Improving a facility layout in the manufacturing industry application on a production site of construction pannels

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MSc Thesis

Improving a facility layout in the manufacturing industry: Application on a production site of construction panels

by

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in Operations Management and Logistics

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ABSTRACT

This Master’s thesis describes the approach and analysis of a location-routing problem. The research project focuses on the layout of facilities of Trespa International B.V., a manufacturing company which produces construction panels. The layout influences the costs of internal transportation between facilities. The aim of the research project is to reduce these costs. A model is developed which computes the costs of internal transportation given a certain defined scenario. Using data from different sources, the current situation is modeled and analyzed first. Thereafter, several layout redesign scenarios have been compared to the current situation to see in what extent the costs of internal transportation can be reduced.

The research project is also the final stage of the Operations Management & Logistics (OML) master program at the Eindhoven University of Technology (TU/e).
MANAGEMENT SUMMARY

The production location of Trespa in Weert consists of several plants. In these plants, the supplied raw materials are processed and finally the high quality panels are the end products. Compared to the ‘original’ production area and its facilities, a lot of plants and locations have been added, adapted or replaced. As a result of the expansion and associated changes, the facilities are not located optimally with respect to each other. The transportation of the materials and semi-finished products is mainly done by regular trucks and forklift trucks of different types. In the master thesis project it is investigated to what extent the layout of the production site can be improved, with respect to the locations of the plants and stocks and the internal transportation routing. The main goal is to minimize the costs, influenced by the layout. The research area and the improvement goals lead to the following main research question for the master thesis project:

| How can internal transportation costs be reduced by a redesign of the production facility layout with certain constraints? |

In order to get an overview of the locations and truck routings at the production area, several different sources are combined, such as a former study of internal transportation, interviews with shift leaders and truck operators, a measurement of truck movements and machinery data from SAP. This has led to important insight in the item flows, locations and trucks. The obtained information is used as input data for the model.

In order to analyze different redesign scenarios for the layout, a model is constructed. Based on knowledge gained by a literature review and information obtained about the real world situation at Trespa, first a mathematical model is made. The mathematical model of the location-routing problem (LRP) is formulated as a mixed integer linear program (MILP). This mathematical program is implemented in AIMMS, a software program that is used for optimization problems. The objective of the model is to minimize the costs of internal transportation. For each item flow, the model has to choose what quantity of the item is transported via what route. This is done by selecting arcs to traverse. As a result, the model is able to analyze different layout scenarios whilst taking into account the real world paths to follow. Because of the practical aspect of the project, the input for redesign scenarios is done manually by changing constraints or the values of the input data set.

For the current situation and every redesign scenario, the model outcomes are described and explained. The main conclusions of the research are summarized below:

- The internal transportation costs depend on the distance and time needed for all item flows. These costs are operator costs, truck fuel costs and truck lease costs.
- A lot of forklift trucks are used at the production site of Trespa. As a result, a considerable amount of lease costs is spent every year. There are a lot of trucks needed to execute special actions, dependent of their size and fork types. Another reason for this large fleet size is that several machines need a truck at an input or output point at certain moments; if no truck is present, the machine cannot operate.
- The number of hours the trucks are used per day is very low on average (about 4 hours per day (24 hours) for the trucks included in the analysis). The two trucks of the presses 6 and 7 are used quite a lot.
- Several machines are very large and the investments needed to relocate them would not be outweighed by the gains. These locations cannot be changed, so the layout scenarios to consider are limited. Most likely and feasible to relocate are the stock points of core material.
In the current situation, the important locations of the production area are placed such that start and end points of item flows are close to each other. Transportation flows are quite in line with the main production process. As several scenarios show, the MHC cannot be reduced significantly given the constraints of this brownfield situation. A reduction of costs for internal transportation seems to be hard by only changing the layout. Switching the current stock locations of core material leads to slightly increased transportation times. The placement of storage racks is therefore a feasible solution of the ‘sticking sheets problem’ regarding internal transportation.

One layout improvement is in execution at the moment. Moving the prepregs on stock from the Bowiehal to location 213-1 (former press5) is nice improvement scenario which will lead to the reduction of about 1 FTE and the lease of one or two forklift trucks.

If item flows of two trucks can be combined in such a way that the actions are executed by only one truck, lease costs can be reduced. This will require an analysis which includes time windows. Using Klima2 and 2B as stock locations for core material will result in an increase of driving time for the core truck: the trucks of the presses can save driving time. Further analysis including time windows is needed to see if the truck of press 7 can perform the actions on its own, which would lead to cost reductions of scrapping truck 135. Another way to reduce lease and direct labor costs is the automation of item flows.

The model created in AIMMS can be used to analyze layout scenarios by calculating the total time needed for item flows. All input data can be changed for calculations, such as possible paths, demands, location coordinates and truck capacities; the possibilities are endless. AIMMS is commercially used software by professionals and has several nice features, such as fast run time, clear programming overview, graphical interface and the possibility to link to Microsoft Excel for importing and exporting data.

The following is recommended, based on the results and insights obtained by this research project:

A lot of forklift trucks are only in use during a small amount of time per shift. In order to save money, it sounds obvious to scrap some trucks by combining the actions performed by separate trucks. The first remark is that truck types differ, so the possible actions to perform are not equal for each truck. Secondly there are trucks which are needed in certain time windows; if they are not available at a certain time, it is possible that the production process is disrupted. A clear example is a truck needed at the output of a machine. If the output buffer is full, the machine cannot operate anymore.

It is recommended to analyze the possibility to combine some trucks. This can be done by making a model which includes time windows. Extending the output buffer of a machine (for example by extending the conveyor length or placing a stacking machine) may increase the possibilities to combine trucks.

A detailed analysis to see if trucks can be combined is recommended for the following trucks:

101 / 107: scrapping truck 101 leads to a reduction of lease costs of €2,378 per month.
106 / 135: scrapping truck 135 leads to a reduction of lease costs of €1,594 per month.

The terminal trailer truck is used a lot to transport the finished products from the presses towards the warehouse. Most of the times the trailer is also transported back to the presses empty (sometimes new pallets are transported on the way back to the presses). Implementing Automated Guided Vehicles (AGVs) might lead to a reduction of direct labor costs.

The pallets with finished products which are transported from the presses towards the warehouse only contain panels of the same type. It is recommended to analyze if this process can be changed; placing more panels on a pallet will lead to a reduction of the amount of times the trailer has to be transported towards the warehouse.
The analysis of the current situation and the redesign scenarios is based on observations and the production data of 2013. It is likely that the process and demands of product types will change over time. Analyses with updated data are needed to see what the effects will be of layout changes in the future.

Included in the model are only the real driving times of trucks between locations; time spent during handling on locations is not included in the model. An analysis of the handling on locations might lead to new insights and improvements.
PREFACE

This master thesis is the result of a research project, executed in partial fulfillment of the Operations Management & Logistics (OML) master program of the Eindhoven University of Technology (TU/e). The project is executed in cooperation with Trespa International B.V., a company which manufactures high quality panels used for construction and decoration. As a graduation intern, I have had the opportunity to get to know the company and gain experience in various aspects of the manufacturing industry. Although the project was very challenging, I have learned a lot about several aspects of industrial engineering and developed both professional and personal skills.

In this preface I would like to thank all people who have supported me in the past three years of my master study and during this hectic and instructive research project.

The largest part of the research I have been working at the Improve department of Trespa. I would like to thank Barry Timmer, my company supervisor, for giving me the opportunity to conduct my research in a very interesting company. I appreciate the effort and time you put into my project and also learned a lot from our weekly meetings.

Also thanks to all other employees of Trespa, who have helped me during the past months. It was nice to talk to a lot of people from different disciplines who shared their experience and opinion about several subjects.

I would like to thank Behzad Hezarkhani, my university supervisor, for his time and coaching during the past 1,5 years. Your critical view and supporting attitude have helped me to stay focused and be able to keep the project progress. Also thanks to Dmitry Krushynskyi, the second university supervisor, for providing me feedback on the report.

I thank my fellow students Bas, Kevin, Camiel and Bram for their support and motivating attitude during the past years of studying. Thank you very much for the time we spent together for serious studying but also for your laughs and enjoyable moments.

Last but not least, I would like to thank my family and friends. Special thanks to my parents, brother and sister. You always support me and believe in everything I do, for which I am very grateful.

Thank you.

Peter Op de Kamp
November 2014
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1. INTRODUCTION

In this introduction chapter, some background information is given of the cooperating company, Trespa International B.V.. The general methodology of the research project is shown in Section 1.2. Section 1.3 gives a brief overview of the structure of this report.

1.1 Company description

The master thesis project will be conducted in cooperation with a manufacturing company. The company, Trespa International B.V. (Trespa), is a leading innovator in the field of architectural materials, recognized internationally as a premier developer of high quality panels for exterior cladding, decorative façades, and scientific solutions. The premier product line Trespa® Meteon®, Trespa's leading family of architectural panels for façades and exterior applications is created to inspire, engineered to perform and built to endure. Trespa Meteon is a decorative high-pressure compact laminate (HPL) with an integral surface manufactured using Trespa's unique in-house technologies (Trespa, 2014). Figure 1.1 gives an impression of a building on which Trespa panels are applied to create a modern look.

Figure 1.1: Example of the application of Trespa panels

In 1960, the Thermopal business started in Weert as a manufacturer of high pressure laminates. After the introduction of two patented technologies, ‘Dry Forming (DF)’ and ‘Electron Beam Curing (EBC)’, Trespa International B.V. was founded in 1995. In 2001, an innovative press with 30 daylights is put into production, the largest press in the world at that time. The product range has also be extended throughout the years. The production of woodprint decors was introduced in 2003, and since 2008 the ZF panel size (4270x2130 mm) is being pressed. In the past six years, three Trespa Design Centers were opened in New York, Barcelona and Santiago de Chile.

Nowadays, Trespa is a quite large company with its headquarter in Weert, the Netherlands. At this location also the production of the panels takes place. The production location has a lot of different plants, varying from resin production, coating paper and the impregnation of paper to the paper pressing. The total production site of Trespa contains about 15 different kinds of plants, which are used to produce all the customer specific panels.
Trespa produces panels, which can be used for a variety of purposes. The four product types are Trespa Meteon (used for balconies and facades), Trespa Toplab (used for scientific furniture), Trespa Athlon (used for interior decoration and scientific furniture with lower chemical resistance requirements) and Trespa Virtuon (used for interior decoration). The panels are standard available in five different sizes, including the newest and largest ZF size panel, which has measures of 4270 x 2130 mm. An overview of the different panel types and sizes is shown in Appendix 1.

A Trespa panel has a lot of properties, such as its size, front and back side color, surface structure, thickness and the core material. The panels are composed of a certain core, combined with a colored front and back decor layer (Figure 1.2). Large presses make sure this package is formed into a homogeneous panel. The standard available color palette that Trespa offers consists of about 400 different colors. Combined with other properties, such as surface options (e.g. texture, gloss and application type), the possible combinations are enormous.

![Figure 1.2: Left: Dry Forming core, wood-based fibers, impregnated with phenolic resin
Right: Kraft core, sheets of impregnated paper](image)

### 1.2 Methodology

The research project follows both a theory-based and design-based approach. The execution is a combination of the research aspect of the university and the practical real life setting of the cooperation with Trespa. As a guideline for the project execution, it is chosen to follow the methodology of business problem solving (BPS) projects, as discussed by Van Aken et al. (2007). This solution-oriented approach follows the five process steps (problem definition, analysis, plan of action, intervention, evaluation) as elaborated in the regulative cycle of Van Strien (1997). Guided by the five process steps, the project is divided into phases (represented by the report chapters), as shown in the project methodology scheme (Figure 1.3). Project steps are interrelated, since information and insights gathered in a certain step influence the process at other steps.
During the first process step, the problem orientation takes place. Trespa has an initial research assignment about improving the production area layout. In order to get a better understanding about this topic a literature study is conducted. This resulted in more theoretical knowledge and insights. On the other hand, it is important to get a feeling about the size and impact of the problem. Interviewing different employees of the company revealed the practical relevance of the analysis. The main goal of this first process step was to define the scope of the project and to formulate a clear research assignment.

The second step of the regulative cycle (analysis) is performed by conducting an analysis about the locations and routing. Several sources are used to get an overview of the different locations, trucks, goods and flows. The information which is obtained is also used for the construction of a model; this model serves as a tool to analyze the current and redesign scenarios.

This model is constructed in the design phase. The gathered data is then used as input for the model. A mathematical model is written and implemented in a software program for optimization. An important design aspect is the validation; the model outcomes have to match with the current situation in real-life. Using several sources to create the input data file increases the validity. Also a small sample of truck times has been gathered by observation to check the truck data.

In the fourth stage several redesigns are analyzed. This is done by creating scenarios, for which the objective function is calculated by the model. Scenarios are defined by changing the input data for the model. The last phase of the research project includes the evaluation, in which the conclusions are drawn and recommendations are given for Trespa and further research.
1.3 Report structure

The schematic overview which reflects the project methodology (Figure 1.3) is taken as a guideline for the project execution and also for the structure of this report. In Chapter 2 the problem statement is explained. This is done by describing the field of research, which includes the manufacturing setting and the production process of Trespa. Also the main research question and scope are defined. Chapter 3 contains an analysis of the current locations and routing of the production area. The most important flows are described. In Chapter 4 the literature study about location-routing problems is summarized. Also the mathematical formulation and model requirements are described. The model of the current situation and associated outcomes are outlined in Chapter 5. Several redesign scenarios are discussed in Chapter 6. Chapter 7 includes the conclusions and recommendations of this research project.
2. PROBLEM STATEMENT

This chapter includes the problem statement of the research. First, the field of research is explained to clarify the research context. This includes the description of the general production process of Trespa. The second section discusses the actual problem description of Trespa which will be analyzed during the research project.

2.1 Field of research

As mentioned before, Trespa is a manufacturing company. Manufacturing is the process of converting raw materials, components, or parts into finished goods that meet a customer's expectations or specifications. Manufacturing commonly employs a man-machine setup with division of labor in a large scale production (BusinessDictionary, 2014). Since the research project is executed at the production location of Trespa in Weert, it is influenced by this manufacturing setting. The research is done in partial fulfillment of the Operations Management & Logistics (OML) master program. OML is a multidisciplinary field that comprises disciplines such as product development, quality management, logistics, information systems and human resource management (TU/e_website, 2014). Because of this setting, the master thesis project has a design component and the goal of the research is to improve a certain logistics aspect. The involvement of two stakeholders (TU/e and Trespa) results in a project with a scientific approach and analysis designed for the situation of Trespa instead of a general model.

The production location of Trespa in Weert consists of several plants. In these plants, the supplied raw materials are processed and finally the high quality panels are the end products. The basic production process is shown in Figure 2.1. Suppliers deliver the resin material, kraft paper rolls, wood chips, coating paste and foil. A resin plant produces the resin, which is combined with kraft paper or wood chips (dependent on the desired core type) in order to make the core material. Kraft cores are made by impregnating several sheets of kraft paper, while the prepgs of wood chips are manufactured by ‘dry forming’ (DF).

