Techno-economic evaluation of a blow molding production plant: the impact of production time, energy and inventory optimization.

Lynn Hendrickx

Supervisors: Prof. dr. ir. Didier Colle, Prof. dr. ir. Sofie Verbrugge
Counsellor: Ir. Marlies Van der Wee

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Industrial Engineering and Operations Research

Department of Information Technology
Chairman: Prof. dr. ir. Daniël De Zutter
Faculty of Engineering and Architecture
Academic year 2014-2015

UNIVERSITEIT GENT

Techno-economic evaluation of a blow molding production plant: the impact of production time, energy and inventory optimization.

Lynn Hendrickx

Supervisors: Prof. dr. ir. Didier Colle, Prof. dr. ir. Sofie Verbrugge
Counsellor: Ir. Marlies Van der Wee

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Industrial Engineering and Operations Research

Department of Information Technology
Chairman: Prof. dr. ir. Daniël De Zutter
Faculty of Engineering and Architecture
Academic year 2014-2015

UNIVERSITEIT GENT

Acknowledgments

This master dissertation is the concluding piece of my study for the degree: Master of Science in Industrial Engineering and Operations Research at the University of Ghent. This would not have been possible without the support of countless people. Therefore, I want to seize the opportunity to thank some people that supported me, not only during this master dissertation, but also throughout my entire academic studies.

Foremost, I would like to thank my supervisors Prof. dr. ir. Didier Colle and Prof. dr. ir. Sofie Verbrugge for their advice and feedback. Secondly, I want to thank my counselor Dr. ir. Marlies Van der Wee for her time and patience during our meetings. Thanks to her, I was able to see things from a different perspective and to discover new ways to handle problems. Her critical reviews have made it possible to achieve this master dissertation. I also want to thank Ludwig Stroobant for the cooperation on the energy scenario and Jonathan Spruytte for improving my Java code.

Next, I want to thank Nervia Plastics and in particular Chris Verbeeck and Stefaan Luca for the pleasant cooperation and the sharing of knowledge. I found it very interesting to apply my theoretical results on the case of Nervia Plastics which would not have been possible without the available detailed input data.

A special thanks goes to my parents, Karin and Luk, who actually deserve more than a single paragraph on this page. I want to thank them for giving me the opportunity to study and for their ongoing support in order to achieve this goal.

In addition, I would also like to thank the rest of my family, friends and fellow students. In particular, I want to thank my roommates for their company and the good times we had together. At last, a final thanks goes to my boyfriend Steven because throughout my academic studies he always managed to calm me down, to motivate me and to give me energy to keep going on.

Overview

Techno-economic evaluation of a blow molding production plant: the impact of production time, energy and inventory optimization.

Lynn Hendrickx

Supervisors: Prof. dr. ir. Didier Colle, Prof. dr. ir. Sofie Verbrugge
Counselor: Dr. ir. Marlies Van der Wee

Master's dissertation submitted in order to obtain the academic degree of Master of Science in Industrial Engineering and Operations Research

Department of Information Technology
Chairman: Prof. dr. ir. Daniël De Zutter
Faculty of Engineering and Architecture
Academic year 2014 – 2015

Keywords: Blow molding, techno-economics, lifecycle cost breakdown, production cost, energy cost, inventory cost

Summary: In an increasingly competitive international environment, production costs of blow molding production plants must continuously and closely be monitored in order to ensure that they are kept under control. Performing a techno-economic evaluation of blow molding production plants will help to gain insights in the corresponding cost profile. This master dissertation develops a lifecycle cost breakdown for the identification and categorization of the different costs consisting of five stages: planning, deployment, migration, operation and teardown. The cost model of blow molding production plants based on the lifecycle cost breakdown is implemented in Java in combination with the BEMES-tool. The cost model has been applied on the current situation of Nervia Plastics, which is a representative Belgian blow molding production company that is known for its experience in extrusion blow molding of polyethylene bottles. The manufacturing process cost is the major cost category accounting for around 60% of the total cost, followed by packaging (10%) and inventory and material handling (5%). The most important cost driver is the raw material cost accounting for more than 50% of the total cost, followed by the labor cost (10%). After having a complete overview and understanding of the different cost categories, it is possible to identify specific cost-saving potentials proving that there exist promising techniques to optimize minor and major cost categories. Three relevant improvement scenarios about production time, energy and inventory are applied on the case of Nervia Plastics. When increasing the production time (producing 7 days instead of 5 days per week), the cost per finished product increases slightly (2% relative to the situation when producing 5 days per week), but 25% of the production lines become redundant impacting the CapEx investments. In the second improvement scenario about energy, several energy-reducing measurements can be implemented leading to a potential energy reduction of 37% in the case of Nervia Plastics. The final scenario deals with inventory optimization opportunities. Applying the EOQ and safety stock model on Nervia Plastics leads to a potential gain of 77% of the inventory holding cost.

