the hardwood and softwood pallets used in the models.

Table 4.2: Properties of hardwood pallets used in the CPT and PRS models

<table>
<thead>
<tr>
<th>Hardwood Pallet</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifespan in handlings</td>
<td>140 - 165</td>
<td>110 – 134</td>
<td>90 – 105</td>
<td>45 – 89</td>
</tr>
<tr>
<td>No of repairs</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Market value</td>
<td>$60</td>
<td>$35</td>
<td>$25</td>
<td>$20</td>
</tr>
<tr>
<td>Probability for False Failure</td>
<td>10%</td>
<td>7%</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Probability for Maintenance</td>
<td>60%</td>
<td>50%</td>
<td>40%</td>
<td>0%</td>
</tr>
<tr>
<td>Probability for End of Life</td>
<td>30%</td>
<td>43%</td>
<td>56%</td>
<td>100%</td>
</tr>
</tbody>
</table>

The depreciation model of pallets is similar to depreciating vehicles. The biggest depreciation takes place at the beginning of the life of the pallet. Over the rest of the lifespan, the pallets depreciate slower before reaching a rest value.

Table 4.3: Properties of softwood pallets used in the PSU and PDU models

<table>
<thead>
<tr>
<th>Softwood Pallet</th>
<th>Pallet Single Use</th>
<th>Pallet Dual Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifespan in handlings</td>
<td>34</td>
<td>68</td>
</tr>
<tr>
<td>Maximum No of repairs</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Market value</td>
<td>$15</td>
<td>$15</td>
</tr>
<tr>
<td>Probability for False Failure</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Probability for Maintenance</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Probability for End of Life</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Within the CPT model, the market value represents the buying and also selling price for every pallet. The market price is only adjusted once a pallet enters the next stage of life. Within the PSU- and PDU system, the original price of $15 is divided by all three instances of the supply chain, as otherwise the retailers would end up having 100% of the losses for disposing those pallets. As for the PRS model, the service provider pays for new pallets as well as for their maintenance, but charges $0.75 per pallet handling. The 75 cents for the service charge is calculated through:

\[ n_{avg} = n_{0avg} + P_{R1} \cdot n_{1avg} + P_{R1} \cdot P_{R2} \cdot n_{2avg} + P_{R1} \cdot P_{R2} \cdot P_{R3} \cdot n_{3avg} \]

With \( n_{kavg} \) being the average lifespan of the particular stage of life in pallet handleings and \( P_{Rk} \) being the probability for repairing the pallet.

\[ n_{avg} = 152.71 + 0.6 \cdot 121.81 + 0.6 \cdot 0.5 \cdot 97.41 + 0.6 \cdot 0.5 \cdot 0.4 \cdot 66.53 \]
\[ n_{avg} = 263 \]

All numbers are based on the results of scenario 1 of the PRS model. Furthermore, it is assumed that the Pallet Rental Service Provider has to pay an interest rate of 10% per year per pallet in order to satisfy the bank. For the first year, this leads to a pallet price of $66. Therefore, a single handling costs $0.25. In order to achieve
competitiveness, it is assumed that the Service Provider charges the price for a single handling multiplied by 3.
5. Analysis of the Results

This chapter focuses on different economic and ecologic aspects of the four pallet management strategies simulated. In most cases, an overview about all ten different simulation scenarios comparing the four strategies with one another is presented. Some aspects are explained at the example of the first scenario. 

*Figure 5.1* gives an overview about all products sold in the different strategies throughout the ten scenarios.

![Products sold in the Different Models](image)

*Figure 5.1*: Products which have reached the retailers and have been sold

When observing Figure 5.1, one can see that the two systems *PSU* and *PDU* show more stable results than the Cost Pass Through and Pallet Rental Services
strategies. The reason behind this behavior lies in a higher number of possibilities within the CPT and PRS strategies, which lead to more complex systems and therefore to more uncertainties. Especially scenario 2 of the CPT strategy indicates a very low number of products that have been sold, which is due to the simulation involving errors at some point. A high volume of products and pallets are stuck in the supply chain due to trucks not leaving the particular participant even when the conditions for leaving are fulfilled. Within all different strategies, 3965 products have been produced and fed into the system throughout a timespan of one year. Due to the transportation strategies of the trucks, products and pallets will be stuck at an instance within the supply chain until the number of products within the waiting queue equals the capacity of the particular truck involved in transportation. However, the number of products, that are stuck in scenario 2 of the CPT strategy is exceptionally high. Figure 5.2 shows the number of pallets used within each system.
Figure 5.2: All pallets involved in the different strategies within all ten scenarios

Figure 5.2 also indicates errors within the 2\textsuperscript{nd} scenario of the CPT strategy, as the number of pallets required is clearly above the average of all scenarios. One can also see that within the Pallet Single Use system, a constant value of 3965 pallets for 3965 products is required. As those pallets are considered \textit{One-way} pallets, this result is expected. It can also be observed that according to the product sales behavior, the pallets required within the PSU and PDU strategies show similar stable dynamics the mean value for each strategy is illustrated by the dotted lines. On average, more pallets are required within the Pallet Rental Services System than the CPT. \textit{Figures 5.3 – 5.6} give an overview about the performances and potential and real usages of the pallets involved within the simulation approaches at the example of scenario 1.
Figure 5.3: Utilization of pallets involved in the different strategies

Figure 5.3 shows the utilization of the pallets involved in each simulation strategy. Within this figure, it can be seen that the PSU strategy utilizes the pallets in the most efficient way with 93.75% reaching the end-of-life state. The two strategies CPT and PRS indicate that only 7.91% (CPT) and 10.19% (PRS) of the pallets involved have reached their end of life. This means, that the full potentials of both strategies have not been met, requiring an extension of the lot size of products to be transported. The Pallet Dual Use System shows a utilization of its pallets of 61.48%.
Figure 5.4: Different stages of life of the pallets involved in the simulation models.

Figure 5.4 points out the different stages of life of all different pallet types involved in scenario 1 and the average lifespan of each stage of life of the particular pallet. The Single Use pallet always has 34 pallet handlings, whereas the PDU pallet has always 68 (see section 4.2). The hardwood Multiple Use pallets of the CPT and PRS strategies show the calculated mean values of each life stage, leading to a total of 438 pallet handlings per pallet. These values translate into transporting one product (PSU), two products (PDU) and 14.2 products (CPT, PRS). The black parts of each bar represent the actual usage of the average pallet. Only 15.85% and 16.34% of the potential usage per average pallet of the CPT and PRS strategies have been utilized. As each next stage of life can only be reached by repairing, it is necessary to outline that reaching the next state of life is the product of the previous repair possibilities. This leads to a total possibility of $P_{R4} = 12\%$ of
all pallets actually reaching the last stage of life, as indicated by the following equation.

\[ P_{R4} = \prod_{k=0}^{3} P_{Rk} \]

\[ P_{R4} = 0.6 \times 0.5 \times 0.4 = 0.12 \]

*Figure 5.5* takes a closer look on the actual numbers of repairs involved in the CPT and PRS strategies. As the majority of the pallets involved in these strategies stays in tact by reaching the end of the simulation, a lower percentage than 12% of all pallets is expected. For the CPT strategy, this means that 12.11% of all pallets have been repaired at least once, 2.47% have been repaired at least twice and 0.00618% have been repaired three times.

*Figure 5.5:* Actual numbers of repairs involved in the CPT and PRS strategies
For the PRS strategy, these percentages translate into 13.00% of all pallets being repaired at least once, 2.42% at least twice and 0.00523% at least three times. 

*Figure 5.6* shows the average distances that a product needs to travel before being delivered to the retailer and sold. All graphs show equal trends, but have minor variations related to the randomness of every simulation run. This randomness determines the number of products sold by each retailer. In case a retailer which is further away from its distributor sells more products in one model than in another, the average distance of that model increases. Especially in scenario 6 of the Pallet Dual Use system, this randomness has the biggest effect on the results.

![Avg. Distance per Product](image)

*Figure 5.6: Average distance a product needs to travel before being sold*

Based on the numbers presented in section 3.2, p. 22, the emissions related to the pallets used in this simulation have been calculated. *Figure 5.7* gives an overview
about the global warming potential of all different simulation models within the ten scenarios.

However, this presentation involves one problem in its comparability. As figure 5.8 shows, some pallets transport more products than others. Therefore, the absolute emissions related to re-usable pallets is higher, than those of the Single Use pallets. On the other hand, the usability is also higher than the aforementioned Single Use pallet. In order to allow better comparability, the emissions and environmental impacts related to pallets will be displayed on the basis of transporting one product only per pallet.