In a color mixing unit (CMU), a coating is made for the decor layer. This coating is combined with foil in the electronic beam curing (EBC) process and results in rolls of colored paper (EB rolls). On basis of the customer’s desired panel size, a roll is placed on a Manuela or Clipper machine, where the required decor sheet is cut to the right size. This sheet is then combined with other sheets (which influence texture, gloss etc.) and so a decor package is composed.

In the press stage, a core is placed between the sheets of the decor package. The core can be composed of impregnated kraft sheets, prepgs or a combination of both. The presses have a certain amount of daylights, and a decor package and core is placed into each daylight. A press charge takes about 25 minutes and in principle, the presses are in operation 24/7. After the pressing process, the end product is finished and undergoes a quality inspection. The panels are then stored in the warehouse until they are shipped to the customer.
Figure 2.1: Basic production process of Trespa
2.2 Problem description

Trespa has to maintain its competitive position in the specific market to stay a financially healthy company. In order to do this, the production of the panels needs to be as efficient as possible. The Improvement department therefore constantly tries to come up with innovative solutions and also aims for a reduction of production cost, expressed in €/kg panel produced. The research project is executed in cooperation with the Improvement department. In Appendix 2, the place of this department within the organizational structure of Trespa is shown (Trespa_Intranet, Organization charts, 2014a).

In a period of 50 years, the production location of Trespa has grown to a diversity of plants. Compared to the ‘original’ production area and its facilities, a lot of plants and locations have been added, adapted or replaced. As a result of the expansion and associated changes, the facilities are not located optimally with respect to each other. In order to produce the end product (panels), the raw materials have to be processed in a set of stages. Each stage in the production process is done in a different plant. As a result, the total production site contains a lot of plants and stock points of semi-finished products (also called work-in-process, WIP) which are located at several locations. An overview of the current production site is shown in Appendix 3.

The transportation of the materials and semi-finished products is mainly done by regular trucks and forklift trucks of different types. In the master thesis project it is investigated to what extent the layout of the production site can be improved, with respect to the locations of the plants and stocks and the internal transportation routing. The main goal is to minimize the costs, influenced by the layout.

The research area and the improvement goals lead to the following main research question for the master thesis project:

**How can internal transportation costs be reduced by a redesign of the production facility layout with certain constraints?**

The goal of the master thesis project is to determine whether the layout can be improved, and if so, how it can be improved, what it will look like and what the possible gains and losses are. In order to get a better understanding of the main research question, additional research questions have been formulated. The questions 2 to 4.2 are answered for a large part by the preliminary literature study. During the actual research part of the project, the remaining questions have to be answered. The formulated additional research questions are shown in Table 2.1.
<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Research questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROBLEM KNOWLEDGE</td>
<td>RQ2</td>
<td>What are the most important aspects of a production facility layout?</td>
</tr>
<tr>
<td></td>
<td>RQ3.1</td>
<td>What objectives can be set for optimizing a facility layout?</td>
</tr>
<tr>
<td></td>
<td>RQ3.2</td>
<td>What are, in general, the sources that cause internal transportation cost (influenced by the layout) and how can these cost be determined?</td>
</tr>
<tr>
<td>MODELING</td>
<td>RQ4.1</td>
<td>What approaches and techniques can be used in order to (re)design a facility layout?</td>
</tr>
<tr>
<td></td>
<td>RQ4.2</td>
<td>How can the (re)design be validated?</td>
</tr>
<tr>
<td></td>
<td>RQ4.3</td>
<td>Which information is needed in order to model the layout?</td>
</tr>
<tr>
<td>COMPANY SPECIFIC</td>
<td>RQ5.1</td>
<td>What are the specifications of the current layout (AS-IS)?</td>
</tr>
<tr>
<td></td>
<td>RQ5.2</td>
<td>What flows seem to have the largest improvement potential?</td>
</tr>
<tr>
<td></td>
<td>RQ5.3</td>
<td>What approach will be used in order to redesign the facility layout of the case study at Trespa?</td>
</tr>
<tr>
<td>DESIGN</td>
<td>RQ6.1</td>
<td>What are possible improvements or scenarios to consider (TO-BE)?</td>
</tr>
<tr>
<td></td>
<td>RQ6.2</td>
<td>What are the given constraints for the redesign(s)?</td>
</tr>
<tr>
<td></td>
<td>RQ6.3</td>
<td>What does the proposed layout look like?</td>
</tr>
<tr>
<td>EVALUATION</td>
<td>RQ7</td>
<td>How can the proposed layout be implemented?</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of additional research questions

In this master thesis project, several layouts will be designed given scenarios with certain constraints. These new solutions will be compared to the current situation to see if improvements can be implemented.

2.3 Project scope

The field of research and the problem description give an idea of the domain in which the project is executed. This section declares some aspects of the project scope in more detail.

2.3.1 Layout: arrangement of facilities

In general, facility layout decisions involve designing the arrangement of elements (departments, machinery, human resources, etc.) in manufacturing systems (Emami & Nookabadi, 2013). The most significant indicator for evaluating the efficiency of a layout is the material handling costs (MHC). Since 20–50% of the total operating costs within manufacturing is attributed to material handling, companies can reduce these costs and improve the productivity if their facilities are arranged effectively (Tompkins et al., 2003). Also according to Schenk et al. (2010), logistics processes represent a significant cost factor. Logistics is characterized by the global consideration of material flows, which are apparent through movement (e.g. a forklift truck), and inventory (e.g. parts in storage), plus information and value flows. Therefore, the main focus of the master thesis project will be on the internal transportation of the production site, which is influenced by the layout. Changeable elements in the layout are coordinates of the facilities and important locations and the possible routes between them which can be traversed for material handling.
2.3.2 Objective: reduce transportation costs

As mentioned before, Trespa aims for a reduction of production costs. The production costs are composed of several factors. One important factor is the direct labor costs; Trespa has set specific targets for the reduction of these direct labor costs per production ton (Trespa_Intranet, 2014b). Improving the production facility layout can lead to a reduction in personnel required for internal transportation. Since each employee has to be paid, a reduction of the workforce results in cost decrease. When facilities are located more optimal with respect to each other, also the total travel distance of internal transportation (trucks) can be reduced. This leads to a decrease in fuel costs and rent and thus these costs are also reduced.

The layout of the production area involves the arrangement of elements. In this case, the layout includes assigning coordinates to facilities and important locations. Structures and obstacles in the area are taken into account. The production processes itself are not changed.

The scope of this project includes direct labor costs and truck costs, both influenced by the layout of the production area. Included item flows for the analysis are further specified in Chapter 3. The costs are further specified and explained in detail in Chapter 4. In Figure 2.2 below the scope definition is depicted.

![Figure 2.2: Process of scope definition](image)

Besides the financial aspect, also safety and the environment are important aspects for Trespa with respect to improvement opportunities. These other two domains are however out of scope for this research project. The cause and effect scheme of the project scope is shown in Figure 2.3.

2.3.3 Method: analyze scenarios

When facilities are placed in a certain layout, the objective function has to be calculated. This is done by using a mathematical model, which is implemented in a software program for optimization. The mathematical program is formulated as a MILP and includes the sets, parameters, variables and constraints to model the problem. For every transportation flow, the path from the start to end point is determined. The sum of all flows and their associated costs results in the total MHC for a specific scenario.

Because of the practical aspect of the project, the model and redesigns need to be evaluated with company employees. Therefore the input for redesign scenarios is done manually by changing constraints or the values of the input data set. In this way it is possible to analyze redesigns which make sense in real life; a model determining the layout by itself would result in non-feasible solutions or require an excessive amount of work. The model is able to analyze a wide variety of scenarios to see how the layout can be improved or what the influence of a certain change is.
2.4 Summary of problem statement

The production location of Trespa in Weert consists of several plants. In these plants, the supplied raw materials are processed and finally the high quality panels are the end products. Compared to the ‘original’ production area and its facilities, a lot of plants and locations have been added, adapted or replaced. As a result of the expansion and associated changes, the facilities are not located optimally with respect to each other.

In the master thesis project it is investigated to what extent the layout of the production site can be improved, with respect to the locations of the plants and stocks and the internal transportation routing. The main goal is to minimize the costs, influenced by the layout. Changeable elements in the layout are the coordinates of the facilities and important locations and the possible routes between them which can be traversed for material handling.

The main internal transportation is done by forklift trucks. Therefore, the costs of material handling are composed of direct labor costs and truck cost, such as fuel costs and rent.

Several layout redesigns are analyzed. The objective function of a certain layout redesign is calculated by a mathematical model, implemented in a software program for optimization. Because of the practical aspect of the project, the input for redesign scenarios is done manually by changing constraints or the values of the input data set.
3. LOCATION-ROUTING ANALYSIS

In this chapter the important locations and routings of the current situation are analyzed. A more detailed description is given about the production process and important components. The goal is to get a better view of the relevant item flows to include in the model and further analysis. The retrieved information of this chapter is important since it influences the building of the model.

3.1 Analysis sources and approach

At the production plant of Trespa, a lot of items are transported between a diversity of locations. Retrieving information about the item flows can be seen as a case study at the company. According to Blumberg et al. (2011) three types of sources can be used for a case study: interviews, archival records and observations. In order to get a clear overview of all important transportation flows between locations, these sources have been combined. An overview of the used sources is shown in Figure 3.1 below.

<table>
<thead>
<tr>
<th>1. Interviews</th>
<th>2. Archival records</th>
<th>3. Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Improve coordinator (former study)</td>
<td>• Former study truck movements</td>
<td>• Own observations during measurement</td>
</tr>
<tr>
<td>• Shiftleaders production</td>
<td>• Fill lists measurement for truck operators (10 days)</td>
<td>• Time measurement (used later for validation)</td>
</tr>
<tr>
<td>• Forklift truck operators</td>
<td>• SAP production data (used later as model input)</td>
<td></td>
</tr>
<tr>
<td>• Production engineers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

First, a former study of internal transportation is reviewed together with the improve coordinator who conducted the study. In this study of 2006, a list is made of all important transportation flows of Trespa at that time. Appendix 8 shows the graphical overview of the flows according to the 2006 study. At that time, an overview of flows was made by physical observation and the duration of each action has been timed. This approach leads to nice data but is also very time consuming. Now, a few years later, several facility locations have been changed and also added. The data of this former study can therefore not be used directly as input data. Since the global production process has not changed, the study is used to define the important item flows. It is also used to check the assumptions made for model construction and the validation.

Another source for acquiring information about item flows includes talking to shift leaders and forklift truck operators. These people have a lot of experience and face the item flows every day at work. Interviews with employees from different production departments (e.g. production engineers) has also led to more insight about the flows.

Along with observations in the production area, a measurement is done in cooperation with truck operators. For every forklift truck included in the measurement, a list is filled in advance with important routes for that specific truck. Preparation of the measurement, including defining several routes in advance, is done in cooperation with shiftleaders. In this way, truck operators only have to tally stripes and can add some undefined routes occasionally. This approach is chosen to make sure that the measurement is as accessible as possible for the truck operators during their regular actions. The truck operators have filled out a list during their shifts for a period of 10 days, since this is the time span of the total shift rotation cycle. An example of such a list is shown in Appendix 9. At the end of the measuring period, the lists included all traversed routes and the number of times they were traversed. Although the lists give a nice overview of the internal transportation, the data contains a lot
of noise and errors. For example, some operators were too busy with their main tasks to fill the lists properly or machines were shut down for maintenance actions.

The most reliable data source is the SAP BW system of Trespa, since these values are objective and not influenced by human errors. The input and output of machines is specified and stored in this system. Important production figures are retrieved by consulting industrial engineers which have a lot of experience in this SAP software. Values of core material production and the use of the presses is shown in Appendix 10. The values from the SAP system are used in a later stage as model input data for the current situation.

3.2 Important in- and output points

The analysis of item flows leads to insight in important in- and/or output points of the production area. These locations have to be included in the model. At in- and output points, a certain material handling action takes place, such as picking up or putting down a product. Most of these points are input/output locations of machinery or stock points.

In order to get an overview of the locations in a structured way, a map of the total production area is used. By placing a grid over the map, the line intersections represent coordinates.

Several coordinates are linked to important locations. In this way, each location has its own ID number which reveals its location on the area. The coordinates are set for the current situation, but might be changed when analyzing other scenarios. Figure 3.2 below gives an impression of some defined in- or output points. The total overview is shown in an illustration and in a list in Appendix 6 and 7, respectively. These locations are defined as nodes in the input dataset of the model, along with other nodes needed to define certain paths (see Section 4.4).

Figure 3.2: Impression of defined in- and output points (blue nodes)

3.3 Trucks overview

Trespa has a fleet which consists of a considerable amount of trucks and vehicles. Some of the trucks are bought and others are leased for a specific period. Most of the trucks are assigned to a specific department and have a fixed set of tasks to fulfill.

For the analysis of the current locations and routing, it has to be defined which trucks are within the scope of the project. Excluded from the analysis are trucks which are not part of the main production departments (e.g. maintenance) and trucks which are not used for transportation between locations. Namely, if certain actions are performed within a specific location, those costs can only be influenced
by changes in the process itself; the truck actions remain the same if a location is changed. A list of the total truck fleet is displayed in Appendix 5.

For the model, the speed of each truck is needed. Because of safety reasons, the maximum speed of a truck is limited, dependent on the type of truck. Indoor trucks are allowed to drive 6 km/h; outdoor trucks can drive somewhat faster. The truck speed is also shown in the list.

3.4 Item flows of departments

In order to manufacture the panels several production departments are involved, as described in the basic production process. The raw materials are processed into semi-finished products (WIP), stored at stock points and eventually used to produce the high-pressure laminates. Moving materials results in several item flows. The most important flows of each department are described in this section. Besides the four production departments, there are also the Support, Maintenance and Infra departments. Since most of the actions of these departments occur at random, the routes of these three departments are not taken into account.

Excluded item flows for the analysis and model are the following:
- Flows which are not part of the main production process (e.g. maintenance)
- Supporting flows across the production area (e.g. waste collection)
- Flows which occur on the location itself (because this does not make any difference in a redesign)
- Flows which occur a lot at random (not traceable, so redesign impact not known)

General order process

Customer orders are specified in panel type, size, color, quantity, etc. This information is further processed at the planning department. In order to maintain its competitive position, Trespa tries to deliver the panels to the customers within a short and reliable time period. On the other hand, the company aims for the inventory being as low as possible. For some materials, the customer order decoupling point (CODP) is placed before the pressing department (see Figure 2.1); the core and decor department produce make-to-level materials, whereas the pressing department mainly produces make-to-order based on the specific demand of customers.

Core department

The core department produces the core material. Two main types of core can be distinguished: kraft sheets and prepregs. The kraft sheets are produced at the Impregnation line. External suppliers deliver rolls of kraft paper. These rolls are unloaded outside close to the impregnation line and are stored until they are transported to the impregnation line. Pallets with sheets of impregnated kraft paper are transported to several stock points, dependent on the resin type and size. Kraft sheets with fire retardant (FR) resin F33 are stored in racks to prevent the sheets from sticking. Prepregs are produced by the DF line. A pallet of prepregs needs to be stored for at least three days to make sure some gasses are vaporized to a certain level. After this period the prepregs can be used in the pressing stage.