Extended abstract

This section is confidential.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

ABC	Activity-Based Costing
BEMES	Business Modeling and Simulation
BPD	Business Process Diagram
BPMN	Business Process Modeling and Notation
CapEx	Capital Expenditures
CODIF	Composition and Distribution Function
CONWIP	Constant Work In Progress
CSL	Cycle Service Level
C	Material Cost
CC	Cooling Cost
$\mathbf{C_D}$	Disposal cost per unit volume (EUR/m^3)
$\mathbf{C_E}$	Energy cost per unit consumption (EUR/kWh)
$\mathbf{C_{HEQ}}$	Handling equipment cost per hour (EUR/h)
$\mathbf{C_M}$	Mold cost per hour (EUR/h)
$\mathbf{C_{MA}}$	Machine cost per hour (EUR/h)
$\mathbf{C_{MOP}}$	Mold production cost (EUR)
$\mathbf{C_{MP}}$	Labor cost per hour (EUR/h)
$\mathbf{C_P}$	Packaging material cost per unit volume (EUR/m^3)
$\mathbf{C_{PM}}$	Packaging machine cost per hour (EUR/h)
$\mathbf{C_{RC}}$	Recycle cost per unit volume (EUR/m^3)
$\mathbf{C_{RM}}$	Raw material cost per unit volume (EUR/m^3)
$\mathbf{C_{RW}}$	Rework cost per unit volume (EUR/m^3)
$\mathbf{C_S}$	Mold sampling cost (EUR)
$\mathbf{C_{SEQ}}$	Storage equipment cost per hour (EUR/h)
$\mathbf{C_{TEQ}}$	Transport equipment cost per hour (EUR/h)
$\mathbf{C_W}$	Water cost per unit volume (EUR/m^3)
D	Demand
DDUP	Demand During Uncertainty Period
DMAIC	Define, Measure, Analyze, Improve and Control
EOQ	Economic Order Quantity
ESRC	Expected Shortage per Replenishment Cycle
$\mathbf{E_C}$	Energy consumption (kWh)
FT	Flow Time
FTTH	Fiber To The Home
Fr	Fill rate
G&A	General and Administration rate
H	Holding cost
HAZOP	Hazard and Operability Analysis
HEM	High Efficiency Motors

$\mathbf{H_C}$	Cooling hours (h)
$\mathbf{H_{EQ}}$	Equipment hours (h)
$\mathbf{H_M}$	Machine hours (h)
$\mathbf{H_{MP}}$	Labor hours (h)
$\mathbf{H_{PM}}$	Packaging machine hours (h)
JIT	Just In Time
L	Lead time
LCA	Life Cycle Assessment
MAP	Manufacturing process cost
MH	Material handling cost
MO	Mold cost
MPR	Maximum Power Requirement
MRP	Manufacturing Resources Planning
OP	Operational planning cost
OpEx	Operational Expenditures
PA	Packaging cost
POLCA	Paired-cell Overlapping Loops of Cards with Authorization
Q	Order lot size
$\mathbf{Q^*}$	Optimal order quantity
R & D	Research and Development
RBM	Risk-based maintenance
$\mathbf{r_b}$	Bottleneck rate
S	Fixed order cost
SEC	Specific Energy Consumption
SMED	Single-Minute Exchange of Die
SG & A	Selling, General and Administration rate
SS	Safety Stock
$\mathbf{T^*}$	Optimal reorder interval
$\mathbf{T_0}$	Raw process time
TAC	Total Annual Cost
TD	Teardown cost
TH	Throughput
VSD	Variable Speed Drive
$\mathbf{V_{RM}}$	Volume of raw material (m^3)
$\mathbf{V_P}$	Volume of packaging material (m^3)
$\mathbf{V_{TD}}$	Volume of faulty products, unsold stock and outdated molds (m^3)
WIP	Work In Progress
$\mathbf{W_C}$	Water consumption per hour (m^3/h)
$\mathbf{W_P}$	Waste coefficient packaging material (%)
$\mathbf{W_{RM}}$	Waste coefficient raw material (%)
Z	Safety factor