![Global Warming Potential per Pallet](image)

*Figure 5.7: CO₂ equivalent emissions related to transporting pallets*
Figure 5.8: Average number of products transported per pallet

Figure 5.7 and figure 5.9 show the global warming potential in kg CO₂ eq. per pallet and product.
When compared to figure 5.6, it can be observed that the biggest impact on the global warming potential is the average distance covered by each pallet and/or product. The presented emissions only consider delivery related emissions including the pallet. The different number of pallets used within each system as well as the different numbers of end-of-life pallets, lead to emissions as well. Also, the differences of average distances between each system relate to the emissions offset. Concerning its global warming potential, in some scenarios the PSU system can be less environmentally damaging than the PDU system. This behavior can be explained by emissions related to transportation including the process of returning pallets to the start of the supply chain, outweighing the emissions generated by producing and heat-treating more single use pallets. Other pallet-
related emissions and environmental impacts include Ozone Layer Depletion, Respiratory Organics, Aquatic Ecotoxicity, Terrestrial Ecotoxicity, Land Occupation, Aquatic Eutrophication, Aquatic Acidification and the usage of non-renewable Energy. *Figure 5.10* and 5.11 show the Land Occupation and Terrestrial Ecotoxicity. The other factors are listed in *table 5.1* and include the values of all models for scenario 1.

![Land Occupation](image)

*Figure 5.10*: Land Occupation related to pallets used in the simulation models

The land occupation clearly shows excessive use of land within the PSU system, due to the highest number of pallets produced within this system. The results are mainly based on the production and end-of-life of pallets. If pallets are put into a landfill, the end of life significantly contributes to land usage as well.
Figure 5.11: Terrestrial ecotoxicity related to transporting products and pallets

The terrestrial ecotoxicity indicates that the production volume including heat treatment, as well as average distances traveled influence the impact on contaminating soil significantly. The distinctive offset between the different pallet management strategies is explained by the varying numbers of pallets used in every system.
Table 5.1: Overview of environmental impacts related to the usage of pallets within scenario 1

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Unit</th>
<th>CPT</th>
<th>PRS</th>
<th>PSU</th>
<th>PDU</th>
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<tbody>
<tr>
<td>Ozone Layer Depletion</td>
<td>kg CFC-11 eq.</td>
<td>1.12E-05</td>
<td>1.08E-05</td>
<td>1.23E-05</td>
<td>1.17E-05</td>
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<td>Respiratory Organics</td>
<td>kg C₂H₄ eq.</td>
<td>0.46</td>
<td>0.45</td>
<td>0.47</td>
<td>0.47</td>
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<tr>
<td>Aquatic Ecotoxicity</td>
<td>kg TEG water</td>
<td>1091.29</td>
<td>1054.33</td>
<td>1481.19</td>
<td>1254.94</td>
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<tr>
<td>Terrestrial Ecotoxicity</td>
<td>kg TEG soil</td>
<td>168.18</td>
<td>159.89</td>
<td>267.33</td>
<td>203.33</td>
</tr>
<tr>
<td>Land Occupation</td>
<td>m² org. arabale</td>
<td>0.98</td>
<td>0.90</td>
<td>2.51</td>
<td>1.5</td>
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<tr>
<td>Aquatic Acidification</td>
<td>kg SO₂ eq.</td>
<td>0.191</td>
<td>0.183</td>
<td>0.234</td>
<td>0.207</td>
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<tr>
<td>Aquatic Eutrophication</td>
<td>kg PO₄ P-lim</td>
<td>4.19E-04</td>
<td>3.85E-04</td>
<td>9.82E-04</td>
<td>6.08E-04</td>
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<tr>
<td>Global Warming</td>
<td>kg CO₂ eq.</td>
<td>29.63</td>
<td>28.98</td>
<td>33.68</td>
<td>32.19</td>
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<tr>
<td>Non-renewable Energy used</td>
<td>MJ primary</td>
<td>147.56</td>
<td>140.30</td>
<td>236.33</td>
<td>179.06</td>
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</table>

Figures 5.12 – 5.14 represent the economic aspect of the simulation and give an overview about the different cost models. All results of the costs are calculated as the budget spent on pallets minus Pallet Sales (CPT), sum of rent paid for pallet usage (PRS) and budget spent on pallets divided by the three participating groups of each supply chain (PSU, PDU).
Figure 5.12: Costs of all consumer product manufacturers within the different models

It can be observed that the PRS, PSU and PDU strategies show more stable behavior than the CPT. The reason behind this is the capital commitment involved in the CPT system. The graph of the CPT only levels out once a pallet has left the particular instance and therefore is sold to the next instance. Until then, the costs are increased by the price of the pallet, as the particular instance still owns it. As the number of pallets used within the CPT system directly influences all budgets spent on pallets, the risks of higher budgets is taken by all instances directly. The PSU and PDU models spread the risks of committed capital equally, whereas within the PRS system, it is the service provider who takes 100% of the investment risks. In the PRS system each participant of the supply chain only pays for the
number of pallet handlings used instead of the pallet itself. This leads to a cost model which is independent from the number of pallets required for all instances within the supply chain. The PSU and PDU system follow the approach of not selling any pallets, but splitting the costs between all three instances of the supply chain equally and then disposing the pallets once they have reached their end of life.

*Figure 5.13*: Costs of all distributors within the different models

*Figure 5.13* shows a similar behavior of all systems, compared to the behavior displayed in *figure 5.12*. The biggest difference is the lower costs of the Pallet Rental System, which is explained by a lower number of pallet handlings carried out within the processes of the distributors.
Figure 5.14: Costs of all retailers within the different models

It can be seen that through all different lines of the supply chain, the costs spent on pallets within the CPT system vary the most. This is due to factors such as which instance is affected the most by breakdowns of pallets on average and therefore realizes losses when selling the pallet. Also, errors such as those which occurred in scenario two can lead to a high number of pallets being trapped in the supply chain, which leads to increased cost. Figures 5.13 and 5.14 indicate that high volumes of pallets are trapped at the distributors and retailers, but not at the CPM within scenario 2. All in all, throughout every scenario and instance, the Pallet Dual Use system shows the most cost-effective solution followed by the Pallet Single Use system. As the PDU represents a what-if-case or rather an iteration of
an increased usability of single use pallets including all of their advantages, it is obvious that the results are lower than in the PSU case. Also, all costs related to running trucks have not been considered in any model. Renting pallets can be a sustainable and cost-effective solution. However, Figure 5.15 shows the costs of the Pallet Rental Service Provider.

![Costs of Pallets for the Rental Service Provider](image)

*Figure 5.15: Spendings, Earnings and Profit of the Service Provider (SP) within the PRS system*

It can be seen that the service provider gains minor profit in some scenarios, but also takes losses in others. This is mainly due to the small size of the experiment, as the potential of the pallets which are rented out are not reached. On the other hand, the SP has to provide the required number of pallets and therefore has to pay for them, leading to high investments. On a longer term, by increase the size
of the experiment, the business model of the SP might gain more profit. At this point, the SP struggles to reach the break even point in some scenarios. *Figure 5.16* shows the trade-offs of the four different pallet management strategies in the context of costs of the Consumer Product Manufacturer versus the global warming potential.

*Figure 5.16*: Costs involved for all CPMs versus global warming potential of each strategy in the scenarios

*Figure 5.16* shows that the costs involved for the PSU and PDU strategies remain stable, even though the global warming related emissions rise. The reason behind this behavior is that the costs involved in the transportation processes are not considered within any model. The distances however, affect the emissions significantly. As the distances do not affect the costs, *figure 5.16* does not consider all factors of a real-world trade off. The differences between the PRS and CPT
trendlines are limited to the number of pallets bought, sold, repaired and broken down. In order to achieve a valid conclusion about a trade-off of cost versus environmental impacts, it is necessary to incorporate the distances traveled into the cost model as well.
6. Summary and Critical Review

Within this thesis, the economic and ecologic behavior of four different pallet management strategies has been modelled using ten different simulation scenarios each. All of the different models have been created from scratch and follow a generic approach when creating a scenario. The scenarios involved in these models are based on the randomness of different normal distributions in Microsoft Excel and Anylogic. For simulating a systems behavior, fictive supply chains including one consumer product manufacturer, three distributors and twelve retailers has been embedded in all scenarios.

The results of the experiments carried out within the thesis indicate that a lot of factors need to be considered when assessing the sustainability of different pallet management strategies. Differences in the freight volume, distances traveled or the economies of the supply chain lead to favoring one strategy or another. The biggest factor when evaluating the ecological footprint of a wooden pallet is the average distance and therefore the emissions related to this distance. The results also indicate that using wooden pallets only once leads to the least sustainable solution, as more resources are required for transporting the same freight volume. However, in some cases, Single Use Pallets can still be less environmentally damaging than reusable pallets. In situations with large distances, such as oversea distances that have to covered within the supply chain, the environmental impact of disposing the pallet can be smaller than returning it to the start of the supply
chain. The impacts of the PSU system on land occupation and aquatic eutrophication, however remain the biggest of all models. Within all scenarios, Single Use Pallets remain to be the second cheapest solution. Only for the consumer product manufacturers, the cost pass through model offers an advantage, as the CPM uses all pallets involved for the first time.

The PDU approach shows the possibility of increasing the sustainability potential of single use pallets, if they can be reused a second time. This approach represents a what-if case and remains questionable in its applicability within real world scenarios. In most cases, the positive effect of reusing the pallets outweighs the production and disposal of new pallets that are used only once. The PDU system also represents the cheapest solution for supply chains in all scenarios. As the softwood dual use pallets involved in this model are equal to the single use pallets of the PSU system, scenarios involving long distances such as those mentioned in the previous paragraph are favored for these pallets as well. Returning the pallets afterwards can lead to more emissions than disposing and reproducing them, resulting in questionable outcomes of this scenario.