Decor department

The decor department makes rolls of colored paper with a certain texture. These rolls are produced by the EBC process and form the outer layer of the panel. Rolls with foil and rolls with substrate paper are unloaded from the truck of external suppliers and stored. In order to produce an EB roll, a roll of
substrate paper and a roll of foil is transported towards the EBC location. A completed EB roll is transported and stored in a roll storage location. When about 10 EB rolls are ready they are loaded into a terminal trailer, which is transported outdoor by a trailer truck to Klima4. The rolls are unloaded and stored in racks.

**Compose decor and pressing department**
The planning department releases pressing orders. Before the panels can be pressed, the decor sheets have to be cut to the right size. EB rolls in Klima4 are transported from the rack towards a Clipper or Manuela machine, where the rolls are cut into sheets. After the cutting, the rolls are placed back into the racks. Since the roll transportation is executed inside Klima4, this transport flow is not taken into account. The cut sheets (decor packages) are placed onto carriers, which are then stored in Klima3. The trucks of press 6 and 7 have to transport the carriers towards the input points of the presses. One carrier contains all decor packages of two press charges. Every press charge, a number of panels is produced equal to the number of daylights the press has.

The trucks of the presses also have to drive towards the stock points of core material and have to place the core material pallets onto the conveyors at the press input points. When the panel size which is being pressed changes, the non-empty pallets of core material have to be returned to the stock points. Empty core material pallets are transported towards the empty pallet storage so they can be re-used at the DF and Impregnation4 line.

Trucks of the presses make sure the output buffer is emptied in time by taking finished products from the press output conveyors. A few pallets of finished products are placed into a terminal trailer. When the trailer is full, it is transported outdoor towards the warehouse. The empty trailer is driven back to the presses or is used to pick up empty pallets at the pallet factory which is located at the other side of the production terrain. These empty pallets are unloaded outside near the presses and placed in the press output buffers by the forklift trucks of press 6 and 7.

**Warehouse and shipping department**
All finished products are transported from the presses towards the warehouse by the terminal trailer. Then the terminal trailer is unloaded and all pallets are stored in warehouse hall 1. The forklift trucks of the warehouse and shipping (W&S) department repack and prepare the pallets for shipping. Pallets with finished products are loaded into the trailers of external transportation companies, which will finally ship the panels to the customers.

An overview of the most important item flows is illustrated in Figure 3.3 below. The flows, depicted by department separately, can be found in Appendix 4.
3.5 Summary of location-routing analysis

In order to get an overview of the locations and truck routings at the production area, three types of sources are used. Combining sources, such as a former study of internal transportation, interviews with shift leaders and truck operators, a measurement of truck movements and machinery data from SAP, has led to important insight in the item flows. A lot of locations are identified, such as in- and/or output points of machinery and stocks.

An overview of all trucks, which execute the actions for the transportation, has been created. For the analysis of the current locations and routing, it has to be defined which trucks are within the scope of the project. Excluded from the analysis are trucks which are not part of the main production departments (e.g. maintenance) and trucks which are not used for transportation between locations.

As a result of this analysis, a lot of item flows have been identified for the departments of ‘Core’, ‘Decor’, ‘Compose decor and pressing’ and ‘Warehouse and shipping’. These item flows are used as input data for the model.
4. LOCATION-ROUTING MODEL

In order to analyze different scenarios, a model is constructed. Based on knowledge gained by a literature review and information obtained about the real life situation, a mathematical model is made. Solving the model is done by implementing it in software packages. This chapter describes the steps taken to create the location-routing model. The components needed and their relations are shown in Figure 4.1 below.

![Figure 4.1: Components needed to create the location-routing model](image)

4.1 Literature study

Besides the practical relevance of the project, also a scientific approach is needed since the master thesis is done for the fulfillment of the OML study at the TU/e. In order to accomplish a mix of both practical and theoretical aspects, first a literature review has been done about the subject and research area (Op de Kamp, 2014). This section highlights the most important issues of the literature review. The review is used as a basis for the research proposal, since important aspects and decisions are revealed.

The combination of finding the best facility layout when taking into account the routing problem seems to describe best the real-world problem to improve the layout of Trespa. A literature search process consisting of five steps has been done, as proposed by Blumberg et al. (2011). As result, a better understanding has been gained about the facility layout problem, routing problem, related subjects and possible solution techniques.

The most important findings of the literature study are summarized below:

- The efficiency of a layout can be indicated by the material handling costs (MHC). Since a large part of the total operating costs within manufacturing is attributed to material handling, companies can reduce these costs and improve the productivity if their facilities are arranged effectively (Tompkins et al., 2003).
- The output of a traditional facility layout problem (FLP) is called a block layout, which specifies the relative locations and shapes of the departments in the area (Kulturel-Konak &
Konak, 2011). The input and output points of facilities are determined after a block layout is obtained (Kim & Kim, 2000). In a manufacturing FLP, the input and output points are taken into account when analyzing the layout.

- Although the most common objective for a FLP is to minimize the MHC, also other quantitative factors (such as rearrangement cost, closeness rating and required area) and qualitative factors (such as plant safety, flexibility of layout, noise and aesthetics) can be considered (Singh & Sharma, 2006; Lacksonen, 1997; Current & Marsh, 1993). Reduced material movement lowers work-in-process levels and throughput times and also results in less product damage, simplified material control and scheduling, and less congestion. Hence, the minimization of MHC also entails the achievement of other objectives (Singh & Sharma, 2006).

- Vehicle routing problems (VRP) are traditionally classified in node routing problems (NRP) and arc routing problems (ARP). In NRP the service activity occurs at all (or at some subsets of) the vertices, whereas in ARP a single vehicle or a fleet of vehicles service all (or some subsets of) the edges and/or arcs (Bosco et al., 2013). The most popular method so solve the shortest path problem is due to E.W. Dijkstra (Hochstättler & Schliep, 2010).

- Combining the location problem (FLP) with the routing problem (shortest path) results in a location-routing problem (LRP). The LRP can be seen as a hierarchical problem, whereby the aim is to solve a FLP (the “master problem”), but in order to achieve this simultaneously the VRP (the “subproblem”) has to be solved (Nagy & Salhi, 2007).

- Both the general FLP and the VRP have been shown to be difficult to solve exact, especially for problems of a large size. This is also true for LRP, the combination of both problems (Nagy & Salhi, 2007). An optimal solution can be determined only for relatively simple problems, by means of a branch-and-bound algorithm (Ghiani et al., 2004). In order to solve larger problems, a lot of heuristics have been studied to obtain good solutions, such as the Tabu Search, Local Search, Simulated Annealing, Genetic Algorithm and hybrid techniques (Prodhon & Prins, 2014; Ghiani et al., 2004; Tuzun & Burke, 1999; Min et al., 1998).

- The LRP can be classified with regard to its problem perspective by the classification scheme of Min et al. (1998). Since the FLP, VRP and LRP are related to each other, there is some overlap in the included properties. Analysis assumptions have to be determined, such as static vs. dynamic, continuous plant floor vs. a grid, greenfield vs. brownfield, facility centers vs. in- and output points, diagonal distances vs. inner structures included, time windows, hypothetical vs. real-world data and the objective function (McKendall Jr. & Hakobyan, 2010; Paul et al., 2006; Tompkins, 2003; Kim & Kim, 2000, Min et al., 1998)

### 4.2 Theoretical framework

The process of optimizing a LRP involves two steps, namely the modeling of the FLP and the development of a solution approach. For the modeling step, the use of mathematical tools seems to be the most feasible one for the master thesis research. Constructing the LRP as a mixed integer linear program (MILP) is a widely used technique. A MILP is a model which has both continuous and integer variables. Integer variables can be used both to model quantities which can only take integer values as to represent yes/no decisions (called 0-1 variables or binary variables). In the mathematical MILP model it is described what the objective function is and what the constraints are. In this way, a problem is specified. Ghiani et al. (2004) extensively discussed the formulation of MILP models in several settings (e.g. single- and multicommodity flow problems).
In a certain scenario, facilities are assigned to coordinates to form the production area layout. The costs, defined in the objective function, have to be calculated for each scenario. This is done by using a mathematical model, which is implemented in a software program for optimization. The mathematical program is formulated as a MILP and its representation in the software program includes the sets, parameters, variables and constraints to model the problem. For every transportation movement, the shortest path from the start to end point is determined whilst the constraints are taken into account. Calculating the sum of all paths and their associated costs results in the total MHC (which can be expressed in distance, time and money).

The mathematical program is implemented in AIMMS, a software program that is used for optimization problems. The obtained data, stored in Microsoft Excel worksheets, is linked to the optimization program to serve as input data.

4.3. Mathematical formulation

The layout of the production area influences the costs of internal transportation. The production process includes many transportation routes between locations, each with a certain distance, truck type and intensity. In order to automatically compute the length and costs of all routes, a mathematical program is formulated. The notation is derived from the format of Ghiani et al. (2004). The model elements are further explained in Section 4.4.

The following assumptions, sets, parameters and variables have been defined:

Assumptions:
- Each specific flow of an item that has to be transported has its own ‘item flow’ ID number. Such a flow includes information about the material output location and the demand (input) location, the amount that has to be transported and information about the assigned truck.
- The demand of a location is fulfilled by transportation from one other location (demand is not divisible).
- Demand (input) of a facility is deterministic, as retrieved from the gathered data from SAP and the field study (fill lists). This demand is based on the total annual values.
- The demand (input) of all items for all locations has to be met. This leads to a stable process without leftover or missing items.
- The problem is static, meaning the area and internal transportation has to be determined for only one moment in time (e.g. a year, data dependent on scenario).
- The total production area is divided into blocks, so facilities are placed as nodes on the grid (no continuous area).
- There are several kinds of materials that have to be transported, so the material flows are not homogeneous (multi-commodity).
- The model is designed to represent the current situation (AS-IS); this scenario is also analyzed first. Other scenarios can be analyzed by changing constraints or input data.
- The model calculates the costs of material handling between locations. Additional costs of changing the layout itself are not included. For example when arcs or nodes are added which entail additional construction cost, these have to be estimated and manually included in the costs when analyzing a scenario.
- Transportation costs include both the direct labor costs (operator wage) and truck costs (fuel).
- The model includes multiple item flows and determines for each flow what amount of material is transported via which arcs. Total costs are the sum of the costs of all item flows.
The terminal trailer truck can only be used for outdoor transportation and has some one-way routes. Diesel forklift trucks are also not allowed to be used indoor. The main manufacturing process cannot be changed.

Sets:
- \( G \) Complete directed graph \( G = (V, \alpha) \)
- \( V \) Set of facilities or important points in the area (nodes) \( i, j \in V; V = \{1, 2, ..., n\} \)
- \( V \times V \) Set of all two node combinations (from node \( i \) to node \( j \)) \( (i, j) \in V \times V; i, j \in V; i \neq j \)
- \( A \) Set of all existing arcs; subset of \( V \times V \) \( (i, j) \in A; i, j \in V; i \neq j \)
- \( A' \) Set of all existing indoor arcs; subset of \( A \) \( (i, j) \in A'; i, j \in V; i \neq j \)
- \( K \) Set of item flow IDs \( k \in K; K = \{1, 2, ..., m\} \)

Parameters:
- \( m_{ij} \) Distance in meters associated with arc \( (i, j) \) \([\text{m}]\)
- \( d_{ik} \) Net demand of facility \( i \) of item flow \( k \) \([\text{units/year}]\)
- \( C_k \) Capacity of the truck assigned to item flow \( k \) \([\text{units}]\)
- \( v_k \) Average speed of the truck of item flow \( k \) \([\text{m/s}]\)
- \( c_{\text{op}} \) Truck operator costs per second (wage) \([\text{€/s}]\)
- \( c_{\text{tr}}^k \) Truck costs per second for item flow \( k \) \([\text{€/s}]\)

\[
\begin{align*}
  w_k &= \begin{cases} 
    1 & \text{if the item flow } k \text{ is a one-way route (traverse 1 time)} \\
    2 & \text{if the item flow } k \text{ is a return route (traverse 2 times)} 
  \end{cases} \\
  I_k &= \begin{cases} 
    0 & \text{if the item flow is transported by an outdoor truck} \\
    1 & \text{otherwise} 
  \end{cases}
\end{align*}
\]

Variables:
- \( NI_{ik} \) Inflow of node \( i \) of item flow \( k \) \([\text{units/year}]\)
  \[ NI_{ik} = \sum_{j \in V} x_{jik} \]
- \( NO_{ik} \) Outflow of node \( i \) of item flow \( k \) \([\text{units/year}]\)
  \[ NO_{ik} = \sum_{j \in V} x_{ijk} \]

Decision variables:
- \( x_{ijk} \) Amount of item flow \( k \) which is transported via arc \( (i, j) \) \( (i, j) \in A; k \in K \)
The following objective function minimizes the costs of internal transportation. These costs depend on whether or not an arc is traversed when transporting a certain item flow (so the amount which is transported via each arc) and the corresponding costs of traversing that arc.

Objective function:

Minimize

$$\sum_{k \in K} \left( \sum_{(i,j) \in A} \left[ x_{ijk} \cdot m_{ij} \cdot \frac{w_k}{v_k \cdot c_k} \right] \cdot (c^{op} + c^{truck}_k) \right)$$

subject to

$$\sum_{j \in V} x_{ijk} - \sum_{j \in V} x_{ijk} \geq d_{ik} \quad \forall i \in V; k \in K \mid d_{ik} > 0 \quad (1)$$

(Or: $NI_{ik} - NO_{ik} \geq d_{ik}$)

$$\sum_{j \in V} x_{ijk} - \sum_{j \in V} x_{ijk} = 0 \quad \forall i \in V; k \in K \mid d_{ik} = 0 \quad (2)$$

(Or: $NI_{ik} - NO_{ik} = 0$)

$$x_{ijk} = 0 \quad \forall (i,j) \in A'; k \in K \mid I_k = 0 \quad (3)$$

$$\sum_k \left( \frac{x_{ijk} \cdot w_k}{c_k} + \frac{x_{ijk} \cdot w_k}{c_k} \right) \leq z \quad \forall (i,j) \in A; k \in K \quad (4)$$

$$x_{ijk} \in \mathbb{Z}^+ \quad \forall (i,j) \in A; k \in K \quad (5)$$

Constraint (1) ensures that the demand is satisfied for all nodes. Demand nodes of an item flow ID will have a positive inflow $NI_{ik}$, supplying nodes will have a positive outflow $NO_{ik}$. The nodes which are only traversed for an item flow ID without being the start or end point have a demand of 0. Constraint (2) makes sure that the inflow equals the outflow for these ‘zero demand’ nodes, so there are no items ‘left in the system’. It is possible to merge the first two constraints, but separated constraints for input nodes and zero demand nodes give a better overview. The model outcomes and run time are not influenced.

Constraint (3) makes sure that the outdoor trucks (e.g. terminal trailer truck) only use the roads for outdoor transportation, since it is not allowed to enter the indoor area. Indoor arcs are defined by subset $A'$, item flows transported by outdoor trucks have a value 0 for $I_k$.

