MASTER

Capacitated lot sizing in a dynamic make-to-order production environment with practical inventory restrictions on warehouses

Coppens, T.M.M.

Award date:
2013

Eindhoven, September 2013

Capacitated lot sizing in a dynamic make-to-order production environment with practical inventory restrictions on warehouses

By Tim Coppens

BSc Mechanical Engineering, 2010
Student identity number 0617684

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
Bart Fredrix MSc, DAF Trucks N.V.
Remco Evers MSc, DAF Trucks N.V.
Dr. ir. H.P.G. van Ooijen, TU/e, OPAC
Dr. ir. N.P. Dellaert, TU/e, OPAC

TUE. School of Industrial Engineering.
Series Master Thesis Operations Management and Logistics

Subject headings: dynamic lot sizing, make-to-order, job shop environment, multi-items, capacitated machines, limited warehouse capacity, inventory bounds

Abstract

This master thesis project describes the decision making process of lot sizes in a dynamic capacitated production environment with inventory restrictions in warehouses. In literature and practice, both the terms lot sizing and batch sizing are used to define the quantity to put in an order. In this master thesis, only the term lot sizing is used to prevent confusion in further reading and enable comprehensibility of the report.

Every manufacturing company is confronted with the problem of finding the most economic order quantity to manufacture. This is caused by the fact that almost every production process can only start after the required resources have been set up. This setup process usually requires significant setup time and therefore setup costs. As a consequence, a lot size decision arises because management has to make decisions on a tactical level about whether future demand has to be produced on stock to save setups. This lot size decision dates back to the early twentieth century and is still a general problem that plays an important role in the global market of today challenged by balancing low production cost and low inventory cost.

Most problems have to deal with practical constraints which are also the case in this master thesis. The research is done within a company; the Sheet Metal Component Plant of DAF Trucks N.V. located in Eindhoven. DAF produces light, medium and heavy trucks. The market of trucks is a dynamic market. This behaviour is leading in the upstream supply chain and plays a key role in the decision making process of production lots. The Sheet Metal Component Plant has capacitated resources; machines and warehouses have constraints. These practical issues are considered as input for this project and will be incorporated in the decision making process of lot sizes in this study.

The aim of this study is to get insights in the decision making process of determining appropriate lots in a make-to-order production environment which result in acceptable due date performance without incurring excessive inventory in the warehouses.

Preface

The report you are reading is the result of my graduation project at the logistic department of the Sheet Metal Component Plant within DAF Trucks N.V. in Eindhoven. This master thesis is the final requirement of the study Operations Management and Logistics at the Eindhoven University of Technology (TU/e). The research focuses on lot size decisions in a dynamic make-to-order production environment with practical restrictions on inventory in warehouses.

In August 2012 Bart Fredrix and Remco Evers hired me as a graduation student at DAF Trucks N.V. The first four months I did my literature study parallel with some experience days at different production departments in the Sheet Metal Component Plant within DAF. These days were very useful to get experienced with the practical relevance of the problem under study; I want to thank the people who guided me through the departments these days.

I want to thank my company supervisors Bart and Remco for giving me the opportunity to do my master thesis within DAF Trucks and for their daily guidance and support during the project. Next to the people of DAF, I want to thank my first supervisor Henny van Ooijen for his academic support and his high availability for feedback. Also a word of thanks goes to my second supervisor Nico Dellaert for his critical feedback and advice during the project.

At the end of this acknowledgement, I would like to thank my family and friends. Special thank goes to my parents who gave me full support during my whole study. I want to thank them for given me the opportunity to let me explore my talent and the support to finish this study.

I hope you will enjoy reading this master thesis,

Tim Coppens
Eindhoven, the Netherlands
September 2013

Management summary

This master thesis extends research on the capacitated lot sizing problem in a dynamic make-to-order production environment with practical inventory restrictions on warehouses. We have analysed the production environment of a Truck manufacturer and came up with an algorithm to determine economical lot sizes. This algorithm is tested with a case study and its performance is analysed in detail.

Problem introduction

Every manufacturing company is confronted with the problem of finding the most economical quantity to manufacture in putting through an order (Harris, 1913). This is caused by the fact that almost every production process can only start after the required resources have been set up. This setup usually requires a setup time and/or causes setup costs. As a consequence, a lot sizing problem arises because management has to make decisions on a tactical level about whether future demand has to be produced to stock to save setups.

However in many practical applications, multiple items do not only compete for manufacturing capacities but also compete for storage prior to or after manufacturing. This main gap found in literature is the general research opportunity for this research. The research assignment for this master thesis is defined as: *Develop a lot size supporting tool that minimizes the relevant operational costs with the following company characteristics taking into account:*

- *Complex job shop environment;*
- *Capacitated machines;*
- *Capacity restrictions on warehouses;*
- *Significant setup times.*

The lot size supporting tool is in the first place developed for the Press Shop department of the Sheet Metal Component Plant within DAF Trucks N.V. The developed model specifically aims in providing insights in the decision making process of lot sizes. Therefore the main research question is formulated as:

"How can manufacturing companies determine the optimal lot size for multiple items that minimizes the operational costs in a capacitated production environment with inventory restrictions and relevant product characteristics taken into account?"

Research approach

The methodology used is based on the regulative cycle of van Strien (1997). The first three steps of the regulative cycle are executed in this master thesis: problem definition, analysis & diagnosis and plan of action. Based on the problem definition as summarised above in combination with a detailed analysis of the products and processes, a conceptual model is developed. The model incorporates both restrictions on machines and warehouses. The calculation method is mathematical optimization based on the selection of a best element taken from a set of available alternatives. The elements are calculated with a developed cost function. The cost function is based on a trade-off between fixed costs per lot and inventory holding costs in the warehouses.

The fixed costs are the setup costs per lot, independent of the size of the replenishment. Fixed costs include total machine setup time, logistic activities like transportation and the administration cost of the lot to their related warehouses. The inventory holding costs include the opportunity cost of the money invested (interest), the cost of deterioration (risk) and the cost of the physical storage in warehouses (space).

The solution state space for all combinations of lot sizes within our context is NP-hard, therefore the solution space is restricted by four restrictions:

- The optimal solution without restrictions, the Silver Meal heuristic.
- Restriction on a set of machines regarding available capacity.
- Restrictions on one warehouse or a set of warehouses regarding available storage space.
- Restriction on a maximum lot size to guarantee flexibility of the process.

In order to provide insights in the decision making process of lot sizes in a make-to-order production environment, complete enumeration is used. The developed approach consists of the following four steps:

- Step 1: initial solution with a lot for lot rule, starting point of the procedure.
- Step 2: making the schedule feasible regarding machine capacity.
- Step 3: optimization process of the whole production schedule.
- Step 4: practical roundup procedure by model user.

The output of step 3 is the final output of the theoretical model. The output of the developed decision tool is a suggestion for a production schedule. This production schedule contains dynamic production lots on different time periods.

Results

The performance of the model is tested with a case study within DAF Trucks N.V. All results are compared with the solutions produced by the central system within the company. The Key Performance Indicators (KPI's) used to measure the performance of the developed model are separated in three groups; KPI's for the 9 stamping machines, KPI's for the 5 warehouses and KPI's based on operational costs. Four simulation runs are executed; first a run for the optimized lot sizes with bounded machine capacity. This run shows a decrease in the average machine utilization (-6%) as well as the setup part of the utilization rate (-7%). Therefore the average lot size of the machines increases with on average 1,3 hour. The average utilization of the warehouses also decreases with the optimized solution (-50 m^3). This double sided positive effect is the contribution of the item level analysis and optimization tool. Finally the operational costs significantly decrease with 26%.

To increase the flexibility of the process a maximum lot size of 12 hours is introduced. The average utilization rate of the machines increases for 2 machines with on average 4%. The occupation rate regarding setups increases for 6 machines with on average 3%. The positive effect of the maximum lot size is the decrease of the average lot sizes on different machines (-0,5 hour). The logical consequence of smaller lot sizes is a decrease in warehouse utilization with 5%. The introduction of a maximum lot size of 12 hours results in a 6.7% increase in total operational costs compared to simulation 1.

The third simulation run is executed with practical capacity constraints on warehouses. The average utilization rate of the machines increases on average with 2% as well as the occupation rate regarding setups (4%). The utilization rate in warehouses significantly decreases with 16%. The introduction of practical capacity constraints in warehouses results in our case study to a 10.4% increase in operational costs in comparison with the uncapacitated solution (simulation run 1). Finally the model is run with both constraints, the operational costs decrease with 19.3% compared to the solution of the central system.

Two sensitivity analyses are conducted (with both restrictions) to test the robustness of the developed model. When multiplying the holding cost component space ($€/\text{m}^3$) with a factor 2, the total cost function shows a sensitivity of 3% which is a small deviation. On the other hand, an increase of the demand rate with 20% leads to a 101.2% increase in operational cost. After correction of the correlated demand costs, the model is sensitive for this demand increase.

Conclusions and recommendations

The developed model performs better on all KPI's than the control parameters of the main system of DAF Trucks N.V. The optimized lot sizes deviate a lot from the current situation. Some conclusions can be drawn based on the findings of the case study:

- Taking relevant product characteristics into account results in a significant better lot sizing procedure.
- Both a maximum lot size as well as capacity constraints on warehouses lead to an increase in operational costs. However the problem becomes more practical and therefore has more usability for practical situations.
- Some important points need to be done before the implementation of the decision tool can be started within the operational planning process.

Some practical recommendations are:

- Small research on the accuracy of the demand data is needed. This is useful data to make a decision on the frequency of the runs during the planning period.
- Run more scenarios to get a better impression of the introduced restrictions; these scenarios could consist of predefined workforce schedules, incorporating preventive maintenance schedules and incorporating flexible warehouse capacity in the model to further investigate the effect of sizing storage availability.
- Based on the results of the practical validation phase, first implement the decision tool based on the calculated decision variables in the main system of DAF Trucks N.V. After this process, investigate the possibilities for the design of a standalone software package.
- Start a research project to sequence dependent setup times within the Press Shop, this is essential to succeed in practice with the developed model.
- Finally, make somebody responsible for the model. To succeed this project the model has to be owned by, or committed to, a person who strives for final implementation.

Theoretical contribution

The main theoretical contribution of this research is a contribution to the literature that incorporates warehouses in the decision making process of lot sizes in a make-to-order production environment. In many practical applications, multiple items do not only compete for manufacturing capacities related to machines but in addition for limits on available inventory in the warehouses in the manufacturing supply chain. Furthermore in the literature of capacitated lot sizing with limited storage capacity, items are taken as Stock Keeping Units (SKU's), so limits on inventory are calculated with integer numbers instead of the physical volumes of items. In this research, an extensive analysis is conducted where the physical volume of items is taken into account in the decision making process. The results presented in this research bring the problem scenario more realistic to the dynamic manufacturing environment of today.

List of abbreviations

TU/e	Eindhoven University of Technology
1LO	Warehouse for unpainted items
1MW	Warehouse for painted items (internal)
2MW	Warehouse for painted items (external)
1TO	internal stock point for items which have to be transported to other companies
1SM	Internal stock within the Sheet Metal Component Plant for relatively small items
5WF	Internal stock in the Truck Factory
BPoU	Best Point of Use
EOQ	Economic Order Quantity
EP	Engine Plant
FOP	Fabricage Order Besturing
CLSP	Capacitated Lot Sizing Problem
MRP	Material Requirements Planning
OLS	Paint shop
PPS	Paccar Production System
SOP	Standard Operations Procedure
SMCP	Sheet Metal Component Plant
TPS	Toyota Production System
TF	Truck Factory
WIP	Work In Progress
OFTF	Order-Fill-Time-Fence
SKU	Stock Keeping Unit
VC	Variability Coefficient
KPI	Key Performance Indicator
L4L	Lot for Lot decision rule

Contents

1. Introduction

This chapter starts with a short description of DAF Trucks N.V. in section 1.1. Section 1.2 describes the used production philosophy which plays a key role in today's manufacturing environment. The general supply chain within DAF Trucks is discussed in section 1.2.1. Next the department under study, the Sheet Metal Component Plant, is introduced in section 1.3. The environment in general and the role of the warehouses within the company in specific, which are input in this study, are shortly explained in respectively section 1.3.1 and 1.3.2. Finally the report outline is introduced in section 1.4.

1.1 DAF Trucks N.V.

DAF Trucks N.V. is one of the largest producers of heavy trucks in the world (DAF, 2013). The company was founded in 1928 by two brothers; Hub and Wim van Doorne. After several years of manufacturing truck trailers, the production of trucks started in 1949. The company name was changed to "Van Doorne's Automobiel Fabriek", also cars were produced by this renamed company. In 1975 the company was sold to Volvo and the production of DAF cars ended. In 1996, DAF was acquired by the North American Cooperation Paccar Inc. Paccar Inc. is a holding company of several truck manufacturers of light, medium and heavy trucks under the Kenworth, Peterbilt and DAF brands.

The head office of DAF is located in Eindhoven. Approximately 8.000 employees are working within DAF which generated total revenue of 3.6 billion euro over 2012. The core activities of DAF Eindhoven are focused on the development, production, marketing and sales of medium and heavy-duty commercial vehicles (DAF, 2013). The production facilities of DAF N.V. are located in Eindhoven, Westerlo (Belgium) and Leyland (United Kingdom). The axles and cabins are produced in Westerlo. The Engine Plant (EP), the Sheet Metal Component Plant (SMCP) and the Truck Factory Assembly plant (TF) for the medium and heavy type trucks are located in Eindhoven. The assembly plant of the light trucks is located in Leyland.

The product of DAF contains the full range of trucks divided in three main categories; LF-series, CF-series and the XF-series, figure 1. The types LF45 and LF55, produced in Leyland, are the small trucks which are mainly used by customers for city or local transport. The types CF65, CF75 and CF85 are the medium trucks produced by DAF Eindhoven which are mainly used for national transport or for special purposes in for example the construction industry. The DAF XF105 and the XF-euro 6 are the largest trucks in the full range of products DAF offers to its customers. The XF-truck is developed for long distance transport applications and is therefore mainly used for international transport by its customers.

Figure 1 – CF, XF & LF series (from l to r)

The three categories of trucks are divided in seven types. The actual number of different trucks which are produced by the company is more than seven. For every truck, the customer can choose for a broad range of main components like different engines, cabins and axles (Appendix A) in combination with a broad range of options, e.g. air conditioning. This leads to a very broad range of different end-products which DAF offers to the market. The market of medium and heavy-duty commercial vehicles is dynamic and relatively unpredictable nowadays. This is caused by the financial crisis and the competitive market of truck manufacturers.

1.2 Production Philosophy

The broad range of DAF end-products are produced with a make-to-order policy. DAF Trucks N.V. strives to be a lean organization and supports that philosophy with their Paccar Production System (PPS). This system is derived from the well-known Toyota Production System (TPS). The core principle of the system is to maximize the added value by the operator to the production system, called lean material flow. One of the characteristics of the lean material flow is to manage the material flow in such a way that the right materials are delivered in the right quantity at the right time, the One Piece Flow concept is one element which supports this building block. Besides One Piece Flow, Best Point of Use (BPoU) and the Pull System also support the lean concept. These two elements are not directly related to the main topic of this master thesis, therefore both concepts are shortly explained in the list of concepts.

One piece flow literally means a lot size of one. This should be considered as an ultimate purpose. The two main goals of the one-piece flow philosophy within DAF are:

- Each individual product must move individually and as fast as possible through the entire production process / supply chain.
- Creating and maintaining a continuous flow of supply of materials.

The characteristics of the one piece flow concept are:

- The lot size is as small as possible, when products are produced in lots, buffers arise and this means waiting time (waste in the lean literature).
- Low or no setup times.
- Reducing the lot size, or even proceed to produce in a pure one piece flow, requires a certain degree of predictability of the process and the constant availability of staff, machinery, materials and methods.
- Cycle times of the operations are derived from customer demand.

1.2.1 Supply chain of DAF Trucks N.V.

The supply chain of DAF Trucks Eindhoven consists of a Sheet Metal Component Plant (SMCP), external suppliers, a paint shop with two warehouses for unpainted (1LO) and painted (1MW) parts, a central warehouse (2MW) and an assembly plant (TF), figure 2. The flow of goods occurs as follows; parts are supplied by external suppliers or by internal production in the Sheet Metal Component Plant to the warehouse 1LO. After storage in the warehouse for unpainted parts, the parts are transported to the paint shop for the painting process. After this process, different storage locations are possible; storage in 1MW, storage in 2MW, storage in the central warehouse or direct transportation to the assembly line in the TF. The parts which are stored in the warehouses are transported to the assembly plant TF triggered on their line demand. Parts which are stored in the central warehouse for external transport are transported to a DAF company for a subassembly process or a third party for further processing of a DAF item.

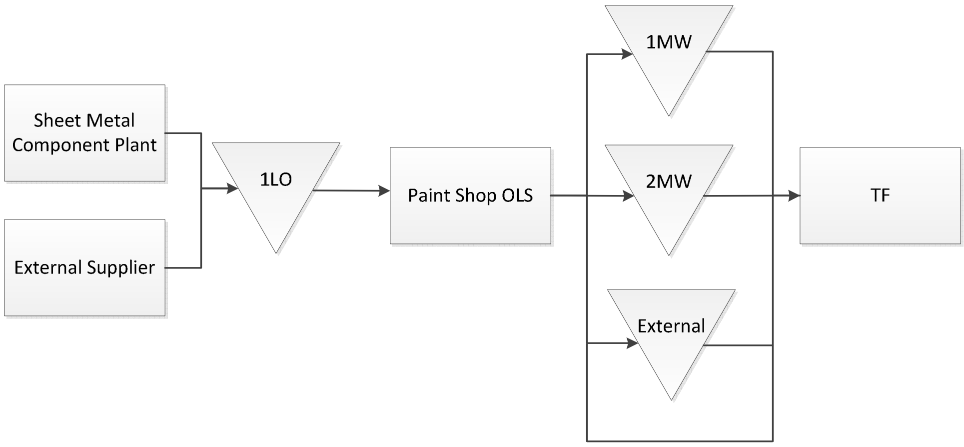

Figure 2 – Schematic overview supply chain DAF Trucks Eindhoven

The one-piece-flow philosophy as described in the previous section cannot be realized in practice. The production stages in the supply chain have significant setup times which necessitate production lots. The one-piece-flow philosophy on the one hand and the lot sizes due to significant setups on the other hand are competing phenomena's. Managers have to make a trade-off between both concepts, this trade-off is the main problem area in this master thesis project.

The focus of this research will be on the manufacturing facilities located in Eindhoven, the starting point of this study is the Sheet Metal Component Plant. This stage is the most upstream production stage in the supply chain of DAF Eindhoven, figure 2. The reason for this starting point is based on earlier conducted research within DAF which is further explained in the problem definition in section 3.1. The Sheet Metal Component Plant and the characteristics of the different warehouses will be explained in next section.

1.3 Sheet Metal Component Plant

The Sheet Metal Component Plant (SMCP) is an internal supplier of DAF Trucks N.V. This plant manufactures a broad range of metal parts and components for the total range of trucks as described in section 1.1. The SMCP is organized as a functional complex job shop environment which incorporates several departments that are shortly explained in this section. There is a high variety in the mix of parts which flow through the plant in a sequence over different department(s). The different departments are mainly separated by the characteristics of their products, machines, demands and production techniques. The departments within the SMCP with their basic characteristics are shortly described.

Welding department; this department consists of several welding robots in combinations with several welding boxes where different types of products are made. The welding robots mainly produce large series while the welding boxes are more flexible and are able to produce different products in different series. Setup times play a significant role when a change-over takes place between different products.

Chassis parts department; this department is the largest department regarding internal deliveries within the plant. For a lot of items, the routing starts in this department. The machinery consists of a diverse scale of production machines; for example punching, cutting, laser cutting and bending machines. The demand variety is high as well as the variety in current lot sizes between these products.

Press shop; this department consist of three large stamping machines (figure 3) added up to a diverse scale of small stamping units. These machines are mainly characterized by high setup times and therefore produce relative large lots compared to other departments.

Bending department; this department produces all kind of products which have pipe as raw material, the used production techniques are sawing, bending and other pipe manufacturing production techniques. These machines are also characterized by relatively high setup times.

"NVP" department; this department is a special department based on their yearly demand. Items with significant low demand have no tools available for "automated production". The products made within this department are very broad and setup times are very relevant because of the absence of these production tools.

The side rail production department and the "*Paint shop"* which is decoupled in the supply chain with a stock point 1LO, see figure 2, are outside the scope of this research. The total scope of this research project is further elaborated in chapter 2.

Figure 3 – Stamping machine SMCP

1.3.1 Environment/demand

The SMCP is exposed to dynamic demand; the make-to-order production policy is the main reason for this. This lean element is one of the most important principles of the DAF strategy (DAF, 2013). The demand can further be characterized by a very broad range of products which are primarily planned by the MRP planning system of the company. These products are part of an ordered truck as described in section 1.1. Due to the high item variety and dynamic demand, items are typically divided in three categories by the internal customer (Truck Factory).

- A-items > 60% of the yearly demand (fast movers)
- B-items > 10% and < 60% of the yearly demand (moderate movers)
- C-items < 10% of the yearly demand (slow movers)

The criterion for this classification is based on the frequency used over the yearly demand and the available space at the assembly line. Due to the limited floor space, the lot sizes in the TF are restricted to a maximum. Besides the variety in demand, the products also differ in their volume, setup time and the unit price which is relevant input for this study. Classifications based on these characteristics are not present within DAF Trucks. Demand needs to be further explained and analyzed to make an appropriate assumption in the modelling phase. A complete analysis is done in chapter 3 of this report.

1.3.2 Warehouses

As already described in section 1.2.1, the internal supply chain of DAF (figure 2) contains several stock points; the warehouse for unpainted items (1LO), the warehouse for painted items for internal use (1MW), the warehouse for painted items for external use (2MW) and for completeness the central warehouse for external companies. These external companies are suppliers of DAF and deliver their items to the paint shop for the painting process. The flow of these items is not related to the lot sizing problem in the SMCP and therefore outside the scope of this study. Within the SMCP, routings are decoupled by internal stock points, "Supermarkets", as already mentioned in section 1.2.1. Further explanation of the warehouse is needed because this is one of the restrictions incorporated in the model.

In short, SMCP can be described as a company with the following characteristics:

- Complex job shop environment.
- Many different types of departments with a diverse range of machinery.
- Many different routings for a very broad range of products.
- Production units and departments are decoupled by internal and external stock points.

1.4 Report Outline

The structure of this report is based on the conceptual model of problem solving in organisations (van Strien, 1997). The structure of this model is further explained in section 2.5 of this report. The remainder of this report is structured as follows: Chapter 2 describes the research project. Subsequently the problem context, the literature and the gaps around this subject are discussed and the research assignment is presented. Furthermore, the scope and the boundary conditions of the research are elaborate on in this chapter. In chapter 3 a detailed process analysis is made including a cost analysis of the process. In chapter 4 the mathematical models that are used to solve the problem for this study are explained and verified. In chapter 5 the models are combined and the conceptual model is elaborated. The developed model is tested with a case study within DAF Trucks N.V. The results of this case study are presented in chapter 6. In chapter 7 the implementation plan of the developed model is given. Finally in chapter 8 the conclusions of this study are given accompanied with practical recommendations and the theoretical contribution with opportunities for further research.

2. Research project

In this chapter the research project is discussed. In section 2.1 the problem context is given based on earlier conducted research within the DAF supply chain. The existing literature in the research area of capacitated lot sizing followed by the found gaps is elaborated in section 2.2. In section 2.3 the problem definition for this research is elaborated followed by the research assignment, which will be the core of the to-be-performed master thesis project. Section 2.4 contains the general research question supported with five sub questions. Section 2.5 describes the used project approach. Finally the research scope and the boundaries are elaborated in section 2.6.

2.1 Problem context

As already mentioned in the introduction, earlier research about lot sizes within DAF N.V. is conducted; “Lot Size Decisions in the DAF Supply Chain” (Grolleman, 2012). The author of this project has investigated what lot size per location (stage) in the supply chain minimizes the total supply chain costs. The authors’ lot size perspective was Truck Factory (TF) oriented with the important assumption that the available space for inventory at the assembly line is limited. Therefore this assumption is considered as a hard constraint which has significant influence on the upstream echelons in the supply chain. Besides this hard constraint, the author made more important assumptions which have significant impact on the practical relevance of the obtained results within DAF N.V. and in specially for the SMCP:

- The job shop environment of the SMCP is complex and considered as a black box, therefore only machine setup activities are taken into account.
- These machine setup activities (logistic activities) are independent of the lot size.
- The machine capacities are not taken into account.
- There are no limits on capacity in the warehouses.
- The products do not have a maximum sojourn time in the warehouses.

The author selected 145 items from in total more than 10.000 items based on their product characteristics; demand categories, high variety in machine setup times and a variety in item prices. The author did a simulation study for these 145 items and concluded that the optimized lot size, that result in the minimum total supply chain costs, is on average a factor 3.7 higher for the SMCP and a factor 2.3 higher for the paint shop OLS compared to the current applied lot size based on 125 of the 145 items simulated. This results in greater lots in the SMCP and storing inventory more upstream in the supply chain (stock point 1LO in figure 2). For the remaining 20 items, which are characterized as slow moving items (section 1.4.1), the optimized solution fulfilled the maximum lot size constraint in the assembly TF.

The author made the recommendation that the SMCP should start a setup time reduction project in the SMCP in order to reduce costs and to produce the current lot sizes more economically. These high setup times are prevalent in combination with the practical restrictions on machines and warehouses; further investigation of the decision variables, lot sizes, within the Sheet Metal Component Plant is needed and therefore an opportunity for further research within the company under study. The next section describes the existing literature in the problem area of capacitated lot sizing with inventory bounds.

2.2 Literature

In literature, batch sizes are often described as lot sizes. Because of the scientific focus of this project, the term lot size is further used in this report. In this section, a short summary of the capacitated lot sizing literature is described.

Most literature starts with classifying the lot sizing problem based on different features which are taken into account. The first important characteristic is the nature of demand experienced by the company. If the demand pattern is known over time, the demand is defined as deterministic demand otherwise defined as stochastic probabilistic demand. Besides the nature of the demand, the lot sizing problem depends on the following features (Karime et al, 2003): the length of the planning horizon in combination with the size of the time bucket, the number of end items or final products, the number of levels of the products, the capacity and resource constraints taken into account, the setup structure and finally if inventory shortage is allowed in the manufacturing environment.

After characterizing the lot sizing problem, different variants of the lot sizing problem can be described (figure 4). The coordinated capacitated lot sizing problem is the most general problem class considering multiple items, product family, setup cost per item and the existence of capacity limitations on the maximum number of items that can be replenished in a time period. Relaxing the capacity constraints, the joint setup structure and limiting the number of items to one result in the uncapacitated lot sizing problem (ULSP). The ULSP is often related to the well-known EOQ formula from Camp (1913) according to the similarities in assumptions made. This uncapacitated problem is very often used and solved as a sub system in several algorithms or heuristics for more complex lot sizing problems; in our case the capacitated dynamic lot sizing problem (CLSP).