From an ecological point of view, the CPT and PRS systems show the best possible results. However, within both approaches, the pallets involved have overall not reached their full possible potential. In order to gain more knowledge about the long-term performance of those systems including reaching the full possible potential of the pallets, increasing the run size of the experiments is
necessary. The Cost Pass Through strategy appears to be the most expensive strategy, which is due to the financial risks being taken by the participants of the supply chain directly and independently. The Pallet Rental System shows more stable results in the context of budgets spent using pallets. However, the service provider business model often does not reach the break even point, which is due to the full potential of the pallets not being reached, but full prices for new pallets being spent. Furthermore, the concept of pallet renting based on the number of pallet handlings carried out by the particular instance remains questionable, as the service provider will not be able to track the number of handlings involved in the processes of the renting instance. A more realistic approach would involve monthly costs for renting, uncoupled from the number of handlings.

In order to compare the results of this research with the initially introduced results of the paper Selection of pallet management strategies from the perspective of supply chain cost with Anylogic software [2], it was found, that the original conclusion about pallet rental strategies representing the overall optimal solution is invalid. However, concluding that the cost pass through model represents a long-term solution has been confirmed. The point with varying maintenance cost has also been proven to be invalid. Either multiple use pallets are involved within the particular system, or single use pallets. Multiple use pallets always require maintenance. In case that maintenance is carried out by the pallet rental service provider, the cost involved in fixing broken pallets will ultimately be returned to the customer in some way. Therefore, there is no necessity to distinguish between the
instance carrying out the maintenance. Single Use pallets, however, are designed to be disposed, once they reach the end of the supply chain. Conclusively, this pallet model cuts the cost for maintenance short and leads to overall reduced prices, but also reduced usability. Also, the environmental impact of single use pallets has proven to be worse than the impact of multiple use pallets. An overall conclusion about which pallet management strategy represents the best solution is not possible. When adapting the knowledge from this thesis to a real-world problem, it is necessary to evaluate the best strategy for the particular supply chain involved individually. Therefore, the generic design of the simulation models presented in this thesis can be adapted with minor changes. Depending on the run size of the experiment, distances involved, budget and environmental awareness, a conclusion about which strategy is most suitable for a particular problem can be drawn. However, this research has proven that the different strategies involved, working under equal conditions lead to clear results favoring a pallet dual use system using cheap softwood pallets from a cost perspective. Environmentally, the pallet rental system has proven to be the least damaging system followed by the cost pass through system. Single Use pallets have shown the worst impact on the environment.
7. Outlook

This thesis represents a basic research approach within the evaluation of the sustainability of different pallet management strategies under aspects of economy and ecology. As the simulation program involved has offered limiting factors within the run size of the experiment, the simulation has not been able to reach the full potential of the pallets involved in two out of four cases. Therefore, increasing the run size for gaining further knowledge is necessary. This thesis does not claim to deliver overall answers for complex questions. Many assumptions involved in the simulation models might work under different circumstances in real world scenarios leading to different results. For real world applications, factors such as crowded cities and therefore effects on delivery times need to be considered as well, when choosing a location for a factory.

As the values for the environmental impacts of wooden pallets have been gained from literature research, further investigation about varying numbers needs to be carried out. It is questionable, if producing, using and disposing a softwood pallet creates the same impacts as hardwood pallets. Furthermore, the locations, which lead to different emissions have to be taken into consideration individually. A pallet will have a worse environmental impact, if long distances are involved in the production and disposing processes.
Further investigations are recommended within the field of pallet management strategies. The level of details can be increased to a holistic approach considering all factors involved in a cradle-to-the-grave analysis. These details include exact details about the distribution of end-of-life pallets for further uses, incinerations, landfill or others. Also, the environmental impacts involved in attaining the raw material involved has to be evaluated individually per real world problem. Processes involved in the supply chain as well as rental business models have to be adapted to real world scenarios. As this research follows a generic approach in order to allow drawing non-specified conclusions, the product remained undefined. A higher level of detail can be achieved by defining the product, as well as the environment and circumstances defining the supply chain. It is likely that pallets, which are involved in logistic operations of grocery market chain last longer than those involved in the construction business. Therefore, the choice of the pallet-type as well as the strategy will be affected as well. The choice of the matching pallet management strategy will also be affected by factors such as domestic production and sales versus international production and sales. In case traveling long distances is involved in a real-world scenario, returning the pallet may cause excessive, unnecessary emissions. The simulation models involved in this research offer great potential for functioning as a basis for further investigations including a high level of detail and can also be adapted for other supplemental transportation devices such as packing blankets. In order to simulate other devices than pallets, it is necessary to adapt the models of wear and tear, repairability and cost models.
9 Appendices

1 Locations of the simulation models

Scenario 2

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<th>Location</th>
<th>To Instance</th>
<th>Location</th>
<th>Distance (mi)</th>
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**Scenario 3**

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Scenario 4

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**Scenario 5**

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Scenario 8

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Scenario 9

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112
<table>
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### Scenario 10

<table>
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<th>From Instance</th>
<th>Location</th>
<th>To Instance</th>
<th>Location</th>
<th>Distance (mi)</th>
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</table>

2 Code

Main:

Function: adding_Product_information

//Setting the production time for the products

```java
int i=0;          //counting variable products
double sum_Rates=0;     //sum of arrival rates or arrival times

while (i<amountProducts){
    products(i).spawn_Time=products(i).arrival_Rate+sum_Rates;
    sum_Rates=products(i).spawn_Time;
    //sum_Rates = sum of arrival times until
product i
    products(i).prod_Number=i;
    //Assigning product number
    products.get(i).initial_Location=locations.getCellStringValue("Location_CPM", 2, 1);
    products(i).initial_Location2=map.searchFirst(products(i).initial_Location);
    products(i).setLocation(products(i).initial_Location2);
    i++;
}
```
Function route_Product

//Routing to Distributor

int i=0; //counting variable Distributors
int n=0; //counting variable Product
double sum_Share_Dist=0; //setting sum_Share Distributor zero
sum_Share_Dist=distributors(i).market_Share; //setting sum_Share as distributors (i) market share

while (n<amountProducts){
    while (i<amountDistributors){

        if (products(n).random_number_Dist<sum_Share_Dist){

            products(n).route_To_Dist_Number=distributors(i).number; //Defining the products way through distributors catchment area number
            products(n).route_To_Dist=distributors(i);
            i=amountDistributors;
            //i=amountDistributors for ending the while loop as route_To_Dist has been specified by now
        }
        else{
            i++;
            sum_Share_Dist=sum_Share_Dist+distributors(i).market_Share;
            products(n).route_To_Dist_Number=distributors(i).number;
            products(n).route_To_Dist=distributors(i);
        }

        //System.out.println("sum_Share_Dist="+sum_Share_Dist);
        //System.out.println("i="+i);
        //System.out.println("n="+n);
        //System.out.println("route_To_Dist="+products(n).route_To_Dist);
    }
    n++;
}

//System.out.println("products(n).route_To_Dist="+products(n).route_To_Dist);
//System.out.println("sum_Share_Dist="+sum_Share_Dist);
//System.out.println("i="+i);
//System.out.println("n="+n);
//System.out.println("route_To_Dist="+products(n).route_To_Dist);
n++;
i=0;
sum_Share_Dist=distributors(i).market_Share;
}

/*
   //no longer necessary
   //Initializing ini_sum_Share_Ret
   int u=0;        //counting variable Retailer
   int t=0;        //counting variable Product

   while (t<amountProducts){
       while (u<amountRetailers){

           if (products(t).route_To_Dist_Number==retailers(u).belongs_To_Dist){

               products(t).ini_sum_Share_Ret=retailers(u).market_Share;
               u=amountRetailers;
           }
           else{
               u++;
           }

           t++;
           u=0;
       }
   }*/

   //Routing to Retailer

   int o=0;        //counting variable Retailer
   int p=0;        //counting variable Product
   double sum_Share_Ret=0; //setting sum_Share Retailer zero
   //double sum_Share_Ret_final=0; //final market share of retailers (for print out purposes only)

   while (p<amountProducts){
//sum_Share_Ret=products(p).ini_sum_Share_Ret;

while (o<amountRetailers) {

    if (products(p).route_To_Dist_Number==retailers(o).belongs_To_Dist) {

        //System.out.println("p"+p);
        //System.out.println("o"+o);

        //System.out.println("sum_Share_Ret"+sum_Share_Ret);

        if (products(p).random_number_Ret<=sum_Share_Ret+retailers(o).market_Share) {

            //sum_Share_Ret_final=sum_Share_Ret+retailers(o).market_Share;

            //System.out.println("p"+p);
            //System.out.println("o"+o);