Constraint (4) includes a maximum value for the congestion factor which may not be exceeded, for example because of safety reasons. The congestion factor is defined as the number of times a certain arc is traversed in total. This constraint can be used for a sensitivity analysis, for example to show what the impact on the solution is when the total number of flows on a certain arc and in a certain
period are limited. The congestion factor can influence the chosen routing of the layout and might be more important when production numbers are increased. Constraint (5) ensures that the decision variable \( x_{ijk} \) is a non-negative integer so there are no negative flows.

### 4.4 Model requirements

#### 4.4.1 Model input

The input for the model is a dataset, which is created in Microsoft Excel. This dataset contains several worksheets with values for the sets and parameters, as explained below.

Important points of the facility area are included in the set of nodes \( V \). These nodes may for example be facilities, stock points or important points to indicate corridors. A grid is placed on the production area drawing and coordinates are assigned to all X and Y line intersections. These lines are placed 20 meters apart from each other. The drawing is shown in Appendix 6. Every node has an X and Y coordinate of both 3 digits, so the 6 digits of a node’s ID also reveal its location. For example, node 470290 is located 470 m on the X axis and 290 m on the Y axis from the origin. The list of nodes of the current situation is shown in Appendix 7.

A matrix with all nodes on the horizontal and vertical axis includes all possible two node combinations (set \( V \times V \)). All elements of this matrix are filled with a value 0 (‘not existing’) or 1 (‘existing’) to indicate if that arc exists in real life. All existing arcs are included in \( A \), a subset of \( V \times V \). The set of indoor arcs \( A' \) is in its turn a subset of \( A \).

The item flows set \( K \) includes the main transport of materials to create the panels. Not included are transportation flows on the location itself and the random transport, like waste collection. For every \( k \in K \) it is specified how much is transported from and towards which node.

Each item flow \( k \) has its own item flow ID number. In practice, one item flow ID may consist of several arcs from nodes \( i \) to \( j \) which are traversed in a certain order to fulfill the demand. The demand values of the product flows are retrieved from the SAP system. Based on the demand values, a demand matrix is automatically filled. The matrix includes the net demand of a certain item flow ID \( k \) for all nodes.

The distance in meters \( m_{ij} \) between two nodes \( i \) and \( j \) is given as a parameter in the model input data. The values are already calculated in Microsoft Excel. Because the layout of the production location of Trespa is composed of rectangular shaped facilities and roads, it is chosen to compute the distance \( m_{ij} \) as the Manhattan distance. The Manhattan distance is the sum of the horizontal and vertical distances between two nodes. It can be computed as follows:

\[
m_{ij} = |X_j - X_i| + |Y_j - Y_i|
\]

with

\( (X_i, Y_i) \quad \text{rectangular coordinates of node } i \)
\( (X_j, Y_j) \quad \text{rectangular coordinates of node } j \)
In general, a specific truck of the associated department is assigned to a material to transport it. For each item flow the truck load capacity $C_k$ and speed $v_k$ are given, since these parameters are dependent on the truck type.

Some transportation routes include a one way drive to transport the item. In real life, however, most of the times the truck also has to traverse the same arc back while it is empty (return route). In order to correct this ‘error’, the variable $w_k$ multiplies the route distance by 1 or 2.

Most trucks of Trespa are electrical trucks with a battery for the power supply. There are also some trucks and a special terminal trailer truck which use diesel. The diesel trucks are not allowed to drive indoor. The variable $l_k$ therefore shows whether or not the item flow can be transported indoor.

The costs of material handling between locations both have a personnel and a truck component. The direct labor costs depend on the wage of the truck operator. In the real life setting, the operators working in the 5-shift system earn an extra fee compared to the operators with working times of a regular working week. An average 5-shift salary is taken and so the direct labor costs are assumed to be independent of the item flow.

Several types of trucks are used, dependent on the needed capacity and application, for instance. Each truck has its own specifications about the fuel consumption. Therefore the truck cost parameter of each item flow can vary.

The two cost factors are both influenced by the total time needed for the transportation. Reducing the size of the workforce or the truck fleet can lead to a further reduction of costs by for example a reduction of rental costs. These costs are not automatically included in the model but have to be discussed when analyzing a scenario.

Sets and parameter values can be changed to analyze different redesign scenarios. Since the input data is stored in worksheets of Microsoft Excel, creating scenarios can be done in a systematical way.

4.4.2 Model output

The objective of the model is to minimize the costs of internal transportation. For each item flow, the model has to choose what quantity of the item is transported via what route. This is done by selecting arcs to traverse, as indicated by the decision variable $x_{ijk}$: $x_{ijk}$ is the amount of item flow $k$ which is transported via arc $(i,j)$. Linked to this variable are both the inflow $NI_{ik}$ and outflow $NO_{ik}$ of a certain item at a node.

As a result, the cost of each route can be calculated and expressed in a financial value (money), distance (meters) and time (seconds). The sum of the costs of all routes will indicate the costs of that specific scenario.

Changing the layout, and thus the coordinates of locations, will influence the total costs. These costs are dependent on the total transportation distance or time between locations; the time required for actions on the location itself (e.g. picking pallets) however are not changed when changing the layout. Therefore the output of the model contains strictly the time needed for transportation between facilities.
4.5 Solving the mathematical model

A lot of combinations of decision variable values can be set for the MILP. This makes solving a MILP hard and time consuming. Therefore, a special software tool is used to set the decision variable values and to calculate the objective value of the optimal solution given a scenario. The mathematical model of Section 4.3 is programmed in the commercial software tool AIMMS and input data for the parameters is stored in Microsoft Excel worksheets. AIMMS was introduced as a mathematical modeling tool, an integrated combination of a modeling language, a graphical user interface, and numerical solvers (Bisschop, 2014).

The combination of models and computers enhances the speed of finding good solutions for the MILP problem. Another advantage is the graphical interface of AIMMS. The production area and solver solutions are depicted for each item flow. This visualization of a scenario makes the analysis more clear.

Appendix 14 shows the most important content of the model, constructed in both Microsoft Excel and AIMMS. A brief description is given about the steps that are taken to calculate the objective value given a certain scenario.

In order to make clear how the model works and how its components are defined, the illustration below is created. Figure 4.2 shows the defined possible arcs and the best route (colored in green), chosen by the model. The example is elaborated for one item flow.

![Diagram of model with possible arcs and best route](image)

**Figure 4.2: Illustration of model, simple example of one item flow**

The following input data is set:

<table>
<thead>
<tr>
<th>$d_{ik}$</th>
<th>$m_{ij}$</th>
<th>$k$</th>
<th>$v_{10}$</th>
<th>$C_{10}$</th>
<th>$w_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-50$</td>
<td>$3$</td>
<td>$10$</td>
<td>$2$ [m/s]</td>
<td>$1$ [pallet]</td>
<td>$2$ (return route)</td>
</tr>
</tbody>
</table>

The model gives the following solution:

<table>
<thead>
<tr>
<th>$x_{ijk}$</th>
<th>$x_{1,2,10}$</th>
<th>$x_{2,3,10}$</th>
<th>$x_{2,5,10}$</th>
<th>$x_{3,4,10}$</th>
<th>$x_{5,6,10}$</th>
<th>$x_{6,4,10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$50$</td>
<td>$50$</td>
<td>$0$</td>
<td>$50$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

With objective function value:
The implemented model in AIMMS determines the value for variable \( x_{ijk} \) for all arcs and item flows. These values are then exported to a Microsoft Excel output file. In this way, all model values are available to analyze a certain scenario.

### 4.6 Summary of location-routing model

In order to analyze different redesign scenarios for the layout, a model is constructed. Based on knowledge gained by a literature review and information obtained about the real world situation at Trespa, a mathematical model is made. The combination of finding the best facility layout when taking into account the routing problem seems to describe best the real-world of Trespa. Combining the location problem (FLP) with the routing problem (shortest path) results in a location-routing problem (LRP).

The mathematical model of the LRP is formulated as a mixed integer linear program (MILP), a widely used technique. This mathematical program is implemented in AIMMS, a software program that is used for optimization problems. The input for the model is a dataset, which is created in Microsoft Excel. This dataset contains several worksheets with values for the scenario sets and parameters. The objective of the model is to minimize the costs of internal transportation. For each item flow, the model has to choose what quantity of the item is transported via what route. This is done by selecting arcs to traverse. As a result, the model is able to analyze different layout scenarios whilst taking into account the real world paths to follow.

A lot of combinations of decision variable values can be set for the MILP. Given a certain scenario, the optimal solution of the objective function has to be calculated with the associated decision variable values. In order to quickly find the right solution for the MILP, the optimization software AIMMS is used. Another advantage is the graphical interface of AIMMS. The production area and solver solutions are depicted for each item flow. This visualization of a scenario makes the analysis more clear.
5. MODEL CURRENT SITUATION

The current layout of the production area is analyzed in the current situation (AS-IS) model. This can be seen as the first scenario that the mathematical model has to solve. The current situation model is important since the other redesign scenarios have to be compared to the current situation. This chapter describes all input data which is gathered and prepared to run the current situation scenario and the associated results.

5.1 Data current situation

The model in AIMMS is programmed to import the Excel input data set. In this section, the values of all input parameters are described for the current situation.

5.1.1 Time horizon

The dataset for the current situation model is composed with production information of the facilities. The time horizon for the data set is the year 2013. Taking these annual production figures results in a large sample size, which increases the reliability of the model. Figure 5.1 shows the weekly production of panels in the year 2013. In general, pressing the panels is a batch process with a continuous (24/7) production, so the production level is kept quite constant throughout the year. Only in week 1 and 52 the production is not fully in operation because of the holidays. From the 365 days in 2013, Trespa did not produce any panels during 8 days. Therefore, the annual production data is aggregated for a time horizon of 357 days.

![PANELS PRODUCTION 2013](image)

Figure 5.1: Weekly panels production in 2013

5.1.2 Nodes and arcs

The current situation model is constructed by setting all parameters to match with the current situation. The nodes and arcs sets in the model match with the current production area. Coordinates of facilities and stock points are taken from the grid and stored in a large matrix in an Excel file. An important issue when specifying the current layout is to reveal important constraints for routing, such as gates, walls and narrow paths for example. By creating additional nodes, all possible arcs are defined, as can...
be seen in Appendix 6 and 7. Special constraints for certain truck or flow types are defined in the mathematical model in Section 4.3.

5.1.3 Transportation flows
The input data for the model consists for a large part of all transportation flows. Each flow is assigned to an item flow ID number. The analysis of transportation flow at the production site of Trespa is extensively discussed in Section 3.1. Combining several approaches and sources has led to good insight in the item flows and based on this analysis a large table is filled in Microsoft Excel. In this table, several parameter values are filled for each item flow included in the model.

An example of an item flow ID and the associated parameter values is shown below in Figure 5.2. The total list of all item flow IDs can be found in Appendix 11.

![Figure 5.2: Example of one line of parameter values, for one item flow ID](image)

Linked to this table, a matrix is automatically filled with the net demand $d_{ik}$ of each node $i$ for each item flow ID $k$. As Figure 5.3 shows, node 530270 has a positive demand of 8523.12 of item flow ID 12. Furthermore, the outflow node has a negative net demand and all other nodes have a net demand which equals 0 for $k = 12$. Values of this matrix are thus in line with the values shown in Figure 5.2.
5.1.4 Direct labor and truck costs

The objective function tries to minimize the variable costs of both direct labor and trucks given a certain scenario. As explained in Section 4.4, the direct labor costs are independent on the item flow ID. One Full Time Equivalent (FTE) of direct labor is assumed to cost €60,000 per year. The truck costs, however, depend on the truck type which is used for the transportation. The parameter values of the variable costs are shown in Appendix 15. These costs are assumed to be stable, so they are not changed when analyzing different redesign scenarios.

Although a change in truck costs (fuel) of a certain scenario will directly lead to a reduction of total costs in real life, a change in direct labor costs will not change this easy. This is due to contracts with employees which include a certain amount of hours that are paid. The implementation of a possible change has to be analyzed in more detail. For example, changes can be made in an operators contract, tasks or schedule.

Besides the variable costs, also fixed costs are paid. Important costs are the monthly lease costs for the trucks. An overview of the amounts is shown in Appendix 5. Since the model does not change the truck fleet, possible changes in the fixed truck costs have to be adjusted manually per scenario.

5.2 Outcomes of current situation model

The complete dataset is analyzed and the solution of the objective function is calculated by the AIMMS model. As a result, the current scenario is shown in several tables with numerical values for variables and parameters in the Excel output file. Also a graphical representation of all transportation flows between facilities is displayed.

Table 5.1 shows that the total time of transportation between locations is 7216,094 hours per year, according to the model. This time is thus used to complete all material handling which is included in the model and is solely used for the driving between locations. The total distance associated with this time is 55344,382 km.
Trucks are used for executing certain actions both between locations and on locations itself. During an average day of 24 hours, the time consumption of each truck can thus be divided into three types: being idle (not in use), used for transportation on a location and used for transportation between locations. A graphical illustration of the ratio between these types gives insight in the potential of each truck and is related to its actions.

Most of the trucks are leased from Jungheinrich, a truck company. This company keeps track of the forklift trucks: a device on the truck stores all time stamps when the truck is turned on or off. With this data, an overview is created of the idle times of each truck. Combining the model output (which shows the time needed for transportation between facilities) and the data of Jungheinrich leads to the graph of Figure 5.4.

**Table 5.1: Model output: total flow times and distances per truck**

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Flow time total [h]</th>
<th>Flow distance total [km]</th>
<th>Operator costs [€]</th>
<th>Truck fuel costs [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>576.626</td>
<td>3459.758</td>
<td>€18.803,03</td>
<td>€1.191,53</td>
</tr>
<tr>
<td>104</td>
<td>542.246</td>
<td>5853.477</td>
<td>€30.725,42</td>
<td>€1.347,03</td>
</tr>
<tr>
<td>106</td>
<td>1822.406</td>
<td>10934.437</td>
<td>€59.426,29</td>
<td>€3.765,77</td>
</tr>
<tr>
<td>107</td>
<td>464.022</td>
<td>2784.133</td>
<td>€15.131,16</td>
<td>€988.84</td>
</tr>
<tr>
<td>109</td>
<td>248.580</td>
<td>1491.380</td>
<td>€8.105,22</td>
<td>€513.62</td>
</tr>
<tr>
<td>113</td>
<td>453.104</td>
<td>2718.625</td>
<td>€14.775,14</td>
<td>€936.28</td>
</tr>
<tr>
<td>11784144</td>
<td>1083.823</td>
<td>13005.880</td>
<td>€35.342,07</td>
<td>€2.239.59</td>
</tr>
<tr>
<td>501-506</td>
<td>789.625</td>
<td>4737.750</td>
<td>€25.748,64</td>
<td>€1.631,66</td>
</tr>
<tr>
<td>991</td>
<td>219.583</td>
<td>1317.500</td>
<td>€7.160,33</td>
<td>€1.475,82</td>
</tr>
<tr>
<td>992</td>
<td>616.097</td>
<td>9241.452</td>
<td>€20.090,13</td>
<td>€4.140,79</td>
</tr>
<tr>
<td>Grand total</td>
<td>7216.094</td>
<td>55344.382</td>
<td>€235.307,42</td>
<td>€18.800.94</td>
</tr>
</tbody>
</table>

Total variable costs: €254.108,36
Figure 5.4: Average time consumption per truck per day

The parts of the graphs colored in red are retrieved from the data of Jungheinrich. During the red blocks the truck was not in use (idle). The total time of the green and blue parts together is therefore known, but their ratio is filled out by the model. The total time that is used for transportation between facilities (according to the model) is shown in blue.