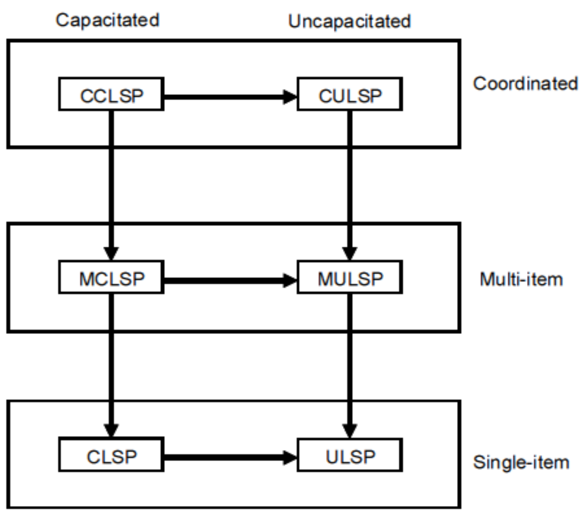

Figure 4 – Taxonomy of deterministic dynamic demand lot-sizing problems (Robinson, 2009)

The CLSP deals with the problem of determining time phased production quantities that meet both customer demand and the given capacity limits of the production system. The CLSP is called a large bucket problem because several items can be produced per period; the problem is often represented as a LP problem. Solving this problem optimally suffers from the NP-hardness property and therefore many authors have developed heuristics to cope with this. These approaches are based on the features taken into account as described in the beginning of this section. The problem which matches with the problem context is based on multi-item, single level, capacitated, dynamic lot sizing with setup times. In literature, setups are both treated as a cost aspect as well as a time component. There is a difference between both approaches regarding the problem formulation for the coordinated lot sizing problem (joint setup structure). Setup costs are stated in the objective function while setup times are related to the capacity constraints of the production facility which makes the capacity constraint nonlinear (Coppens, 2013). This issue is also the case in our research and shall further be explained in the remaining report.

Another important topic addressed in literature is the role of warehouses in the supply chain within companies (Lee et al., 2012). One of the major factors that influences storage sizing is certainly the storage assignment policy that defines the method of assigning items to storage locations. Frequently used policies in industry are randomized storage, dedicated storage and class based storage. In random storage, all items correspond to one class and may be assigned to any location in the warehouse. In the case of dedicated storage, it is more convenient for facilities where data-sharing is a problem. In this strategy different zones are set for each specified product type. Class-based storage use rates of return of items by using cube-per-order indexes which is the ratio of an item's ending-period inventory relative to its demand. Studies considering storage policy in limited storage capacity environments are scarce.

The last aspect considered in this section is the constraint on the on-hand inventory in warehouses in combination with the capacitated lot sizing problem (Atamtürk et al., 2005). This limited warehouse capacity is a direct outcome of an adapted storage allocation policy in warehouse activities as described in the previous paragraph. The papers presented in this literature research address different approaches for solving both problems. In the paper of Iris and Yenisey (2012) an algorithm is presented which is able to simultaneously solve the lot sizing and pre-defined storage allocation problem. The used allocation policies are the described policies in the previous paragraph. Most assumptions made by the author are quite logical except two important remarks; first the single-level product structure does not require setup time as an individual parameter in the algorithm because, setup times are incorporated into unit processing times. With this remark the author made the assumption that setup times are independent of the batch size. Second assumption, items are taken as Stock Keeping Units (SKU's) and with this real number, limits on inventories are calculated. The physical volume of items, which is very relevant in some industries, is not taken into account. This paper and the questionable assumptions are the starting point of the master thesis project. The shortcoming of this research will further be explained in chapter 4 of this report.

The above described research area is relatively young and, from an application point of view, mainly treated independently. However in many practical applications, multiple items do not only compete for manufacturing capacities but also compete for storage prior to or after manufacturing. This main gap found in literature is the general research opportunity for further research. Future work on this topic should be aimed at considering more warehouse constraints to bring the problem scenario more realistic to the dynamic manufacturing environment. The more specific gaps found in the conducted literature study (Coppens, 2013) are:

- Capacitated lot sizing problem (CLSP) with single-family or multi-family joint setup structure.
- CLSP in combination with a storage allocation policy in limited storage environments.
- In the CLSP research, setup times are often incorporated into unit processing times. This questionable assumption is the third research opportunity in combination with a storage allocation policy.
- In the research of CLSP with limited storage capacity, items are always taken as Stock Keeping Units (SKU's), so limits on inventory are calculated with integer numbers instead of the physical volume of items. This questionable assumption is the fourth research opportunity.
- In literature, it is assumed in literature that interdependencies between costs for individual products do not exist, this is the fifth interesting topic for further research.

2.3 Research assignment

As described in the problem context, within the company under study high setup times are prevalent in combination with the practical restrictions on machines and inventory. This problem context matches first with the main gap found in the conduced literature study (Coppens, 2013). Second, the more specific gaps: the CLSP in combination with a storage allocation policy in limited storage environments and the assumption that limits on inventory are always calculated with the number of SKU's instead of the physical volumes leads to a research assignment. The general research assignment is formulated as follows:

Develop a lot size supporting tool that minimizes the relevant operational costs with the following company characteristics taking into account:

- *Complex job shop environment.*
- *Capacitated machines.*
- *Capacity restrictions in warehouses.*
- *Significant setup times.*

This assignment refers to the activities that are executed in this master thesis project; these activities are based on several sub assignments which support the research question (next section) and the main assignment as formulated above. These sub assignments are distinguished by practical (relevance) and scientific (rigor) aspects as the master thesis project should encompass both a practical applicability for DAF Trucks N.V. and a scientific applicability for the University of Technology.

2.4 Research question

Because of the important assumptions made in previous research (Grolleman, 2012) followed by the dynamic demand experienced by the company, a research study which shows the relation between the relevant cost variables in the lot size decision process is useful. It is unclear for the decision makers what lot size minimizes the total relevant operational costs within DAF with the relevant restrictions taken into account. This need is strengthened by the introduction of the new Euro 6 truck within the company under study. This new truck raises existing machine utilization and has an impact on the utilization rate of the warehouses in the internal supply chain of DAF. The gap found in literature study (Coppens, 2013) in combination with the problem definition as described in section 2.1 result in the following general research question:

How can manufacturing companies determine the optimal lot size for multiple items that minimizes the operational costs in a capacitated production environment with inventory restrictions and relevant product characteristics taken into account?

The five sub questions which are described below support this main research question. What are the characteristics of the process under study?

1. Which parameters play a role in the decision making process of lots, and what are the characteristics of these input variables within the company under study?
2. What are the relevant cost drivers which influence the lot size decision?
3. What are feasible heuristics that deal with the characteristics found?
4. How can the developed heuristic be incorporated in a decision tool?

5. What is the performance of the decision tool based on relevant KPI's?

2.5 Research methodology

As already mentioned in the introduction of this report, the methodology used within this project is based on the regulative cycle of van Strien (1997), which is extensively discussed in van Aken, Berends & van Bij (2007), the regulative cycle is depicted in figure 5. The regulative cycle has five basic process steps; problem definition, analysis and diagnosis, plan of action, intervention and evaluation.

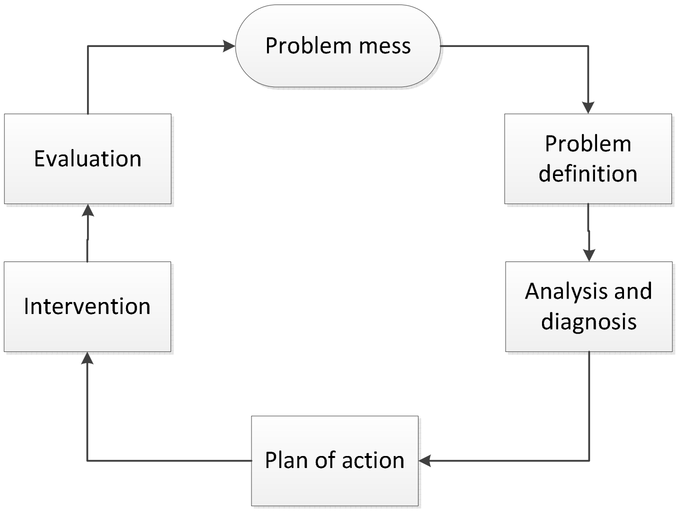

Figure 5 – The Regulative Cycle (van Aken et al. 2007)

The first step, problem definition, is performed in this research proposal as a preparation of the actual master thesis project. The problem definition starts with the initial problem stated by the company i.e. the "problem mess" (figure 5). The definition of the problem should be done in contact with this problem mess and should respect this; noted that the final problem statement can differ from this initial problem statement. In accordance, the project plan and the project approach belong to this first step which is both elaborated in the conducted master thesis proposal (Coppens, 2013).

The next step, analysis and diagnosis, has to be performed. This is the analytical part of the project where most of the traditional business research methods can be applied. This is the first step of the actual master thesis project. The goal of this stage is to create specific knowledge about the nature and the context of the problem (Van Aken et al. 2007), chapter 3 describes the analysis and diagnosis step of this research.

The third step in this master thesis project and the final step is the plan of action step. The goal of this step is to design the solution for the defined problem (chapter 5) and a corresponding change plan for implementation of this solution (chapter 7). According to Van Aken et al. (2007) the designer can use valid knowledge in this design phase, however field-tested and grounded technological support is the most powerful support. Ideally the proposed solution should become apparent by a systematic review of the literature within the field, which has already been done in the preparation phase for this master thesis project, summary of this literature study is given in section 2.2 of this chapter.

As already mentioned, the complete intervention and evaluation step of the regulative cycle are not performed within this project due to time limitations. However, the developed tool is tested with a case study within DAF Trucks N.V. But the actual performance of the system needs to be monitored and compared to the current situation after the case study, the evaluation step of the regulative cycle. A detailed project approach is given in the appendix B.

2.6 Research scope

Research boundaries are important in order to define the scope of the project. The Sheet Metal Component Plant contains of many departments with department dependent restrictions. Ultimately the goal is to define the boundaries of the research in such a way that the taken scope is representative for the whole factory.

The department under study is the Press Shop as depicted in section 1.3. The indication within the company is that this department is characterized by significant setup times, high demand variation, high variation in volume of items, high variation in price and finally variation in processing times of the manufactured items, these process parameters are further analyzed in chapter 3. These characteristics play a key role in the design of the decision tool. Supply chain optimization regarding clustering due packaging units or round ups on raw materials will be out of the scope of this master thesis project. Research is already done on this topic by Grolleman (2012) and can be used after this research project.

2.6.1 Boundary conditions

Assumptions are important in order to find specific literature that is applicable to the situation of DAF and to make the problem more manageable. The most important assumption made in this research project is that sequence dependent setup times are not incorporated in this research. The data available for this project are corrected for this practical problem with a tool provided by the financial department of DAF Trucks. The details about the sequence dependent setup times and the tool used are stated in appendix C. As investigated in the literature, the coordinated capacitated lot sizing problem is a separate research area and therefore out of the scope of this project.

The following important assumptions are made for this project:

- Infinite source of raw materials; raw materials are supplied by external suppliers with a delivery performance of 100% on the day of production. When some raw material is not present for the process, urgent deliveries are executed.
- Finite planning horizon of 35 days from now, part of the demand is forecasted.
- Each product/item has its known volume, based on their packaging unit and roundup on this packaging unit.
- No restrictions on transport between machines or stock points.
- Machine substitution is not taken into account.
- Down time of machines is not taken into account.
- Flexible workforce regarding machine capacity, i.e. workforce is never limiting on machine capacity.
- Backlogging is not allowed, a stop of the assembly line (the customer of the SMCP) is very costly so backlogging is not permitted under any circumstances.

- All demand will be produced within the SMCP, decisions to outsource demand is not incorporated in the model.

2.6.2 Research restrictions

The research is restricted in the following way:

- Analysis of the process is restricted to one department, the Press Shop.
- The developed model is restricted to one department, the Press Shop.
- Only “make-items” are incorporated in the research. Purchased items are out of scope in this analysis due to the missing lot size information for these items.

The research projected is started with a detailed analysis of the process in the next chapter.

3. Detailed analysis

This section describes the detailed analysis of all relevant aspects of the process under study, being the production process in the Press Shop of the Sheet Metal Component Plant (SMCP). First the characteristics of the products produced within the Press Shop are described and analysed in section 3.1. In section 3.2, the main characteristics of the production process are analysed. These process characteristics are divided in the physical material flow, the information flow through the company, the way of controlling the production process and the current policy regarding lot size determination within the Press Shop. Section 3.4 describes the important characteristics of the warehouses in the supply chain of DAF Trucks N.V. Finally the cost drivers in the production process are described and analysed in section 3.5.

3.1 Product characteristics Press Shop SMCP

The range of products produced within the SMCP is very extensive, more than 15.000 items are produced for the internal customers (Truck Factory, Cabin- and axle plant). Within the project scope, +/- 450 items are produced in the Press Shop. These items vary from different brackets to doors for the cabin of a truck, both depicted in figure 6.

Figure 6 – Example products Press shop, Door (left) and bracket (right)

Each produced item has their unique product characteristics which play a role in the planning process. The following characteristics are analysed in this research:

- Unit processing times of the items.
- Unit setup times of the items.
- Volumes of the items.
- Prices of the items.
- Safety leads times of the items.

In table 1, some general statistical values are shown which are further explained in the next paragraph.

Table 1 – Characteristics item dependent variables

Variable	Average	MIN	MAX	Standard deviation
Unit processing time [periods*]	0,73	0,08	4,3	0,53
Unit setup time [periods*]	210	14	2100	281,8
Unit volume [cm³]	16,7	0,07	117	21,8
Unit price [€]	13,53	0,27	194,7	18,7
Safety lead time [days]	1,1	0	2	0,63

**The unit processing and setup times are in periods, this unit measure is used within the DAF Trucks N.V. 100 periods is equal to 1 hour.*

1. *Unit processing time*

The total unit processing time of an item is the time needed for the production of that item on related machine(s). The processing times of the items for every separate machine are given in appendix J. These processing times are in most cases needed for the capacity calculations. The average total processing time is 0,73 periods which is equal to 27 seconds. The minimum processing time is 3 seconds and the maximum processing time is 3 minutes. The standard deviation is 19 seconds which is quite large in this industry.

2. *Unit setup time*

The unit setup time of an item is the total time needed for the setup process on the machine(s) which is further described in section 3.1.1. There is a distinction made between the setup times needed for the total setup process and the setup times needed for the machine. This machine setup time is the period while the machine is idle. The setup times for every machine are depicted in appendix K with box plots. The average total setup time of an item is 210 periods which is equal to 2:06 hours of work. The maximum total setup time is 21 hours of work; the minimum total setup time is 8 minutes and 40 seconds. The standard deviation is 2 hours and 49 minutes which is quite large.

3. *Unit volume*

The physical volume of the items is another important characteristic which could be incorporated in the lot size decision tool. Especially with the introduction of the warehouse restriction, a measure for this restriction is needed in the design phase. As found in the literature study (Coppens, 2013), the warehouse space is often measured in SKU's (section 2.2). In this master thesis, the measurement of volume of the physical items is introduced. This volume is not present within the company under study and therefore calculated in the following way:

$$Volume\ item\ i = \frac{Volume\ packaging\ unit\ item\ i}{Capacity\ packaging\ unit\ item\ i}$$

The average physical volume of an item in the Press Shop is 16,7 cm^3. The minimum volume is 0,07 cm^3 and the largest item has a volume of 117 cm^3. The standard deviation is 21,8 cm^3.

4. *Unit price*

The unit price of each item is expressed in Euros. The exact unit price of each item is difficult to determine. However one thing is certain; it is seldom the conventional accounting or "book value" assigned by the organisation. The unit value of an item should measure the actual amount of money that has been spent on the unit to make it available for assembly or other purposes. The unit price is important for two reasons. First, the acquisition or production costs per year clearly depend on this value. Second, the cost of carrying an item in inventory depends on the unit price; this shall further be explained in the next section. The unit price within DAF Truck N.V. is calculated by the financial department by incorporating the following cost elements:

- Value of the raw material.

- Fee on the value of the raw material.
- Fee on material expenses.
- Wages.
- Fee on wages.

The average unit price of the items in the Press Shop is € 13,53. The most expensive item has a unit price of € 194,7 and the cheapest item has a price of € 0,27. The standard deviation is € 18,7.

5. *Safety lead time*

The safety lead times of the items is expressed in days. The detailed description of the safety lead times is given in section 3.2.3. The minimum safety lead time is equal to 0 days and the maximum number of days is set to 2. On average items have a safety lead time of 1,1 days in the warehouses.

3.2 Process characteristics Press Shop SMCP

The first step of the process analysis is the flow of goods within DAF Trucks N.V. followed by the flow of goods within the SMCP. The flow of goods can be divided in the Material Management (MM) part and the physical distribution of the items. In this research, the physical distribution of items through the network is first described. This is needed because these activities are lot dependent activities which causes time and therefore costs in the process. The schematic flow of goods on the highest abstract level within DAF Trucks N.V. is already presented in figure 2 in the introduction of this report. The flow of goods within the research scope on intermediate level is described in section 3.2.1.

3.2.1 Physical material flow in the Press Shop

The physical material flow in the Press Shop starts as soon as the production decision is made for an order. The fork lift driver drives to the sheet metal stock point and searches for the needed raw material. These items are transported to the relevant stamping machine and the production process can start. After the production process on a stamping machine, there are two main activities that can be executed:

1. The product is finished and need to be transported to their main stock point.
2. The product is not yet finished and needs a second or third processing step in the Press Shop; the product will be stored in the Press Shop for further processing, being work in progress.

The process under study contains 9 stamping machines; a layout of the factory is depicted in appendix D. The process characteristics of these machines are given in appendix E. All machines have their capacity restriction (number of shifts during the day) which will play a key role in capacity planning. As already mentioned in the previous section, +/- 450 different items are made in the Press Shop. Information about the number of items on the machines and their specific routing is presented in table 2. 72% of the items needs one operation on a machine in the Press Shop, 24% of the items needs two operations on two machines etc. After the processing step(s) 36% of the items are stored in stock point 1SM, 35% in 1TO etc. The description of the five stock points is given section 3.3.

Table 2 – Routing items on machines and warehouses

Routing items machines	
1 machine	72 %
2 machine	24 %
3 machine	3 %
4 machine	2 %

Routing items warehouses	
1SM	36 %
1TO	35 %
1MW	18 %
2MW	7 %
5WF	4 %

As soon as all material is present at the stamping machine, the production of the items can be started. The following activities need to be executed for this process:

1. Setup of the stamping machine, the to-be-used press tool(s) will be removed from the stamping machine and the needed tool(s) needs to be installed.
2. The first product will be made.
3. The produced item has to be measured by the Press Shop employee that is responsible for qualty to guarantee the requirements of the item.
4. Adjust the press tool(s) when the produced item does not match with the requirements.
5. Repeat step 2, 3 and 4 till the product meets the requirements.

These five steps can be named as the setup process which is the main cost driver and therefore the most important reason why lots have to be made for economic reasons. After completion of the above process, the production of the whole lot can start. During the production of the lot, the items are frequently measured to prevent production errors. This process is lot independent and therefore excluded from our research. The 5 steps of the process are schematically depicted in the figure 7.

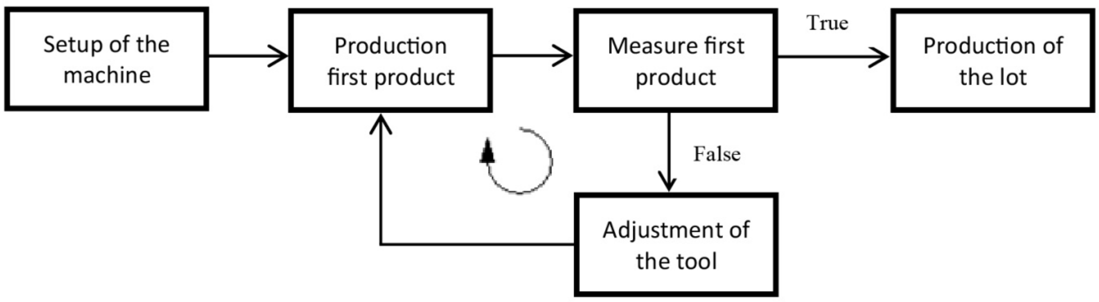

Figure 7 – The setup process in the Press Shop

There are a lot of different items with a unique routing through the production network. This lead to a complex system for determining economical lot sizes. The schematic flow of goods is depicted in figure 8. After the detailed analysis of the material flow, the information flow of de Press Shop can be analyzed.

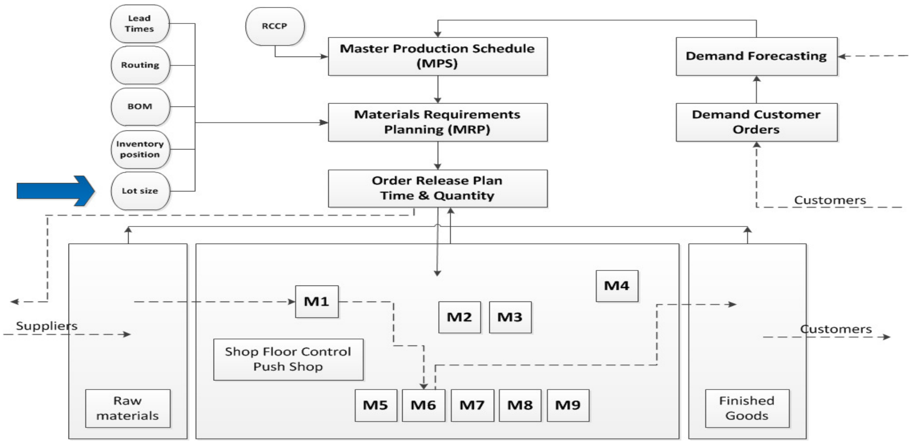

Figure 8 – Routing information and material flow Press Shop department

3.2.2 Information flow in the Press Shop

The main information flow which is an important factor for this research is the sales information from customers and dealers, figure 8. Based on this sales information, the marketing and sales department is able to give input for a production plan for the Press Shop that is based on both actual sales as well as forecasted sales. This information is given to Business Logistic Department (BLD) which is able to make the conceptual production plan. In cooperation with Material Management (MM), the Master Production Schedule (MPS) can be developed for the coming periods. To be able to control the internal and external suppliers, the MPS is exploded to the Material Requirement Planning (MRP). This MRP gives the net demand on item level per time bucket for each internal or external supplier. The Press Shop uses this net demand for their production plan for the upcoming periods. This information is available on a daily basis within the whole company by downloads from the central system. This is relevant information in the design phase of the project.

DAF Trucks N.V. aims to deliver a sold truck within six weeks (internal delivery time). Six weeks before delivery, the planning of that order will be "frozen" within the time horizon. From this moment only sold trucks are in the MPS. This point in time is called the Order-Fill-Time-Fence (OFTF). Within this period, trucks are completely assembled on order as described in section 1.3.

3.2.3 Control of the Press Shop

The way of controlling a department or company determines the efficiency of the production unit. The Press Shop department is controlled by a "fob order" system. Controlling based on this system results in some orders which have to be produced within a time bucket. The next machine or department has also some time period to do the next processing of that order till it is finished and in most of the cases ready to put on inventory in the warehouse or transported to another factory in the DAF Supply chain. Hence the production department on the floor has some flexibility within that time bucket to decide about the sequence of the orders. The throughput time in production is the sum of all those time periods. In figure 9, a schematic throughput time schedule is given to increase the understanding of this process.

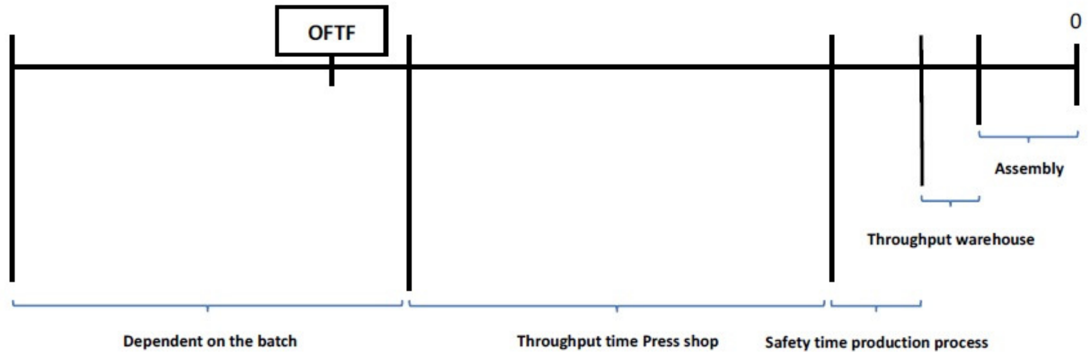

Figure 9 – General time schedule production process

Besides the production throughput time, there are some more throughput times to control the system for process activities and their uncertainties;

- Administration throughput time; when an order is finished, it will be send to their main stock point where the batch is administrated in the warehouse system to control the inventory position of all items.
- Warehouse throughput time; when the item is needed for assembly, the order will be picked by a fork lift driver for further processing in the supply chain. In this throughput time, the safety stock is incorporated to control for uncertainty in that processes.
- Extra setup throughput time; this time is needed when the setup process is subject to significant uncertainty.
- Extra processing throughput time; this time is needed when the processing of items is subjected to significant uncertainty.
- External throughput time; when the routing of an order incorporates an external supplier who has to do one or more operations. This leads to uncertainty in the supply chain which can be controlled by this external throughput time.

This kind of throughput times is named as safety lead time in literature. The most important safety lead times in this research are the times which are dependent on the lot size and have significant influence on the restrictions of the model. None of these throughput times (excluding production throughput time) is dependent on the lot itself. The warehouse throughput time has significant influence on the used capacity in the warehouses. A figure of the occupation rate is shown in appendix F. The way of determining these safety lead times in the warehouses is depicted in appendix G.

3.2.4 Current policy regarding lot sizing SMCP

The Press Shop department is able to get information from the ERP software (central system) to control their main production processes. In this ERP system, all demand is available and visible for already sold and forecasted demand (3.2.2). The material planner is able to get the net demand from the Requirements Planning System (RPS). The software shows a lot suggestion based on the control parameters set in the system. These control parameters are introduced to determine the lot size on item level; a screenshot of the screen is depicted in appendix H. The following control parameters for lot size determination are relevant for this research:

- Number of days over the rolling planning horizon which determines the exact lot size in units.
- Roundup of the lot size in units based on the size of sheet metal.

- Roundup of the lot size in units based on the size of the packaging unit (example packaging unit in section 3.3).

In most cases, the material planners determine their "own" lot size with the control parameters in the system based on their experience. As soon as there is some response from the production department, this lot size might be changed by changing the parameters. The performance of the material planners is not based on throughput time but mainly on availability of their products. This is therefore leading in determining their lot sizes. No clear Standard Operations Procedure (SOP) is available. In general the planners must strive for high reliability with a low cost perspective.

3.3 Role of the warehouse in the supply chain

As already mentioned in the introduction of this report, the supply chain of DAF contains several stock points. As noted in literature, the efficiency and effectiveness in any distribution network is largely determined by the operations of the nodes in such a network (Lee et al., 2012). In general, the role of the warehouse in the supply chain can fulfil two functions; the first and most common function is a control function (used for example as replenishment function) for the supply of goods downstream the supply chain. The second warehouse function is the "simplest" function, a storage device caused by lot sizes in the production process, more common in a make-to-order environment. This means that when the company is able to produce in a one-piece-flow concept with no uncertainties (described in section 1.3). No warehouses are needed as storage device in the supply chain of the total production process.

Because of the restrictions and the significant setup times on the stamping machines, production in lots greater than one is necessary in practice. Therefore warehouses are present in the supply chain of DAF Trucks N.V. Five main warehouses are present within DAF which are related to the routing of the 450 items under study (table 2):

1. 1SM, supermarket; this is the internal stock point (decoupled) in the SMCP for relatively small products.
2. 1MW; main warehouse for unpainted parts, decoupling of the whole process in the SMCP and the paint shop / assembly plant.
3. 2MW; central warehouse of DAF Trucks, this is a central warehouse operated by DAF. This warehouse is suitable for many types of packaging units. Transport between this warehouse and the SMCP takes place by means of a train on the DAF location.
4. 5WF, assembly plant; stock point near the Truck Factory.
5. 1TO; this is the stock point where items will be sent to external companies, most items which are produced in the Press Shop go to the cabin factory in Westerlo.