            //System.out.println("sum_Share_Ret_final"+sum_Share_Ret_final);

            products(p).route_To_Ret=retailers(o);
            o=amountRetailers;
            //o=amountRetailers for ending the while loop as route_To_Ret has been specified by now
        }
        else {

            sum_Share_Ret=sum_Share_Ret+retailers(o).market_Share;
            o++;
        }
    }
    else {

        o++;
    }
}

//System.out.println("sum_Share_Ret"+sum_Share_Ret);
//System.out.println("o"+o);
Function read_Market_Shares

//Market Shares for three distributors

//Distributor with No. 1 = East
//Distributor with No. 2 = Mid
//Distributor with No. 3 = West

int i=0; //counting variable of distributors
//System.out.println("amountDistributorTrucks="+amountDistributorTrucks);

while (i<amountDistributorTrucks){ //i < number of distributors

distributors.get(i).market_Share=locations.getCellNumericValue("Locations_Distributors_adv", 2+i, 5);
    //System.out.println("i="+i);

    i++;
}

//Market Shares for twelve retailers

int k=0; //counting variable of all retailers
int l=0; //counting variable of retailers_East
int m=0; //counting variable of retailers_Mid
int n=0; //counting variable of retailers_West
//System.out.println("amountDistributorTrucks="+amountDistributorTrucks);

while (k<amountRetailers){ //k < number of retailers

retailers.get(k).belongs_To_Dist=locations.getCellNumericValue("Locations", 2+k, 2);
    if (retailers(k).belongs_To_Dist==1){
        retailers.get(k).market_Share=locations.getCellNumericValue("Retailers_East",2+l, 6);
        l++;
    }
    if (retailers(k).belongs_To_Dist==2){
        retailers.get(k).market_Share=locations.getCellNumericValue("Retailers_Mid",2+m, 6);
        m++;
    }
    if (retailers(k).belongs_To_Dist==3){
        retailers.get(k).market_Share=locations.getCellNumericValue("Retailers_West",2+n, 6);
        n++;
    }
    //System.out.println("k="+k);
    k++;
}

Function assign_Destinations

//Assigning Destinations for distributors
int l=0; //counting variable for number of distributors
int q=0; //counting variable for number of retailers

while (l<amountDistributors){
    while (q<amountRetailers){
        if (distributors(l).number==retailers(q).belongs_To_Dist){
            distributors(l).retailers_1.addFirst(retailers(q));
        }
        q++;
    }
    l++;
}
q=0;
l++;}

//Destinations for Consumer Product Manufacturer Trucks
int o=0; //counting variable of sum of trucks

while (o<amountCPMTrucks){
    truck_CPMs(o).destinations=truck_CPMs(o).distributors;
    o++;
}

//Destinations for Retailers
int z=0;  //counting variable for number of retailers
int y=0; //counting variable for number of Consumer Product Manufacturers
while (z<amountRetailers){
    while (y<amountCPMs){
        retailers(z).destinations.addFirst(consumer_Product_Manufacturers(y));
        y++;
    }
    y=0;
    z++;
}

Function create_Trucks

//creating truck_Distributor
amountDistributorTrucks=(int)locations.getCellNumericValue("Locations_Distributors_adv", 5, 4);

int m=0; //counting variable of sum of trucks
int k=0; //counting variable of trucks per distributor
int i=0; //counting variable of distributors
while (m<amountDistributorTrucks){

    while (i<amountDistributors){ //i < number of distributors

        distributors.get(i).no_Of_Trucks=(int)locations.getCellValue("Locations_Distributors", 2+i, 2);
        //System.out.println("i="+i);
        //System.out.println("k="+k);
        //System.out.println("m="+m);
        if (k<distributors(i).no_Of_Trucks){
            //truck_Distributors(i).noOfTrucks)
            Agent a=add_truck_Distributors();

            truck_Distributors.get(m).capacity=(int)trucks.getCellValue("Truck_Distributor", 2+i, 1);
            truck_Distributors.get(m).loading_Time=trucks.getCellValue("Truck_Distributor", 2+i, 2);
            truck_Distributors.get(m).unloading_Time=trucks.getCellValue("Truck_Distributor", 2+i, 3);
            truck_Distributors.get(m).speed=trucks.getCellValue("Truck_Distributor", 2+i, 4);
            truck_Distributors.get(m).initial_Location=locations.getCellStringValue("Locations_Distributors", 2+i, 1);
            //truck_Distributors(m).initial_Location2=truck_Distributors(m).initial_Location;
            truck_Distributors.get(m).catchment_Area=locations.getCellCellValue("Locations_Distributors_adv", 2+i, 3);
            truck_Distributors(m).initial_Location2=map.searchFirst(truck_Distributors(m).initial_Location);
            truck_Distributors(m).setLocation(truck_Distributors(m).initial_Location2);
            truck_Distributors(m).actual_Truck=m;
            truck_Distributors(m).belongs_To_Dist=distributors(i);
        }
    }
}
//setLocation(truck_Distributors(m).initial_Location2)

    k++;
    m++;

} else{
    k=0;
    i++;
}
}

//creating truck_CPM
amountCPMTrucks=(int)locations.getCellNumericValue("Location_CPM_adv", 3, 2);

int o=0; //counting variable of sum of trucks
int p=0; //counting variable of trucks per Consumer Product Manufacturer
int q=0; //counting variable of Consumer Product Manufacturers

while (o<amountCPMTrucks){

    while (q<amountCPMs){ //q < number of Consumer Product Manufacturers

        consumer_Product_Manufacturers.get(q).no_Of_Trucks=(int)locations.getCellNumericValue("Location_CPM_adv", 2+q, 2);
        //System.out.println("o="+o);
        //System.out.println("p="+p);
        //System.out.println("q="+q);
        if (p<consumer_Product_Manufacturers(q).no_Of_Trucks){
            //truck_Distributors(i).noOfTrucks){
                Agent a=add_truck_CPMs();

        truck_CPMs.get(o).capacity=(int)trucks.getCellNumericValue("Truck_CPM", 2+q, 1);
truck_CPMs.get(o).loading_Time=trucks.getCellNumericValue("Truck_CPM", 2+q, 2);

truck_CPMs.get(o).unloading_Time=trucks.getCellNumericValue("Truck_CPM", 2+q, 3);

truck_CPMs.get(o).speed=trucks.getCellNumericValue("Truck_CPM", 2+q, 4);

truck_CPMs.get(o).initial_Location=locations.getCellStringValue("Location_CPM", 2+q, 1);

//truck_CPMs(o).initial_Location2=truck_Distributors(o).initial_Location;

//truck_CPMs.get(o).catchment_Area=locations.getCellNumericValue("Location_CPM_adv", 2+q, 3);

truck_CPMs(o).initial_Location2=map.searchFirst(truck_CPMs(o).initial_Location);

truck_CPMs(o).setLocation(truck_CPMs(o).initial_Location2);

truck_CPMs(o).actual_Truck=o;

//setLocation(truck_CPMs(o).initial_Location2);
p++;
o++;
}
else{
p=0;
q++;
}

//creating truck_Retailer
amountRetailerTrucks=(int)locations.getCellNumericValue("Locations_Retailers_adv", 1, 3);

int r=0;  //counting variable of sum of trucks
vorher o
int s=0;  // counting variable of trucks per Retailer
t=0;     // counting variable of Retailers

// System.out.println("amountRetailerTrucks="+amountRetailerTrucks);
while (r<amountRetailerTrucks){
    while (t<amountRetailers){  // t < number of Retailers
        retailers.get(t).no_Of_Trucks=(int)locations.getCellNumericValue("
Locations_Retailers_adv", 2+t, 2);
        // System.out.println("r="+r);
        // System.out.println("s="+s);
        // System.out.println("t="+t);
        if (s<retailers(t).no_Of_Trucks){
            Agent a=add_truck_Retailers();

            truck_Retailers.get(r).capacity=trucks.getCellNumericValue("Truck_Retailer", 2+t, 1);
            truck_Retailers.get(r).loading_Time=trucks.getCellNumericValue("Truck_Retailer", 2+t, 2);
            truck_Retailers.get(r).unloading_Time=trucks.getCellNumericValue("Truck_Retailer", 2+t, 3);
            truck_Retailers.get(r).speed=trucks.getCellNumericValue("Truck_Retailer", 2+t, 4);
            truck_Retailers.get(r).initial_Location=locations.getCellStringValue("Locations_Retailers", 2+t, 1);
            // truck_Retailers(r).initial_Location2=truck_Distributors(o).initial_Location;

            truck_Retailers.get(r).catchment_Area=locations.getCellNumericValue("Location_CPM_adv", 2+t, 3);

            truck_Retailers(r).initial_Location2=map.searchFirst(tuck_Retailers(r).initial_Location);
truck_Retailers(r).setLocation(truck_Retailers(r).initial_Location2);

truck_Retailers(r).belongs_To_Ret=retailers(r);

//setLocation(truck_CPMs(r).initial_Location2);
s++;

r++;
}

else{
    s=0;
    t++;
}
}

Function read_Information

//Reading information for Consumer Product Manufacturer

int f=0;  //counting variable Consumer Product Manufacturers

while (f<amountCPMs)
{
    consumer_Product_Manufacturers.get(f).location=locations.getCellStringValue("Location_CPM", 2+f, 1);  //Getting String value of locations of CPMs
    f++;
}