- Truck 101 is the large forklift truck of the Impregnation4 line. It is able to carry the large ZF size pallets kraft and its main task is the transportation of core material from the impregnation line to the different stock locations. At the impregnation line, also another small truck is used to transport materials on the location; this second truck is needed i.a. to perform actions for which the 101 truck is too large.
- Truck 104 and 106 are the trucks used by press 6 and press 7 respectively. These locations require a lot of actions performed by a truck, like placing carriers onto the press input conveyor, loading the end products into the trailer, picking core material, get empty pallets, et cetera. The presses are in operation 24/7 in principle, so this explains the relatively high usage of these two trucks.
- Truck 107 is the forklift truck of the DF line. It is used to transport pallets of prepregs from the output conveyor of the line towards the prepreg stock locations. Routes of the main item flows are very short and do occur once in about 20 minutes when the DF line is in operation. The prepregs have to be taken out of the DF output conveyor regularly to make sure there is sufficient output buffer space.
- Truck 109 is idle for a large part of an average day. This truck has a special pin to carry EB rolls, so the low usage can be explained by having a specific task: carrying rolls from the EBC department towards the roll storage room.
- Truck 113 is used by the decor department. It is able to carry small racks with the forks, but also able to carry rolls when the small forks are placed towards each other. The main task is the transportation of rolls and materials form the roll storage towards the EBC location.
Truck 992 is the terminal trailer truck. It is used to transport trailers outdoor at the production area. Mostly transported trailers are filled with finished panels or empty pallets.

Trucks 117 and 4144 are displayed combined in the graph. These trucks are both of the same type, namely outdoor diesel trucks. They are both mainly used for transportation of prepreg pallets from the DF line towards the Bowiehal and back (after the vaporization period). Since there is no Jungheinrich data available of the idle time of truck 4144, the trucks are combined in the graph. The trucks are used by the Support department, from Monday till Friday during the morning shift.

Trucks 501-506 are trucks of the W&S department. They are excluded from the graph since they are only used inside the W&S halls and to unload the trailer with finished products. All six trucks are used to execute the same actions. The W&S halls are seen as one location number and not studied in detail. Actions inside the halls can possibly be performed more efficient, but such an analysis is outside the scope of this project.

The average number of hours that a truck is used per day is remarkably low. Therefore, the data of Jungheinrich is studied in more detail. An overview of trucks and their average idle time is shown in Appendix 13. It can be seen that the departments have a shift system. The truck use is the highest during morning shifts; during this time, all departments are present. Employees of the Support department only work during morning shifts from Monday till Friday, which explains the drop of usage in the afternoons. Employees of the W&S department do not work the night shifts, causing a drop in usage during night shifts.

This detailed view of truck idle times shows that some trucks are used equally spread during the week and that other trucks are used with more variability, depending on the time of the day.

A graphical illustration and table of the top 10 most congested arcs are shown in Appendix 12. Mostly used are the paths on which the end product is transported from the presses towards the terminal trailer, the paths used to unload the trailer at the warehouse and the corridor which is traversed to bring core material towards the presses.

A pallet of end products contains only identical panels. Therefore, quite a lot of pallets with end products are used which all have to be transported towards the warehouse. All panels which are pressed on press 6 and 7 first have to be transported towards the trailer through a small hall, which makes this path relatively highly used. Unloading the trailer at the warehouse requires a lot of driving back and forth because of the same reason.

Core material is stored on several locations. There is however only one indoor corridor which connects all storage locations to the presses. This explains the high congestion of this path.

The congestion results sound very likely to match with the real life situation.

The set-up of the production halls and ‘main indoor road’ results in few alternatives for indoor transportation. Although no maximum values for the congestion are set, it is wise to check the changes when analyzing redesign scenarios. Congested paths can result in reduced safety and an increase in transportation times since the trucks have to wait for each other.

5.3 Validation and verification

The quality of the research and the model have to be assessed. In the end, it is important for the research and the associated outcomes to be true and valid. The most important research-oriented quality criteria are controllability, reliability and validity (van Aken et al., 2007). Controllability is a prerequisite for the evaluation of validity and reliability. Research results can be made controllable by
describing the methods used to execute the study. What data is used, the way data is collected and in what circumstances, are aspects which are mentioned in the previous sections. The results of a study are reliable when they are independent of the particular characteristics of that study and can therefore be replicated in other studies (van Aken et al., 2007). Although the research is conducted in cooperation with Trespa, the method itself is reliable and so the replication should give comparable results when applied in another company and setting. Assessing reliability of the solution is done by running the optimization model several times and see if the solution remains the same. If a solution is not unique, AIMMS gives a warning. Reliability of the solution is therefore confirmed.

According to van Aken et al. (2007), there are three types of validity: construct validity, internal validity and external validity. Construct validity refers to the quality of the operationalization of the model. Therefore, the measurement of the (objective) concepts have to correspond with the meaning of the concepts. Minimizing the MHC is expressed in time, distance and money. The evaluation of experts is one way to ensure the construct validity of the model. Since both the company and the university are involved in the project and also have a lot of professionals in the field, this validation type can be affirmed. The internal validity refers to the adequacy of conclusions about causal relationships. In this research project, the outcomes of the objective function must have adequate relationships with the layout of facilities. The objective function is related to the total distance of transportation. Since the distance between locations depends on their coordinates, the model is internally valid. However, because of the size of the analysis, not all input data can be investigated exactly in real life (e.g. precise truck speed, capacities and all flows included). The variability depends on the error of aggregated values.

A research is externally valid if its results are generalizable. The project is executed in cooperation with a specific company and setting. However, it can be assessed whether comparable results are to be expected when the research is executed in another company. A lot of researchers have investigated the FLP, VRP and LRP and the relation between MHC and facility locations. Also the model formulas can be applied generally.

Model verification is defined as ensuring that the computer program of the computerized model and its implementation are correct (Sargent, 2003). Therefore, the algorithms and formulas have to be programmed in a correct way. The Microsoft Excel and AIMMS software both did not give any errors when performing calculations. A sample of model outcome values (item flow IDs and associated costs) are compared to small manual calculations to verify the model programming. The use of Excel/AIMMS also contributes to the verification since this is widely used commercial software which is developed by professionals.

The outcomes of the current situation model should match with the existing situation at Trespa and should look like a previously conducted study of the internal transportation movements in 2006 (Appendix 8). Although the numeric values cannot be compared because a lot of aspects are changed throughout the years, the main flows and process steps look similar. Combining data sources (described in Section 3.1) increases the validity of the model and its outcomes.

Both validation and verification are tested by a sample analysis from forklift truck 106, which is used quite a lot. This truck has been followed during two shifts to see what percentage of total time was spent on transportation between facilities. Truck movements are observed in detail by writing down all actions and the times. Results are shown in Figure 5.5.
In the validation sample, the truck was in use for a much larger percentage of time compared to the yearly average. The difference can be explained by some different causes. First, the presses are shut down for cleaning during a few hours every week. In this period, the trucks are not in use. Second, the trucks are not in use sometimes due to repair or maintenance actions. This is shown in Figure 5.6, which is a detailed overview of the truck 106 use for every shift in a certain period. A back-up truck can be used to perform the actions at the press, since the press cannot be in operation without an available forklift truck. The average number of hours the truck was in use per shift if the maintenance days are excluded (colored in green) differ significantly from the yearly average.

A smaller difference is shown for time used for ‘transportation between locations’ between the model and the sample. This difference can be explained by the pressing schedule and the small sample size. Panels are pressed in charges (batches) of the same size and core type. The time needed for transportation between locations is influenced by the core material location and also the number of finished panels per pallet. The several actions a truck driver performs during a shift do not follow a fixed pattern. According to the truck operators, there was quite some core material stored next to the press already, which reduces the time needed for transportation between locations during the sample measurement. Variability in all these factors results in differences between the model and the validation sample.
The sample is, combined with sample data of other indoor trucks, also used to verify the average indoor truck speed. An observed average truck speed of 6,67 km/h does not differ a lot from the 6 km/h used in the model; the model truck speed appears to be realistic.

5.4 Summary of current situation model

The current layout of the production area is analyzed in the current situation model. All input data which is gathered and prepared to run the current scenario is described. Demand figures of several locations are retrieved from the SAP system. The annual production data is aggregated for a time horizon of 357 days.

According to the model, the total time of transportation between locations is 7216,094 hours per year. This time is thus used to complete all material handling which is included in the model and is solely used for the driving between locations. The total distance associated with this time is 55344,382 km. The outcomes of the model are specified for each truck; each truck is assigned to certain item flows to perform the associated actions.

The average number of hours that a truck is used per day is remarkable low. Besides the transportation time needed according to the model, also the time a truck is idle or in use is studied. Jungheinrich, the company from which most of the trucks are leased, keeps track of the forklift trucks: a device on the truck stores all time stamps when the truck is turned on or off. These data are used for model validation and verification. Also a small sample of truck observation is used. The difference between the sample and the model are explained by occasional truck maintenance time, variability in the pressing schedule and the small sample size. Combining data sources to create the input data also increases the validity of the model and its outcomes.

Mostly used are the paths on which the end product is transported from the presses towards the terminal trailer, the paths used to unload the trailer at the warehouse and the corridor which is traversed to bring core material towards the presses. The set-up of the production halls and ‘main indoor road’ however results in few alternatives for indoor transportation.
6. MODEL REDESIGNS

After the analysis of the model and the current situation, several redesign scenarios are created. These scenarios are translated to input data by manually changing several constraints and/or values in the Excel input file. Each scenario is analyzed by the model to see what the outcome is of a possible to-be situation. The redesign scenarios are described in Section 6.1. In Section 6.2, the implementation aspects are discussed and form the summary of redesigns.

6.1 Redesigns (scenarios)

Scenarios are created on basis of interviews with employees and insights which are gained during the project. As shown in Appendix 13, the trucks 104 and 106 are by far the most used trucks and are therefore assumed to have the most potential in reducing the MHC. Since these trucks are used by the presses, the focus on most of the redesigns is on changing the locations of core material stock points. Another reason is the feasibility of changing those locations; large machinery, such as the presses, are very expensive and relocating them would include large investments. Trespa aims for a return on investment time of two years. Interviews with several employees who are involved in layout decisions has led to the conclusion that the presses and warehouse cannot be moved. It is also very unlikely that the investments required for relocating the Klima4, DF line and Impregnation4 line will be outweighed by the benefits.

Redesign 1: Storage prepregs is moved from Bowiehal to location 213-1.

Prepregs are sheets of core material which are produced at the DF line. Several gasses have to vaporize for at least three days before a prepreg can be used to press a panel. At the moment, new-made prepregs are transported from the output conveyor of the DF line toward gate13 by an indoor truck. From this gate, an outdoor truck moves the prepregs towards the Bowiehal, where they are stored for at least three days. At a certain point in time, the prepregs are transported back towards gate13 and placed in hall 213-2 by the indoor truck. At this location, they are stored until a forklift truck of a press picks them up to use for panel pressing. This situation is illustrated in Figure 6.1.

Trespa currently works on the execution of an investment which changes the process described above. Location 213-1 will replace the Bowiehal and become a new stock location for prepregs. The arguments for this change are the following:
- The Bowiehal does not meet the requirements for fire safety anymore (adjustments are expensive).
- Because of the outdoor environment and transportation, the prepregs are exposed to a higher risk of being damaged by water.
- Transporting the prepregs to an outdoor location and back is labor-intensive.

The new situation is illustrated in Figure 6.2.
Figure 6.1: Redesign 1, current situation

Figure 6.2: Redesign 1, new situation

The results of the model are depicted in Table 6.1 below.
In this scenario, the total time needed for transportation between locations is 6032.843 hours. This is 1183.252 hours less compared to the current situation. The pallet handling is also reduced; in this scenario prepregs are picked up and put down approximately 6 times between the DF line and the press, compared to 10 times in the current situation. Since this handling time will also be reduced, about 1 FTE (about 1840 net working hours) of direct labor costs can be reduced. The forklift truck lease contracts of the two outdoor trucks 117 and 4144 are not renewed, saving another €4547.08 per month. The truck of the DF line, 107, is needed about 170 hours less. This 0.5 hour (daily average) can be used for executing other actions. The top 10 of most congested paths has changed somewhat, but most paths are still part of the main indoor corridor.

Positive scenario aspects:
- Reduce direct labor costs with €60,000 per year (1 FTE)
- Reduce truck lease costs with €4547.08 per month = €54,564.96 per year
- Reduce truck fuel costs with €2,445.04 per year
- Prepreg pallets are only transported indoor, so reduced chance of damage or displacement on pallet

Negative scenario aspects:
- Preparing location 213-1 costs €42,800
- Emission of certain gases will rise, so possible climate control devices have to be implemented. If needed, then there will be additional costs varying from €20,000 - €50,000

Redesign 2: Storage locations of kraft sheets are changed according to the stickiness-analysis solution 1

Kraft sheets are core material and made at the Impregnation4 line. The sheets can be classified according to 4 resin types and 5 sheet sizes. Kraft sheets which are used for the production of fire-retardant (FR) panels are produced with resin F30 and F33. A disadvantage of these resins is that sheets become very sticky, dependent on the pressure that is exercised upon them. In order to improve the manufacturing process, Trespa is working on a certain project. For the implementation of this development, a prerequisite is that sheets do not stick onto each other. A solution is the placement of storage racks, so the pallets with kraft sheets are not stacked onto each other. An implementation plan, described in detail in a preliminary study at Trespa, has been made in which the new locations are specified for each type and size of kraft material (see Table 6.2 and Figure 6.3). The destinations of the storage locations are thus changed.