The lot size affects the average inventory level and the frequency of logistic activities for all the above warehouses. One of the major factors that influences storage sizing is the storage assignment policy that defines the method of assigning items to storage locations (Iris et al., 2012). The reason for this is that storage size strongly depends on the amount of storage space required; in turn storage space is determined by the storage assignment policy used. Frequently used policies in industry are randomized storage (RAN), dedicated storage and full turnover-based storage policy (FULL). In the case of DAF Trucks, random storage is used. The warehouses within the supply chain of DAF are designed based on a broad range of packaging units. These storage locations are flexible in the sense that different packaging units can share one storage location. The total range consist of 71 different packaging units which differ in volume from 0,009 m³ till 6,6 m³. Two examples of packaging units are depicted in figure 10.

Figure 10 – Examples packaging units Press Shop

Besides the lot size inventory, there are two more causes which lead to inventory and therefore have a need for storage capacity. The first one comes from the roundup on packaging. In practice, lot sizes are rounded for efficiency reasons, this lead to more production than demand, further named as starting inventory at t=1 of the planning horizon. The second cause of inventory comes from the safety time introduced to cope with uncertainty in the process (section 3.1.3). In conclusion, three kinds of inventory are present and play a role in the design of the decision tool regarding the capacity bounds on warehouses; starting inventory caused by roundups, safety stock caused by safety lead times and lot size inventory to prevent for costly repeating setups.

3.4 Demand of the items in the Press Shop

Besides the product characteristics, the demand of the products itself experienced by the Press Shop play an important role in the decision making process of determining lot sizes on capacitated machines with inventory restrictions (Coppens, 2013). The nature of the demand in the Press Shop can mainly be characterized as dynamic demand (figure 11). In literature, the variability of the demand pattern should exceed some threshold value before it makes sense to characterise it as dynamic demand. A useful measure of the variability of a demand pattern is the Variability Coefficient. This statistic is denoted by the VC in literature and can be calculated on the following way (Silver et al., 1998).

$$VC = \frac{Variance\ of\ demand\ per\ period}{Square\ of\ average\ demand\ per\ period}$$

The variability coefficient is an important indicator for the to-be-developed approach in the conceptual model phase (Coppens, 2013). The literature says that if the VC is smaller than 0.2, use a simple EOQ taking average demand over the planning period as the demand estimator. If the VC is greater or equal to 0.2, make use of a heuristic. The VC values are calculated for the demand curves under study, this is depicted in appendix I. 64% of the 450 items have a VC value above 0.2.

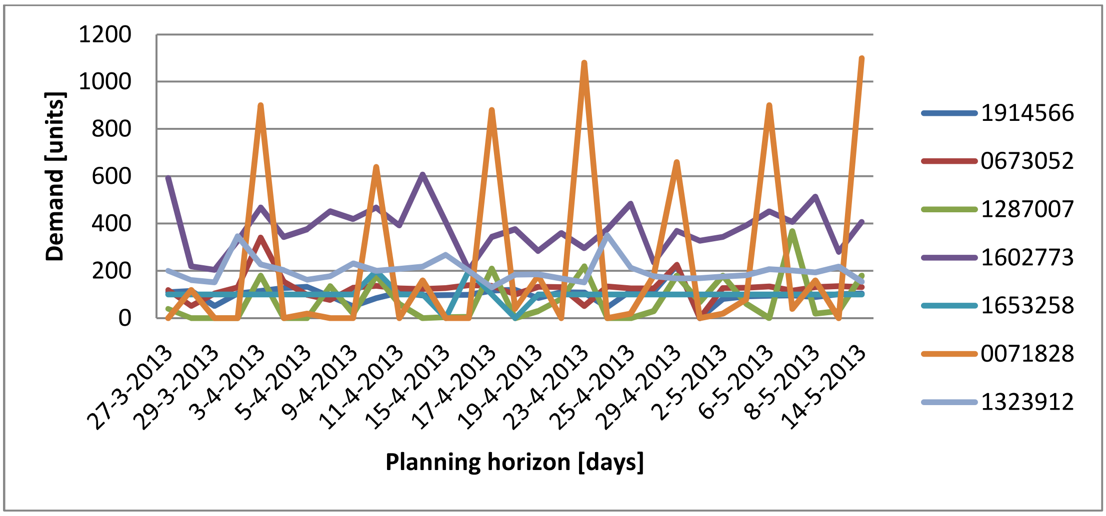

Figure 11 – Dynamic demand pattern of 7 items in press shop

Besides the nature of demand, important issues related to the demand found in the conducted literature study (Coppens, 2013) are:

- Length of the planning horizon.
- Size of the time bucket.
- Number of end items or final products.
- Number of levels of the product.

1. *Length of the planning horizon*

The length of the planning horizon depends on the accuracy and availability of the demand data. The accuracy is dependent on some factors:

- Economic situation; when more trucks are ordered, the forecasted part of the Master Production Schedule is relatively small and therefore the accuracy increases (section 3.2.3)
- Accuracy of the forecasted data provided from clients and dealers.
- Accuracy of the already ordered trucks in the system.

The length of the planning horizon can have a substantial influence on the total relevant costs of the selected strategy. Now we have to use the demand information over a finite planning horizon, extending from the present, when determining the appropriate level of the current replenishment quantity.

2. *The size of the time bucket*

The size of the time bucket is another important variable in the decision making process of lots, the time bucket determines the "fineness" and applicability of the model output. The time bucket also depends on the requirements for the output of the model. The output is the lot size for production with as minimum lot size daily demand for each specific period. Another important issue is the demand pattern during the time bucket. This is unknown within the SMCP, the produced items can have different end users:

- Truck assembly, Eindhoven
- Cabin assembly, Westerlo
- Axle assembly, Westerlo

- Parts for distribution centre, Eindhoven
- Demand for the new assembly plant, Brazil
- Research Centre, Eindhoven
- Test products for production engineering, Eindhoven

3. *The number of end items or final products*

The number of end items or final products differs day by day, production development is continuously improving the truck, standardization and improvements are the main drivers for new product developments. As already mentioned in this chapter, the number of end items in the department under study is +/- 450 items.

4. *The number of levels of the product*

As already mentioned in the introduction (section 1.2.2) the production process is decoupled with internal stock points. Three very general routings can be identified in the production process:

- The product passes one or more machine(s) over different departments, the end-item is placed on stock in warehouse 1LO for the painting process.
- The product passes one or more machine(s) within one or more department(s), the item is placed on stock in an internal stock point “waiting” for the next production process.
- The product passes one or more machines within one or more department(s), the end item is directly transported to the paint shop.

In the previous sections, sub question 1 “Which parameters plays a role in the decision making process of lots, and what are the characteristics of variables within the company under study?” is answered. Based on the analysis, modelling on item level is needed in the design phase of the project. The described parameters lead to cost; the following section describes the cost drivers which actually determine the decision making process of lot sizes.

3.5 Cost drivers in the process

The result of this cost analysis is a cost function which is the key part of the to-be-developed lot size decision tool. As already mentioned in literature, the lot size decision is based on a trade-off between fixed costs per lot and the inventory holding costs in the warehouses. First the components of the fixed costs are elaborated.

3.5.1 Fixed costs

The setup costs are the fixed costs per lot, independent of the size of the replenishment. These fixed costs per lot include all logistic activities independent to the lot size. These activities include total machine setup time as explained in the previous section, logistic activities like transportation and administration of the lot to the related warehouses.

1. *Setup of the machine*

The machine setup activities which take place in the Sheet Metal Component Plant are described in section 3.2.1. The time and therefore the costs of these activities are known within DAF and given in the ERP system. The costs are calculated by multiplying the setup time for each machine with an hour rate used within the company, € 34,98.

The production setup costs includes the wages of the total number of people involved in the setup process as described in section 3.1. Several factors of these setup cost can become quite complicated. For example the wages of the operators who perform the setups. If this person is only paid when setting up the machine, the wages are clearly part of the setup costs. So when to include these setup times depends on the used time of the operators when he is not setting up machines, and on whether a long term or short term perspective is taken.

If the operator would be involved in other activities, including setting up other machines or simply he is involved in the production process, these costs should be included. Also a long term perspective is taken. A long term view suggests that the person could be laid off, so the decision to set up infrequently affects the long term costs of the firm.

2. *Transportation of the lot*

The transportation of lots is related to the activities described in section 3.2.1, physical material flow in the Press Shop. The time and costs of these logistic activities are partly unknown and therefore based on assumptions. The activities are shown in table 3 with their estimates.

Table 3 - logistics activities Press Shop SMCP, 100 periods = 1 hour (DAF)

	Activity	**Time [periods]**	**Time [min]**
1	Transport machine to sheet metal warehouse	8	00:04:48
	Search for material in the sheet metal warehouse	5	00:03:00
	Transport to the related stamping machine	8	00:04:48
2	Transport of bins/tool etc (optional)	20	00:12:00
3	Transport lot from machine to machine	8	00:04:48
4	**Transport to related warehouse**		
4a	1SM	5	00:03:00
4b	1MW	8	00:04:48
4c	2MW	16	00:09:36
4d	5WF	12	00:07:12
4e	1TO	6	00:03:36

Activity 1 is needed for all items which have to be produced in the Press Shop. Activity 2 is an optional activity, some materials needs additional tools in their manufacturing process. Activity 3 is related to the number of machine needed for production, section 3.2.1. Finally activity 4 depends on the main warehouses where items will be stored after production.

3. *Administration of the lot*

When the production lot finished their final operation, and the transportation to the stock point is finished, the lot has to be registered in the system. The time for this administration of the lots is known; 146 seconds for each lot in each warehouse is needed. This time is also multiplied with an hour rate of € 34,98.

3.5.2 Inventory costs

The inventory costs, also known as holding costs are in most literature determined by a percentage of the items unit value (section 3.1). The cost of an item and hence the inventory carrying costs will increase downstream the supply chain. This phenomenon is not important in our study because the supply chain is decoupled and therefore each decoupled item has a unique item code and therefore a unique unit price.

In literature, the costs of carrying items in inventory includes the opportunity costs of the money invested, the expense incurred in running a warehouse, handling and accounting costs, the costs of special storage requirements, deterioration of stock, damage, theft, obsolescence, insurance and taxes (Silver et al., 1996). In this research, the opportunity cost of the money invested (interest); the cost which incorporate the risk of deterioration and the cost of the physical storage in warehouse are incorporated. The last costs incorporate some rates which will be explained further in this chapter.

1. *INTEREST*

By far the largest portion of the carrying charge is made up of the opportunity costs of capital tied up that otherwise could be used elsewhere in an organisation and the opportunity cost of warehouse claimed by the inventories. The opportunity cost of capital can be defined easily, theoretically, the return on investment that could be earned on the next most attractive investment opportunity that cannot be taken advantage of because of a decision to invest in the available funds in inventory (Silver et al., 1996). In practice such factors are difficult to determine; the cost of capital is set at some level by degree and is changed only if major changes have taken place in a company's environment. The average return on investment within the SMCP is 8%. The average return on investment within the DAF Company is 40%. The SMCP can be seen as a separate company within DAF so 8 % is taken as rate for interest.

2. *RISK*

The cost of capital used is also depended on the degree of risk of an investment. As a result, in practice the opportunity cost in capital can range from the bank's prime lending rate to 50% and even higher. Inventory investment is usually considered to be a relatively low risk because in most cases it can be converted to cash relatively quickly. Within DAF Trucks, the make-to-order policy results in a relatively low risk profile. There is some demand that is produced on forecasted data, therefore in corporation with the financial department the risks rate is set on 5%.

3. *SPACE*

The inventory holding cost not only depends on the relatively riskiness and interest of the SKU, it also depends on the cost of storage that is a function of bulkiness, weight, special handling requirement, insurance, and possibly taxes (Silver et al., 1996). Such detailed analysis is seldom applied to all items as investigated in the literature study (Coppens, 2013). In this research, this analysis is done because of the importance and great influence in the decision making process when incorporating capacity restrictions to warehouses. The cost per square meter warehouse within DAF N.V. incorporates the following cost components:

- Depreciation of the warehouse.
- Maintenance and cleaning of the warehouse.
- Costs of energy.
- Insurance of the warehouse.
- Workforce in the warehouse.

Other cost related to the space is the workforce in the warehouse. This workforce can be divided in direct and indirect workforce; this is also part of the exploitation cost of the warehouse. The total storage costs are calculated on 512 €/m^3/year.

3.6 Conclusion

As mentioned in the beginning of this chapter, a trade off has to be made between fixed costs and holding costs. The ratio fixed costs/holding costs is kind of an indicator to the priority of that item, a schematic overview of this ratio is given in appendix I. The above described data will be downloaded from the central system and will be applied to the lot size model in chapter 5, design of the decision tool. Research question 2 is now answered: “What are the cost drivers which influence the lot size decision?”

4. Conceptual models

In this chapter multiple mathematical models are searched for and constructed to tackle the problem as defined in chapter 2. With the theoretical and practical models presented, we want to provide insights in how to determine optimal lot sizes in a capacitated make-to-order production environment with inventory restrictions. We will start in section 4.1 with the model context followed by some simple heuristics which could be input for the design phase in the next chapter. Section 4.2 describes the heuristics found in literature with their misfit regarding the model context and the gaps found in the conducted literature study (Coppens, 2013).

4.1 Model context

The main problem context of this research is the decision making process of lot sizes in a dynamic make-to-order production environment with inventory restrictions. It is unclear for the decision makers what lot size minimizes the operational cost. The problem is schematically depicted in figure 12. On the one hand, the philosophy of one-piece-flow production is costly because of the significant setup times which are prevalent in practice. This philosophy is often restricted by machine capacities because of high occupation for machine setups. On the other hand, the EOQ formula of Camp (1913) is often used in practice to determine lot sizes, this formula lead to relatively large lot sizes which are often restricted by the capacity in warehouses. Therefore the assignment of this research is defined as: develop a lot size supporting tool that minimizes the relevant operational costs with the following company characteristics taking into account.

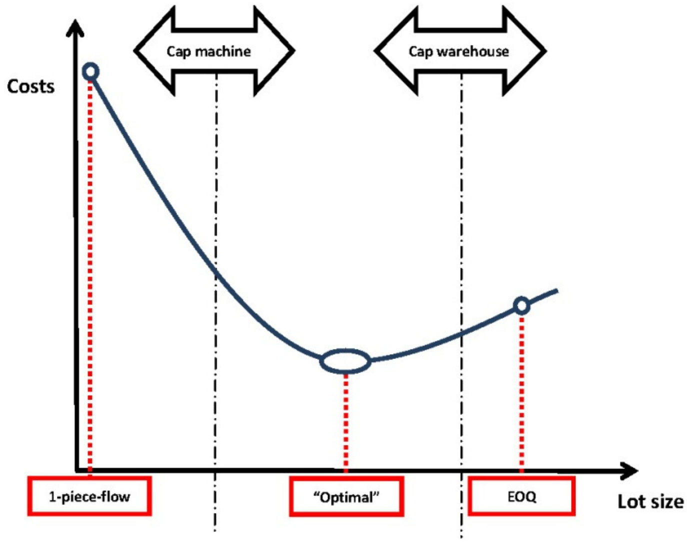

Figure 12 – Schematic presentation of the problem definition

- Complex job shop environment.
- Capacitated machines.
- Limits on capacity in warehouses.
- Significant setup times.

4.1.1 EOQ versus Silver Meal

The first research for the economic order quantity was done in 1913 by Camp. The goal of this model is to determine the constant reorder quantity of an item that minimizes the average annual costs, finding the equilibrium between the fixed setup cost and the holding cost of the inventory. The main and most important assumptions made for this model are the following:

- Demand is deterministic, constant and continuous.
- No capacity on production and storage.
- Setup cost and holding cost are deterministic over time.

Based on the detailed analysis described in chapter 3, it can be concluded that the EOQ formula only holds for specific assumptions in specific environments. These assumptions violate the practical usability of this theory within our problem context. As mentioned in the literature study, the restricted problem suffers from NP-hardness and in combination with dynamic demand; we have to search for feasible heuristics which deal with our context. In literature, a simple heuristic which deals with dynamic demand is presented by Silver Meal (1975). Other simple heuristics which could deal with dynamic demand are explained in appendix N.

Silver Meal

The Silver Meal or Least Period Cost heuristic is a single item, forward looking approach. This method is the counterpart of the EOQ formula and selects the replenishment quantity based on the total relevant cost per unit time for the duration of the replenishment quantity are minimized. If replenishment arrives at the beginning of the first period and it covers requirements through to the end of the *T*th period, then the criterion function can be written as:

$$TRCUT = \frac{(Setup\ cost) + (Total\ carrying\ costs\ to\ the\ end\ of\ period\ T)}{T}$$

The assumptions which hold for this heuristics are stated in appendix O. The heuristic is only looking for single items with no restrictions. This approach can probably be used in the design phase to combine multiple items with limits on inventory and production taken into account.

4.1.2 Heuristics for capacitated dynamic demand with inventory restrictions

Since the introduction of the classical EOQ formula, a lot of extensions have been developed to the model. These extensions are related to the assumptions made (single stage, unconstrained capacity and constant demand) for the classic EOQ formula as described in the previous section. Bahl et al. (1986) give a review on the lot sizing problem and present a framework in order to place some lot sizing problems in categories, this framework is presented in appendix P.

Based on the framework, the problem in this research is single stage, constrained resources with dynamic demand. A mathematically optimal solution is out of the question when we are dealing with this multi-item, time varying, capacitated case (Coppens, 2013). The introduction of the second restriction, warehouse capacity, makes the problem area complete in the sense that it matches with the problem context. As already investigated in the literature study, studies considering capacitated lot sizing problems with limited storage capacity are scarce.

The most relevant paper found in the conducted literature study is published by Iris et al. (2012). This paper focuses on how to obtain a multi-item dynamic lot sizing strategy with production and warehouse capacities with different storage allocation policies in a manufacturing environment. The presented heuristic algorithm is able to simultaneously solve the lot sizing and pre-defined storage allocation problem. In the modeling phase, assumptions are made which partly matches with the problem context of this research except one practical restriction in a job shop environment, being intercorrelation between machines and items. The developed model by Iris et al.is applied to one machine.

The philosophy maintained in this research is transferring a certain amount of lots from one period to another regarding bounds reflected by storage allocation policies. Note that the warehouse capacity is incorporated in the model as a dynamic parameter.

There are three fundamental decisions that should be made by transferring these lots to other periods in the planning horizon:

1) The period to shift a lot from/to.
2) The item that will be shifted to the chosen period
3) The amount of products that will be subtracted and added between consecutive pre-determined periods.

The approach presented in the paper is based on the simulated annealing meta-heuristic with restricted search space. Simulated annealing deals with acceptance of a taken move by controlling the objective function; minimize total cost of production, holding, setup and regular time activities. This method is quite popular in mathematical problems like this one. The model contains a trade-off between cost of setup and holding a unit of inventory on stock. The trade-off occurs because in periods where demand results in idle capacity, it will be logical to produce more in advance than making repeating setups in each time period.

The proposed algorithmic structure starts with an easy-to-implement constructive heuristic with the Lot for Lot rule. Results obtained from this rule are given as input to an improvement heuristic. Since L4L may produce an infeasible solution regarding the capacity constraint. In the improvement heuristic, a move is generated by forward or backward transferring a lot to another period in order to restore feasibility of capacity constraints or improve the objective function. Transferring a lot between periods will result in a cost change by changing the indices of related cost parameters. Forming a dominance property on one-at-a-time lot transferring may be useful, these properties help to limit the search space, and result in high efficiency search procedures.

Backward transferring an amount of Δ from t_2 to t_1 is dominant if; starting from the period with the highest load and an item with highest gap in total holding and production cost with previous period will form a dominance set of the backward scheduling procedure. The maximum quantity that can be shifted depends on the production capacity in that period and the warehouse capacity for the ending period inventory.

Forward transferring an amount of Δ from t_1 to $t_2$depends on the performance of the maximum quantity that may be shifted and the inventory on hand in the analyzed period t_1. The maximum quantity that can be transferred is also dependent on the storage allocation policy.

There is mentioned in the paper that the forward looking approach is not always working, in a lot of practical cases there is no on-hand inventory at the end of each planning period because of the assumption that no shortages are allowed. This is also the case within our problem context and should be incorporated in the design phase in the next chapter. In the paper, the authors warn for nervousness. Also transferring production lots from one period to another with an appropriate neighborhood structure might sometimes lead to local optima, but in this procedure search for global optima dominates the algorithm (Iris et al. 2012).

Looking to the technical structure of the algorithm, when significant setup times are prevalent the dominance of local optima rises. When a neighborhood approach is used in for example period 1, only the opportunity costs for period 2 are considered. But the opportunity for using the idle capacity in period 1 for producing demand in period 3 or period 4 etc. is not considered in their decision making process. This shortcoming followed by the one machine approach as explained in the literature in combination with warehouse restrictions based on the physical volume of items is input for the design phase of this master thesis.

4.2 Conclusion

Research question 3, "what are feasible heuristics that deal with the characteristics found?" is answered in this chapter. In the next chapter a four step approach is developed by the author who incorporates both restrictions on machines and warehouses. The way of calculation is mathematical optimization based on the selection of a best element taken from a set of available alternatives. The solution space is restricted by a simple to implement heuristic, Silver Meal as explained in section 4.1.1. This heuristic guarantees optimal solution when no restriction is present at that iteration. Further explanation of this procedure is given in the next chapter.

5. Detailed design of the lot sizing model

In this chapter, the detailed design of the lot sizing model is explained. The chapter starts in section 5.1 with the description of the input variables of the model depicted in mathematical terms followed by the objective function and the mathematical restrictions. The developed four step approach is elaborated in detail in section 5.2. Finally, the conceptual output of the model is presented in section 5.3.

5.1 Mathematical model with input variables

As described in the problem context, section 2.1, the problem area of this research consists of several capacitated machines with, in the first case, one capacitated warehouse. The extension to more warehouses is relatively easy. The storage allocation policy is assumed to be random storage based on the analysis explained in section 3.3. Based on the process analysis and the research for feasible heuristics, the following variables are analyzed and selected as important variables in the design phase of the lot size decision tool.

Variables

$D_{i,t}$ = Netto demand corrected for safety lead times
I_{0_i} = Starting inventory of item i at the start of the rolling planning horizon $(t = 1)$
$cp_{i,m}$ = Unit processing time of item i at machine m
$cs_{i,m}$ = Unit setup time required for item i at machine m
$ws_{i,m}$ = Workforce setup time needed for item i at machine m
$MaxGrW_t$ = Maximum gross warehouse capacity in period t
$MaxNetW_t$ = Maximum net warehouse capacity in period t
$MaxC_{m,t}$ = Maximum capacity of machine m in period t
PU_i = Packaging unit of item i in the warehouse
th_i = Warehouse safety lead time of item i in days
c_i = Unit production cost of item i (price of the item in Euros)
α = Ratio which determines the net capacity in the warehouse
A = Set of total number of items over the planning horizon
N = End period of the planning horizon
M = total number of machines

V_i = Volume cost of item i in €/m^3
h_i = Unit holding cost of item i in period t expressed in %
$s_{i,m}$ = Setup cost of item i at machine m
s_i = Total setup cost of item i in period t
ct_i = Transportation cost of item i to the warehouse
$C_{m,t}$ = Consumed regular production capacity of machine m in period t
$Y_{i,m,t}$ = Binary setup variable for setup of item i on machine m in period t

These variables are available within DAF Trucks N.V. on a daily bases using downloads from the central system (for order system as explained in section 3.2.3). The chosen time bucket is therefore one day, this size is quite common in the automotive industry (Yagyu, 2012). The reason is significant setup times in manufacturing in combination with the production rates. Within DAF, 35 days of demand is known from downloads provided by the Information Technology Department (ITD). The cost parameters are calculated with manual data in combination with information from the available downloads. Besides the input variables, the central decision variable (output of the model) is the lot size of item i in period t:

$$X_{i,t} = Lot\ size\ of\ item\ i\ in\ period\ t$$

The integer programming model considering capacitated lot sizing with both machines and warehouse capacity is as follows:

$$Minimize\ X_i \sum_{t=1}^{t=N} \sum_{i=1}^{i=A} h_i * I_{i,t}^{€} + V_i * I_{i,t}^{m^3} + S_i * Y_{i,t} + ct_i * Y_{i,t} \quad (1)$$

$$C_{m,t} \leq MaxC_{m,t} \quad (2)$$

$$I_t^{m^3} \leq MaxNetW_t \quad (3)$$

$$C_{m,t} = \sum_{i=1}^{i=A} \left(cp_{i,m} * X_{i,m,t} + cs_{i,m,t} * Y_{i,t}\right) \quad (4)$$

$$I_{i,t}^{€} = I_{0_{i,t}}^{€} + I_{SS_{i,t}}^{€} + I_{lot_{i,t}}^{€} \quad (5)$$

$$I_{i,t}^{*} = I_{0_{i,t}}^{*} + I_{SS_{i,t}}^{*} + I_{lot_{i,t}}^{*} \quad (6)$$

$$I_{i,t-1} + X_{i,t} - I_{i,t} = D_{i,t} \quad (7)$$

$$Y_{i,t} = \sum_{m=1}^{M} \mathrm{Y_{i,m,t}} \quad (8)$$

$$MaxNetW_t = \alpha * MaxGrW_t \quad (9)$$

The objective is to minimize the operational costs by determining lot sizes in specific periods over the planning horizon N. All demand $D_{i,t}$ in a specific period needs to be satisfied before or within the determined time period. Constrain (2) ensures that the capacity on machine m in period t is equal or smaller than the maximum capacity assigned to that machine in each period. Constraint (3) ensures that the physical inventory is always equal or smaller than the maximum net warehouse capacity in each time period (9). The consumed regular production capacity on machine m in period t is calculated by incorporating the unit processing time and the unit setup time required for each setup on each specific machine. This setup is triggered in the formula by a binary setup variable for setup of item i on machine m in period t (8). These calculations have to be done over all items in each time period (4). The physical inventory is calculated in two units of measure, inventory in Euros (5) and inventory in physical volume (6). This is done because of inventory costs, interest and risk is given in percent while the costs for space is calculated with a €/m3 cost factor. The inventory balance equation (7) ensures that all demand is satisfied regarding requirements. This equation incorporates warehouse throughput time as described in section 3.2.3.

The goal of the lot sizing model is to provide a near optimal feasible solution. The simplest method to determine optimal solutions of an optimization problem is performing complete enumeration. The disadvantage is that this will result in an inefficient and time consuming method, because one should evaluate all possible solutions. A containment to complete enumeration is a restricted search space. This is a difficult process but proven to be an effective method.

Dynamic programming has a better computational efficiency compared to complete enumeration. A solution is obtained by working backward from the end of a problem toward the beginning, by breaking up a large problem into a series of smaller, more tractable problems also known as stages (Winston, 2004). This method is tested but not applicable for our problem area. When using the backward approach, we get stuck in a local optimum. Two approaches are identified in literature, forward en backward transferring lots over a time period with as starting point an initial solution. Both approaches are respectively depicted in figure 13 and figure 14.

<u>Forward versus backward approach</u>
Transfer of lots to periods can be executed with two approaches, a forward and a backward looking approach, also named in literature as the look-ahead and look-back approach. The forward approach looks to possible combinations in future periods; it starts in the beginning of the planning horizon and makes combinations with periods in future (t+1, t+2 etc) as depicted in figure 13.