//Reading information for Distributors

int i=0;  //counting variable Distributors

while(i<amountDistributors)
{
    distributors.get(i).number=locations.getCellNumericValue("Locations_Distributors_adv", 2+i, 3);  //The distributors number is the rearranged catchment area of the distributor
    i++;
}
distributors.get(i).location=locations.getCellStringValue("Locations_Distributors", 2+i, 1); //Getting String value of locations of Distributors distributors(i).matching_Number=i; i++; }

//Reading information for Retailers
int k=0; //counting variable retailers

amountRetailers=(int)locations.getCellNumericValue("Locations_Retailers_adv", 1, 3);

while (k<amountRetailers){
    retailers.get(k).location=locations.getCellStringValue("Locations_Retailers", 2+k, 1);
    retailers(k).number=k;
    k++;
}

//Assigning number for pallets
int j=0; //counting variable pallets

while (j<amountProducts){
    pallets(j).number=j;
    j++;
}

Agent: Consumer_Product.Manufacturer

Event: Setting_Dist_Destinations

//Assigning distributor numbers for choosing correct destinations
int i=0; //counting variable for total number of distributors

while (i<main.amountDistributors){
    if (main.distributors(i).number==1){
Distributor_1=main.distributors(i);
}

if (main.distributors(i).number==2){
Distributor_2=main.distributors(i);
}

if (main.distributors(i).number==3){
Distributor_3=main.distributors(i);
}

i++;  
}

Event: checking_Truck_Availability
//Event for checking and choosing available truck for
transport of products & pallets to particular distributor

int i=0;  //counting variable for truck_CPM
population

while (i<main.amountCPMTrucks){
  if (main.truck_CPMs(i).status=="available"){
    available_Truck=main.truck_CPMs(i);
    i=main.amountCPMTrucks;
    //no_Truck_Available=false;
  }
  //else{
  //no_Truck_Available=true;
  }
  i++;  
}

Event: writing_Results
main.results.writeFile();
//Write results of each CPM in excel output file

main.results.setCellValue(location, "CPM", 2, 2);
main.results.setCellValue(reuse_Pallet_Counter, "CPM", 2, 3);
main.results.setCellValue(out_Of_Use_Counter, "CPM", 2, 4);
main.results.setCellValue(pallet_Budget_CPM, "CPM", 2, 5);
main.results.setCellValue(pallet_Sales_CPM, "CPM", 2, 6);
main.results.setCellValue(pallet_End_Of_Life.size(), "CPM", 2, 7);
main.results.setCellValue(pallet_Pool.size(), "CPM", 2, 8);
main.results.setCellValue(pallet_Pool_Dist.size(), "CPM", 2, 9);
main.results.setCellValue(pallet_Pool_Ret.size(), "CPM", 2, 10);

State Inventory Control:

//Deciding whether a used or new pallet is required for the particular product

pallet_Demand_2=pallet_Demand;

//Case: New pallet

if (pallet_Demand>0){
    while (pallet_Demand_2!=pallet_Demand-1){
        if (pallet_Pool.size()==0){
            //defining use of a new pallet
            new_Pallet_Number=new_Pallet_Number+1;
            //counter for new pallets
            send ("new pallet",
                main.pallets(main.consumer_Product_Manufacturers(0).new_Pallet_Number));
            actual_Product=main.products(new_Product_Number);
            actual_Product.corresponding_Pallet=main.pallets(new_Pallet_Number);
            actual_Product.corresponding_Pallet.lifespan=actual_Product.corresponding_Pallet.lifespan-
pallet_Handlings_CPM;
            send ("finished", this);
            send ("Pallet attached", actual_Product);
            pallet_Demand_2=pallet_Demand_2-1;
            pallet_Budget_CPM=pallet_Budget_CPM+actual_Product.corresponding_Pallet.market_Value;  //Budget
            actual_Product.corresponding_Pallet.current_Location=location;
        }
    }
}

}
//Case: Used Pallet
if (pallet_Pool.size()>0){ //defining
    reuse_Pallet_Counter=reuse_Pallet_Counter+1;
    actual_Product=main.products(new_Product_Number);
    actual_Product.corresponding_Pallet=pallet_Pool.removeLast();
    //Checking if pallet pool pallets are still usable
    //Sub-Case: Pallet still usable
    if (actual_Product.corresponding_Pallet.lifespan>pallet_Handlings_CPM){
        actual_Product.corresponding_Pallet.lifespan=actual_Product.corresponding_Pallet.lifespan-pallet_Handlings_CPM;
        send("finished", this);
        send("Pallet attached", actual_Product);
        pallet_Demand_2=pallet_Demand_2-1;
        pallet_Budget_CPM=pallet_Budget_CPM+actual_Product.corresponding_Pallet.market_Value;  //Budget
        actual_Product.corresponding_Pallet.current_Location=location;  //assigning current location
    } //Sub-Case: Pallet no longer usable
    if (actual_Product.corresponding_Pallet.lifespan<pallet_Handlings_CPM){
        send("Pallet out of use", actual_Product.corresponding_Pallet);
        out_Of_Use_Counter++;
        pallet_Budget_CPM=pallet_Budget_CPM+actual_Product.corresponding_Pallet.market_Value;  //Budget
        pallet_Sales_CPM=pallet_Sales_CPM+5;  //Sales
actual_Product.corresponding_Pallet.current_Location=location; //assigning current location

State Dispatch

//Deciding waiting Queue for particular distributor

if (actual_Product.route_To_Dist_Number==1){
    product_Queue_Dist_1.addFirst(actual_Product);
}

if (actual_Product.route_To_Dist_Number==2){
    product_Queue_Dist_2.addFirst(actual_Product);
}

if (actual_Product.route_To_Dist_Number==3){
    product_Queue_Dist_3.addFirst(actual_Product);
}

Transition from Branch to Shipping

Condition:
((product_Queue_Dist_1.size()==available_Truck.capacity)||(product_Queue_Dist_2.size()==available_Truck.capacity)||(product_Queue_Dist_3.size()==available_Truck.capacity))

Action:
//Loading Trucks and deleting pallets / products from CPM inventory
int l=0; //counting variable for available spots for pallets on truck bed

if (product_Queue_Dist_1.size()==available_Truck.capacity){
    //Choosing Case 1
    actual_Truck=available_Truck;
    actual_Truck.where_To=Distributor_1;
    while (l<available_Truck.capacity){
    ...
load_Product=product_Queue_Dist_1.removeLast();
pallet_Sales_CPM=pallet_Sales_CPM+load_Product.corresponding_Pallet.market_Value;
available_Truck.product_Queue_Dist.addFirst(load_Product);
l++;
}
available_Truck.status="busy";

if (product_Queue_Dist_2.size()==available_Truck.capacity){
  //Choosing Case 2
  actual_Truck=available_Truck;
  actual_Truck.where_To=Distributor_2;
  while (l<available_Truck.capacity){
    load_Product=product_Queue_Dist_2.removeLast();
pallet_Sales_CPM=pallet_Sales_CPM+load_Product.corresponding_Pallet.market_Value;
available_Truck.product_Queue_Dist.addFirst(load_Product);
l++;
  }
  available_Truck.status="busy";
}

if (product_Queue_Dist_3.size()==available_Truck.capacity){
  //Choosing Case 3
  actual_Truck=available_Truck;
  actual_Truck.where_To=Distributor_3;
  while (l<available_Truck.capacity){
    load_Product=product_Queue_Dist_3.removeLast();
pallet_Sales_CPM=pallet_Sales_CPM+load_Product.corresponding_Pallet.market_Value;
available_Truck.product_Queue_Dist.addFirst(load_Product);
l++;
  }
  available_Truck.status="busy";
l=0;
}

Transition Shipping to Branch:
Action:
send("Leave CPM", actual_Truck);
Transition Branch to Idle_State:
Condition:
\[
((\text{product\_Queue\_Dist\_1.size}() != \text{available\_Truck.capacity})
\land
(\text{product\_Queue\_Dist\_2.size}() != \text{available\_Truck.capacity})
\land
(\text{product\_Queue\_Dist\_3.size}() != \text{available\_Truck.capacity}))
\]

Agent: Distributor

Event setting_Ret_Destinations:
//Assigning retailer numbers for choosing correct destinations

```java
while (0<retailers_1.size()){

    current_Retailer=retailers_1.removeLast();

    if (current_Retailer.number==0)
        retailer_0=current_Retailer;
    if (current_Retailer.number==1)
        retailer_1=current_Retailer;
    if (current_Retailer.number==2)
        retailer_2=current_Retailer;
    if (current_Retailer.number==3)
        retailer_3=current_Retailer;
    if (current_Retailer.number==4)
        retailer_4=current_Retailer;
    if (current_Retailer.number==5)
        retailer_5=current_Retailer;
    if (current_Retailer.number==6)
        retailer_6=current_Retailer;
    if (current_Retailer.number==7)
        retailer_7=current_Retailer;
    if (current_Retailer.number==8)
        retailer_8=current_Retailer;
```
if (current_Retailer.number==9){
    retailer_9=current_Retailer;
}
if (current_Retailer.number==10){
    retailer_10=current_Retailer;
}
if (current_Retailer.number==11){
    retailer_11=current_Retailer;
}