Table 6.1: Model output for redesign scenario 1

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Flow Time Total [h]</th>
<th>Flow Distance Total [km]</th>
<th>Time [h]</th>
<th>Distance [km]</th>
<th>Operator costs [€]</th>
<th>Truck fuel costs [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>576.626</td>
<td>3459.758</td>
<td>0.000</td>
<td>0.000</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
<td>104</td>
<td>959.296</td>
<td>5755.777</td>
<td>17.050</td>
<td>102.800</td>
<td>€555.88</td>
<td>€55.23</td>
</tr>
<tr>
<td>106</td>
<td>1635.191</td>
<td>11011.147</td>
<td>12.765</td>
<td>75.710</td>
<td>€616.39</td>
<td>€26.42</td>
</tr>
<tr>
<td>107</td>
<td>294.866</td>
<td>1769.913</td>
<td>-169.037</td>
<td>-1014.220</td>
<td>-€5512.07</td>
<td>-€340.29</td>
</tr>
<tr>
<td>109</td>
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<td>1491.360</td>
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<td>0.000</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
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<td>0.000</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
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<td>49.773</td>
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<td>-1044.050</td>
<td>-12528.600</td>
<td>-€34.0451.11</td>
<td>-€2.157.46</td>
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<td>€0.00</td>
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<td>€0.00</td>
</tr>
<tr>
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<td>616.097</td>
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<td>0.000</td>
<td>0.000</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
<td>GrandTotal</td>
<td>6032.843</td>
<td>41980.572</td>
<td>-1183.252</td>
<td>-13363.810</td>
<td>-€38.584.29</td>
<td>-€2.445.04</td>
</tr>
</tbody>
</table>

A current situation
Table 6.2: Change of stock location kraft, scenario 2

<table>
<thead>
<tr>
<th>Location</th>
<th>F30</th>
<th>F33</th>
<th>B13</th>
<th>B21</th>
</tr>
</thead>
<tbody>
<tr>
<td>203 (Klima1)</td>
<td>IF</td>
<td>SF</td>
<td>IF</td>
<td>SF</td>
</tr>
<tr>
<td>316 (Klima3)</td>
<td>IF</td>
<td>SF</td>
<td>IF</td>
<td>SF</td>
</tr>
<tr>
<td>213</td>
<td>IF</td>
<td>SF</td>
<td>IF</td>
<td>SF</td>
</tr>
<tr>
<td>211 (Rode hal)</td>
<td>IF</td>
<td>SF</td>
<td>IF</td>
<td>SF</td>
</tr>
</tbody>
</table>

Figure 6.3: Important stock locations for kraft, shown in green
While determining the new locations of the kraft sheets storage, the dimensions of the locations are taken into account. For each type of core material, Trespa maintains maximum stacking heights. An overview of the maximum values is shown in Appendix 16, together with the space needed per core material type. The amount of kraft sheets that are needed on stock is shown in Appendix 17.

The coordinates of the storage points are defined in the input dataset. The model gives the following results:

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Flow Time Total [h]</th>
<th>Flow Distance Total [km]</th>
<th>Time [h]</th>
<th>Distance [km]</th>
<th>Operator costs [€]</th>
<th>Truck fuel costs [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>591,936</td>
<td>3551,618</td>
<td>15,310</td>
<td>91,860</td>
<td>€499,24</td>
<td>€31,64</td>
</tr>
<tr>
<td>104</td>
<td>1021,286</td>
<td>6127,717</td>
<td>79,040</td>
<td>474,240</td>
<td>€2,577,39</td>
<td>€163,33</td>
</tr>
<tr>
<td>106</td>
<td>2069,446</td>
<td>12416,677</td>
<td>247,040</td>
<td>1482,240</td>
<td>€8,055,65</td>
<td>€510,48</td>
</tr>
<tr>
<td>107</td>
<td>464,022</td>
<td>2764,133</td>
<td>0,000</td>
<td>0,000</td>
<td>€0,00</td>
<td>€0,00</td>
</tr>
<tr>
<td>109</td>
<td>248,560</td>
<td>1401,360</td>
<td>0,000</td>
<td>0,000</td>
<td>€0,00</td>
<td>€0,00</td>
</tr>
<tr>
<td>113</td>
<td>453,104</td>
<td>2718,625</td>
<td>0,000</td>
<td>0,000</td>
<td>€0,00</td>
<td>€0,00</td>
</tr>
<tr>
<td>117/414</td>
<td>1083,823</td>
<td>13005,880</td>
<td>0,000</td>
<td>0,000</td>
<td>€0,00</td>
<td>€0,00</td>
</tr>
<tr>
<td>501-506</td>
<td>789,625</td>
<td>4737,750</td>
<td>0,000</td>
<td>0,000</td>
<td>€0,00</td>
<td>€0,00</td>
</tr>
<tr>
<td>991</td>
<td>219,583</td>
<td>1317,500</td>
<td>0,000</td>
<td>0,000</td>
<td>€0,00</td>
<td>€0,00</td>
</tr>
<tr>
<td>992</td>
<td>572,237</td>
<td>8583,555</td>
<td>-43,860</td>
<td>-657,907</td>
<td>-€1,430,23</td>
<td>-€294,79</td>
</tr>
<tr>
<td>GrandTotal</td>
<td>7513,624</td>
<td>56734,816</td>
<td>297,530</td>
<td>1390,433</td>
<td>€9,702,05</td>
<td>€410,65</td>
</tr>
</tbody>
</table>

Table 6.3: Model output for redesign scenario 2

There are only slight differences in the total time needed per truck. Truck 106 will need to transport materials for on average 0,7 hours extra per day. The ZF kraft core material is too large to be transported from the Impregnation4 line towards the stock location 211 through the main corridor and make a turn. Therefore, the truck from the impregnation line uses a special car to transport the ZF towards the end of the straight part of the corridor. From there, truck 106 has to pick up the ZF core material and transport it towards the stock location. Since truck 106 is already quite busy, increasing its occupancy is not favorable.

Positive scenario aspects:
- Terminal trailer truck does not have to transport the kraft sheets outdoor
- More structure in locations, instead of primary and secondary locations. Results in better FIFO and thus reduces costs of expired core material.
- The placement of storage racks can overcome the problem of sticking FR kraft sheets. This is an important requirement for the project of improving the manufacturing process.

Negative scenario aspects:
- Investments needed for placing the storage racks, €415,000 according to a preliminary study
- The number of hours truck 106 has to transport between locations is increased. Since this truck is already busy, this is not favorable. The truck of the DF line can possibly perform the transportation of ZF kraft sheets, but then still extra transportation time is needed.
Redesign 3: Storage locations of kraft sheets are changed according to the stickiness-analysis solution 2

The basis of this scenario is the same as the former one; it is analyzed what the effect on the MHC is when the kraft core material is stocked on another location to avoid the stickiness problem. In this second solution, special flow racks are placed in location 203 (Klima1). The new stock locations are depicted in Table 6.4.

<table>
<thead>
<tr>
<th>Location</th>
<th>Resin type:</th>
<th>F30</th>
<th>F33</th>
<th>B13</th>
<th>B21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Size:</td>
<td>IF</td>
<td>SF</td>
<td>FF</td>
<td>XF</td>
</tr>
<tr>
<td>203 (Klima1)</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
<td>203</td>
</tr>
<tr>
<td>316 (Klima3)</td>
<td>316</td>
<td>316</td>
<td>316</td>
<td>316</td>
<td>316</td>
</tr>
<tr>
<td>213</td>
<td>213</td>
<td>213</td>
<td>213</td>
<td>213</td>
<td>213</td>
</tr>
<tr>
<td>211 (Rode hal)</td>
<td>211</td>
<td>211</td>
<td>211</td>
<td>211</td>
<td>211</td>
</tr>
</tbody>
</table>

Table 6.4: New stock locations kraft, scenario 3

The results are comparable to redesign 2. As Table 6.5 shows, the total flow time is not reduced. Also in this case, the truck 106 has increased occupancy (0.36 hours per day). Changing the stock locations in this way does not seem to be very influential to the total MHC. Therefore this scenario seems a practical feasible one, regarding the internal transportation aspect, of solving the stickiness problem.

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Flow Time Total [h]</th>
<th>Flow Distance Total [km]</th>
<th>Time [h]</th>
<th>Distance [km]</th>
<th>Operator costs [€]</th>
<th>Truck fuel costs [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>611.061</td>
<td>3666.568</td>
<td>34.435</td>
<td>206.610</td>
<td>€1.122.88</td>
<td>€71.16</td>
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<tr>
<td>104</td>
<td>1024.723</td>
<td>6148.537</td>
<td>82.477</td>
<td>494.860</td>
<td>€2.689.46</td>
<td>€170.43</td>
</tr>
<tr>
<td>106</td>
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<td>17713.177</td>
<td>129.490</td>
<td>776.940</td>
<td>€4.212.50</td>
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<td>107</td>
<td>444.032</td>
<td>2784.133</td>
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<td>€0.00</td>
</tr>
<tr>
<td>109</td>
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<td>1491.360</td>
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<td>0.00</td>
<td>€0.00</td>
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</tr>
<tr>
<td>113</td>
<td>453.104</td>
<td>2718.625</td>
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<td>0.00</td>
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<td>€0.00</td>
</tr>
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<td>13005.880</td>
<td>0.00</td>
<td>0.00</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
<td>501-506</td>
<td>789.625</td>
<td>4737.750</td>
<td>0.00</td>
<td>0.00</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
<td>991</td>
<td>219.581</td>
<td>1317.500</td>
<td>0.00</td>
<td>0.00</td>
<td>€0.00</td>
<td>€0.00</td>
</tr>
<tr>
<td>992</td>
<td>592.236</td>
<td>8883.515</td>
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<td>-€180.38</td>
</tr>
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<td>GrandTotal</td>
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<td>1120.483</td>
<td>€7.256.74</td>
<td>€348.78</td>
</tr>
</tbody>
</table>

Table 6.5: Model output for redesign scenario 3
Redesign 4: Relocating the Impregnation4 line closer to the presses 6 and 7

The largest panel size of Trespa, the ZF format, is always composed of ZF kraft sheets as core material. The ZF size is introduced in 2008. A nice feature of this panel type is the high output-per-time-unit ratio; each pressing charge, a lot of m² panels is produced. However, a negative aspect of using this large sized core material is the handling towards the press; the main indoor corridor is not wide enough to transport the ZF format in the ‘standard’ lifting way (wide). Therefore, a special car is used to transport the ZF kraft sheets towards the terminal trailer or indoor towards a stock location. This requires quite some handling time for both the Core and Pressing department.

An idea to overcome this problem in the main corridor is to place the Impregnation4 line closer to the presses. A possible location for the Impregnation4 line and a storage hall is the terrain which is currently rented from Trespa by another company. The new locations for the storage of kraft sheets are depicted in Figure 6.4 below.

![Figure 6.4: Redesign 4 with old (orange) and new (green) locations](image-url)
Because of relocating the impregnation line, the ZF size core material can be transported easily with a forklift truck without using a special car (indoor transport through ‘main corridor’) or the terminal trailer (outdoor transport). As can be seen in Table 6.7, the number of hours the terminal trailer is used for transporting ZF core material is reduced by about 44 hours. In reality, more time is saved because the handling for the terminal trailer transportation (loading and unloading) is not needed anymore. The core material is placed closer to the presses, so 112 hours of transportation is reduced for truck 106 of press7. The truck of the impregnation line (101) does not have to traverse a longer distance compared to the current situation. If the kraft sheets cannot be transported outdoor due to bad weather conditions, the time savings of this redesign will become negligible; additional transportation and handling is needed to store the core material on the specified locations. Investments of this scenario are high and improvements are hardly seen, so the scenario is rejected.

Table 6.6: New stock locations kraft, scenario 4

Table 6.7: Model output for redesign scenario 4

Positive scenario aspects:
- Kraft sheet core material is produced closer to the presses. The ZF size sheets do not have to be transported through the narrow indoor corridor or outside by the terminal trailer. Besides less handling time, 147 hours of transportation between locations can be saved.

Negative scenario aspects:
- The Impregnation4 line has to be moved and the area that is rented by another company at the moment has to be prepared. Possibly also the resin tower has to be moved. In order to realize this scenario, very large investments are needed.
- Kraft sheets cannot be transported outdoor when weather conditions are bad. The terminal trailer truck has to be used or other investments are needed to solve this issue.
Redesign 5: Klima 2 and 2B are used to store core material

At the moment, the Klima2 location is used to store the decor material (melamine) which is needed to press the Athlon panels. In this redesign scenario the Klima2 and 2B will be used to store core material instead of the decor material, since they are located close to presses 6 and 7. The kraft sheets which are used the most are stored in Klima2, 2B and 3. An overview of all types of core material and their usage at the presses is shown in Appendix 18, sorted by descending number of routes (pallets divided by truck capacity). Storage of the ZF kraft is not changed compared to the current situation. Other core material is stored as close to the presses as possible on other locations. The rearrangement is shown in Table 6.8.

Table 6.8: New stock locations kraft, scenario 5

In this way, the truck of the Impregnation4 line has to travel a larger distance to transport the core material, but the truck of press 7 needs to travel 250 hours less a year. This change in time consumption might be useful at press 7, where in the current situation another truck (135) is needed to take the pallets with finished products from the press output conveyor. Further analysis is needed to see if this extra truck can be discarded. Total time needed to transport materials between locations is barely changed by this redesign.

Table 6.9: Model output for redesign scenario 5

Positive scenario aspects:

-Kraft sheet core material is stored closer to the presses. The truck of the impregnation line (101), which is idle 75% of the time in the current situation, takes over the transportation of core material towards the presses from truck 104 and 106. In this extra time, truck 106 can move the finished products off the press 7 output conveyor. A detailed time study is needed to see if the extra truck 135 (monthly lease costs €1.594,65) can be discarded.
Negative scenario aspects:
- Klima2 and Klima2b have to be cleared and prepared to store the core material.
- There is no direct effect on the total time or fuel needed for internal transportation.

Redesign 6: Combining truck 101 and 107
Truck 101 and 107 are both large forklift trucks of the core department. Truck 101 is stationed at the Impregnation4 line and transports kraft sheets towards stock locations. Truck 107 is stationed at the end of the DF line and transports prepregs towards stock locations. Since these trucks are of the same type and are stationed quite close to each other, in this scenario the actions of the two trucks are combined and performed by one truck (107).

Because the impregnation line and the DF line use the same truck in this scenario, extra time is needed to move the truck between the machines. This is simulated in the input data by letting the truck 107 drive back to the DF line after every 4 pallets of kraft sheets produced at the impregnation line.

The results are shown in Table 6.10 below.

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Flow Time Total [h]</th>
<th>Flow Distance Total [km]</th>
<th>Time [h]</th>
<th>Distance [km]</th>
<th>Operator costs [€]</th>
<th>Truck fuel costs [€]</th>
</tr>
</thead>
<tbody>
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<td>-576.626</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
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<td>4518.838</td>
<td>24.531.75</td>
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</tr>
<tr>
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<td>0.000</td>
<td>0.00</td>
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</tr>
<tr>
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<td>2718.625</td>
<td>0.000</td>
<td>0.000</td>
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<td>0.00</td>
</tr>
<tr>
<td>11784144</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>992</td>
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<td>9241.462</td>
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</tr>
<tr>
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<td>1054.080</td>
<td>5.728.70</td>
<td>363.02</td>
</tr>
</tbody>
</table>

Table 6.10: Model output for redesign scenario 6

The extra driving time for the truck between the DF line and impregnation line requires about 0.5 hour per day (24h). According to the Jungheinrich data, truck 101 is used 6.1 hours per day (24h) on average in the current situation. Truck 107 is only used 3.8 hours per day. These data imply that only one truck will be sufficient to perform the actions at both machines. However, the output buffers of the DF line and impregnation line have to be emptied in time when the machines are in operation. A detailed time study is required to see if all flows can be performed by one truck. If this is not possible, increasing the output buffer space of a machine can be the solution; in this way, the truck can be absent for a longer period. This will require investments.

Positive scenario aspects:
- The large truck of the impregnation line (101) is not needed anymore, saving lease costs of €2.378,76 per month (€28.545.12 per year).