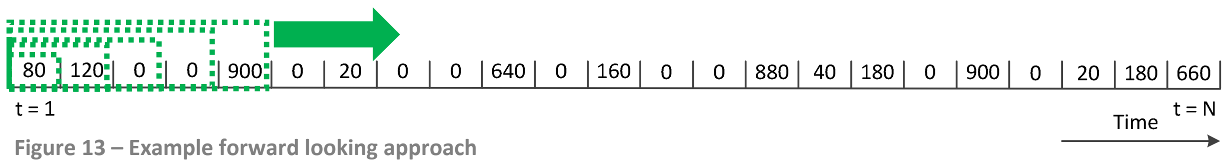

Figure 13 – Example forward looking approach

The backward looking approach starts at the end of the planning horizon and looks back to calculate combinations for transferring lots to other periods (t-1, t-2 etc) as depicted in figure 14.

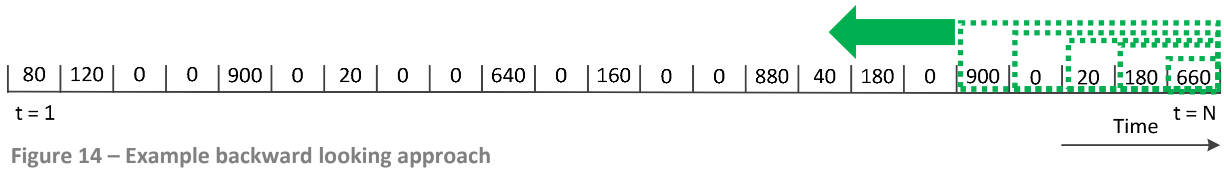

Figure 14 – Example backward looking approach

The decision to choose for an approach is related to the goal of the heuristic and process itself: when you want to decrease the used capacity in a specific period, it is more logical to take a backward approach instead of the forward one. When you use the forward approach, you will probably not start at t=1 because that period is most of the time provided with starting inventory. This period is probably needed for making future periods feasible. These two approached are both used in the developed procedure which is explained in the next section.

5.2 Lot sizing model; 4 step procedure

A four step approach is developed which incorporates both restrictions on machines and a warehouse(s). The calculation method is mathematical optimization based on the selection of a best element taken from a set of available alternatives. The solution space is restricted by four restrictions:

- The optimal solution without restrictions; the Silver Meal heuristic as explained in section 4.1.1.
- Restriction on a set of machines regarding available capacity.
- Restrictions on one warehouse or a set of warehouses regarding available storage space.
- Restricted with a maximum lot size for flexibility of the process.

The developed approach consists of the following four steps:

- Step 1: initial solution with a lot for lot rule, starting point of the procedure.
- Step 2: making the schedule feasible regarding machine capacity.
- Step 3: optimization process of the whole schedule.
- Step 4: practical roundup procedure by model user.

The steps are described in the next sections.

5.2.1 Step 1 - Initial solution with a lot for lot rule

The first step puts an initial solution of the lots into the model with an easy to implement Lot for Lot rule; this is a solution where no restrictions are taken into account. The L4L rule is the net demand per day which has to be made within the finite planning horizon of N days. A schematic example of this first step is depicted in figure 15. In this example, three items have to be produced over 2 machines. When L4L is used, no lot size inventory is available in the warehouse.

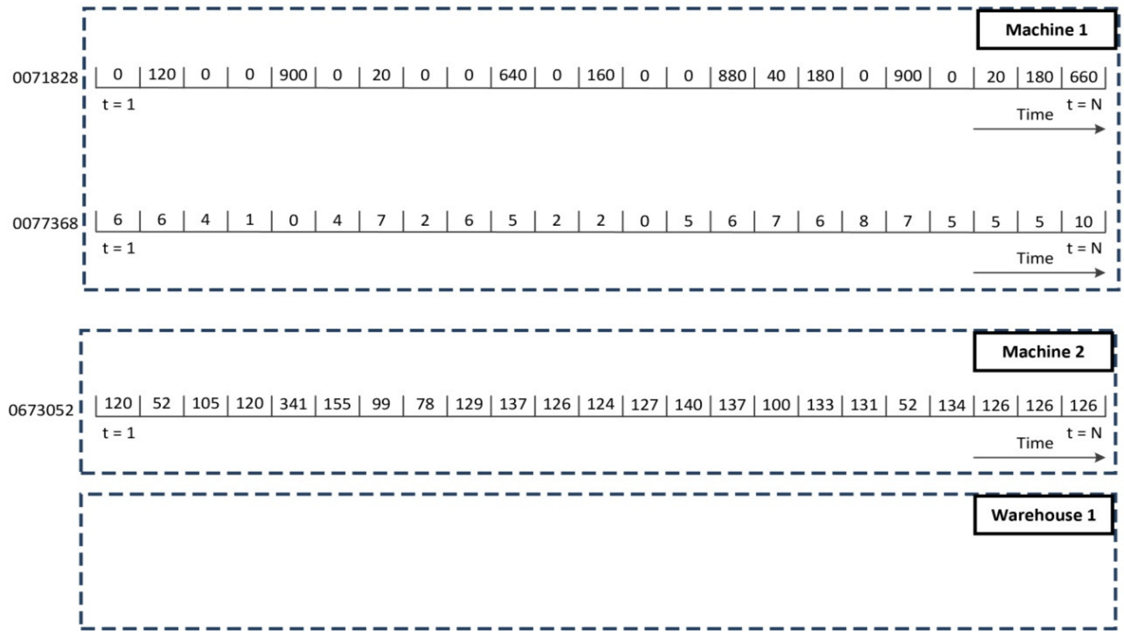

Figure 15 – Initial solution with the lot for lot rule

The effect of this step on the capacity of a machine is shown in figure 16. As already mentioned, this step causes no lot size inventory. Starting inventory and safety lead time inventory are present and depicted in appendix Q. The results from this easy to implement lot for lot rule is input for the following phase; making the production schedule feasibly regarding machine capacities.

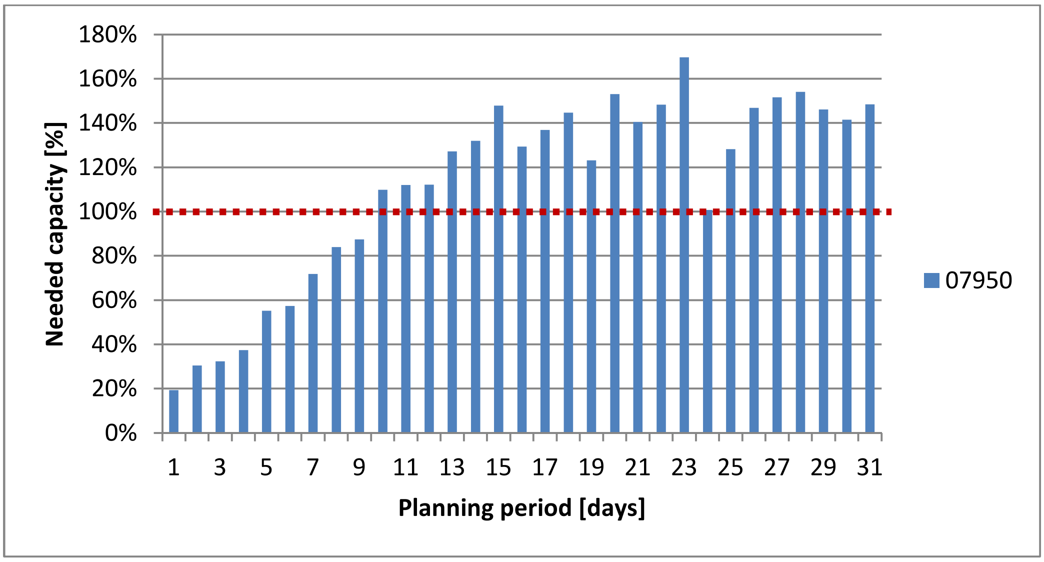

Figure 16 – Capacity machine m after execution of step 1

5.2.2 Step 2 - Making the schedule feasible regarding machine capacities

Since lot for lot may produce an infeasible solution to machine capacities, step 2 is developed to make the production schedule feasible before we can start with the optimization step. This feasibility step incorporates only machine capacities, a smoothing mechanism is adapted. The heuristic is based on a backward approach as explained in section 5.2. We start at t = N, then shifting lots to t = t-1 till feasibility is reached in each period. The smoothing mechanism is based on restricting the search space for backward transfers to neighbour period.

Transferring a lot backward in the time horizon results in a cost change of the objective function. The heuristic starts with making a transfer list within the solution space and looks for the most economical transaction which can be executed; an example of this list is depicted in figure 17. The first column shows for every item the earnings/cost for optimization over a couple of periods expressed in k. So for example € 520 can be earned by taking the demand of five time periods in one time bucket.

Costs for optim	1058	k-value
520		5
230		4
1058		3

Figure 17 – Transfer list combinations

When no feasibility can be reached, another priority rule can be developed, for example based on the biggest gap in processing or setup times. A schematic example of this second step of the four step procedure is depicted in figure 18.

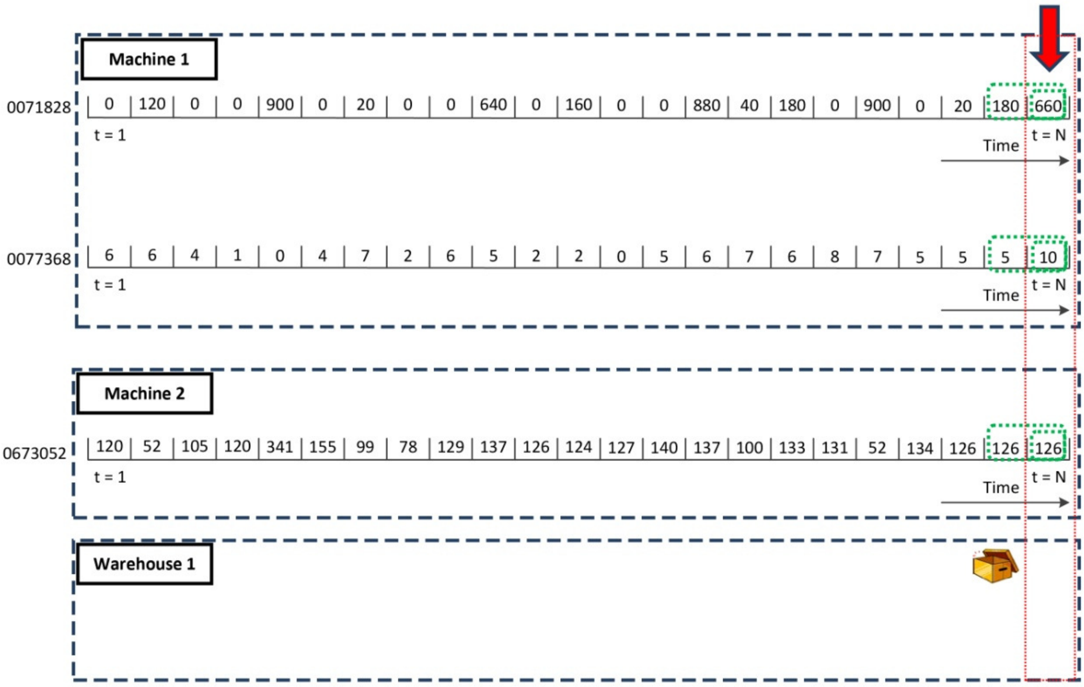

Figure 18 – procedure making feasible schedule

Transferring a lot from period t to period t-1 leads to lot size inventory at the end of period t-1. The effect of this step on the capacity of the machines is shown in figure 19.

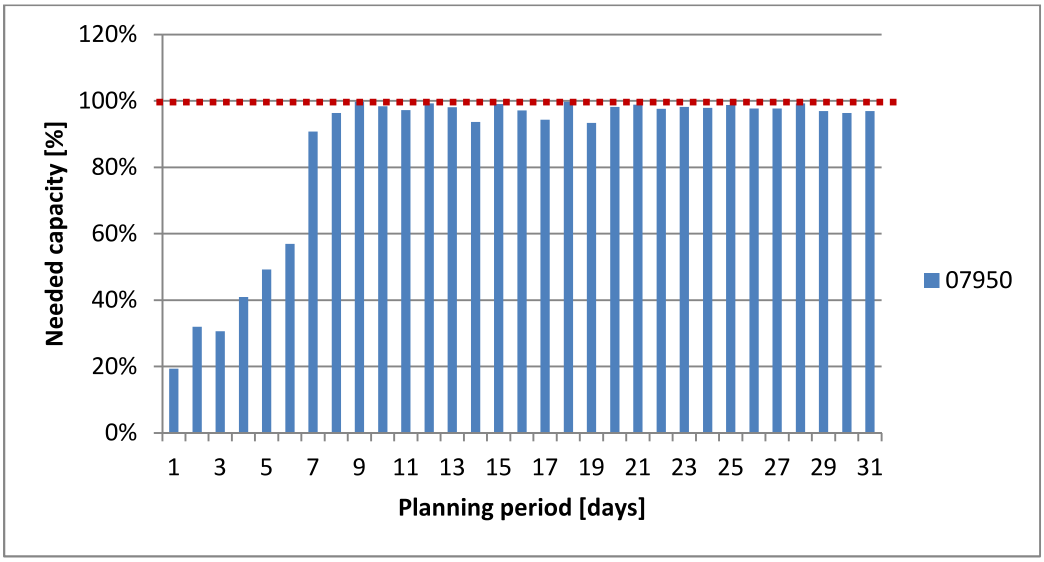

Figure 19 – Capacity machine m after execution of step 2

When all machines have a feasible schedule or tend to have a feasible schedule, the optimization process can be started where the trade-off is made to produce more in advance than making repeating setups in each time period.

5.2.3 Step 3 - Optimization process of the production schedule

The third step is the most complex and time consuming step of the developed procedure. The process is developed by the author of this project because no applicable heuristic was found in literature which deals with the important restrictions in combination with significant setup times on the machines, further explained in section 4.1.2. A forward looking approach with complete enumeration will be conducted in this step.

This procedure includes the opportunity for future periods, in contrast to the heuristic of Iris et al. (2012). Restricted by Silver Meal strives for optimality regarding the rolling planning horizon. Further the forward looking approach is used as a starting point for the optimization heuristic. The heuristic starts by checking for every item in a specific period the feasibility and the improvement of the objective function. All these possible executions of lots are placed in a transfer list. When all combinations are checked, transactions can be executed based on the largest improvement of the objective function. This process continues till a restriction is reached, one complete iteration is then conducted. The procedure starts again with calculating all possible combinations which are possible after iteration 1 and execution of the transfer list will start again. This general procedure repeats till no combination has a positive contribution to the objective function or all restrictions are reached. A detailed procedure of the complete step is given in appendix S. A schematic example of this second step is depicted in figure 20.

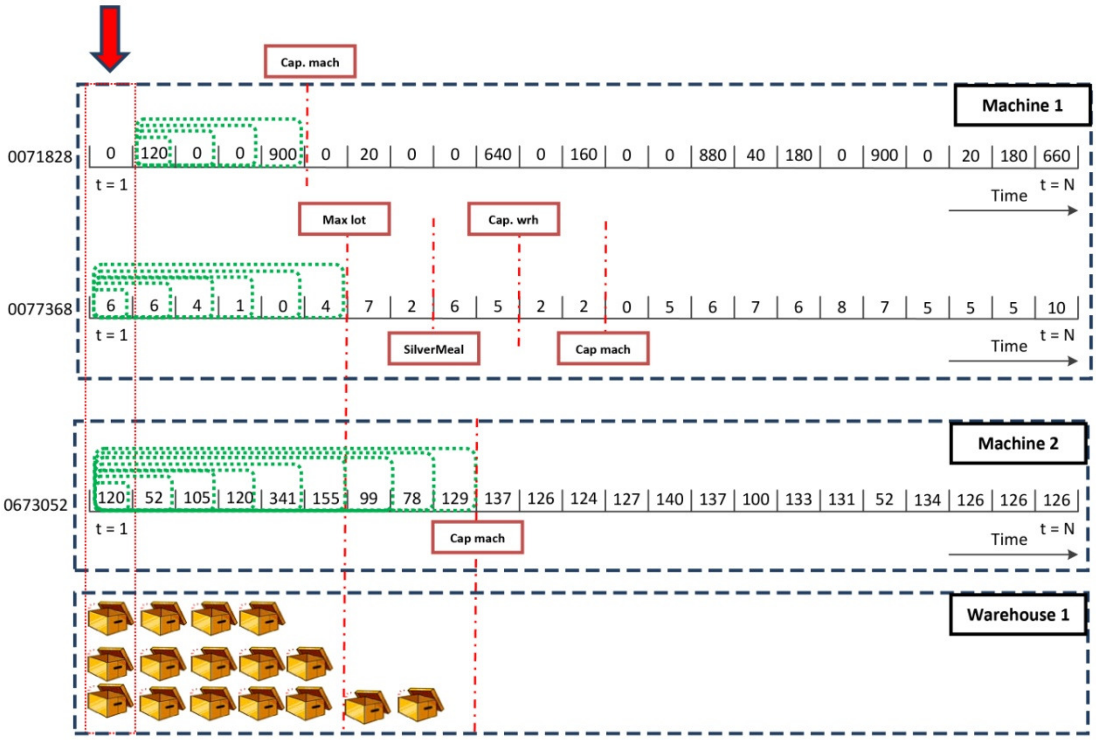

Figure 20 – Procedure optimization of the schedule

For the optimal solution, capacity of the related warehouse(s) in period t, capacity of the related machine(s) in period t and the max lot size on the machine in hours are taken into account. An example of the effect of this step on the capacity of the machines is shown in figure 21.

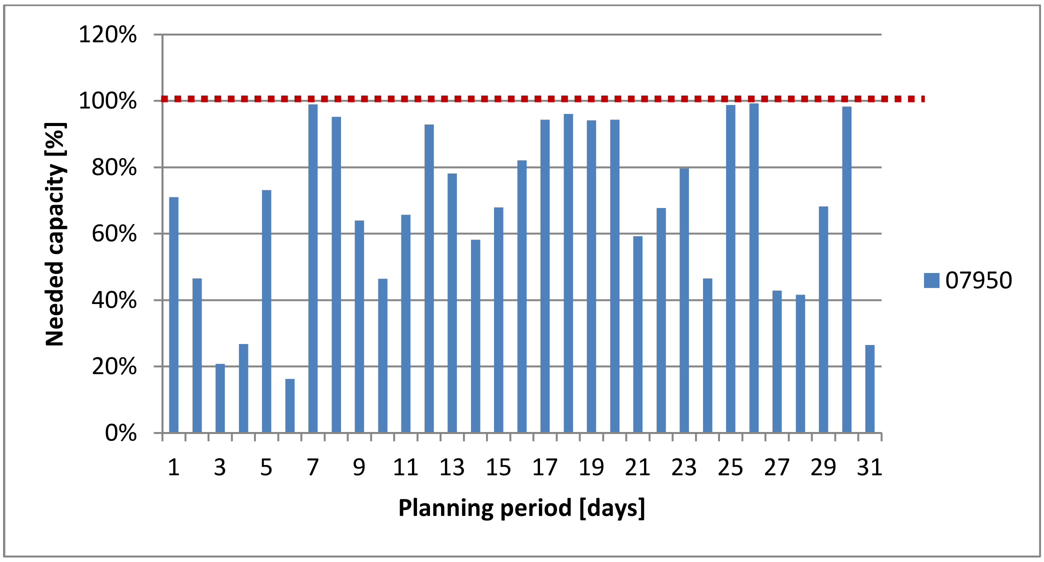

Figure 21 – Capacity machine after execution of step 3

After the optimization step, no positive contribution to the objective function is possible anymore. But based on the practical side of the production schedule, two practical procedures can be executed with step 4 of the developed procedure.

5.2.4 Step 4 - Scheduling and roundup procedure

This step can be executed bases on practical issues related to the department. The practical issues within the Sheet Metal Component Plant come from interviews with the planners of DAF Trucks N.V. First some used capacity can be transferred to another period to smoothen the total used capacity over the planning horizon. This procedure is for example useful when you want a constant utilization rate of the machines during the planning period. Second, the lot sizes can be roundup by some practical issues like packaging units of sheet metal as explained in section 3.1.5.

5.3 Output of the model

The output of step 3 is the final output of the theoretical model. The output of the developed decision tool is a suggestion for a production schedule as shown in figure 22. This production schedule contains on different time periods dynamic production lots. This production suggestion is in most production environments not directly applicable. As already mentioned in the beginning of this section, step 4 can make the schedule more practical by experienced material planners of the department. They are able to roundup the dynamic lot to a feasible lot and they are able to shift total lots to idle periods for smoothing the capacity over the total planning horizon.

	Planning period											
Item	1	2	3	4	5	6	7	8	9	10	11	...
1230075						1231						
1231429	864									1527		
1231430	722						868					
1231433			550				1044				968	
1231434		154						463				
...												

Figure 22 – Example output of the developed model

5.4 Conclusion

Research question 4: "How can the developed heuristic be incorporated in a decision tool?" is answered. The first three steps of the developed four steps procedure is implemented within Excel with VBA. This developed decision tool can be run with a case study within DAF Trucks N.V. The results of this case study are presented and compared to the current situation in the next chapter.

6. Case study DAF Trucks N.V.

This chapter describes the results of the developed lot sizing model with a case study within DAF Trucks N.V. The used data to validate the decision tool is made available by DAF Trucks N.V. The data are already analysed in chapter 4 of this report. The input data needed for the model are made available every day by downloads from the ERP-system. The solutions found by the model will be analysed and compared with the current situation to judge the performance of the developed decision tool. This comparison is based on some Key Performance Indicators which are first explained in chapter 6.1. In section 6.2 actual performance of the model is given based on the actual and calculated lot sizes with only the machine capacity taken into account. Section 6.3 compares both approaches with a detailed cost analysis. In section 6.4, two scenarios, a maximum lot size and a restriction on inventory, are incorporated and their performance is analysed. Finally a sensitivity analysis is conducted in section 6.4 to test the robustness of the developed model.

6.1 Key Performance Indicators to judge the model

The Key Performance Indicators used to measure the performance of the lot size decision model are separated in three groups; performance indicator for the machines, performance indicators for the warehouses (five warehouses are incorporated in this case study, section 3.3) and the main performance indicators based on relevant cost components.

Machines

- Average utilization of the machine over the planning horizon N;
- Occupation rate regarding setups over the planning horizon N;
- Average lot size over the planning horizon N;
- Max lot size on each machine over the planning horizon N;
- Number of periods of overcapacity during the planning horizon N;

As already mentioned in chapter 5, flexibility of the process is important in the production environment of today. Every production process suffers from uncertainty and therefore some flexibility is needed to handle urgent orders in a make to order environment. The flexibility of the machine is measured in the average lot size per machine and the maximum lot size per machine in hours.

Warehouses

- Average utilization in each warehouse measured in m^3 over the planning horizon N;
- Maximum utilization in each warehouse measured in m^3 over the planning horizon N;
- Inventory in euro's in each warehouse over the planning horizon N;

Operational costs

- Total cost regarding the objective function over the planning horizon N;
- Fixed costs over the planning horizon N;
- Inventory costs over the planning horizon N;

The results of the simulation runs are tested with the input parameters as elaborated in chapter 4 of this report. Next section shows the results of the simulation runs for the optimized lot sizes with bounded machine capacity.

6.2 Current versus optimized lot sizes

The data used in the case study are the reference data for both the current situation (solution given by the ERP system of DAF) as well as the optimized lot sizes with the developed decision tool. The current lots are calculated with the decision variables as explained in section 3.1.4; roundup in days, roundup in units regarding efficiency in production and the fixed days to place an order to balance capacity. The result of this run is first compared to the optimized lot sizes without inventory and max lot size restrictions. These restrictions are introduced and simulated in section 6.4 of this chapter. The key performance indicators regarding machines for the current and optimized lot sizes are given in table 4.

Table 4 - Difference between current and uncapacitated lot sizes (optimal) on the machines

	Average utilization machine [%]			Occupation rate - setups [%]			Average lot size [hour]			Max lot size [hour]			#periods of overcapacity in N [days]		
Nr.	*Cur.*	*Optimal*	*Diff*	*Cur.*	*Optimal*	*Diff*	*Cur.*	*Optimal*	*Diff*	*Cur.*	*Optimal*	*Diff*	*Cur.*	*Optimal*	*Diff*
02131	38%	34%	-4%	24%	16%	-8%	1,6	2,3	0,7	5,8	11,9	6,1	0	2	2
02183	29%	26%	-3%	16%	10%	-6%	1,3	2,8	1,5	4,5	10,1	5,6	4	0	-4
02251	47%	43%	-4%	18%	12%	-6%	2,8	3,4	0,6	8,3	15,9	7,7	3	0	-3
03601	96%	86%	-10%	29%	23%	-6%	2,3	3,8	1,5	11,4	16,4	5,0	12	5	-7
03602	46%	40%	-6%	24%	16%	-8%	2,4	3,7	1,3	9,0	15,0	5,9	4	0	-4
07691	73%	62%	-11%	27%	17%	-9%	1,3	2,4	1,1	6,5	15,0	8,6	7	0	-7
07950	70%	62%	-7%	20%	14%	-6%	1,6	2,7	1,1	7,4	10,9	3,6	5	0	-5
16415	45%	39%	-6%	20%	14%	-6%	1,4	2,6	1,2	5,8	11,0	5,1	0	0	0
18358	76%	77%	1%	21%	18%	-3%	2,5	4,9	2,4	65,7	18,9	-46,8	7	1	-6

The average utilization rate of the machines decreases with the optimized solution except machine 18358. The reason for this increase is one specific item with a significant setup and processing time, which result in a lot size of 65,7 hours in the current situation. This decreases the total setup time for that item over the planning horizon and therefore has significant influence on the machine utilization rate. Pictures of the utilization of all machines are shown in appendix U. The setup part of the utilization rate decreases for all machines which shall have a positive influence on the operation costs (will be explained in section 6.3). The average lot size on the machine increases for all machines. This is quit logical because less setup is required to produce the demand over the total planning horizon. This results in an average increase in size of the production lots. A logical cause of the increased lot sizes is the increase in max lot sizes over the planning horizon. This has a negative influence on the flexibility of the company, therefore a restriction is introduced to prevent this. The periods of over capacity decreases for 8 machines, the scheduling function performs better with the developed model instead of the suggestion by ERP system of DAF. The indicators regarding the warehouses are given in table 5.

Table 5 – Difference between current and uncapacitated lot sizes (optimal) in the warehouses

	Average Utilization [m³]			Max utilization [m³]			Total inventory [€]		
Warehouse	*Current*	*Optimal*	*Diff*	*Current*	*Optimal*	*Diff*	*Current*	*Optimal*	*Diff*
1TO	920	845	-75	1291	1130	-161	€ 422.865	€ 366.986	-13,2%
1MW	133	151	18	255	254	-1	€ 78.524	€ 97.299	23,9%
2MW	43	57	14	80	87	7	€ 23.950	€ 35.812	49,5%
1SM	165	156	-9	368	303	-65	€ 66.470	€ 71.649	7,8%
5WF	60	65	5	103	102	-1	€ 29.796	€ 36.308	21,9%

The results show that the average utilization rate of all warehouses decreases with the optimized solution, noted that no restrictions on warehouses is incorporated. The utilization of warehouse 1MW, 2MW and 5WF increases but warehouse 1TO compensates for this. The maximum utilization over the total planning horizon decreases for four warehouses. The behaviour of the inventory over the planning horizon is depicted in appendix V. The total inventory in euro's decrease for the warehouse 1TO. This KPI increases in other warehouses. Besides the performance indicators of the warehouses and machines, the most important indicator at the end of the story is the indicator for the operational costs. The objective function as described in section 3.3. To give an impression of the distribution of the cost parameters, a pie is given in figure 23.