Event checking_Truck_Availability
//Event for checking and choosing available truck for transport of products & pallets to particular distributor

int i=0;  //counting variable for truck_Distributor population
while (i<main.amountDistributorTrucks){
    if (main.truck_Distributors(i).catchment_Area==number){
        if (main.truck_Distributors(i).status=="available"){
            available_Truck_Dist=main.truck_Distributors(i);
            i=main.amountDistributorTrucks;
        }
    }
    i++;
}

Event writing_Results
main.results.writeFile();  //Write results of each distributor in excel output file

main.results.setCellValue(matching_Number, "Distributors", 2+matching_Number, 1);
main.results.setCellValue(location, "Distributors", 2+matching_Number, 2);
main.results.setCellValue(market_Share*100, "Distributors", 2+matching_Number, 4);
main.results.setCellValue(pallet_Budget_Dist, "Distributors", 2+matching_Number, 5);
main.results.setCellValue(pallet_Sales_Dist, "Distributors", 2+matching_Number, 6);
if (number==0){
    main.results.setCellValue("East", "Distributors",
    2+matching_Number, 3);
}
if (number==1){
    main.results.setCellValue("Mid", "Distributors",
    2+matching_Number, 3);
}
if (number==2){
    main.results.setCellValue("West", "Distributors",
    2+matching_Number, 3);
}

Transition Idle to Reviewing_Delivery
Condition:
product_Delivery_Dist.size()!=0;

Reviewing_Delivery state:
//Carrying out pallet handlings & storing pallets / products into outgoing queues.

actual_Product_Dist=product_Delivery_Dist.removeLast();

//Case: attached pallet has enough handlings left
if
(actual_Product_Dist.corresponding_Pallet.lifespan>=pallet_Handlings_Dist){
    actual_Product_Dist.corresponding_Pallet.lifespan=actual_Product_Dist.corresponding_Pallet.lifespan-
pallet_Handlings_Dist;
pallet_Budget_Dist=pallet_Budget_Dist+actual_Product_Dist.
corresponding_Pallet.market_Value; //Budget
    actual_Product_Dist.corresponding_Pallet.current_Location=location;
    //assigning current location
    product_Delivery_reviewed.addFirst(actual_Product_Dist);
    send ("Distributor finished", this);
    actual_Product_Dist.pallet_Solved=true;
}
//Case attached pallet has not enough handlings left and needs exchanging
if (actual_Product_Dist.corresponding_Pallet.lifespan<pallet_Handlings_Dist) {
    send("Pallet out of use",
    actual_Product_Dist.corresponding_Pallet);
    pallet_Budget_Dist=pallet_Budget_Dist+actual_Product_Dist.corresponding_Pallet.market_Value; //Budget
    pallet_Sales_Dist=pallet_Sales_Dist+5; //Sales
    actual_Product_Dist.corresponding_Pallet.current_Location=location;
    //assigning current location
    //In case required, the broken pallet needs to be
    assigned to a new linkedList for repair
    actual_Product_Dist.pallet_Solved=false;
} while (actual_Product_Dist.pallet_Solved==false) {
    //Case new or used pallet is required
    //Case: Used pallet
    if (main.consumer_Product_Manufacturers(0).pallet_Pool_Dist.size()>0) { //defining use of used pallet

        main.consumer_Product_Manufacturers(0).reuse_Pallet_Counter=main.consumer_Product_Manufacturers(0).reuse_Pallet_Counter+1;

        actual_Product_Dist.corresponding_Pallet=main.consumer_Product_Manufacturers(0).pallet_Pool_Dist.removeLast();

        //Checking if pallet pool pallets are still usable

        //Sub-Subcase: First Pallet Pool pallet has
        enough handlings left
        if (actual_Product_Dist.corresponding_Pallet.lifespan>=pallet_Handlings_Dist) {

            actual_Product_Dist.corresponding_Pallet.lifespan=actual_Product_Dist.corresponding_Pallet.lifespan-
pallet_Handlings_Dist;

        }
pallet_Budget_Dist=pallet_Budget_Dist+actual_Product_Dist.corresponding_Pallet.market_Value; //Budget

actual_Product_Dist.corresponding_Pallet.current_Location=location;
//assigning current location

product_Delivery_reviewed.addFirst(actual_Product_Dist);
send ("Distributor finished", this);
actual_Product_Dist.pallet_Solved=true;
}

if (actual_Product_Dist.corresponding_Pallet.lifespan<pallet_Handlings_Dist){

    pallet_Budget_Dist=pallet_Budget_Dist+actual_Product_Dist.corresponding_Pallet.market_Value; //Budget
    pallet_Sales_Dist=pallet_Sales_Dist+5; //Sales

    actual_Product_Dist.corresponding_Pallet.current_Location=location;
    //assigning current location
    send ("Pallet out of use", actual_Product_Dist.corresponding_Pallet);

    main.consumer_Product_Manufacturers(0).out_Of_Use_Counter++;
    actual_Product_Dist.pallet_Solved=false;
}
}

Dispatch State
//Routing products in queue for matching retailer

while (product_Delivery_reviewed.size()!=0){

    inventory_Product=product_Delivery_reviewed.removeLast();

    if (inventory_Product.route_To_Ret==retailer_0){

        pallet_Budge...
product_Queue_Ret_0.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_1){
    product_Queue_Ret_1.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_2){
    product_Queue_Ret_2.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_3){
    product_Queue_Ret_3.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_4){
    product_Queue_Ret_4.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_5){
    product_Queue_Ret_5.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_6){
    product_Queue_Ret_6.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_7){
    product_Queue_Ret_7.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_8){
    product_Queue_Ret_8.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_9){
    product_Queue_Ret_9.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_10){
    product_Queue_Ret_10.addFirst(inventory_Product);
}
if (inventory_Product.route_To_Ret==retailer_11){
    product_Queue_Ret_11.addFirst(inventory_Product);
}
}

Transition Branch to Shipping
Condition:
(product_Queue_Ret_0.size()==available_Truck_Dist.capacity) 
  ||
  (product_Queue_Ret_1.size()==available_Truck_Dist.capacity) 
  ||
  (product_Queue_Ret_2.size()==available_Truck_Dist.capacity)
Action:
//Loading Trucks and deleting pallets / products from Distributor inventory
int l=0; //counting variable for available spots for pallets on truck bed

if (product_Queue_Ret_0.size()==available_Truck_Dist.capacity) {
    //Choosing Case 1
    available_Truck_Dist.where_To=retailer_0;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity){
        inventory_Product=product_Queue_Ret_0.removeLast();
        pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.corresponding_Pallet.market_Value;
        available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
        l++;
    }
}
l=0;
if (product_Queue_Ret_1.size()==available_Truck_Dist.capacity)
{
    //Choosing Case 2
    available_Truck_Dist.where_To=retailer_1;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity)
    {
        inventory_Product=product_Queue_Ret_1.removeLast();
        pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.
        corresponding_Pallet.market_Value;
        available_Truck_Dist.product_Queue_Ret.addFirst(invent
       ory_Product);
        l++;
    }
}
l=0;

if (product_Queue_Ret_2.size()==available_Truck_Dist.capacity)
{
    //Choosing Case 3
    available_Truck_Dist.where_To=retailer_2;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity)
    {
        inventory_Product=product_Queue_Ret_2.removeLast();
        pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.
        corresponding_Pallet.market_Value;
        available_Truck_Dist.product_Queue_Ret.addFirst(invent
        ory_Product);
        l++;
    }
}
l=0;

if (product_Queue_Ret_3.size()==available_Truck_Dist.capacity)
{
    //Choosing Case 4
    available_Truck_Dist.where_To=retailer_3;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity)
    {
        inventory_Product=product_Queue_Ret_3.removeLast();
        pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.
        corresponding_Pallet.market_Value;
        available_Truck_Dist.product_Queue_Ret.addFirst(invent
        ory_Product);
        l++;
    }
}
l=0;

if (product_Queue_Ret_4.size()==available_Truck_Dist.capacity)
{
    //Choosing Case 5
    available_Truck_Dist.where_To=retailer_4;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity) {
        inventory_Product=product_Queue_Ret_4.removeLast();
        pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.
        corresponding_Pallet.market_Value;
        available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
        l++;
    }
}
l=0;

if (product_Queue_Ret_5.size()==available_Truck_Dist.capacity)
{
    //Choosing Case 6
    available_Truck_Dist.where_To=retailer_5;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity) {
        inventory_Product=product_Queue_Ret_5.removeLast();
        available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
        l++;
    }
}
l=0;

if (product_Queue_Ret_6.size()==available_Truck_Dist.capacity)
{
    //Choosing Case 7
    available_Truck_Dist.where_To=retailer_6;
    available_Truck_Dist.status="busy";
    while (l<available_Truck_Dist.capacity) {
        inventory_Product=product_Queue_Ret_6.removeLast();
        pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.
        corresponding_Pallet.market_Value;
        available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
        l++;
    }
}
l=0;