Negative scenario aspects:
- The operator and fuel costs will increase with €6.091,72 per year.
- A detailed time study is needed to check if the output buffers of the machines can be emptied in time.
- If this is not possible, the output buffer space of the DF line has to be increased. This will require investments for placing additional mechanical components at the end of the line.
6.2 Implementation and summary of model redesigns

The layout of the current situation and redesign scenarios are analyzed using the AIMMS model. In the former chapters it is described how the model has been formulated and built. The implementation of all parameter values in the model is explained and also the validation and verification are discussed. The use of different sources for data gathering have resulted in an iterative process of implementing important aspects in the model.

Not all item flows of Trespa are within the scope of the project and in a real world setting there are always exceptions on routes taken and actions performed. Therefore, the model is a simplified representation of the real world and not an exact copy. It is designed to analyze changes in the layout and to see where possible improvement projects are possible.

For every redesign scenario, the model outcomes are described and explained. An overview is created to compare all redesign scenarios and belonging values (Table 6.11).

Table 6.11: Overview of the model values of all redesign scenarios
During the execution of this research project, the implementation of the first redesign scenario was started. Because of safety reasons, the Bowiehal is not suitable anymore for the storage of prepregs. The area of former press 5 is therefore prepared and transformed into a stock location. Time needed for internal transportation of prepregs is reduced significantly with this change. Saving truck lease costs is simply done by not renewing the contracts of two outdoor trucks.

Placing the kraft sheets of FR resins into racks at stock locations seems to be a prerequisite for the project of improving the manufacturing process. Redesigns 2 and 3 have shown that changing the stock locations of core material leads to slightly increased transportation times. The placement of storage racks is therefore a feasible solution of the ‘sticking sheets problem’ regarding internal transportation.

Relocating the impregnation line closer to the presses requires a lot of investments. The gains of this fourth scenario in terms of reduced operator and truck costs are negligible. Implementing this scenario is out of the question.

Klima2 and 2B are locations very close to the presses. Using them as stock locations for core material will result in a shift of driving time needed for the trucks: the truck of the core department has to drive further distances, but the trucks of the presses can save driving time. Further analysis is needed to see if the truck of press 7 can perform the actions on its own, which would lead to cost reductions of scrapping truck 135. Before this scenario can be implemented, all actions of Arpa which now occur in Klima 2B have to move elsewhere.

Combining truck 101 and 107 will lead to cost reduction since then one truck is not leased anymore. According to the model and the truck usage in total time, one truck should be able to execute the actions which are currently done by two trucks. The output buffer spaces of the DF line and impregnation line have to be emptied in time to keep the machines in operation. Therefore, a detailed time study of the trucks and actions is needed before this scenario can be implemented.
7. CONCLUSIONS & RECOMMENDATIONS

In this last chapter, the conclusions of the research project are outlined. Recommendations are given for the company and research in general. Also a reflection section is added which includes a personal view on the total research project.

7.1 Conclusions

The production site of Trespa in Weert consists of several plants and stock locations. For the production of the high-pressure laminates, a lot of materials are transported between the locations. As a result of Trespa’s expansion and associated changes, the facilities are not located optimally with respect to each other. The goal of the research project is to determine whether the layout can be improved and what the possible gains and losses are.

The costs of internal transportation depend on the item flows. Changing the coordinates of locations therefore results in a change of costs. In order to analyze different redesign scenarios, a MILP is designed and implemented in optimization software AIMMS. In this way, the model is able to calculate the total time needed for item flows given a certain layout scenario, while taking into account the real world routes. Scenarios are created by changing the input data for the model. The main conclusions of the research are summarized below:

- The internal transportation costs depend on the distance and time needed for all item flows. These costs are operator costs, truck fuel costs and truck lease costs.
- A lot of forklift trucks are used at the production site of Trespa. As a result, a considerable amount of lease costs is spent every year. There are a lot of trucks needed to execute special actions, dependent of their size and fork types. Another reason for this large fleet size is that several machines need a truck at an input or output point at certain moments; if no truck is present, the machine cannot operate.
- The number of hours the trucks are used per day is very low on average (about 4 hours per day (24 hours) for the trucks included in the analysis). The two trucks of the presses 6 and 7 are used quite a lot.
- Several machines are very large and the investments needed to relocate them would not be outweighed by the gains. These locations cannot be changed, so the layout scenarios to consider are limited. Most likely and feasible to relocate are the stock points of core material.
- In the current situation, the important locations of the production area are placed such that start and end points of item flows are close to each other. Transportation flows are quite in line with the main production process. As several scenarios show, the MHC cannot be reduced significantly given the constraints of this brownfield situation. A reduction of costs for internal transportation seems to be hard by only changing the layout. Switching the current stock locations of core material leads to slightly increased transportation times. The placement of storage racks is therefore a feasible solution of the ‘sticking sheets problem’ regarding internal transportation.
- One layout improvement is in execution at the moment. Moving the prepregs on stock from the Bowiehal to location 213-1 (former press5) is nice improvement scenario which will lead to the reduction of about 1 FTE and the lease of one or two forklift trucks.
- If item flows of two trucks can be combined in such a way that the actions are executed by only one truck, lease costs can be reduced. This will require an analysis which includes time windows. Using Klima2 and 2B as stock locations for core material will result in an increase of driving time for the core truck; the trucks of the presses can save driving time. Further analysis including time windows is needed to see if the truck of press 7 can perform the
actions on its own, which would lead to cost reductions of scrapping truck 135. Another way to reduce lease and direct labor costs is the automation of item flows. Recommendations for further research are given in a separate section.

- The model created in AIMMS can be used to analyze layout scenarios by calculating the total time needed for item flows. All input data can be changed for calculations, such as possible paths, demands, location coordinates and truck capacities; the possibilities are endless. AIMMS is commercially used software by professionals and has several nice features, such as fast run time, clear programming overview, graphical interface and the possibility to link to Microsoft Excel for importing and exporting data.

7.2 Recommendations

- A lot of forklift trucks are only in use during a small amount of time per shift. In order to save money, it sounds obvious to scrap some trucks by combining the actions performed by separate trucks. The first remark is that truck types differ, so the possible actions to perform are not equal for each truck. Secondly there are trucks which are needed in certain time windows; if they are not available at a certain time, it is possible that the production process is disrupted. A clear example is a truck needed at the output of a machine. If the output buffer is full, the machine cannot operate anymore.

It is recommended to analyze the possibility to combine some trucks. This can be done by making a model which includes time windows. Extending the output buffer of a machine (for example by extending the conveyor length or placing a stacking machine) may increase the possibilities to combine trucks.

A detailed analysis to see if trucks can be combined is recommended for the following trucks:

101 / 107: scrapping truck 101 leads to a reduction of lease costs of €2.378 per month.
106 / 135: scrapping truck 135 leads to a reduction of lease costs of €1.594 per month.

- The terminal trailer truck is used a lot to transport the finished products from the presses towards the warehouse. Most of the times the trailer is also transported back to the presses empty (sometimes new pallets are transported on the way back to the presses). Implementing Automated Guided Vehicles (AGVs) might lead to a reduction of direct labor costs.

- The pallets with finished products which are transported from the presses towards the warehouse only contain panels of the same type. This leads to less handling at the warehouse, but a negative effect is that the terminal trailer truck transports a lot of pallets; the volume of pallets in the terminal trailer is close to the volume of panels. It is recommended to analyze if this process can be changed, because placing more panels on a pallet will lead to a reduction of the amount of times the trailer has to be transported towards the warehouse.

- The analysis of the current situation and the redesign scenarios is based on observations and the production data of 2013. It is likely that the process and demands of product types will change over time. Analyses with updated data are needed to see what the effects will be of layout changes in the future.

- Material handling of the trucks includes both actions performed on a location itself and the time needed for handling between locations. Since the processes are assumed to be unchanged, only the handling time between locations is influenced by changes in location coordinates. Included in the model are only the real driving times of trucks between locations; time spent during handling on locations is not included in the model. An analysis of the handling on locations might lead to new insights and improvements.
7.3 Limitations:

- The model is designed to analyze scenarios in which the layout is changed. This means that coordinates of locations are changed, but the production process remains the same. After the analysis of the item flows at Trespa using several sources, it turned out that reducing the fuel costs of trucks has small gains compared to scrapping a truck from the truck fleet; the average truck lease costs are about €1,500 - €2,000 per month. In order to see if a truck can be scrapped, however, a detailed analysis and model is needed which captures time windows of machinery and the truck’s actions.

- The production location of Trespa is in full operation, so redesign scenarios to consider have to be realistic. Building a model which optimizes a brownfield situation with all real world constraints included is very hard and requires a tremendous amount of work. Therefore it is chosen to make a model which is able to catch the real world parameters and calculate the objective function given a certain scenario. A limitation of this approach is that scenarios have to be created manually; there might be nice improvement possibilities which are not seen by the experts in the field.

- The layout is a small area, which makes it difficult to realize large gains by redesigns. Benefits are larger when distances increase (large scale, e.g. countries).

- In order to get the right input data for the model, several sources are used. This makes the data quite reliable and representative for the real world situation. However, a lot of executed material handling actions do not follow a strict pattern. Because of practical reasons there will always be exceptions for material handling which make the data noisy. Combined with the fact that there are a lot of trucks which are analyzed by a single person, it is difficult to catch all real world item flows of Trespa exactly in a model.

7.4 Reflection

At the start of this project, Trespa stated a research assignment which included the optimization of the production area by changing its layout in a greenfield scenario. Based on this initial assignment, a literature review about layout optimization has been conducted. Since the company is already in operation for many years, the greenfield optimization would not add much value and at a certain moment it is decided to change the project into a brownfield analysis; improve the layout of the existing situation.

In order to combine both a theoretical and practical approach, a model is constructed to analyze several layout scenarios. Input for the scenarios is done manually to be sure they are realistic ones. At a certain point it turned out that the redesign scenarios and the gains were limited within the research scope. This has led to frustrations and disappointments at the three parties (company / university supervisors and the student) because the interests and possibilities could not be matched. It is decided to continue with the model and analysis to show the academic skills and to stay within scope. Due to time constraints set by the university for finishing the master thesis in six months, a scope change could not be realized. A possible solution for this problem would have been to involve all stakeholders in an early stage and discuss what alternatives or ideas would have been possible.

A certain path to follow was chosen and decisions were made during the project. A learning point for the future is to first look at the assignment in a broader view before starting to converge in an early stage. Many people with different expertise have been interviewed, but the starting point of this
already was the research assignment and the layout scope. Working in a team instead of performing a stand-alone project also favors me and reduces the possibility to converge too soon.

Improvements for future projects are thus the following:
- The stakeholders of the project were updated regularly. When problems arise, however, they should all discuss this together on time and decide on what steps to take.
- During the scoping, it is important to keep an eye on the bigger picture of the project and aim. Gains and limitations have to be revealed and discussed in an early stage.
- Think more in opportunities instead of threats. The thesis time constraints and project issues have reduced the ability to make progress and come up with nice ideas. A more positive mindset and confidence will improve a project’s outcome.

During the execution of the research project, a lot of personal skills were developed. In order to gain insight in the problem and to collect data for the model, a lot of people from different departments and experience are interviewed. It has been a great experience to gain step by step knowledge in the different disciplines present at the production location of Trespa and to process and filter a lot of information. Also general project execution skills were developed, such as project orientation, making decisions, choosing different approaches, information gathering et cetera. Besides the personal skills, also professional skills were developed such as conducting a case study with both qualitative and quantitative data sources in a large company. I learned how to program in Microsoft Excel and how to build a model in the AIMMS optimization software.

All in all, it has been a challenging project in which I developed a lot of professional and personal skills.
REFERENCES


READING GUIDES

List of abbreviations

AGV  Automated Guided Vehicle
ARP  Arc Routing Problem
CMU  Color Mixing Unit
DF   Dry Forming
EBC  Electronic Beam Curing
FLP  Facility Layout Problem
FTE  Full Time Equivalent
HPL  High-Pressure (compact) Laminate
LRP  Location-Routing Problem
MHC  Material Handling Costs
MILP Mixed Integer Linear Programming
OML  Operations Management & Logistics
TU/e Technische Universiteit Eindhoven (Eindhoven University of Technology)
VRP  Vehicle Routing Problem
WIP  Work In Process
W&S  Warehouse & Shipping

List of definitions

Algorithm  A set of steps to follow intended to solve a specific problem.
http://www.indiana.edu/~p1013447/dictionary/alg_heur.htm

Facility  A place, especially including buildings, where a particular activity happens (e.g. a nuclear research facility, a military facility, a new sports facility)

Facilities  The buildings, equipment, and services provided for a particular purpose (e.g. shopping facilities, medical facilities, sports facilities)
http://dictionary.cambridge.org/dictionary/british/facility_1?q=facility

Greenfield  In many disciplines a greenfield is a project that lacks any constraints imposed by prior work. The analogy is to that of construction on greenfield land where there is no need to work within the constraints of existing buildings or infrastructure.
http://en.wikipedia.org/wiki/Greenfield_project

Heuristics  Algorithms which find solutions among all possible ones, but they do not guarantee that the best will be found, therefore they may be considered as approximately and not accurate algorithms. These algorithms, usually find a solution close to the best one and they find it fast and easily.
http://students.ceid.upatras.gr/~papagel/project/kef5_5.htm

HPL  A panel, composed of multiple core and decor layers, made homogeneous by pressing under high pressure. This is the end product of Trespa.

Kraft sheet  Sheet of paper, impregnated with a certain resin, used as core material for the HPL

Prepreg  Sheet of wood-based fibers, impregnated with a certain resin, used as core material for the HPL
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## APPENDICES

### Appendix 1: Trespa standard panel sizes & types

<table>
<thead>
<tr>
<th>Panel type</th>
<th>Dimensions [mm]</th>
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<tbody>
<tr>
<td>IF</td>
<td>3050 x 1530</td>
</tr>
<tr>
<td>SF</td>
<td>2550 x 1860</td>
</tr>
<tr>
<td>FF</td>
<td>3650 x 1860</td>
</tr>
<tr>
<td>XF</td>
<td>3730 x 1860</td>
</tr>
<tr>
<td>ZF</td>
<td>4270 x 2130</td>
</tr>
</tbody>
</table>

- **Trespa Meteoron**
  - Balconies
  - Facades

- **Trespa Toplab**
  - Scientific furniture (high chemical resistance)

- **Trespa Athlon**
  - Scientific furniture (lower chemical resistance)
  - Interior decoration

- **Trespa Virtuon**
  - Interior decoration (max. hygiene, frequently cleaning)
Appendix 2: Organization chart
Appendix 3: Production location of Trespa in Weert
Appendix 4: Item flows per department

Core (kraft sheets):
Core (prepregs):
Press 7, including terminal trailer truck:
### Appendix 5: Truck fleet

<table>
<thead>
<tr>
<th>#</th>
<th>Model</th>
<th>Capacity</th>
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<tr>
<td>2</td>
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<td>9</td>
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<tr>
<td>10</td>
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Appendix 6: Production area: nodes and possible arcs
Appendix 7: Input data current situation model (nodes)

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Node Description</th>
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<th>Y</th>
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<tr>
<td>1</td>
<td>0700056</td>
<td>70</td>
<td>50</td>
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<td>2</td>
<td>0701010</td>
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<tr>
<td>3</td>
<td>101210</td>
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<td>4</td>
<td>201056</td>
<td>50</td>
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<td>201350</td>
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<td>8</td>
<td>240008</td>
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<td>9</td>
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<td>Bevaatigingsgroep</td>
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<tr>
<td>63</td>
<td>700170</td>
<td>710</td>
<td>120</td>
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</table>

68
Appendix 8: Internal transportation (analysis 2006)
Appendix 9: Fill list measuring internal transportation

Front side of the fill list. The red boxes and remarks are only shown in this report to explain the set-up of the lists.