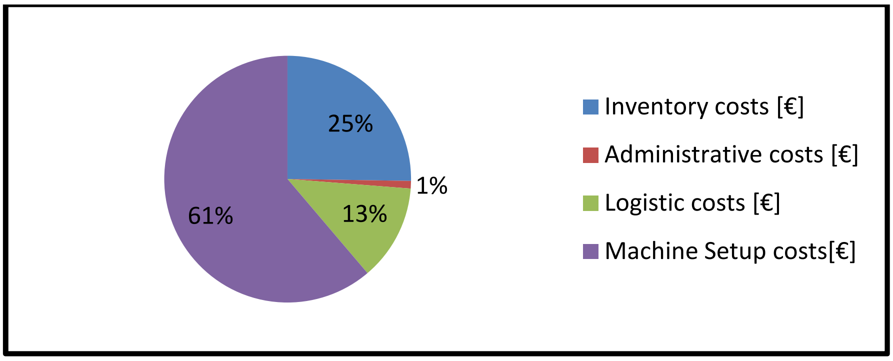

Figure 23 – Distribution total relevant costs lot size decision model

An overview of the difference in cost components is given in table 6.

Table 6 – Costs current situation versus uncapacitated situation (optimal)

	Overview of costs		
Cost component	*Current*	*Optimal*	*Diff*
Inventory costs	€ 38.152	€ 36.310	-5%
Administration costs	€ 2.107	€ 1.305	-38%
Logistic costs	€ 26.297	€ 16.311	-38%
Machine setup costs	€ 103.971	€ 72.538	-30%
Total costs	**€ 170.527**	**€ 126.464**	**-26%**

The difference in total costs gives a good impression of the performance of the developed decision tool. Hence this value contains some mismatch regarding costs for both situations. First, the output of the ERP system of DAF is a suggestion to the material planner and shall not be fully representative for the current situation. Second, the DAF solution (lot size suggestion) is already calculated with roundups on lots in comparison with the optimized solution (result after step 3 of the procedure). Therefore the performance measure based on machine setup costs is more representative than the total costs including inventory holding costs. This shows that the developed model gives a 30% better lot size suggestion than the DAF ERP system.

6.3 Scenario analysis

As already mentioned in the problem context of this thesis, the solution should be feasible with production and warehouse capacity, no shortages are allowed. In this section, two scenarios are simulated with the goal to check the usability of the developed model in practice. First a maximum lot size in hours is introduced followed by restrictions on the five warehouses.

6.3.1 Scenario with max lot size of 12 hour

As already mentioned in the previous section, to increase the flexibility of the production process a maximum lot size is introduced in the decision making process of lots. This scenario is simulated and the results are given in table 7.

Table 7 - Difference between uncapacitated (optimal) and max lot sizes on the machines

	Average utilization machine [%]			Occupation rate - setups [%]			Average lot size [hour]			Max lot size [hour]			#periods of overcapacity in N [days]		
Nr.	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*
02131	34%	34%	0%	16%	17%	1%	2,3	2,3	0	11,9	11,9	0	2	2	0
02183	26%	26%	0%	10%	10%	0%	2,8	2,8	0	10,1	10,1	0	0	0	0
02251	43%	44%	-1%	12%	13%	1%	3,4	3,6	0,2	15,9	11,9	-4,0	0	0	0
03601	86%	90%	4%	23%	26%	3%	3,8	3,3	-0,5	16,4	11,1	-5,3	5	3	-2
03602	40%	41%	-1%	16%	20%	4%	3,7	3,3	-0,4	15,0	11,0	-4,0	0	0	0
07691	62%	62%	0%	17%	18%	1%	2,4	2,4	0	15,0	11,5	-3,5	0	0	0
07950	62%	62%	0%	14%	14%	0%	2,7	2,7	0	10,9	10,9	0	0	0	0
16415	39%	39%	0%	14%	14%	0%	2,6	2,6	0	11,0	11,0	0	0	0	0
18358	77%	80%	3%	18%	22%	4%	4,9	4,4	-0,5	18,9	18,9	0	1	3	2

The average utilization rate of the machine increases for both 03601 and 18358 with respectively 4 and 3 %. The occupation rate regarding setups increases for six machines, this is caused by the fact that on average more setups are required to produce the same demand over the planning horizon. The positive effect of the maximum lot size is the decrease of the average lot size on machine 03601, 03602 and 18358 with respectively 0.5, 0.4 and 0.5 hour (0.5 is equal to 30 minutes). The cause of this decrease is the decrease in max lot sizes of some lots out of the 450 items simulated. The total periods of overcapacity remains the same. The indicators regarding the warehouses are given in table 8.

Table 8 – Difference between uncapacitated (optimal) and scenario with max lot sizes in the warehouses

	Average Utilization [m³]			Max utilization [m³]			Average inventory [€]		
Warehouse	*Optimal*	*Scenario*	*Diff*	*Optimal*	*Scenario*	*Diff*	*Optimal*	*Scenario*	*Diff*
1TO	845	808	-37	1130	1079	-51	€ 366.986	€ 332.279	-9,5%
1MW	151	150	-1	254	254	0	€ 97.299	€ 96.615	-0,7%
2MW	57	54	-3	87	77	-1	€ 35.812	€ 34.116	-4,7%
1SM	156	148	-8	303	285	-18	€ 71.649	€ 69.179	-3,5%
5WF	65	63	-2	102	106	-4	€ 36.308	€ 35.916	-1,1%

Based on the results in table 8, the logical consequence of smaller lot sizes is a decrease in warehouse utilization as shown in table 9. An overview of the difference in cost components for the scenario with a maximum lot size compared to the optimized solution of the developed model is given in table 9.

Table 9 – Costs uncapacitated situation (optimal) versus scenario with max lot sizes

	Overview of costs		
Cost component	*Optimal*	*Scenario*	*Diff*
Inventory costs	€ 36.310	€ 34.050	-6,2%
Administration costs	€ 1.305	€ 1.356	0,08%
Logistic costs	€ 16.311	€ 16.946	3,9%
Machine setup costs	€ 72.538	€ 82.636	13,9%
Total	**€ 126.464**	**€ 134.988**	**6,74%**

The introduction of a maximum lot size of 12 hours leads to a 6,7 % increase in total operational costs. This can be explained by the fact that relatively expensive lots to produce are calculated smaller than optimized. The second scenario introduced is the bounds on inventory in warehouses which is simulated in the next section.

6.3.2 Scenario with restrictions on warehouses

In this scenario, the restriction on the warehouses is simulated and the results are given in table 11. The taken restrictions on warehouses are shown in table 10. These values are based on the maximum values in m³ of starting inventory at the beginning of the planning horizon, this value holds during the total planning horizon.

Table 10 – Restrictions on warehouses in m³

Warehouse	Restriction [m³]
1TO	900
1MW	260
2MW	75
1SM	260
5WF	80

Table 11 – Difference between uncapacitated (optimal) and scenario with restrictions on warehouses

	Average utilization machine [%]			Occupation rate - setups [%]			Average lot size [hour]			Max lot size [hour]			#periods of overcapacity in N [days]		
Nr.	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*	*Opt.*	*Scenario*	*Diff*
02131	34%	35%	1%	16%	18%	2%	2,3	2,2	-0,1	11,9	10,9	-1,0	2	0	-2
02183	26%	27%	1%	10%	13%	3%	2,8	2,1	-0,7	10,1	9,3	-0,8	0	0	0
02251	43%	43%	0%	12%	16%	4%	3,4	2,9	-0,5	15,9	15,9	0	0	0	0
03601	86%	90%	4%	23%	27%	4%	3,8	3,1	-0,7	16,4	14,5	-1,9	5	7	2
03602	40%	42%	2%	16%	19%	3%	3,7	2,9	-0,8	15,0	13,5	-1,5	0	0	0
07691	62%	64%	2%	17%	20%	3%	2,4	2,0	-0,4	15,0	11,3	-3,7	0	0	0
07950	62%	64%	2%	14%	19%	5%	2,7	2,1	-0,6	10,9	10,9	0	0	0	0
16415	39%	39%	0%	14%	18%	4%	2,6	2,4	-0,2	11,0	9,8	-1,2	0	0	0
18358	77%	80%	3%	18%	22%	4%	4,9	4,0	-0,9	18,9	18,9	0	1	2	1

The average utilization rate of the machines increases on average with 2% in comparison with the optimized solution. The occupation rate regarding setups also increases on average with 4%. The average lot size on the machines decreases as well as the max lot sizes which have a positive contribution to the flexibility of the machines. The number of periods of overcapacity increases with one period. The performance indicators regarding the warehouses are given in table 12.

Table 12 – Costs uncapacitated (optimal) versus scenario with restrictions on warehouses

	Average Utilization [m³]			Max utilization [m³]			Average inventory [€]		
Warehouse	*Optimal*	*Scenario*	*Diff*	*Optimal*	*Scenario*	*Diff*	*Optimal*	*Scenario*	*Diff*
1TO	845	746	-99	1130	900	-230	€ 366.986	€ 292.222	-20,4%
1MW	151	153	2	254	254	0	€ 97.299	€ 100.067	2,8%
2MW	57	54	-3	87	75	-12	€ 35.812	€ 33.414	-6,7%
1SM	156	150	-6	303	260	-43	€ 71.649	€ 67.244	-6,1
5WF	65	57	-8	102	80	-22	€ 36.308	€ 30.419	-16,2%

The average utilization in warehouses significantly decreases, especially in the warehouse 1TO. The maximum utilization of the warehouses matches with the taken restrictions. The average inventory in Euros in the warehouses also decreases, this shall have a positive contribution the inventory costs are shown in table 13.

Table 13 – Costs uncapacitated (optimal) versus scenario with restrictions on warehouses

	Overview of costs		
Cost component	*Optimal*	*Scenario*	*Diff*
Inventory costs	€ 36.310	€ 31.190	-14,1%
Administration costs	€ 1.305	€ 1.520	16,5%
Logistic costs	€ 16.311	€ 19.043	16,8%
Machine setup costs	€ 72.538	€ 87.799	21,0%
Total	**€ 126.464**	**€ 139.553**	**10,4%**

The introduction of restrictions on warehouses as given in table 10 lead to a 10,4 % increases in total operational costs. This can be explained by the fact that in some periods, no optimized lot sizes can be produced because of any storage capacity available; therefore the optimal lot is split up in more lots to satisfy demand which lead to 21% more costs regarding setups.

6.4 Sensitivity analysis

In this section it is analysed how robust the model is by doing a sensitivity analysis. It is interesting to analyse how a change in the input parameters influences the output of the model. The two main cost parameters which could be changed are; setup costs of the machine and the inventory holding costs in the warehouses. As mentioned in the problem context of this report, the setup activities are a given based on the explicit request by the company under study. Therefore only a sensitivity analysis is conducted for the holdings costs, the space cost component is taken as change variable.

6.4.1 Sensitivity of holding costs

The results of the sensitivity analysis are given in table 14 and figure 24. The reference (1.0*SPACE) is modelled with both scenarios described in previous section; maximum lot size of 12 hour and with restrictions on warehouses as stated in table 10.

Table 14 – Sensitivity analysis based on the cost component SPACE

	Sensitivity SPACE costs			
Cost component	***0,5*SPACE***	***1.0*SPACE***	***1,5*SPACE***	***2.0*SPACE***
Inventory costs	€ 31.782	€ 30.105	€ 28.650	€ 27.127
Administration costs	€ 1.478	€ 1.505	€ 1.584	€ 1.652
Logistic costs	€ 18.470	€ 18.819	€ 19.832	€ 20.620
Machine setup costs	€ 93.811	€ 91.805	€ 93.833	€ 97.193
Total	€ 145.541	€ 142.234	€ 143.899	€ 146.592

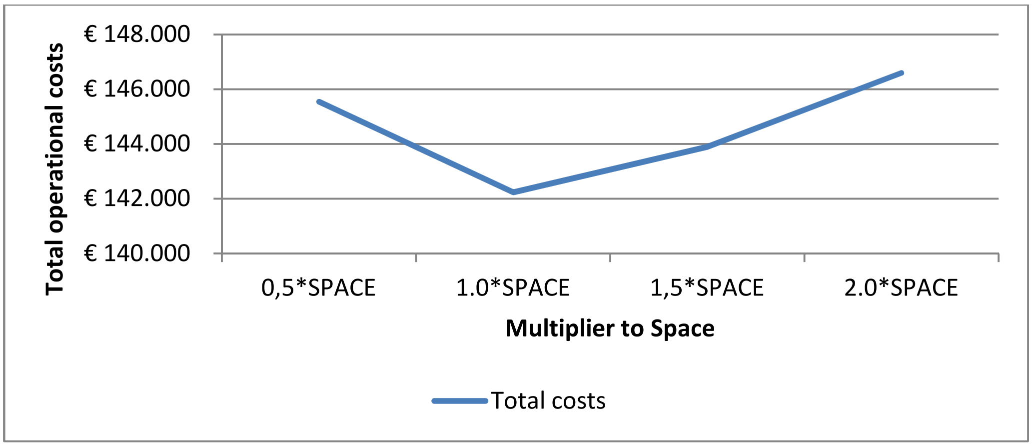

Figure 24 – Sensitivity analysis cost component SPACE, total operational costs function

Increasing the space costs result in on average smaller lots over the planning horizon, this is quite logical when looking to the trade off cost function. When multiplying the cost component with a factor 2, the total cost function shows a sensitivity of 3%.

6.4.2 Sensitivity of Demand rate

The results of the sensitivity analysis are given in table 15 and figure 25. The reference (1,0*Demand) is also modelled with both scenarios as described in section 6.5.1.

Table 15 – Sensitivity analysis based on the demand in the Press Shop

	Sensitivity Demand Press Shop				
Costs component	**0,8*Demand**	**0,9*Demand**	**1,0*Demand**	**1,1*Demand**	**1,2*Demand**
Inventory costs	€ 27.980	€ 29.129	€ 30.105	€ 23.229	€ 28.317
Administration costs	€ 1.189	€ 1.363	€ 1.505	€ 5.709	€ 5.147
Logistic costs	€ 14.935	€ 17.045	€ 18.819	€ 34.058	€ 63.638
Machine setup costs	€ 67.675	€ 80.017	€ 91.805	€ 122.517	€ 189.006
Total	€ 111.779	€ 127.554	€ 142.234	€ 185.513	€ 286.108

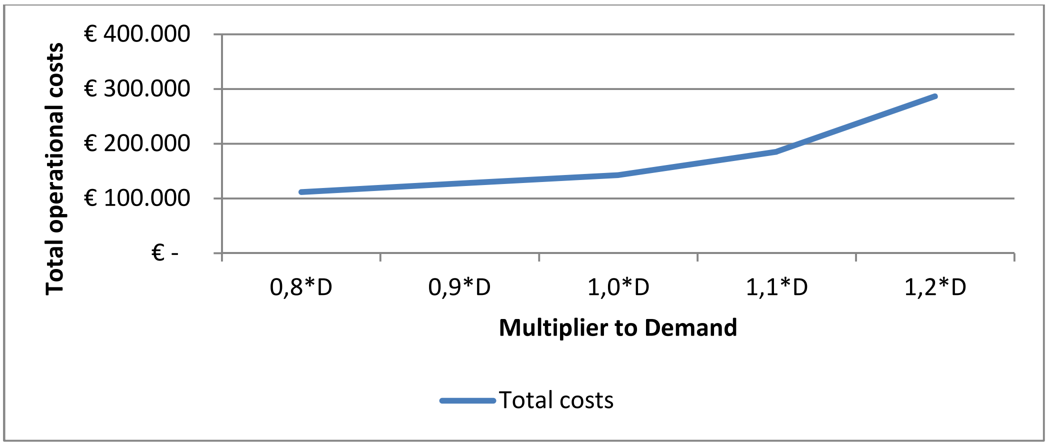

Figure 25 – Sensitivity analysis demand, total operational costs function

Decreasing the demand rate with 20% results in on average a decrease of 21,4% operational costs. When these costs are corrected for the demand decrease itself, the model tends to be insensitive for this decrease. On the other hand, an increase of the demand rate with 20% leads to a 101,2% increase in operational cost. After correction, the model tends to be sensitive for this increase. The reason for this is the decreased space for optimization (step 3) when increasing demand. Noted that the practical constraints are not changed during the analysis.

6.5 Conclusion

Research question 5, “What is the performance of the decision tool based on relevant KPI’s?” is answered in this chapter. The developed model gives in a run with no capacity and maximum lot size restriction a 30% better lot size suggestion than the DAF ERP system regarding costs. Based on this, it can be concluded that the average current lot sizes are too small. The introduction of a maximum lot size of 12 hours leads to a 6,7 % increase in total operational costs compared to the optimized solution. The introduction of the taken restrictions on warehouses leads to a 10,4 % increase in total operational costs. The sensitivity analysis show that the holding costs of inventory is insensitive for change. The model shows a sensitive behaviour when demand in increased with 20%.

7. Implementation plan

The lot size decision tool created in this study is provided to DAF Trucks N.V. in order to determine the lot sizes in the Press Shop based on a cost optimal solution. As shown in the case study, the optimized lot sizes deviate a lot from the current situation. As already mentioned in previous chapters, the planners could run the model every day with the input variables available within the company. However some points need to be done before the implementation of the decision tool can be started within the operational planning process. Therefore this chapter provides a plan for the first phase of the implementation of the decision tool. The practical performance of the decision tool needs to be further tested; this process will be described in section 7.1. Since every tool is confronted with some limitations, some improvement steps of the model are explained in section 7.2. The implementation of the tool itself is left out of this study, the last phase of the regulative cycle of van Strien (1997), because of time limitations as already mentioned in section 2.5 of the report.

7.1 Practical validation phase of the decision tool

In the case study, the developed decision tool is tested with data provided by the company on a time interval in the past. The first step in the implementation phase of the decision tool is validating the tool with recent demand in a practical environment. This means that the output suggestion of the model after step three is input for a logistic engineer to execute step 4 of the procedure. The output of this practical process can be compared to the practical output of the planning process by the material planners. This planning process needs to be monitored because this information is lost in the system when the orders are really manufactured. This monitoring needs to be done for all items in the Press Shop because of interrelationship between items and machines.

The second point which needs to be done is a small research on the accuracy of the most important input data, the demand pattern. The demand in the Press Shop suffers from uncertainty. Items which are delivered directly to the assembly line have a small total throughput time in comparison with sub items which are needed for the subassembly of cabins in for example Westerlo. The moment that the orders have to be set in the system can lie before the OFTF period as described in section 3.1.2. It could be possible that demand will fluctuate for a couple of reasons and therefore some demand is already set in production while it is based on some forecasting error. The results of this analysis gives us also an impression about the frequency of executing the model. When the fluctuation of the demand pattern is very low, the model can be executed for example every week. But when the demand pattern is very sensitive for changes, the model should be run frequently. This last point is crucial for the success rate of the developed tool.

7.2 Improvements of the decision tool

Ending the research here would furthermore not lead to practical and satisfactory recommendations for the whole company under study. The developed decision tool gives reasonable solutions but some issues needs to be improved after the practical validation phase for the success rate and practical usage in the Sheet Metal Component Plant:

- Extension to more departments; the model is now built for the Press Shop but can relatively easily be extended to all departments in the SMCP. This is needed because the incorporated warehouses are interconnected to all production departments and therefore needs to be incorporated in the decision making process of lots to get a representative and applicable total solution.

- Improve the run time of the model; the run time of the model is on a Pentium PC with i3 processors and 64MB more than 10 hours for one department, the Press Shop. First this can be improved by making the VBA code more efficient. Figure 26 shows that a big part of the running time can be improved by restriction of the number of iterations. After two of three iterations, the improved of the objective function is less than 0.2 % for this example. Second the run time can significantly be improved by using another software package to write the algorithm, for example C++.
- Develop a check for the input data, the user has to be aware of the input data. All input data have to be up to date because the lot size decision tool is only successful when all input data is accurate. A check on this is very useful to prevent for imbalances.
- Translate the output of the model into system input for DAF Trucks N.V.; the output of the model can be used in different ways, first the output of the model can be translated to the control variables in the main system of DAF, section 3.1.4. Second and more effective is to make a work around which takes input from the main system, the stand alone model calculates the optimized production schedule and put this whole schedule back in the main system after permission of the material planners.

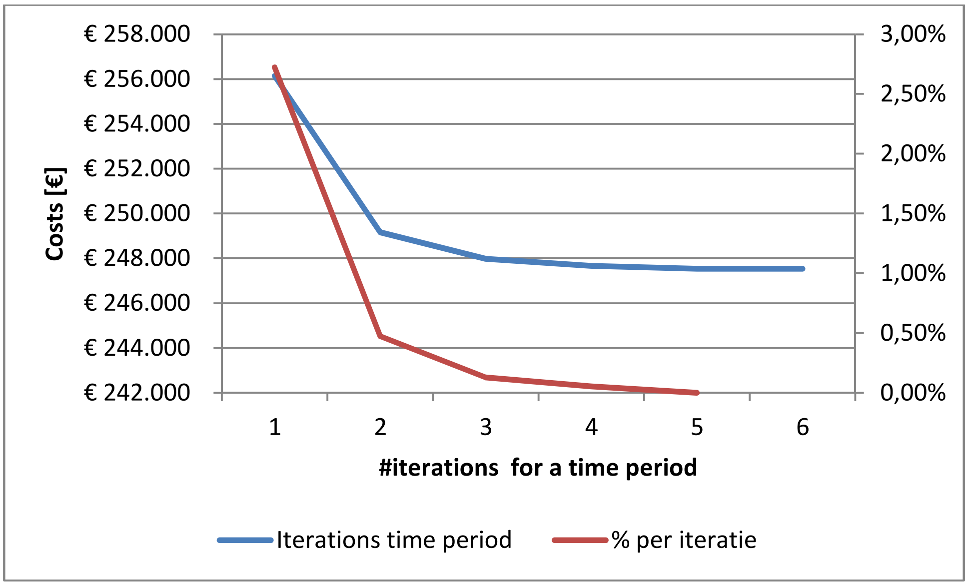

Figure 26 – Performance of the algorithm after every iteration.

8. Conclusions and recommendations

In this chapter the most important conclusions from this report are given. The central research assignment during this project was written as: "*Develop a lot size supporting tool that minimizes the relevant operational costs with the following company characteristics taking into account:*

- *Complex job shop environment.*
- *Capacitated machines.*
- *Limits on capacity in warehouses.*
- *Significant setup times*

In order to achieve this goal a main research question was formulated supported by five sub questions which will be answered in section 8.1. In section 8.2, practical recommendations are given for the company under study. Furthermore the theoretical contribution to literature is given in section 8.3. Finally some advice for future work is defined in section 8.4.

8.1 General Conclusions

The following conclusions are given based on the five sub questions as formulated in the beginning of this research.

1) Which parameters play a role in the decision making process of lots, and what are the characteristics of these input variables within the company under study?

The most important parameter which plays a key role in the process of determining lot sizes is the nature of demand. The variability coefficient (VC) is used to characterise the demand in the company under study. When this value is above 0.2, it can be characterised as dynamic demand. 64% of the demand within the company is above this threshold value so dynamic demand is assumed. Besides the nature of demand, important issues related to the demand are determined in this project: the length of the planning horizon is 35 days, the size of the time bucket is one day which is quite common in the automotive industry, and the number of end products is 450 items with a single level structure. Other important input variables in the decision making process of lot sizes are: unit processing times, setup times, volumes, prices and the safety lead times of the items. All the 450 items have their unique item characteristics which are handled as unique input in the developed decision tool. Granularity of the decision tool is able to manage the uniqueness of the 450 items.

2) What are the relevant cost drivers which influence the lot size decision?

The lot size decision is based on a trade-off between fixed costs per lot and the inventory holding costs. The fixed costs are costs independent of the size of the replenishment. This is separated in three categories; setup costs of the machine, transportation of the lot and the administration of the lot in the warehouses. The setup costs of the machine incorporate all activities which are needed to produce the product with the right specifications. The transportation of the lot is dependent on the product and the end stage of the item. Administration is independent of the item itself.

The inventory cost, also known as holding cost is separated in three categories; interest, risk and space. The interest is the opportunity costs of capital tied up that otherwise could be used elsewhere in the organization. The interest rate used within this study is 8%. The risk is the degree of risk inherent in the investment in lots; the used rate is 5%. The inventory holding costs also depends on the costs to store the lot. This storage costs include; depreciation, Maintenance and cleaning, Costs of energy, Insurance and the workforce in the warehouses. The storage costs calculated in this study are 512 €/m³/year.

3) What are feasible heuristics that deal with the characteristics found?

The first research for the economic order quantity was done in 1913 by Camp. He developed the EOQ formula. This formula is widely used in practice and in contrast with our problem area assumes constant demand. The Silver Meal or Least Period Cost heuristic is a single item, forward looking approach. This method is the counterpart of the EOQ formula and selects a dynamic replenishment quantity based on the total relevant cost per unit time and no restrictions are taken into account. The paper of Iris et al. (2012) focuses on how to obtain a multi-item dynamic lot sizing strategy with production and warehouse capacities with different storage allocation policies in a manufacturing environment. This model takes one machine and with their neighborhood approach, no significant setup times into account which is one of our relevant company characteristics. A four step approach is developed by the author which incorporates both restrictions on machines and warehouses. The way of calculating is mathematical optimization based on the selection of a best element taken from a set of available alternatives.

4) How can the developed heuristic be incorporated in a decision tool?

The developed algorithm is implemented in a decision tool with the developed four step approach. The first step puts an initial solution of the lots into the model with an easy to implement Lot for Lot rule; this is a solution where no restrictions are taken into account. Since lot for lot may produce an infeasible solution to machine capacities, step 2 is developed to make the production schedule feasible before we can start with the optimization step. This feasibility step incorporates only machine capacities, a smoothing mechanism is adapted. Transferring a lot backward in the time horizon results in a cost change of the objective function. Based on the maximum cost reduction, transactions are executed. After the feasibility step, the production schedule can be optimized. A forward looking approach with complete enumeration is conducted. This heuristic starts by checking for every item in a specific period the feasibility and the improvement of the objective function. All these possible executions of lots are placed in a transfer list. When all combinations are checked, transactions are executed based on the largest improvement of the objective function. This process is an iterative process and results in a near optimal schedule with dynamic production lots. After the optimization step, no positive contribution to the objective function is possible. But based on the practical environment of the production schedule, two practical procedures can be executed with step 4 of the developed procedure. First the lot sizes can be roundup by some practical issues like packaging units or a fixed size of sheet metal. Second some used capacity can be transferred to another period to smoothen the total used capacity over the planning horizon.

5) What is the performance of the decision tool based on relevant KPI's?

The developed decision tool is tested with a case study. The Key Performance Indicators used to measure the performance of the lot size decision tool are separated in three groups; performance indicator for the machines, performance indicators for the warehouses and the main performance indicators based on relevant operational costs. The solutions calculated by the developed model are compared with the current situation based on the relevant KPI's. The developed model gives in a run with no capacity and maximum lot size restriction a 30% better lot size suggestion than the DAF ERP system regarding costs. Based on this, it can be concluded that the average current lot sizes are too small. To increase the flexibility of the production process a maximum lot size is introduced in the decision process of lots. The introduction of a maximum lot size of 12 hours lead to a 6,7 % increase in total operational costs compared to the uncapacitated solution. The introduction of restrictions on warehouses lead to a 10,4 % increase in total operational costs. This can be explained by the fact that in some periods, no optimized lot sizes can be produced because of any storage capacity available. Based on these results, the overall conclusion is that both restrictions increase the operational costs. Nevertheless the positive contribution of the restrictions is not yet expressed in money. This is one of the practical recommendations which are explained in the next section.

8.2 Practical recommendations

Based on the analysis and findings of this report some practical recommendations are given.