if (product_Queue_Ret_7.size()==available_Truck_Dist.capacity)
   //Choosing Case 8
   available_Truck_Dist.where_To=retailer_7;
   available_Truck_Dist.status="busy";
   while (l<available_Truck_Dist.capacity){
      inventory_Product=product_Queue_Ret_7.removeLast();
      pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.corresponding_Pallet.market_Value;
      available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
      l++;
   }
}
l=0;

if (product_Queue_Ret_8.size()==available_Truck_Dist.capacity)
   //Choosing Case 9
   available_Truck_Dist.where_To=retailer_8;
   available_Truck_Dist.status="busy";
   while (l<available_Truck_Dist.capacity){
      inventory_Product=product_Queue_Ret_8.removeLast();
      pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.corresponding_Pallet.market_Value;
      available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
      l++;
   }
}
l=0;

if (product_Queue_Ret_9.size()==available_Truck_Dist.capacity)
   //Choosing Case 10
   available_Truck_Dist.where_To=retailer_9;
   available_Truck_Dist.status="busy";
   while (l<available_Truck_Dist.capacity){
      inventory_Product=product_Queue_Ret_9.removeLast();
      pallet_Sales_Dist=pallet_Sales_Dist+inventory_Product.corresponding_Pallet.market_Value;
      available_Truck_Dist.product_Queue_Ret.addFirst(inventory_Product);
      l++;
   }
}
l=0;
if (product Queue Ret_10.size()==available Truck Dist.capacity)
    //Choosing Case 11
    available Truck Dist.where To=retailer_10;
    available Truck Dist.status = "busy";
    while (l<available Truck Dist.capacity)
        inventory Product=product Queue Ret_10.removeLast();
        pallet Sales Dist=pallet Sales Dist+inventory Product.
        corresponding Pallet.market Value;
        available Truck Dist.product Queue Ret.addFirst(inventory Product);
        l++;
    }
}
l=0;
if (product Queue Ret_11.size()==available Truck Dist.capacity)
    //Choosing Case 12
    available Truck Dist.where To=retailer_11;
    available Truck Dist.status = "busy";
    while (l<available Truck Dist.capacity)
        inventory Product=product Queue Ret_11.removeLast();
        pallet Sales Dist=pallet Sales Dist+inventory Product.
        corresponding Pallet.market Value;
        available Truck Dist.product Queue Ret.addFirst(inventory Product);
        l++;
    }
}
l=0;

Transition Shipping to Branch:
Action:

send("Leave Distributor", available Truck Dist);

Transition Branch to Idle:
(product Queue Ret_0.size()! = available Truck Dist.capacity)
    &&
    (product Queue Ret_1.size()! = available Truck Dist.capacity)
    &&
    (product Queue Ret_2.size()! = available Truck Dist.capacity)
    &&
    (product Queue Ret_3.size()! = available Truck Dist.capacity)
(product_Queue_Ret_4.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_5.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_6.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_7.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_8.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_9.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_10.size() != available_Truck_Dist.capacity) &&
(product_Queue_Ret_11.size() != available_Truck_Dist.capacity)

Agent truck_CPM
Transition At_CPM to Loading
Timeout: loading_Time;

Transition Loading to Moving_To_Distributor:
Message: "Leave CPM"
Action: moveTo(where_To);

Unloading State:
Entry action:

//Unloading Trucks and deleting pallets / products from truck bed

while (product_Queue_Dist.size() > 0){
    unload_Product = product_Queue_Dist.removeLast();
    unload_Product.corresponding_Pallet.no_Of_Transactions =
    unload_Product.corresponding_Pallet.no_Of_Transactions + 1;
    where_To.product_Delivery_Dist.addFirst(unload_Product);
    send ("at Distributor", unload_Product);
}

Transition Unloading to Moving_To_CPM:
Timeout: unloading_Time;
Action: moveTo(main.consumer_Product_Manufacturers(0));

Transition Moving_To_CPM to At_CPM:
Action:
status="available";
where_To=null;
unload_Product=null;

Agent Retailer
Event: setting_CPM_Destinations:
//Assigning retailer numbers for choosing correct destinations

while (0<destinations.size()){
    destination=destinations.removeLast();
}

Event: checking_Truck_Availability:
//Event for checking and choosing available truck for transport of products & pallets to particular retailer
int i=0;  //counting variable for truck_Retailer population

while (i<main.amountRetailerTrucks){
    if (main.truck_Retailers(i).belongs_To_Ret==this){
        if (main.truck_Retailers(i).status=="available"){
            available_Truck_Ret=main.truck_Retailers(i);
            i=main.amountRetailerTrucks;
        }
    }
    i++;
}

Event: writing_Results
main.results.writeFile();  //Write results of each distributor in excel output file
main.results.setCellValue(number, "Retailers", 2+number, 1);
main.results.setCellValue(location, "Retailers", 2+number, 2);
main.results.setCellValue(sink.size(), "Retailers", 2+number, 3);
main.results.setCellValue(market_Share*100, "Retailers", 2+number, 4);
main.results.setCellValue(pallet_Budget_Ret, "Retailers", 2+number, 5);
main.results.setCellValue(pallet_Sales_Ret, "Retailers", 2+number, 6);

Transition Idle to Reviewing_Delivery
Condition:
product_Delivery_Ret.size()>0;

Reviewing_Delivery State:
//Carrying out pallet handlings & storing pallets / products into outgoing queues.

//Detaching pallet from product
actual_Product_Ret=product_Delivery_Ret.removeLast();
actual_Pallet_Ret=actual_Product_Ret.corresponding_Pallet;
//actual_Product_Ret.corresponding_Pallet=null;
sink.addFirst(actual_Product_Ret);

//Case pallet has enough handlings left
if (actual_Pallet_Ret.lifespan>=pallet_Handlings_Ret){
    actual_Pallet_Ret.lifespan=actual_Pallet_Ret.lifespan-
pallet_Handlings_Ret;
pallet_Budget_Ret=pallet_Budget_Ret+actual_Pallet_Ret.
market_Value; //Budget
actual_Pallet_Ret.current_Location=location; //assigning current
location
return_Pallets.addFirst(actual_Pallet_Ret);
send ("Retailer finished", this);
}

//Case attached pallet has not enough handlings left and needs exchanging
if (actual_Pallet_Ret.lifespan<pallet_Handlings_Ret){
    send("Pallet out of use", actual_Pallet_Ret);
pallet_Demand_Ret=pallet_Demand_Ret+1;
pallet_Budget_Ret=pallet_Budget_Ret+actual_Pallet_Ret.
market_Value; //Budget
pallet_Sales_Ret=pallet_Sales_Ret+5; //Sales
actual_Pallet_Ret.current_Location=location; //assigning current
location
//In case required, the broken pallet needs to be assigned to a new linkedList for repair
}
\begin{verbatim}
while (pallet_Demand_Ret>0) {
    // Case new or used pallet is required
    // Subcase: removing first pallet from Pallet Pool
    if (pallet_Demand_Ret>0 &&
        main.consumer_Product_Manufacturers(0).pallet_Pool_Ret.size ()>0)
    {
        actual_Pallet_Ret=main.consumer_Product_Manufacturers(0).pallet_Pool_Ret.removeLast();
        main.consumer_Product_Manufacturers(0).reuse_Pallet_Counter=main.consumer_Product_Manufacturers(0).reuse_Pallet_Counter+1;
    }
    // Sub-Subcase: First Pallet Pool pallet has enough handlings left
    if (actual_Pallet_Ret.lifespan>=pallet_Handlings_Ret)
    {
        actual_Pallet_Ret.lifespan=actual_Pallet_Ret.lifespan-pallet_Handlings_Ret;
        pallet_Budget_Ret=pallet_Budget_Ret+actual_Pallet_Ret.market_Value;  // Budget
        actual_Pallet_Ret.current_Location=location;  // assigning current location
        return_Pallets.addFirst(actual_Pallet_Ret);
        pallet_Demand_Ret=pallet_Demand_Ret-1;
        send ("Retailer finished", this);
    }
    // Sub-Subcase: First Pallet Pool pallet has not enough handlings left
    else {
        send("Pallet out of use", actual_Pallet_Ret);
        pallet_Budget_Ret=pallet_Budget_Ret+actual_Pallet_Ret.market_Value;  // Budget
        pallet_Sales_Ret=pallet_Sales_Ret+5;  // Sales
        actual_Pallet_Ret.current_Location=location;  // assigning current location
    }
}
\end{verbatim}
//Subcase: No pallets left in Pallet Pool, new pallet required
if (pallet_Demand_Ret>0 &&
    main.consumer_Product_Manufacturers(0).pallet_Pool_Ret.size()==0){

    main.consumer_Product_Manufacturers(0).new_Pallet_Number=main.consumer_Product_Manufacturers(0).new_Pallet_Number +1;
    send ("new pallet",
        main.pallets(main.consumer_Product_Manufacturers(0).new_Pallet_Number));

    actual_Pallet_Ret=main.pallets(main.consumer_Product_Manufacturers(0).new_Pallet_Number);

    actual_Pallet_Ret.lifespan=actual_Pallet_Ret.lifespan-pallet_Handlings_Ret;

    pallet_Budget_Ret=pallet_Budget_Ret+actual_Pallet_Ret.market_Value;          //Budget
    actual_Pallet_Ret.current_Location=location;          //assigning current
    location
    return_Pallets.addFirst(actual_Pallet_Ret);
    pallet_Demand_Ret=pallet_Demand_Ret-1;
    send ("Retailer finished", this);
}