Back side of the fill list. On this side the goal of the measurement is explained and it is illustrated how to fill it out.
Appendix 10: Input data current situation model: production figures SAP

<table>
<thead>
<tr>
<th>Finished products (panels)</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Press</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>x</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Production EB rolls</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of rolls</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Total m1</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Total m2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Total weight [kg]</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
## Prepreg use per press

<table>
<thead>
<tr>
<th>Naar pers</th>
<th>x</th>
</tr>
</thead>
</table>

### Data

<table>
<thead>
<tr>
<th>Type hars</th>
<th>Formaat</th>
<th>Sum of Weight [kg]</th>
<th>Sum of # Pallets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Totaal B24

- **Totaal B24**: 14.102.845.09 kg
- **Sum of # Pallets**: 8.519.26

### Totaal F30

- **Totaal F30**: 5.913.26 kg
- **Sum of # Pallets**: 3.86

### Eindtotaal

- **Eindtotaal**: 14.108.758.35 kg
- **Sum of # Pallets**: 8.523.12
# Kraft sheets production

| Naar pers | (All) |

| Data |
|---|---|---|---|
| Type | Formaat | Sum of Weight [kg] | Sum of # Pallets |
| F30 | IF | 3.24 | 3.098,19 |
| | SF | 1.835.383,95 | 809,15 |
| | FF | 3.394.993,30 | 1.496,72 |
| | XF | 93.705,52 | 41,31 |
| | ZF | 2.990.210,01 | 1.318,27 |
| F33 | IF | 1.055.924,43 | 459,99 |
| | SF | 607.380,60 | 264,59 |
| | FF | 1.230.251,15 | 535,94 |
| | ZF | 869.959,21 | 378,98 |
| B13 | IF | 3.483.823,59 | 1.540,10 |
| | SF | 2.813.191,30 | 1.243,63 |
| | FF | 2.114.309,81 | 934,68 |
| | XF | 572.129,05 | 252,92 |
| | ZF | 4.579.791,96 | 2.024,60 |
| B21 | IF | 563.987,71 | 249,32 |
| | SF | 255.359,12 | 11,289 |
| | FF | 184.000,73 | 81,34 |
| B21 Total | | 1.003.347,56 | 443,55 |
| Grand Total | | 29.887.499,64 | 13.174,20 |
### Kraft use per press

<table>
<thead>
<tr>
<th>Type</th>
<th>Formaat</th>
<th>Sum of Weight [kg]</th>
<th>Sum of # Pallets</th>
</tr>
</thead>
<tbody>
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<td>F30</td>
<td>IF</td>
<td>2.015.224,02</td>
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<td>SF</td>
<td>1.295.860,11</td>
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<td>FF</td>
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<td>XF</td>
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<td><strong>Totaal F30</strong></td>
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<td>F33</td>
<td>IF</td>
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Appendix 12: Congestion top 10 of current situation
Appendix 13: Data of average truck usage

Average usage per truck in 24 hours (data Jungheinrich)

Avg. # hours in use per shift / truck

Working shifts of the departments:

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<th>Morning (Mo-Fr)</th>
<th>Afternoon (Mo-Fr)</th>
<th>Weekend (Sa-Su)</th>
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- Decor
- Core
- Pressing
- W&S
- Support
Appendix 14: Model in Microsoft Excel and AIMMS

In Microsoft Excel, several sheets in the input data workbook contain tables and matrices with important values. Based on the scenario, the values are filled out for Node IDs, Node X and Y coordinates, Truck IDs, Truck speeds, Arcs possible, Arcs indoor, Arcs distance, Item flow IDs with demand and capacity, and the net demand per node. Most of these parameter values are shown in foregoing appendices 4, 5, 6, 7, 10 and 11.

First, the right Excel workbook name to retrieve the data from has to be entered in the AIMMS software:
“Model” tab → “Input Data” → “Declaration of Excel information” → “ExcelWorkbookName” → “Definition” → Enter workbook name

In order to solve the model, click the button to Solve and Export:
“Pages” tab → “v3_SOLVE-All commodities 1-300” → click the “Solve and Export 1_300” button
The input data of a scenario is then imported automatically in AIMMS using the following code:

```aimms
!EMPTY ALL SETS AND PARAMETERS FROM "Data from Excel"
empty V_Nodes, Node_X, Node_Y, a, m, K_CommodityFlowIDs, d;

!SET THE ACTIVE EXCEL SHEET NAME TO READ FROM
Spreadsheet::SetActiveSheet(ExcelWorkbookName, "Nodes Arcs");
ExcelSetActiveSheet(ExcelWorkbookName, "Nodes Arcs");

!IMPORT DATA OF ALL COMMODITY FLOW IDS: k=1-300
!NODES X AND Y COORDINATES ARE RETRIEVED if (not ExcelRetrieveTable(ExcelWorkbookName, Node_X, "C7:C206", "B7:B206", "", 1)) then DialogError(CurrentErrorMessage); endif;
if (not ExcelRetrieveTable(ExcelWorkbookName, Node_Y, "D7:D206", "B7:B206", "", 1)) then DialogError(CurrentErrorMessage); endif;

!POSSIBLE ARCS AND THE DISTANCE OF EACH ARC if (not ExcelRetrieveTable(ExcelWorkbookName, a, "H427:GY626", "G427:G626", "H426:GY426", "", 1)) then DialogError(CurrentErrorMessage); endif;
ExcelSetActiveSheet(ExcelWorkbookName, "Arcs_distance");
if (not ExcelRetrieveTable(ExcelWorkbookName, m, "H7:GY206", "G7:G206", "H6:GY6", "", 1)) then DialogError(CurrentErrorMessage); endif;

!NODES WITH INPUT OR OUTPUT ARE RETRIEVED WITH X AND Y COORDINATES ExcelSetActiveSheet(ExcelWorkbookName, "Points");
if (not ExcelRetrieveTable(ExcelWorkbookName, NodeInOut_X, "I5:I54", "H5:H54", "", 1)) then DialogError(CurrentErrorMessage); endif;
if (not ExcelRetrieveTable(ExcelWorkbookName, NodeInOut_Y, "J5:J54", "H5:H54", "", 1)) then DialogError(CurrentErrorMessage); endif;

!NODE DEMAND: ID, COMMODITY, AMOUNT ExcelSetActiveSheet(ExcelWorkbookName, "Demand");
if (not ExcelRetrieveTable(ExcelWorkbookName, d, RangeDemand1_300, "U7:U206", RangeDemandColumns1_300, 1)) then DialogError(CurrentErrorMessage); endif;

!C1: Check to only include commodity k if data is completely filled out >> C1(ka) ExcelSetActiveSheet(ExcelWorkbookName, "Demand");
if (not ExcelRetrieveTable(ExcelWorkbookName, C1, "D7:D306", "G7:G306", "", 1)) then DialogError(CurrentErrorMessage); endif;

!DESCRIPTION OF THE COMMODITIES: WHAT, FROM, TO ExcelSetActiveSheet(ExcelWorkbookName, "Demand");
```
if ( not ExcelRetrieveTable( ExcelWorkbookName, Comm_All_Description,"F7:F306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, C_FROM,"I7:I306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, C_TO,"K7:K306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!Amount(ka)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, Amount,"L7:L306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!Truck_ID(ka)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, Truck_ID,"N7:N306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!Capacity(ka)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, C,"P7:P306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!Speed(ka)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, v,"R7:R306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!Way12(ka)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, w,"S7:S306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!Indoor(k)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, Indoor,"LN7:LN306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
!c_truck(k)
ExcelSetActiveSheet( ExcelWorkbookName, "Demand" );
if ( not ExcelRetrieveTable( ExcelWorkbookName, c_truck,"LO7:LO306", "G7:G306", "", 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;
ExcelSetActiveSheet( ExcelWorkbookName, "A' (indoor)" );

!ARCS INDOOR ARE RETRIEVED
if ( not ExcelRetrieveTable( ExcelWorkbookName, Aprime_ArcsIndoor,"H7:GY206", 
"G7:G206", "H6:GY6" , , 1 ) ) then 
    DialogError( CurrentErrorMessage ) ;
endif ;

if ( not ExcelRetrieveTable( ExcelWorkbookName, a_indoor, "H7:GY206", "G7:G206", 
"H6:GY6" , , 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;

if ( not ExcelRetrieveTable( ExcelWorkbookName, a_outdoor, "HC7:OT206", 
"HB7:HB206", "HC6:OT6" , , 1 ) ) then
    DialogError( CurrentErrorMessage ) ;
endif ;

After importing the data, the model has to assign values to the variables to fulfill the objective function:

solve MinimizeTotalMHC ;

!If the status after solving implies that the problem is infeasible, we should notify the user.
if MinimizeTotalMHC.ProgramStatus = 'Infeasible' or MinimizeTotalMHC.ProgramStatus = 'IntegerInfeasible' or MinimizeTotalMHC.ProgramStatus = 'InfeasibleOrUnbounded' then 
    DialogError("The input data supplied caused the model to be infeasible", 
    "Infeasible model") ;
Endif

It takes the model a small amount of time to run and find the optimal solution. This results in an overview of the arcs chosen to fulfill the demand of the item flow ID and the quantity which is traversed over each arc. The chosen arcs can be depicted in the layout of the production area for each item flow ID:

"Pages" tab  →  “v3_OUTPUT-Graph FlowDistTime_single”

The illustration on the next page shows the arcs chosen by the model to fulfill a certain item flow.
After solving, the output data is exported to the Microsoft Excel output file.

```plaintext
!Export data k1-300
ExcelSetActiveSheet( ExcelWorkbookOutput, "PAGE1" );
Spreadsheet::ClearRange( ExcelWorkbookOutput, "C7:Z306" );

!CLEAR CONGESTION MATRIX
Spreadsheet::ClearRange( ExcelWorkbookOutput, "AJ6:EE200" );

!Spreadsheet::SetActiveSheet( ExcelWorkbookOutput, "Output1" );
ExcelSetActiveSheet( ExcelWorkbookOutput, "PAGE1" );
Spreadsheet::SetActiveSheet( ExcelWorkbookOutput, "PAGE1" );

!Spreadsheet::AssignSet( ExcelWorkbookOutput, KA_Commodities_All, "G7:G306" );
Spreadsheet::AssignSet( ExcelWorkbookOutput, K_CommodityFlowIDs, "G7:G306" );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, C1, "D7:D306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Comm_All_Description, "F7:F306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, C_From, "I7:I306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, C_To, "K7:K306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Amount, "L7:L306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Truck_ID, "N7:N306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, C, "P7:P306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, v, "R7:R306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, w, "S7:S306", sparse: 1 );
```
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Route_Distance, "T7:T306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Route_Time_min, "V7:V306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Flow_TimeTotal_h, "W7:W306", sparse: 1 );
Spreadsheet::AssignParameter( ExcelWorkbookOutput, Flow_DistanceTotal_km, "Z7:Z306", sparse: 1 );

!THE CONGESTION MATRIX IS FILLED, ALSO ON PAGE1 OF THE OUTPUT SHEET
Spreadsheet::AssignTable(ExcelWorkbookOutput, Congestion, "AK7:IB206","AJ7:AJ206","AK6:IB6", sparse: 1 );

!Spreadsheet::SetActiveSheet( ExcelWorkbookName, ExcelSheetName) ;
Spreadsheet::CloseWorkbook( ExcelWorkbookOutput, 1 ) ;

In the same folder as where the Excel input workbook is stored, the output workbook can now be found, called “ExcelWorkbookOutput”. This file can be used to create tables and figures and to analyze the data, as illustrated in the figure below.
Appendix 15: Parameter values for direct labor costs and truck costs

### Truck costs

<table>
<thead>
<tr>
<th>Truck ID</th>
<th>Truck type</th>
<th>fuel consumption driving</th>
<th>Price (€/unit)</th>
<th>Efficiency charging</th>
<th>Fuel costs (incl. eff.) (€/unit)</th>
<th>Costs x costs, (€/h)</th>
<th>c truck (€/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sources:
- a) www.jungheinrich.com
- b) date finance (Hans Gedeon)
- c) datasheet Maintenance (Manz Schröjan)
- d) http://wiki.etronics.com/index.php/LiFePo4_Lithium_Ion_Battery_Applications

### Direct labor costs

<table>
<thead>
<tr>
<th>Truck operator costs</th>
<th>Net working hours</th>
<th>Net operator costs</th>
<th>c op</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
## Specifications for Storage FR core in Racks.

<table>
<thead>
<tr>
<th>Description</th>
<th>IF</th>
<th>SF</th>
<th>EF</th>
<th>FF</th>
<th>FF/FF</th>
<th>ZF</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pallet Size length (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Pallet Size width (mm)</td>
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<tr>
<td>Pallet height inclusive pallet max. (mm)</td>
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<td></td>
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<td></td>
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<tr>
<td>Max. Pallet Weight (Kg)</td>
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<td></td>
<td></td>
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<tr>
<td>max. bending (mm)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Entrance height (Uitrijtuimte hoogte) (mm)</td>
<td></td>
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<tr>
<td>Entrance length (Uitrijtuimte lengte) 2x 200(mm)</td>
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<tr>
<td>Location Width (mm)</td>
<td></td>
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<tr>
<td>Location Height (mm)</td>
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<tr>
<td>Location Depth (mm)</td>
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<tr>
<td>Number of required locations**</td>
<td></td>
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<tr>
<td>Size standard (mm)</td>
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<td></td>
</tr>
<tr>
<td>Size Beam (ligger) (mm)</td>
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<tr>
<td>Number of locations in height</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Needed Length racks (Lopende meters)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Surface Racks: (m2)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Surface for forklift (m2)</td>
<td></td>
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<tr>
<td>Total surface (m2)**</td>
<td></td>
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<tr>
<td>Load per store (Kg)</td>
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<td></td>
</tr>
<tr>
<td>Max. lift height current forklift***</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Width aisle (gangpad) current forklift (mm)</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
### Appendix 17: Amount of core material needed on stock

<table>
<thead>
<tr>
<th></th>
<th>2012 Aantal pallets</th>
<th>2013 Aantal pallets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hars Formaat Kleur</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gemiddeld op voorraad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totaal verbruik</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Procentuele afname</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gemiddeld op voorraad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximaal op voorraad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voorraad druksto week</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totaal verbruik</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Procentuele afname</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- For FR geimpregneerd Kraft
- Non-FR geimpregneerd Kraft
- Geimpregneerd Kraft
Appendix 18: Use of all core material types, sorted by decreasing pallets/capacity

<table>
<thead>
<tr>
<th>Type</th>
<th>Resin</th>
<th>Size</th>
<th># Pallets</th>
<th>Capacity truck</th>
<th># Pallets/Cap</th>
</tr>
</thead>
</table>