- Run more scenarios to get a better impression of the introduced restrictions; these scenarios could consist of predefined workforce schedules, incorporating preventive maintenance schedules and incorporating flexible warehouse capacity in the model to further investigate the effect of sizing storage availability.
- Based on the results of the practical validation phase, first implement the decision tool based on the calculated decision variables in the main system of DAF Trucks N.V. After this process, investigate the possibilities for the design of a standalone software package.
- Start a research project to sequence dependent setup times within the Press Shop, this is essential to succeed in practice with the developed model.
- Integrate the supply chain approach model of Grolleman (2012) with the lot size decision tool developed in this study. Further investigate if this model is applicable for the other production units within the supply chain of DAF Trucks N.V. A graphical picture is given in figure 27.
- Investigate the feasibility to extend the concept to other factories within the DAF supply chain, for example the Engine Factory in Eindhoven.
- Finally, make somebody responsible for the model. To succeed this project the model has to be owned by a person who strives for final implementation.

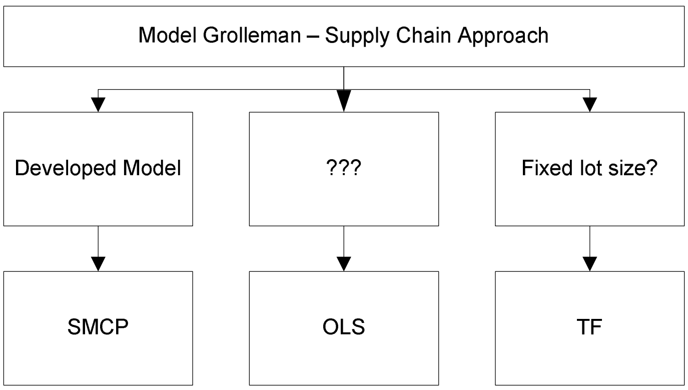

Figure 27 – Position of the developed lot sizing models within the model hierarchy

8.3 Theoretical contribution

The main theoretical contribution of this research is in general a contribution to the literature which incorporates warehouses in the decision making process of lot sizes in a make-to-order production environment. In many practical applications, multiple items do not only compete for manufacturing capacities related to machines but in addition for limits on available inventory in the warehouses in the manufacturing supply chain. Furthermore in the literature of capacitated lot sizing with limited storage capacity, items are taken as Stock Keeping Units (SKU's), so limits on inventory are calculated with integer numbers instead of the physical volumes of items. In this research, an extensive analysis is conducted where the physical volume of items is taken central in the decision making process. The results presented in this research bring the problem scenario more realistic to the dynamic manufacturing environment of today.

Regarding the paper of Iris et al. (2012), the author of this report extended the usability to the make-to-order environments with significant setup times in their processes. Furthermore the model can be used in a multi machine arrangement. In the paper of Iris et al. dominance properties were leading in the decision which lot to transfer to a specific period. In the developed model by the author, the objective function is leading in the decision making process of transferring lot over the planning horizon.

8.4 Future research

The following topics could be considered in further research:

- Research on capacitated transportation in the lot size decision.
- Research on the procedure of roundup on lot sizes for efficiency reasons.
- Research on capacitated lot size decisions with extreme dynamic demand in a make-to-order environment.

References

Aken, J.E. van, Berends, H., Bij, H. van der, (2006), Problem Solving in Organizations: A methodological handbook to business students, Technische Universiteit Eindhoven, Eindhoven.

Atamtürk A., Kücükyavuz S. (2005). Lot sizing with inventory bounds and fixed costs: polyhedral study and computation. *Operations Research, 53(4), pp. 711-730*

Coppens T.M.M. (2013) Literature study, Lot sizing with capacitated production and limited warehouse capacity in a dynamic production environment.

DAF Trucks N.V. (2013). *Webportal*

DAF Trucks N.V. (2012), Annual Report

Dijkman R. (2013). Lecture sheets Data & Process mining, *TUe*

Ellram, L.M., Maltz, A.B. (1995). The Use of Total Cost of Ownership Concepts to Model the Outsourcing Decision, *The International Journal of Logistics Management, 6(2), pp. 55-66*

Grolleman, M. (2012). Batch Size Decision in the DAF Supply Chain.

Haris, F.W. (1913). *What quantity to make at once.* Factory, the magazine of management Series, 10(2), pp. 150-181.

Iris C., Yenisey M.M. (2012). Multi-item Simultaneously Lot Sizing and Storage Allocation with Production and Warehouse Capacities. *ICCL, LNCS 7555, pp. 129-141*

Karimi B., Fatemi Ghomi S.M.T., Wilson J.M. (2003). The capacitated lot sizing problem: a review of models and algorithms. *Omega, 31, pp. 365-378*

Lee M.K., Elsayed E.A. (2012). Optimization of warehouse storage capacity under a dedicated storage policy. *International Journal of Production Research, 43(9), pp. 1785-1805*

Minner S. (2008). A comparison of simple heuristics for multi-product dynamic demand lot-sizing with limited warehouse capacity. *International Journal of Production Economics, 118, pp. 305-310*

Robinson P., Narayanan A. and Sahin F. (2009). Coordinated deterministic dynamic demand lot sizing problem: A review of models and algorithms. *Omega, 37(1), pp. 3-15*

Silver, E.A., Pyke, D.F. and R. Peterson (1998). Inventory Management and Production Planning and Schduling. Wiley, New York.

List of concepts

Production utilization:	The production utilization described the amount of time the machine is busy with the production of items. Other states of the machine could be for example setup time, maintenance time or idle time.
Best Point of Use:	This is the location in the manufacturing cell or at the assembly line that is optimal for the user (operator) of the material.
Pull System:	Pull systems ensure that the signal to supply new materials or start-up a new process comes in at exactly the right time, so that material is available at the time of consumption by the customer, regardless of the fact that production may be ahead of or behind schedule at that particular point in time.
Mainframe:	Planning program DAF Trucks N.V. (ERP system)
Lot size	Synonym for batch size, the amount of items which you can put through an order.
Occupation rate setups	Part of the utilization rate which is used for the setup process. This occupation rate is an indicator for the efficiency of the production schedule.

Contents

Appendix A – Axle and cabin configuration DAF Trucks N.V.

Rigid chassis		LF45	LF55	CF65	CF75	CF85	XF105
FA 4 x 2		•	•	•	•	•	•
FAR 6 x 2	single mounted trailing axle				•	•	•
FAS 6 x 2	dual mounted trailing axle				•	•	•
FAG 6 x 2					•	•	
FAN 6 x 2			•		•	•	•
FAT 6 x 4					•	•	•
FAK 8 x 2	dual mounted trailing axle					•	•
FAQ 8 x 2						•	
FAC 8 x 2	dual mounted trailing axle					•	
FAX 8 x 2						•	
FAD 8 x 4					•	•	•

Tractor chassis		LF45	LF55	CF65	CF75	CF85	XF105
FT 4 x 2			•		•	•	•
FTP 6 x 2						•	•
FTR 6 x 2	single mounted trailing axle					•	•
FTS 6 x 2	dual mounted trailing axle					•	•
FTG 6 x 2						•	•
FTT 6 x 4						•	•
FTM 8 x 4							•

steered axle driven axle trailing axle

Figure A1 – Layout Sheet Metal Component Plant

		Day Cab	Sleeper Cab	Space Cab		Super Space Cab		Engine Euro 5 / EEV
LF45								FR103 / 140 hp FR118 / 160 hp FR136 / 185 hp FR152 / 207 hp GR165 / 224 hp GR184 / 250 hp
LF55								FR136 / 185 hp FR152 / 207 hp GR165 / 224 hp GR184 / 250 hp GR210 / 286 hp
LF55 18t								GR165 / 224 hp GR184 / 250 hp GR220 / 300 hp
CF65								GR165 / 224 hp GR184 / 250 hp GR220 / 300 hp
CF75								PR183 / 249 hp PR228 / 310 hp PR265 / 360 hp
CF85								MX265 / 360 hp MX300 / 408 hp MX340 / 462 hp MX375 / 510 hp
XF105								MX300 / 408 hp MX340 / 462 hp MX375 / 510 hp

Figure A2 – Layout Sheet Metal Component Plant

Appendix B – Detailed research approach

For the investigation of the process under study, the student interviewed employees, did some observations and read some documents which were available within DAF Trucks N.V. If the student found some limitations during this process regarding literature, a follow-up of the literature study was performed.

The source of data, which was needed for the first step in the project, was the software package "Mainframe" which incorporates all present and historical data that is logged in the production process. After data collection, the data was analyzed in depth. This analysis is supported with some data mining techniques found in literature (Dijkman, 2012). After some general statistical analysis, some more extensive techniques were used. One of the available data mining techniques was k-means clustering; this technique might result in some relevant matrices for classification. There is some classification done based on demand and available space at the assembly line in the TF (section 1.3.1), but items also differ in their volume, setup time and unit price which was important information for the next step in the project, investigation of relevant cost drivers. The data is finally classified with an outlier analysis.

The cost drivers found in literature were already present within DAF; other relevant cost drivers related to the lot size decision were explored in sub question 3 of this study. The student interviewed employees from the financial department to discuss these statements. A good starting point was the structure of the calculated cost price of the product. The main cost driver as already mentioned in section 3.3 was the volume of the product as dependent factor. This volume of the item has also impact on the utilization rate of the warehouse which is a constraint in the development phase of the decision tool.

The heuristics found in the literature study were the starting point of this sub question. Further investigation for suitable heuristics is continued after the classification of demand and the calculated utilization rate for the chosen machine(s). The way of calculation and optimization need to be investigated by analyzing the collected heuristics in combination with the process parameters explored in question 2 of this research assignment. The next step was the implementation of the heuristic in a decision tool in excel (sub question 5). The student already knew basic elements of the VBA programming languages used in excel.

The developed decision tool is tested and validated. First, the calculated lot sizes are compared to the current batch size used by the planning system. This gave insights in the differences and therefore consequences of the developed model can be analyzed. Furthermore a sensitivity analysis (Morris analysis) is conducted to get insights in the sensibility of the input parameters (for example the cost drivers). After that, conclusions and recommendations are made followed by opportunities for further research.

Appendix C – Sequence dependent setup times

Sequence dependent setup times:

1. To products which are produced by one process step of the machine, these parts are produced in equal amounts.
2. Products which have to be made in sequence, these parts can be produced in different amounts.
3. Products which have t be made in a cyclic order, the tool needed for both product need some time to make some changes.

The used tool to correct for setup time is provided by the financial department. This tool is built in excess and consists a list of all items which have some sequence dependent setup time.

Appendix D – Layout DAF Trucks N.V.

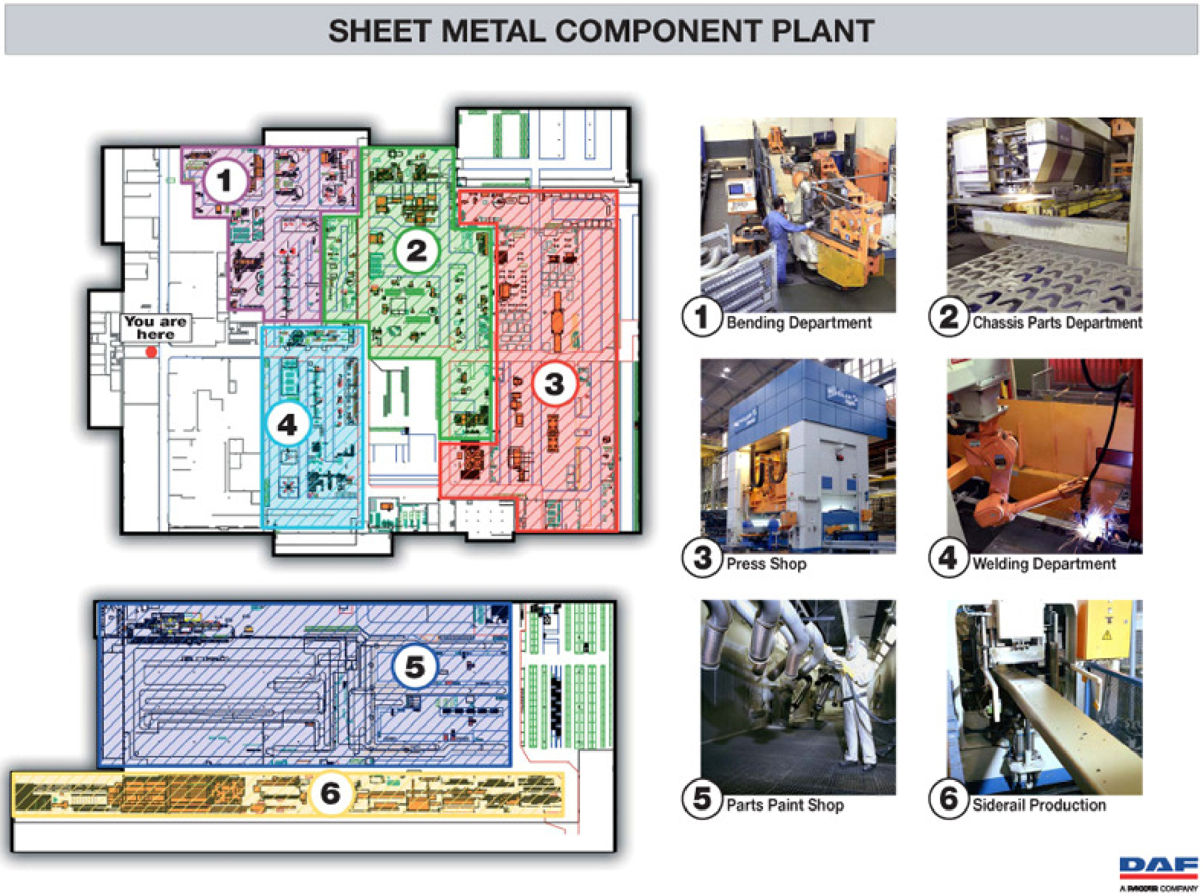

Figure A3 – Layout Sheet Metal Component Plant

Appendix E – Stamping machines Press Shop

Table A1 – Characteristics machines Press Shop department

Number	Supplier	Working-principle	#operators		Pressure [ton]
			MIN	MAX	
3601	Müller	Hydraulic	4	9	2000
3602	Müller	Hydraulic	4	9	2000
18358	Schuler-SMG	Hydraulic	4	6	1800
7691	SMG	Hydraulic	2	5	900
7950	Emanuel	Hydraulic	2	2	400
2251	Krupp	Mechanic	2	2	300
2131	Müller	Hydraulic	2	4	250
2183	Krupp	Mechanic	1	1	200
16415	Schoen	Hydraulic	2	4	200

Appendix F – Occupation rate warehouses

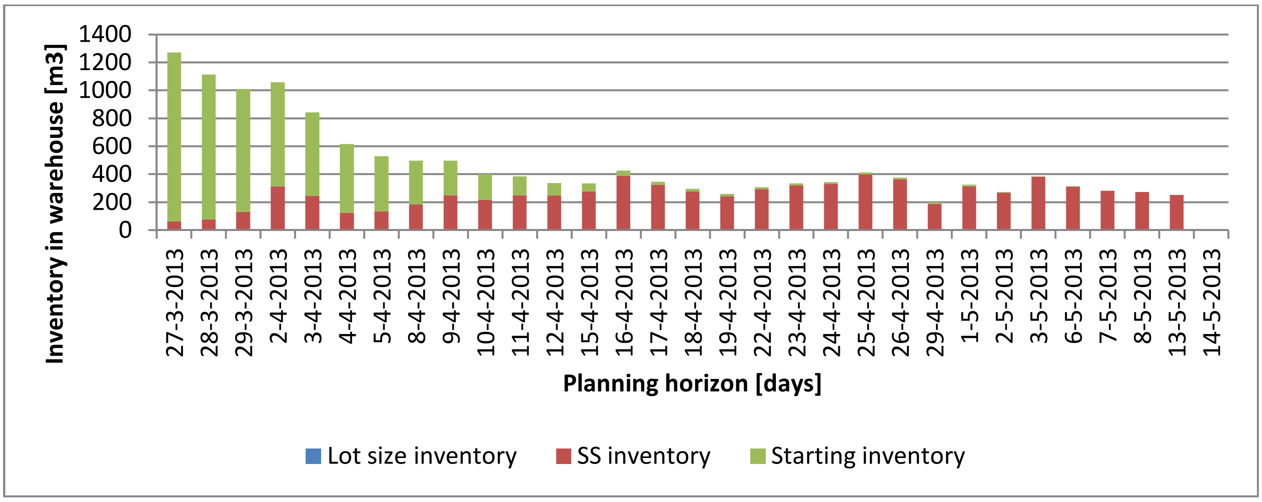

Figure A4 – Occupation rate warehouses, no lot size inventory available

Appendix G – Determining safety lead times

Table A2 – Matrix to determine safety lead times

Interne doorlooptijd YL-98 delen										
YL	1	2	3	4	VRDVEIDAG	ADMDLTDAG	MAGDLTDAG	INSDLTDAG	NBWDLTDAG	EXTDLTDAG
98	PKF/1VM	1MW			0	0	1	0	0	0
98	PKF/1VM	2MW			0	0	1	0	0	0
98	PKF/1VM	5CU			0	0	1	0	0	0
98	PKF/1VM	6MW			0	0	2	0	0	0
98	PKF	1LO	EC	1MW	0	0	0	0	1	0
98	PKF	1LO	EC	2MW	0	0	0	0	1	0
98	PKF	1LO	EC	5CU	0	0	1	0	1	0
98	PKF	1LO	EC	6MW	0	0	2	0	1	0
98	PKF	1LO	Aflak	1MW	0	0	1	0	2	0
98	PKF	1LO	Aflak	2MW	0	0	1	0	2	0
98	PKF	1LO	Aflak	5CU	0	0	1	0	2	0
98	PKF	1LO	Aflak	6MW	0	0	2	0	2	0
98	PKF	1OB	EC		0	0	1	0	-1	0
98	PKF	1OB	Aflak		0	0	1	0	-1	0

98	PKF	2VZ	Loa-lak	2MW	0	0	1	0	7	0
98	PKF	2VZ	Erogal	2MW	0	0	1	0	10	0
98	PKF	2VZ	Thermamax	1MW	0	0	2	30	0	0
98	PKF	2VZ	Thermamax	5CU	0	0	2	30	0	0

Interne doorlooptijd YL-99 delen										
	1	**2**	**3**	**4**	**VRDVEIDAG**	**ADMDLTDAG**	**MAGDLTDAG**	**INSDLTDAG**	**NBWDLTDAG**	**EXTDLTDAG**
99	PKF	1LO	EC	1VM	0	0	1	0	1	0
99	PKF	1LO	EC	1MW	0	0	1	0	1	0
99	PKF	1LO	EC	2MW	0	0	1	0	1	0
99	PKF	1LO	Aflak	1VM	0	0	1	0	2	0
99	PKF	1LO	Aflak	1MW	0	0	1	0	2	0
99	PKF	1LO	Aflak	2MW	0	0	1	0	2	0