Transition Branch to Shipping
//Loading Trucks and returning pallets to Consumer Product Manufacturer
int l=0;                          //counting variable for available spots
                                //for pallets on truck bed

if (return_Pallets.size()==available_Truck_Ret.capacity){
    while (l<available_Truck_Ret.capacity){
        load_Pallet=return_Pallets.removeLast();
        pallet_Sales_Ret=pallet_Sales_Ret+load_Pallet.market_Value;
        available_Truck_Ret.pallet.Queue_CPM.addFirst(load_Pallet);
        l++;
    }
}
available_Truck_Ret.where_To=destination;
available_Truck_Ret.status="busy";
}
l=0;

Transition Shipping to Branch
Action:
send("Leave Retailer", available_Truck_Ret);

Transition Branch to Idle
Condition:
(return_Pallets.size()!=available_Truck_Ret.capacity)

Agent truck_Distributor
Transition At_Distributor to Loading
Timeout: loading_Time;

Moving_To_Retailer State
Entry action:
moveTo(where_To);

Unloading_State
Entry action:
//Unloading Trucks and deleting pallets / products from truck bed

while (product_Queue_Ret.size()>0){
    unload_Pallet=product_Queue_Ret.removeLast();
    unload_Pallet.corresponding_Pallet.no_Of_Transactions =unload_Pallet.corresponding_Pallet.no_Of_Transactions+1;
    where_To.product_Delivery_Ret.addFirst(unload_Pallet);
    send ("At Retailer", unload_Pallet);
}

Transition Unloading to Moving_To_Distributor
Timeout: unloading_Time;
Action: moveTo(belongs_To_Dist);

Transition Moving_To_Distributor to At_Distributor
Action:
status="available";
where_To=null;
unload_Pallet=null;
Agent Product
Transition Order_Income to At_CPM
Timeout: spawn_Time
Action:
main.consumer_Product_Manufacturers(0).new_Product_Number=prod_Number;

At_CPM state
Entry action:
send ("product needs pallet",
main.consumer_Product_Manufacturers(0));

Agent Pallet
Order_Income State:
Entry action:
lifespan_0=lifespan;

Transition Order_Income to Idling
Message: "new pallet"
Action: status="used";

main.results.writeFile(); //Write specifications of each pallet in excel output file
main.results.setCellValue(lifespan_0, "Pallets", 2+number, 6);
main.results.setCellValue(lifespan_1, "Pallets", 2+number, 7);
main.results.setCellValue(lifespan_2, "Pallets", 2+number, 8);
main.results.setCellValue(lifespan_3, "Pallets", 2+number, 9);

In_Use State:
Entry action:
main.results.writeFile(); //Write results of each pallet in excel output file
main.results.setCellValue(lifespan, "Pallets", 2+number, 3);
main.results.setCellValue(status, "Pallets", 2+number, 2);
main.results.setCellValue(current_Location, "Pallets", 2+number, 4);
main.results.setCellValue(no_Of_Transactions, "Pallets", 2+number, 5);
main.results.setCellValue(no_Of_Repairs, "Pallets", 2+number, 10);

**Transition In_Use to Idling**
Timeout: 50000

**Transition In_Use to Branch**
Message: "Pallet out of use"

**Transition Branch to Maintenance**
Condition: no_Of_Repairs<max_no_Of_Repairs
Action: if (no_Of_Repairs==0 && decision_Probability_0>0.1 && decision_Probability_0<=0.7){
    lifespan=lifespan_1;
    //setting up 1st repair life stage
    market_Value=35;
    //setting up 1st repair market value
    false_Failure=true;
    //re-setting false Failure option
    //Writing repair status of pallet to results file
    main.results.writeFile();
    main.results.setCellValue(no_Of_Repairs+1, "Pallets", 2+number, 10);
    main.results.setCellValue("x", "Pallets", 2+number, 12);
    main.results.setCellValue(current_Location, "Pallets", 2+number, 13);
} else if (no_Of_Repairs==1 && decision_Probability_0>0.07 && decision_Probability_0<=0.57){
    lifespan=lifespan_2;
    //setting up 2nd repair life stage
    market_Value=25;
    //setting up 2nd repair market value
    false_Failure=true;
    //re-setting false Failure option
    //Writing repair status of pallet to results file
    main.results.writeFile();
    main.results.setCellValue(no_Of_Repairs+1, "Pallets", 2+number, 10);
    main.results.setCellValue("x", "Pallets", 2+number, 14);
if (no_Of_Repairs==2 && decision_Probability_0>0.04 && decision_Probability_0<=0.44){
lifespan=lifespan_3;
  //setting up 3rd repair life stage
market_Value=20;
  //setting up 3rd repair market value
false_Failure=true;
  //re-setting false Failure option
//Writing repair status of pallet to results file
main.results.writeFile();
main.results.setCellValue(no_Of_Repairs+1, "Pallets", 2+number, 10);
main.results.setCellValue("x", "Pallets", 2+number, 16);
main.results.setCellValue(current_Location, "Pallets", 2+number, 17);
}
no_Of_Repairs=no_Of_Repairs+1;
  //Adding repair

Transition Maintenance to Idling
Action:
main.consumer_Product_Manufacturers(0).pallet_Pool.addLast(this);

Transition Branch to Idling
Condition: (no_Of_Repairs==0 && decision_Probability_0<=0.1 && false_Failure==true)||(no_Of_Repairs==1 && decision_Probability_1<=0.07 && false_Failure==true)||(no_Of_Repairs==2 && decision_Probability_2<=0.04 && false_Failure==true)
Action:
if (no_Of_Repairs==0 && decision_Probability_0<=0.1 && false_Failure==true){
lifespan=40;
market_Value=60;
false_Failure=false;
main.consumer_Product_Manufacturers(0).pallet_Pool.addLast(this);
//Writing false failure of pallet to results file
main.results.writeFile();
main.results.setCellValue(1, "Pallets", 2+number, 11);
}

if (no_Of_Repairs==1 && decision_Probability_1<=0.07 && false_Failure==true){
lifespan=30;
market_Value=35;
false_Failure=false;
main.consumer_Product_Manufacturers(0).pallet_Pool.addLast(this);
//Writing false failure of pallet to results file
main.results.writeFile();
main.results.setCellValue(2, "Pallets", 2+number, 11);
}

if (no_Of_Repairs==2 && decision_Probability_2<=0.04 && false_Failure==true){
lifespan=15;
market_Value=20;
false_Failure=false;
main.consumer_Product_Manufacturers(0).pallet_Pool.addLast(this);
//Writing false failure of pallet to results file
main.results.writeFile();
main.results.setCellValue(3, "Pallets", 2+number, 11);
}

Transition Branch to End_of_Life:
Condition: (no_Of_Repairs==0 && decision_Probability_0>0.7)
|| (no_Of_Repairs==1 && decision_Probability_1>0.57) || (no_Of_Repairs==2 && decision_Probability_2>0.44) || (no_Of_Repairs==3)
Action:
status="end of life";

main.results.writeFile(); //Write results of each pallet in excel output file
main.results.setCellValue(lifespan, "Pallets", 2+number, 3);
main.results.setCellValue(status, "Pallets", 2+number, 2);
main.results.setCellValue(current_Location, "Pallets", 2+number, 4);
main.results.setCellValue(no_Of_Transactions, "Pallets", 2+number, 5);
main.results.setCellValue(no_Of_Repairs, "Pallets", 2+number, 10);

Sink state:
Action:
main.consumer_Product_Manufacturers(0).pallet_End_Of_Life.addFirst(this);

Agent truck_Retailer
Transition At_Retailer to Loading
Timeout: loading_Time;

Moving_To_CPM state
Entry action: moveTo(where_To);

Unloading state
Entry action:
//Unloading Trucks and deleting pallets from truck bed
int i=0; //counting variable for unloading pallets

while (pallet_Queue_CPM.size()! = 0) {
    unload_Pallet=pallet_Queue_CPM.removeLast();
    unload_Pallet.no_Of_Transactions=unload_Pallet.no_Of_Transactions+1;
    if (i<capacity-3){
        where_To.pallet_Pool.addFirst(unload_Pallet);
    }
    if (i>=capacity-3 && i<capacity-1){
        where_To.pallet_Pool_Dist.addFirst(unload_Pallet);
    }
    if (i>=capacity-1 && i<capacity){
        where_To.pallet_Pool_Ret.addFirst(unload_Pallet);
    }
    i++;
}

Transition Unloading to Moving_To_Retailer
Timeout: unloading_Time;
Action: moveTo(belongs_To_Ret);

Transition Moving_To_Retailer to At_Retailer
status="available";
where_To=null;
unload_Pallet=null;
9 Bibliography