Appendix H – Mainframe parameters for determining lot sizes

Figure A5 – Screenshot mainframe with control parameters for lot sizes

Appendix I – VC values demand Press Shop

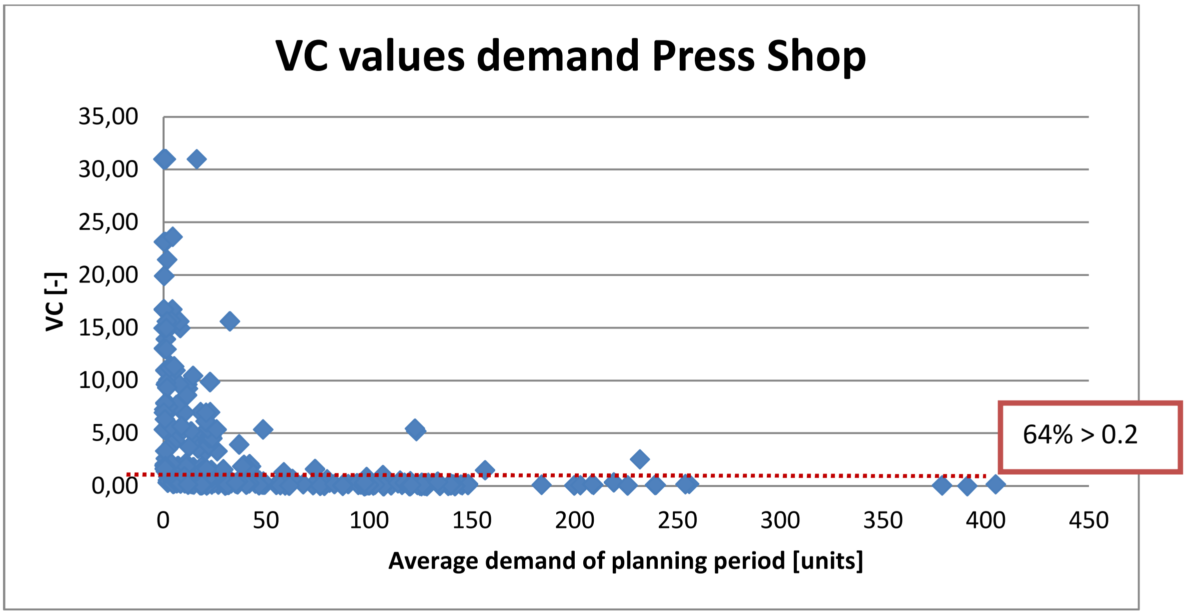

Figure A6 – VC values 450 items Press Shop

Appendix J – Boxplot input data

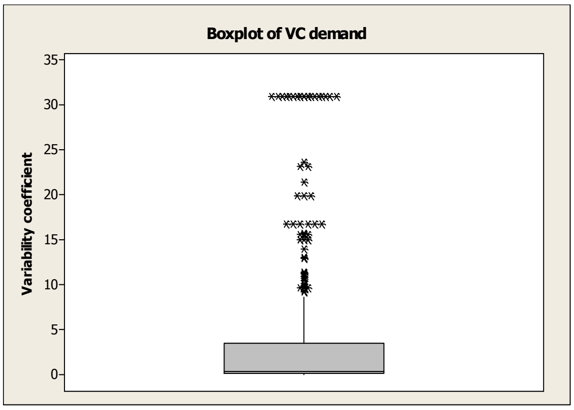

Figure A7 – Box plot VC demand

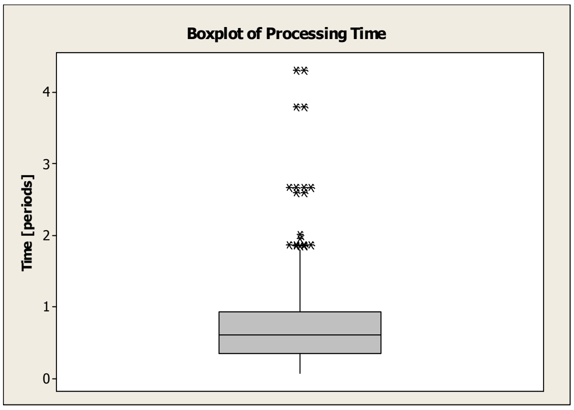

Figure A8 – Box plot processing times

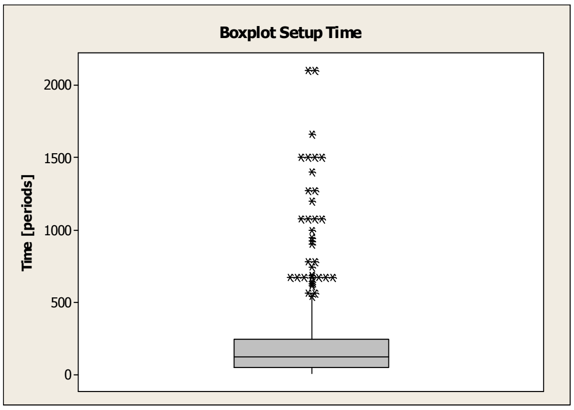

Figure A9 – Box plot Total setup times items

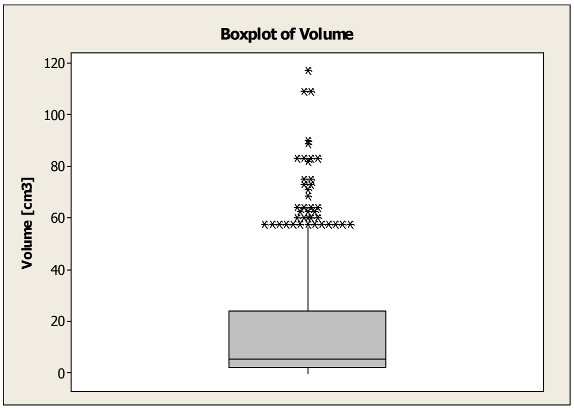

Figure A10 – Box plot Volume of items

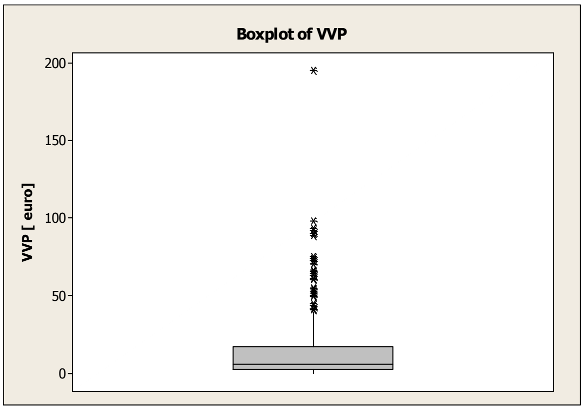

Figure A11 – Box plot VVP

Appendix K – Setup time per machine – Outlier analysis

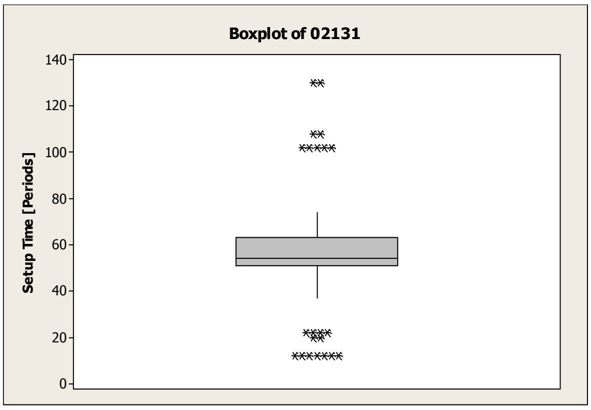

Figure A12 – Box plot setup time 02131

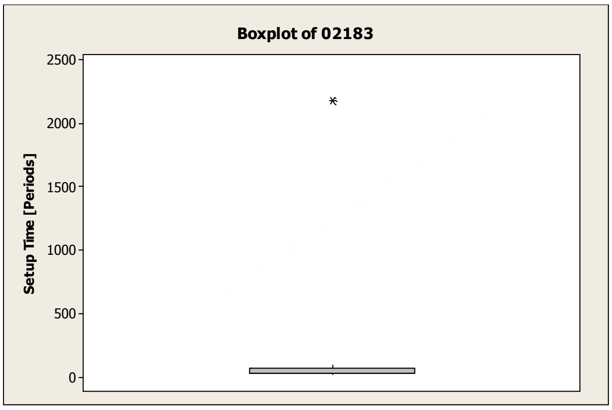

Figure A13 – Box plot setup time 02183

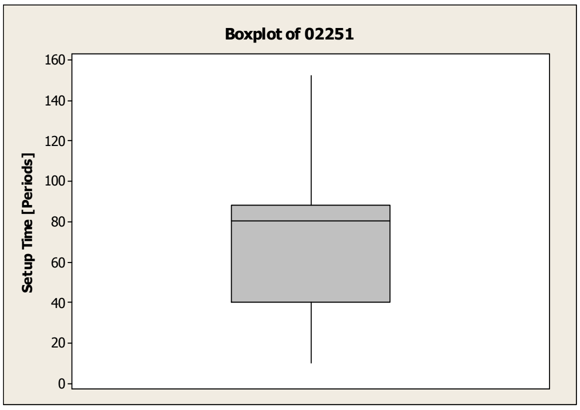

Figure A14 – Box plot setup time 02251

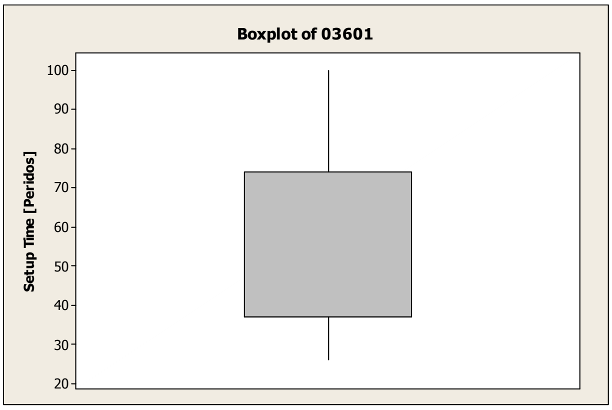

Figure A15 – Box plot setup time 03601

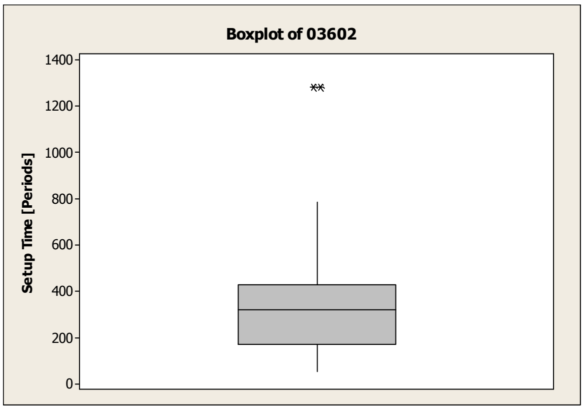

Figure A16 – Box plot setup time 03602

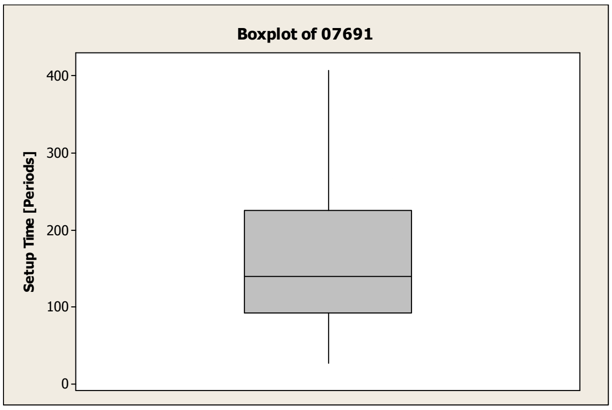

Figure A17 – Box plot setup time 07691

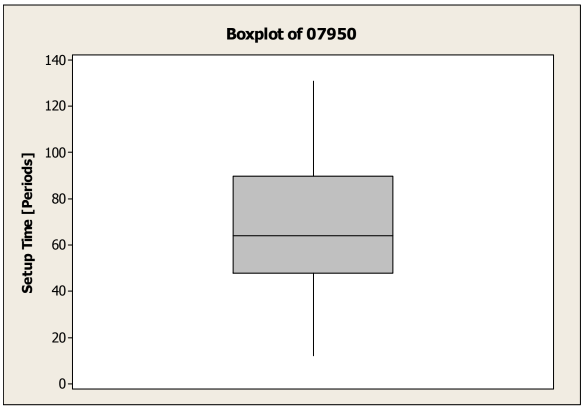

Figure A18 – Box plot setup time 07950

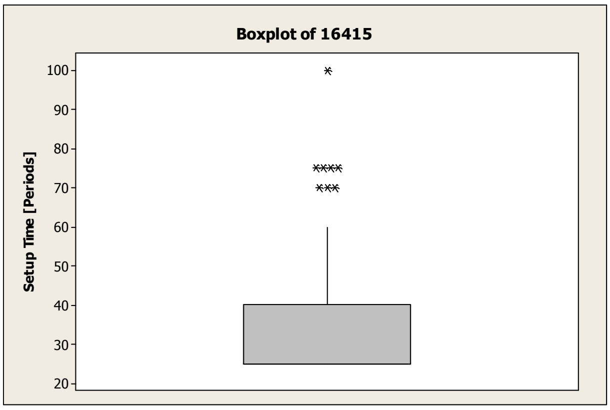

Figure A19 – Box plot setup time 16415

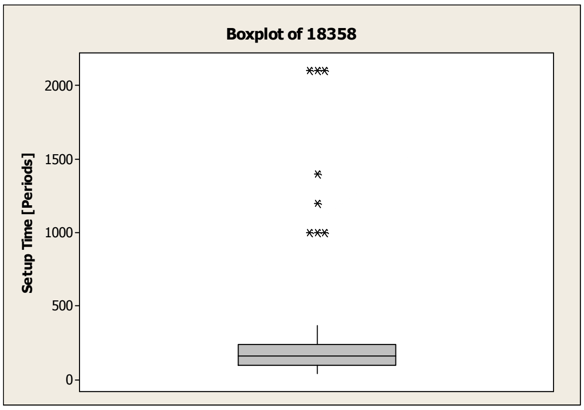

Figure A20 – Box plot setup time 18358

Appendix L – Ratio A/r

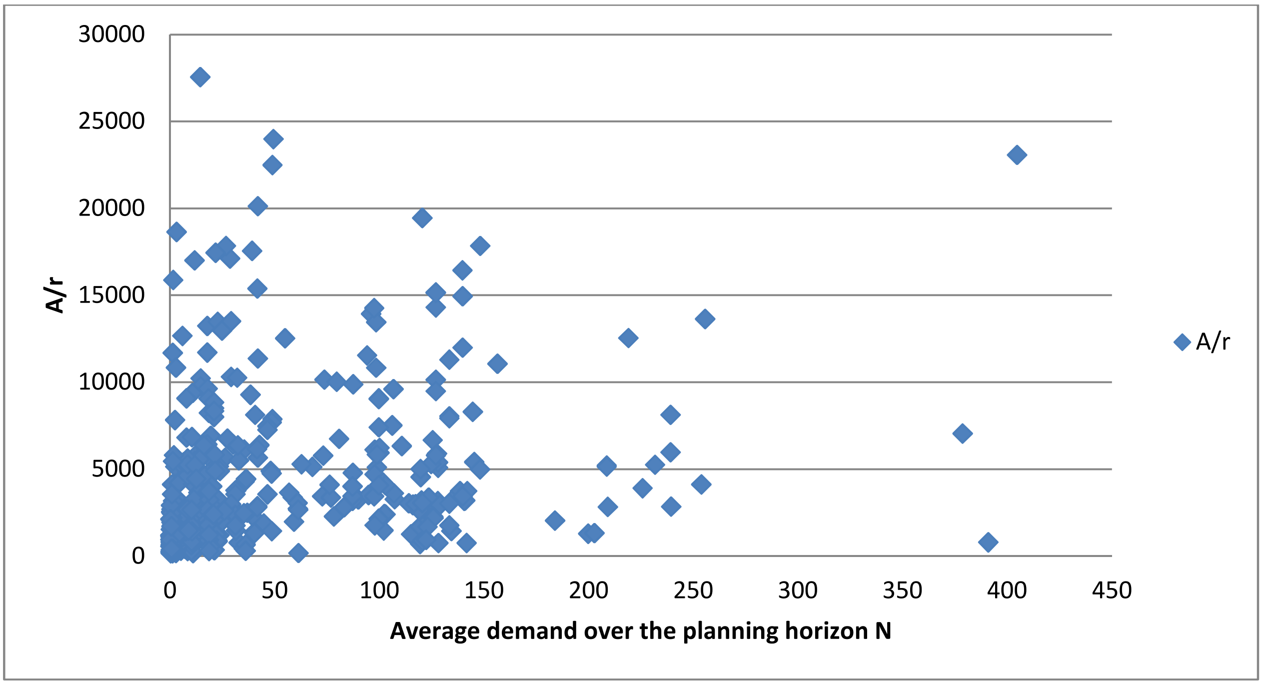

Figure A21 – Average demand versus ratio A/r

Appendix M – EOQ formula

Assumptions EOQ formula:

- Yearly demand is deterministic, constant and continuous.
- No capacity on production and storage.
- Setup cost and holding cost are deterministic over time.
- The batch size does not need to be an integer number.
- Zero lead time is considered.
- No shortages are allowed.
- Two relevant cost factors; holding cost and setup cost.

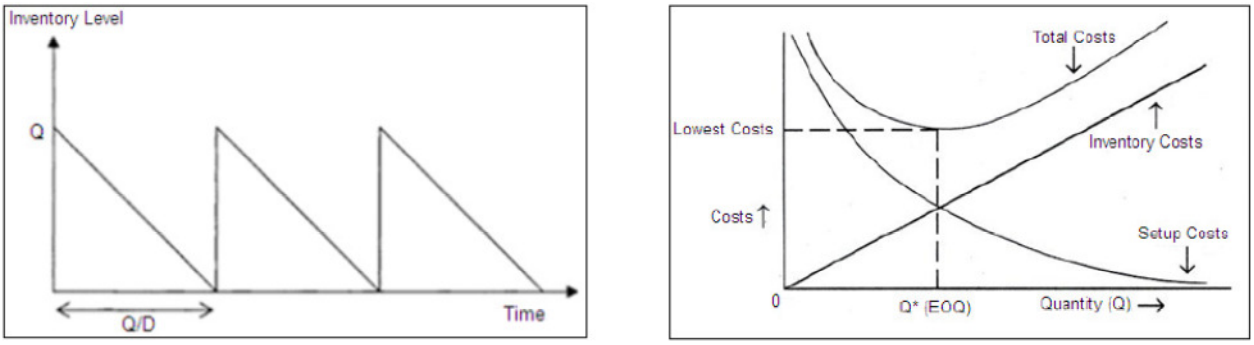

Figure A22 – Behavior inventory and cost function EOQ

The next cost function consists of fixed setup costs A dependent on the setup frequency D/Q and the variable holding cost h.

$$C = \frac{D}{Q} * A + \frac{Q}{2} * h$$

The term Q/2 is the average stock with holding costs h per year. The inventory level will vary over time as shown in the figure below.

Differentiating the cost function with respect to Q results in the classical EOQ formula as shown below:

$$EOQ = \sqrt{\frac{2*A*D}{h}}$$

Appendix N – Heuristics dynamic demand

There are a lot of heuristics which deals with dynamic demand. In literature, there are essentially three approaches when dealing with the case of a deterministic, time varying demand pattern:

- *Use of the basic economic order quantity.* This is a very simple approach. Use of a fixed EOQ based on the average demand rate out of the horizon, anytime a replenishment is required. As would be expected, this approach makes sense when variability of the demand pattern is low; that is the constant demand rate assumption of the fixed EOQ is not significantly violated.
- *Use of the exact best solution to a particular mathematical model of the situation.* As we will see, under a specific set of assumptions, this approach, known as the Wagner-Whitin algorithm, minimizes the total of certain costs.
- Use of an approximate or heuristic method. The idea here is to use an approach that captures the essence of the time-varying complexity but at the same time remains relatively simple for the practitioner to understand, and does not require lengthy computations.

Now we will explain some simple heuristic approaches for a significant variable demand pattern (VC value greater than 0.2).

1. **Silver-Meal heuristic**

The Silver Meal or Least Period Cost heuristic is a single item, forward looking approach. This method is the counterpart of the EOQ formula and selects the replenishment quantity based on the total relevant cost per unit time for the duration of the replenishment quantity are minimized. If replenishment arrives at the beginning of the first period and it covers requirements through to the end of the *T*th period, then the criterion function can be written as:

$$\frac{(Setup\ cost) + (Total\ carrying\ costs\ to\ end\ of\ period\ T)}{T}$$

2. **The Economic Order Quantity Expressed as a Time Supply**

The EOQ expressed as time supply is a slightly different method. This method uses the average demand over the period, namely:

$$T_{EOQ} = \frac{EOQ}{D_{avg}} = \sqrt{\frac{2 * A}{D_{avg} * h}}$$

The result of this formula is rounded to the nearest integer greater than zero. Then, the replenishment of the item is large enough to cover exactly the requirements of this integer number of periods.

3. **Lot-for-Lot (L4L)**

The easiest approach found in literature is the lot for lot replenishment rule. This method simply orders the exact amount of items needed for each period. Thus inventory holding costs are zero in this case. This method is commonly used as initial solution in more complicated optimization procedures.

4. Least Unit Cost (LUC)

The Least Unit Cost heuristic is identical to the Silver Meal heuristic accept that it accumulates when the cost per unit time increases. A disadvantage of this method is some sub optimisation.

5. Part Period Balancing

This lot sizing rule is based on selection of the number of periods covered by the replenishment such that the total carrying costs are made as close as possible to the setup cost. Refinement of the part-period balancing method requires more computational effort. One refinement is called a look-ahead / look-back technique. The look-ahead technique evaluates the cost of moving an order later in time.

Vollmann, whybark and Berry (1992) investigated that replenishments based on batch sizes in days instead of pieces is a procedure to reduce holding cost in a dynamic environment. To produce in days means that the lot sizes are also dynamic. The described heuristics have been tested against the Wagner-Within algoritm, the EOQ and other heuristics on a wide range of examples. But none of these heuristics takes capacity constraint into account.

Appendix O – Assumptions Silver Meal heuristic

1. Demand rate is given in the form of D_j to be satisfied in period j (j = 1, 2, …., N) where the finite planning horizon is at the end of period N.
2. The entire requirements of each period must be available at the beginning of that period.
3. The unit variable cost does not depend on the replenishment quantity; in particular, there are no discounts in either the unit purchase cost or the unit transportation cost.
4. The cost factors do not change appreciably with time; in particular, inflation is at a negligible low level.
5. The items are treated independently of other items; benefits from joint setup structures do not exist or are ignored.
6. The replenishment lead time is known with certainty.
7. No shortages are allowed.
8. The entire order quantity is delivered at the same time.
9. For simplicity it is assumed that the carrying cost is only applicable to inventory that is carried over from one period to the next.

Appendix P – Framework for classification of the lot sizing problem

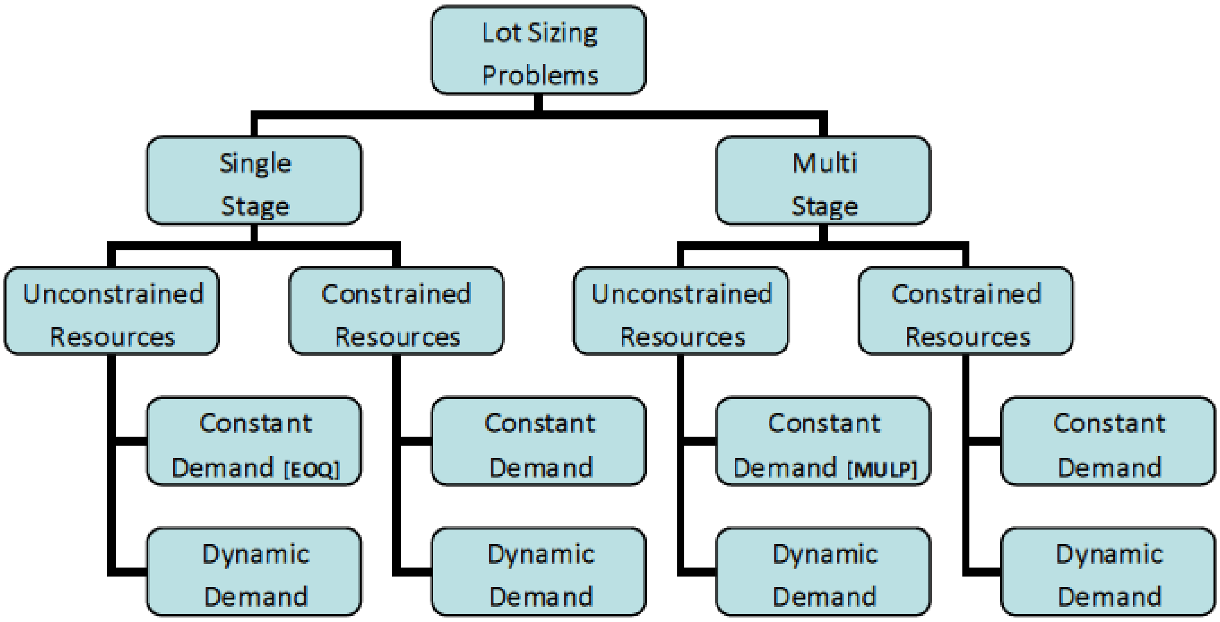

Figure A23 – Classification of the lot sizing problem

Appendix Q – Warehouse capacity after each step

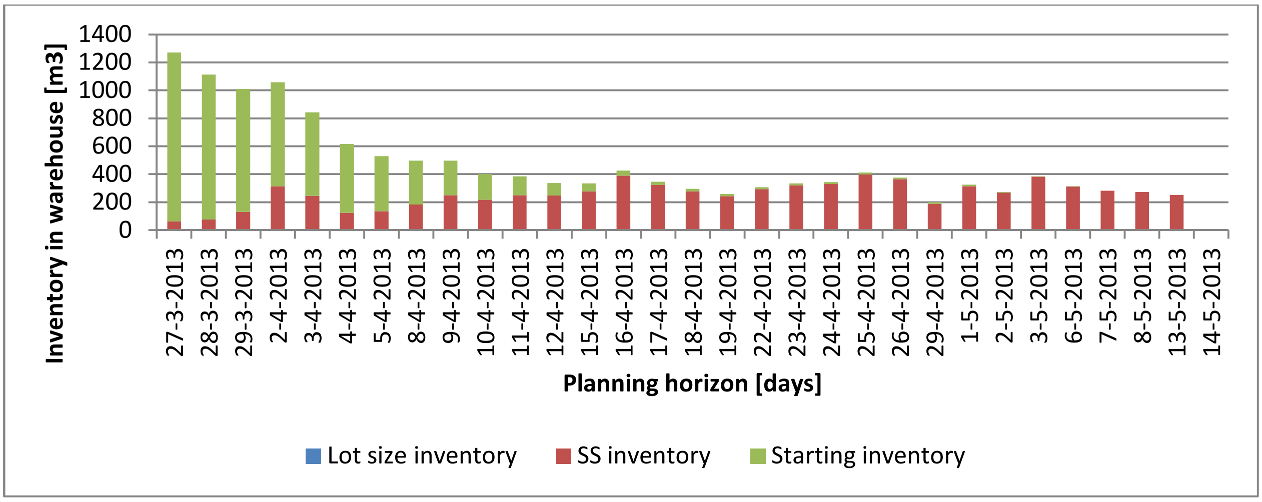

Figure A24 – Total inventory in the warehouse after step 1

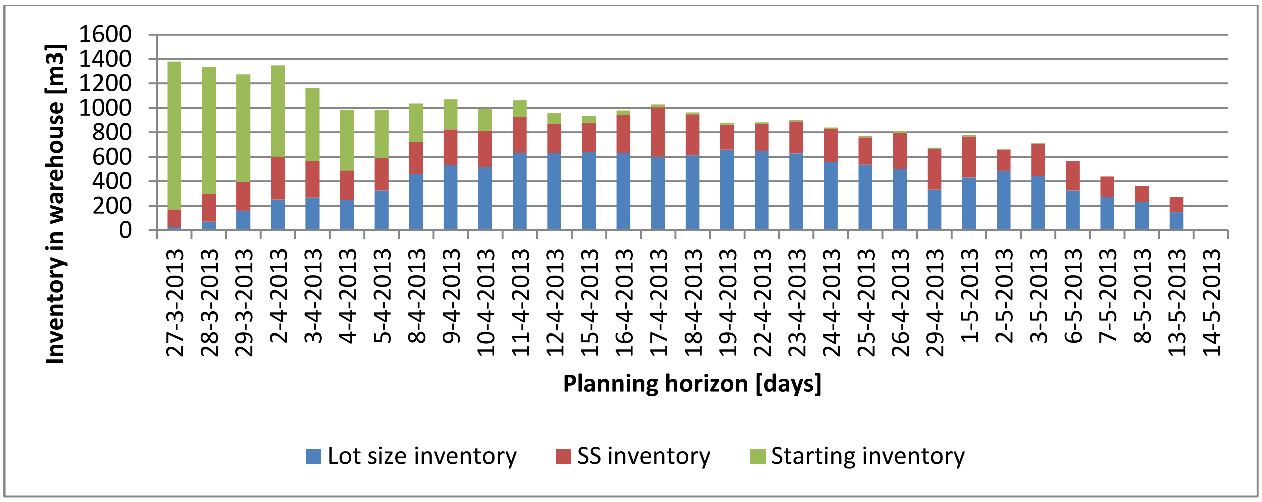

Figure A25 – Total inventory in the warehouse after step 2

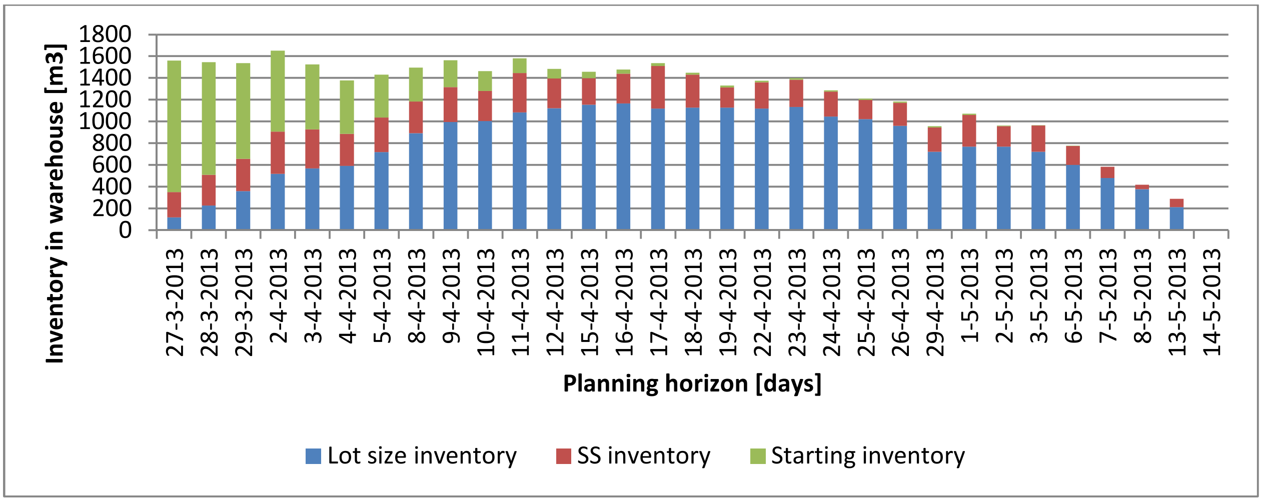

Figure A26 – Total inventory in the warehouse after step 3

Appendix R – Machine capacity input and overview

	1 - wo	2 - do	3 - vr	4 - ma	5 - di	6 - wo	7 - do	8 - vr	9 - ma	10 - di	11 - wo	12 - do	13 - vr	14 - ma	15 - di	16 - wo	17 - do
	Capacity Total - [%]																
02131	3%	5%	33%	65%	90%	13%	47%	27%	55%	17%	42%	32%	27%	100%	100%	15%	22%
02183	26%	9%	0%	35%	22%	74%	50%	27%	46%	48%	25%	1%	8%	100%	27%	38%	51%
02251	28%	12%	77%	18%	76%	68%	61%	9%	13%	70%	21%	99%	99%	33%	53%	22%	9%
03601	99%	99%	100%	97%	97%	96%	80%	99%	96%	97%	96%	98%	100%	95%	91%	100%	100%
03602	27%	27%	42%	90%	36%	36%	43%	98%	93%	34%	43%	27%	97%	19%	28%	36%	88%
07691	46%	45%	98%	88%	77%	69%	89%	53%	100%	70%	32%	92%	100%	100%	90%	68%	32%
07950	75%	50%	21%	27%	85%	54%	99%	97%	99%	60%	98%	88%	46%	62%	97%	87%	91%
16415	84%	36%	51%	25%	42%	24%	45%	46%	21%	19%	9%	98%	28%	48%	31%	88%	68%
18358	23%	100%	53%	97%	70%	100%	80%	100%	94%	95%	97%	99%	99%	99%	87%	99%	65%

Figure A27 – Overview used capacity all machines in press shop

	1 - wo	2 - do	3 - vr	4 - ma	5 - di	6 - wo	7 - do	8 - vr	9 - ma	10 - di	11 - wo	12 - do	13 - vr	14 - ma	15 - di	16 - wo	17 - do
	Available capacity / machine / time unit [%]																
02131	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
02183	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
02251	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
03601	120%	120%	120%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
03602	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
07691	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
07950	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
16415	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
18358	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure A28 – Overview available capacity all machines in press shop

Appendix S – Detailed description of step three, developed procedure

Main code to call sub procedure in the whole script

```
't = 1 starting period of step 3
z = 13
x = 2
c = 1
'Backup dashboard
   Call Backup
'SilverMeal period t=1
   Call ClearResults
   Call CompleteDemand
   Call FindSMall
   Call SMtoDashboard
Do
If Range("CP1") > 0 Then
   Call OptimizationDashboard
   c = c + 1
   Else: Exit Do
   End If
Loop
Cells(464, z).Value = c     'Count the total number of iterations of the optimization process
```

Sub OptimizationDashboard()

```
'"Forward approach is used"
Application.ScreenUpdating = False
'Clear the columns for the process
   Range("AS2:AS450").Select
   Selection.ClearContents
      Range("CO2:CO450").Select
   Selection.ClearContents
      Range("CQ2:CQ450").Select
```

```
    Selection.ClearContents
'difference costs
    Range("CI2:CI450").Select
    Selection.Copy
    Range("CJ2").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
'z = 13     'column t = 1
x = 2
'Check for every t value if production can take place, if yes, call for check reduction procedure.
Do While x <> 451
    If Cells(x, z) > 0 Then
    Call CheckReduction
    End If
    x = x + 1
Loop
'All combinations are present in the transfer list, now decision for the most economical lots is needed.
Do
    Call Backup
        If Range("CP1") > 0 Then        'When transfer list is empty, stop procedure
        Call SearchOptimization
    Else: Exit Sub
    End If
'Check for capacity on the machines and warehouses, when condition is met, call back previous solution
    'Machine 02183
    If Cells(p, 4) = 1 And (Cells(454, z) > Cells(468, z)) Then
    Call CallBackMatrix2
    Exit Sub
    End If
        'Machine 02251
    If Cells(p, 5) = 1 And (Cells(455, z) > Cells(469, z)) Then
```

```
Call CallBackMatrix2
Exit Sub
End If
'Machine 03601
If Cells(p, 6) = 1 And (Cells(456, z) > Cells(470, z)) Then
Call CallBackMatrix2
Exit Sub
End If
'Machine 03602
If Cells(p, 7) = 1 And (Cells(457, z) > Cells(471, z)) Then
Call CallBackMatrix2
Exit Sub
End If
'Machine 07691
If Cells(p, 8) = 1 And (Cells(458, z) > Cells(472, z)) Then
Call CallBackMatrix2
Exit Sub
End If
'Machine 07950
If Cells(p, 9) = 1 And (Cells(459, z) > Cells(473, z)) Then
Call CallBackMatrix2
Exit Sub
End If
'Machine 16415
If Cells(p, 10) = 1 And (Cells(460, z) > Cells(474, z)) Then
Call CallBackMatrix2
Exit Sub
End If
'Machine 18358
If Cells(p, 11) = 1 And (Cells(461, z) > Cells(475, z)) Then
Call CallBackMatrix2
```

```
    Exit Sub
    End If
    'Warehouse 1TO
    If Range("CT455") > Range("CT456") Then
    Call CallBackMatrix2
    Exit Sub
    End If
    'Warehouse 1MW
    If Range("EC455") > Range("EC456") Then
    Call CallBackMatrix2
    Exit Sub
    End If
    'Warehouse 2MW
    If Range("FL455") > Range("FL456") Then
    Call CallBackMatrix2
    Exit Sub
    End If
    'Warehouse 1SM
    If Range("GU455") > Range("GU456") Then
    Call  CallBackMatrix2
    Exit Sub
    End If
    'Warehouse 1TF
    If Range("ID455") > Range("ID456") Then
    Call CallBackMatrix2
    Exit Sub
    End If
Loop
End Sub
```

```
Sub CheckReduction()

'This is a sub to check for the combinations for reduction of the objective function, four conditions are taken into account in this procedure:

'(1) Capacity machines

'(2) Capacity warehouses

'(3) Maximum lot size

'(4) Restriction on Silver Meal heuristic

Application.ScreenUpdating = False

k = 1

Do

'cheching the sum of the periods

   Cells(x, 45).Formula = "=SUM(" & Range(Cells(x, z), Cells(x, (z + k))).Address(False, False) & ")"

    Cells(x, 45).Select

   Selection.Copy

   Cells(x, z).Select

   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

   :=False, Transpose:=False

   Cells(x, (z + k)).Select

   Selection.ClearContents

'Check max lot size

   If Cells(x, 45) > Cells(x, 46) Then

   Call CallBackMatrix

Exit Do

   End If

'Check max capacity warehouse

   'Machine 02131

   If Cells(x, 3) = 1 And Cells(453, z) > Cells(467, z) Then

   Call CallBackMatrix

   Exit Do

   End If
```

```
'Machine 02183
If Cells(x, 4) = 1 And Cells(454, z) > Cells(468, z) Then
Call CallBackMatrix
Exit Do
End If
'Machine 02251
If Cells(x, 5) = 1 And Cells(455, z) > Cells(469, z) Then
Call CallBackMatrix
Exit Do
End If
'Machine 03601
If Cells(x, 6) = 1 And Cells(456, z) > Cells(470, z) Then
Call CallBackMatrix
Exit Do
End If
'Machine 03602
If Cells(x, 7) = 1 And Cells(457, z) > Cells(471, z) Then
Call CallBackMatrix
Exit Do
End If
'Machine 07691
If Cells(x, 8) = 1 And Cells(458, z) > Cells(472, z) Then
Call CallBackMatrix
Exit Do
End If
'Machine 07950
If Cells(x, 9) = 1 And Cells(459, z) > Cells(473, z) Then
Call CallBackMatrix
Exit Do
End If
```

```
    'Machine 16415
    If Cells(x, 10) = 1 And Cells(460, z) > Cells(474, z) Then
    Call CallBackMatrix
    Exit Do
    End If
    'Machine 18358
    If Cells(x, 11) = 1 And Cells(461, z) > Cells(475, z) Then
    Call CallBackMatrix
    Exit Do
    End If
'Check max capacity warehouse
    If Range("AV455") > Range("AV456") The
    Call CallBackMatrix
Exit Do
    End If
'Check Silver Meal value
    If Cells(x, 45) = Cells(x, 47) Then
    Cells(x, 89).Select
    Selection.Copy
    Cells(x, 93).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
    'Call back matrix
    Range(Cells(x + 998, z), Cells(x + 998, 43)).Select
    Selection.Copy
    Cells(x, z).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
    Cells(x, 95).Value = k  'k-value plakken om straks te gebruiken bij wissen vraag dashboard
Exit Do
    End If
```

Appendix T – Example number of iterations for every run

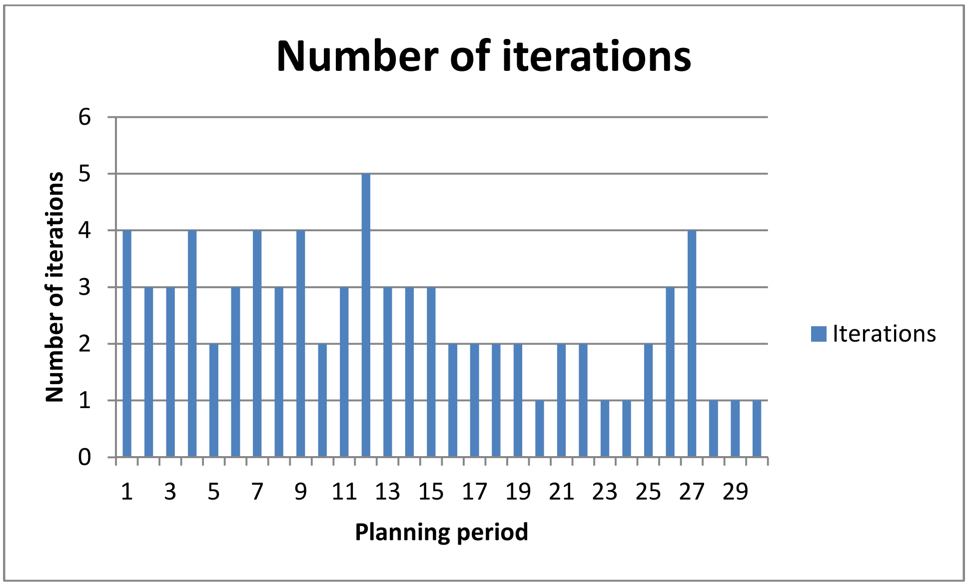

Figure A29 – Number of iterations optimization step

Appendix U – Machine capacity current versus optimized solution

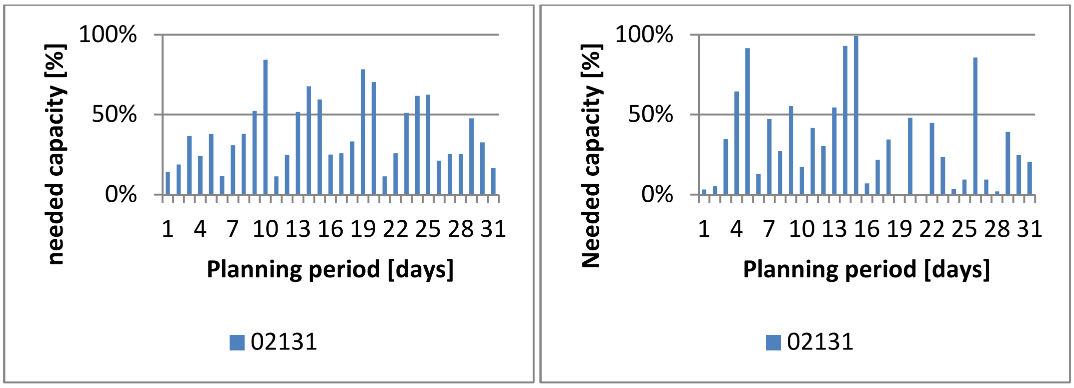

Figure A30 – Difference used capacity over planning horizon current and optimized policy machine 02131

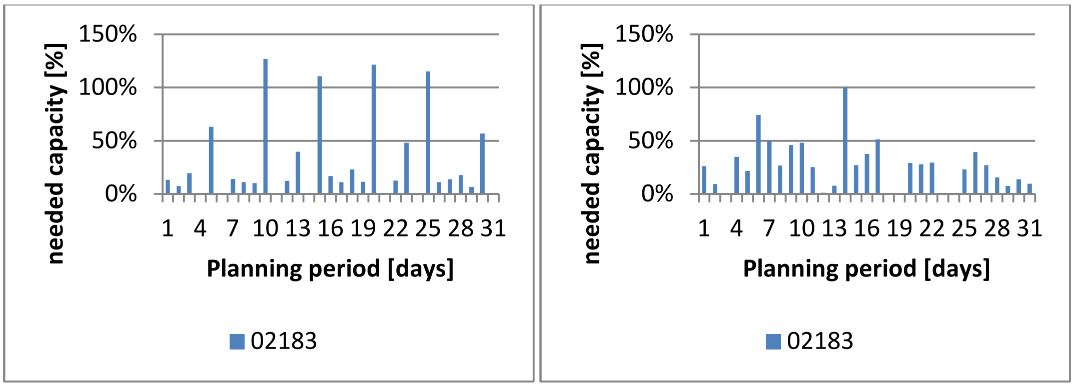

Figure A31 – Difference used capacity over planning horizon current and optimized policy machine 02183

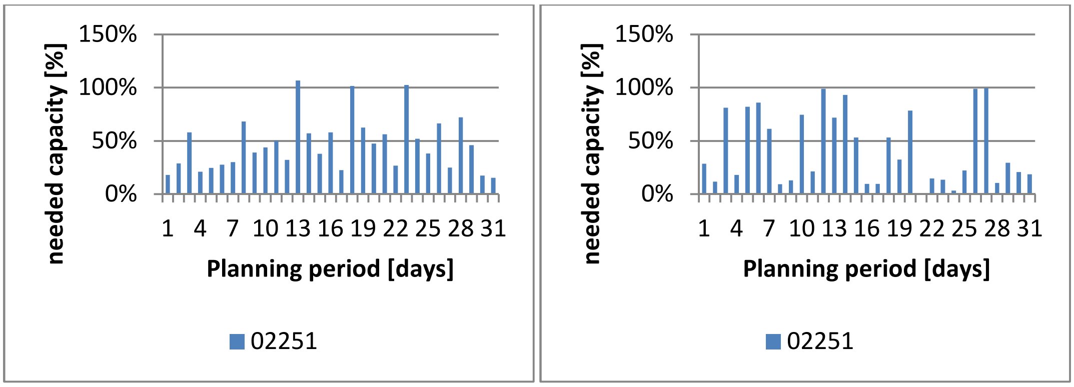

Figure A32 – Difference used capacity over planning horizon current and optimized policy machine 02251

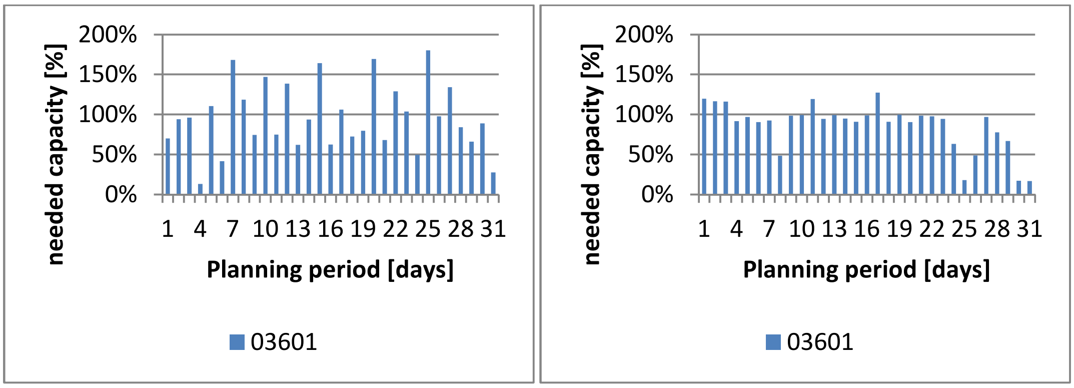

Figure A33 – Difference used capacity over planning horizon current and optimized policy machine 03601

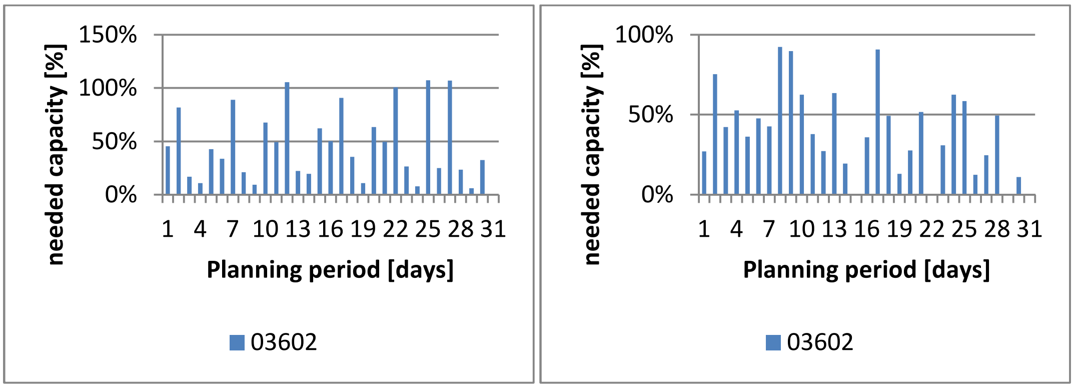

Figure A34 – Difference used capacity over planning horizon current and optimized policy machine 03602

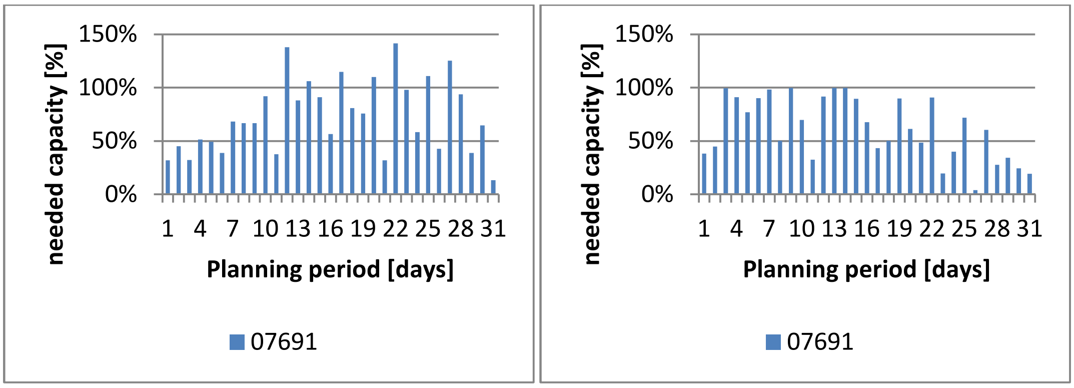

Figure A35 – Difference used capacity over planning horizon current and optimized policy machine 07691

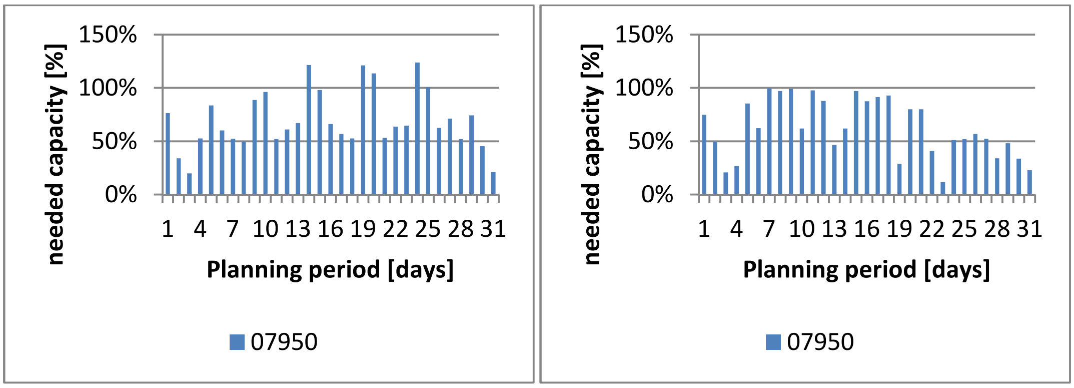

Figure A36 – Difference used capacity over planning horizon current and optimized policy machine 07950

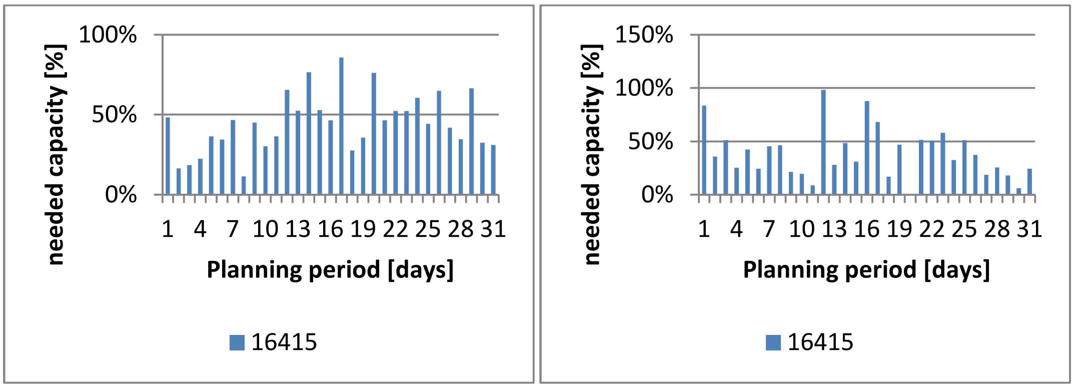

Figure A37 – Difference used capacity over planning horizon current and optimized policy machine 16415

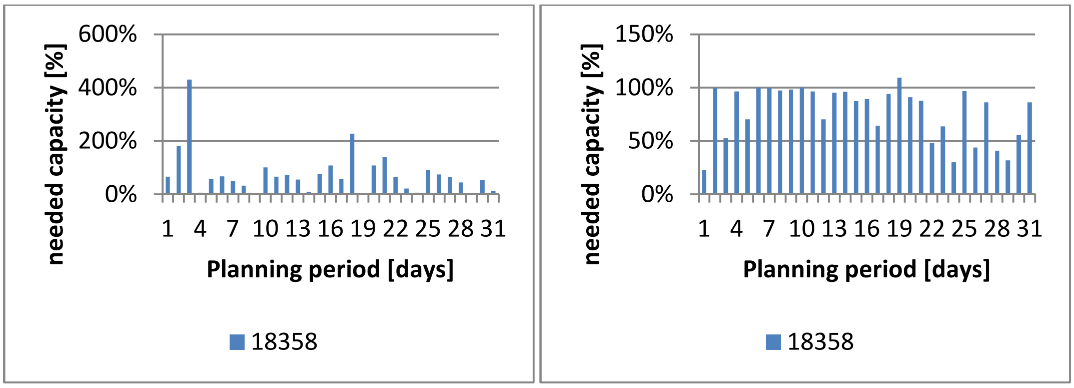

Figure A38 – Difference used capacity over planning horizon current and optimized policy machine 18358

Appendix V – Inventory behavior warehouses DAF Trucks

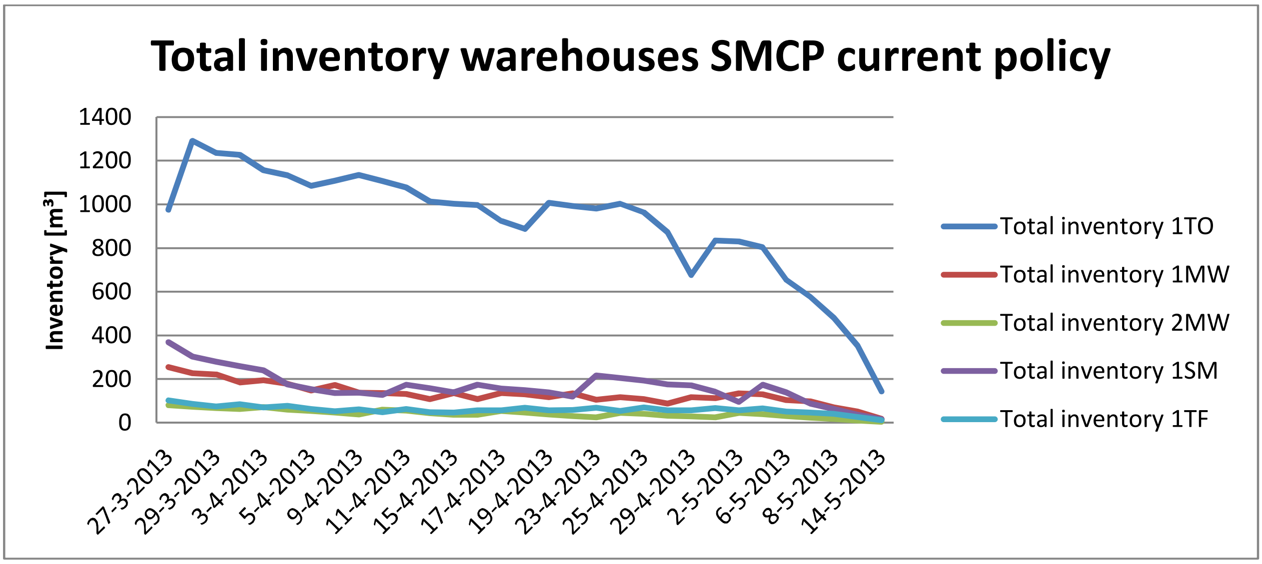

Figure A39 – Total inventory warehouses SMCP current policy

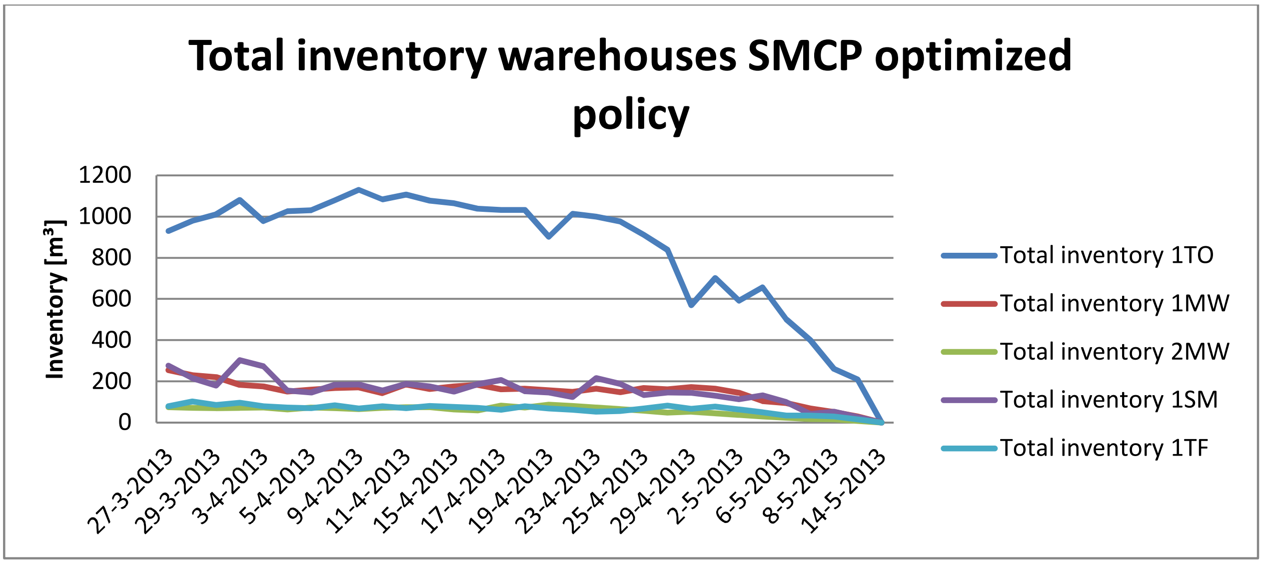

Figure A40 – Total inventory warehouses SMCP developed model

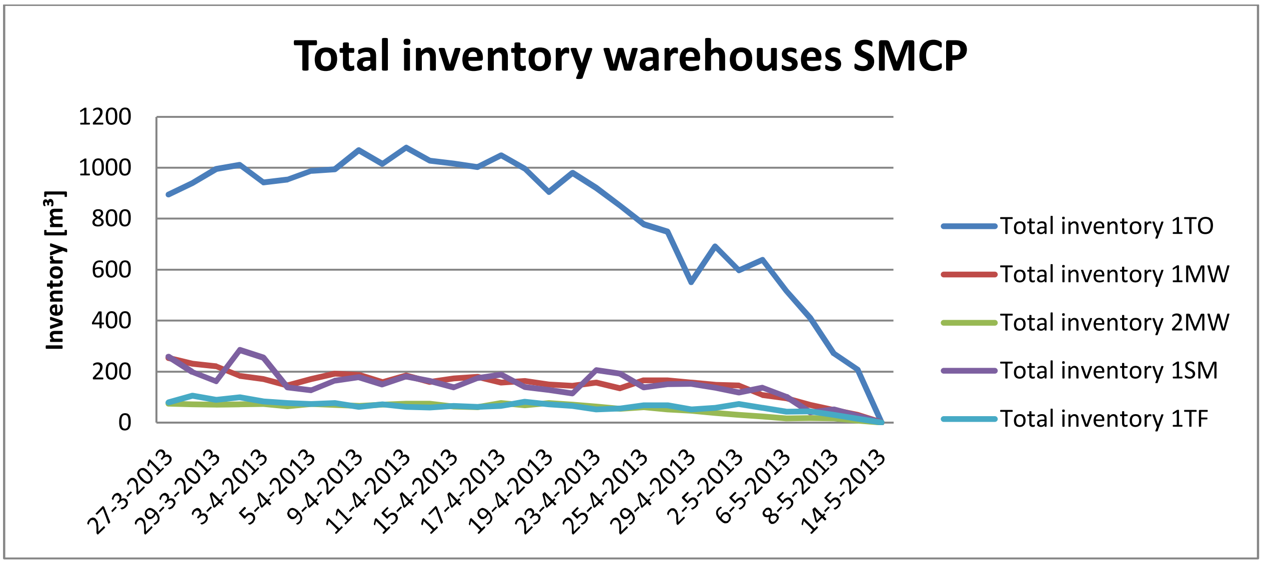

Figure A41 – Total inventory warehouses SMCP with max lot size of 12 hour

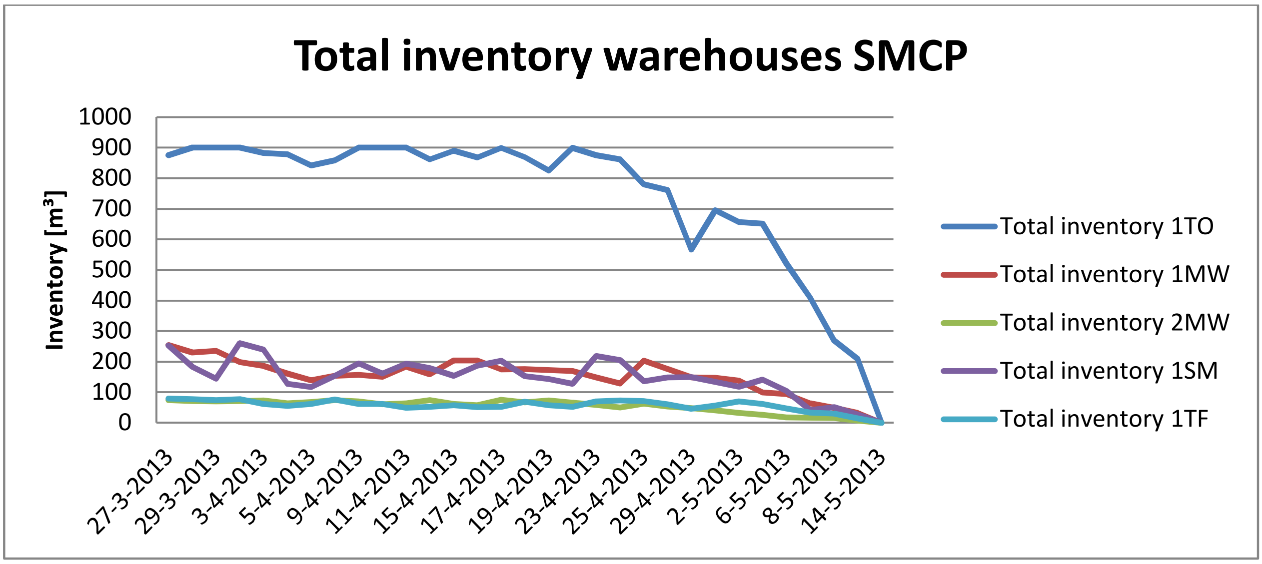

Figure A42 – Total inventory warehouses SMCP with bounded inventory