α	Probability of rework
β	Probability of recycling
γ	Probability of disposal
σ	Standard deviation

1
Introduction

Growing continuously for more than 50 years, the global plastics production in 2013 rose to 299 million tonnes, a 3.9% increase compared to 2012. The plastics industry in Europe had a turnover of 320 billion euro in 2013. Europe ranks second in the global plastics materials production, accounting for 20% of the total plastic materials production. The European plastic industry is an industry in which more than 60,000 companies operate, mostly small and medium-sized enterprises. It gives direct employment to 1,450,000 people of which 1,267,000 people work in plastic converting companies. In Europe, the largest application sector for the plastics industry is packaging, representing 39.6% of the total plastics demand. [2]

Blow molding is a manufacturing process that is used to create hollow plastic parts by inflating a heated plastic tube until it fills a mold and forms the desired shape. Blow molded parts can be formed from a variety of thermoplastic materials, such as polyethylene, polypropylene and polyvinyl chloride. As part of the plastic material converting stage, blow molding production plants form an important part of the plastics industry.

The European plastics industry has to deal with several competitive global challenges. Asia benefits from the opportunity of low-cost labor compared to Europe. Furthermore, the rapid exploitation of shale gas in the US has improved its competitive position in plastics production. The availability of low-cost energy and raw materials in the Middle-East caused a serious migration of production from the EU to the Gulf. [1]

The principal challenges for Belgium are the high labor costs and energy prices. In Belgium, industrial wages are still high due to the associated charges. The recent rise in unit labor costs has outpaced developments in some other European countries such as Germany and France. [3] Regarding the energy cost, it must be said that Belgium's geology is unfavorable for energy resources. In Belgium, nuclear energy plays a major role in the energy supply. As Belgium has no competitive renewable energy plan, the nuclear phase-out in 2025 will undoubtedly lead to higher energy prices. In March

2013, the first benchmark study of electricity prices in Belgium and its neighboring countries revealed that the cost of electricity is significantly higher in Belgium than in France, Germany and the Netherlands. Given the rising global demand and competition for resources, it is of the utmost importance that Belgium develops a sustainable energy supply. [4]

In response to the growing competitive pressures, industry in western countries has tried to secure productivity gains by making more intensive use of modern capital equipment which incorporates technological progress. Many enterprises try to refocus on their core business. It should be noted that the globalization is not only a source of challenges, but also offers opportunities via the development of major markets. [4]

As stated above, the plastics industry including blow molding production concerns many companies and creates a lot of employment in Europe. In an increasingly competitive international environment, production costs must continuously and closely be monitored in order to ensure that they are kept under control. The labor and energy consumption should be minimized as to reduce the total labor and energy cost and, given the current position of Belgium as stated above, this is of utmost importance in our country. Performing a techno-economic evaluation of blow molding production plants will help to gain insights in the corresponding cost profile. A techno-economic evaluation is a cost analysis taking into account technological as well as economic aspects. It consists in general of four practical steps: scope, model, evaluate and refine. [5] After obtaining an overview of the different costs related to blow molding production plants; it is possible to propose improvement strategies in order to reduce the production cost.

In addition to the general motivation, I also have a personal interest in techno-economic research. Having a bachelor in Chemical Engineering ensures that I am familiar with the blow molding technique. During my master in Industrial Engineering and Operations Research, I learned how to analyze, design and optimize operational systems. Besides my main study directions, a lot of my elective courses dealt with economic topics proving my interest in techno-economic research. I also preferred a master dissertation with direct application in the work field and in collaboration with a company as I value experiencing the impact of my research results.

As stated above, the aim of this master dissertation is to develop a techno-economic evaluation of a blow molding production plant. The focus lies on (extrusion) blow molding production plants where a variety of batches, each requiring a specific mold, can be produced. In this respect, following research questions are formulated:

1) *How can the different costs be divided into categories and what drives these costs?*
   In order to get an overview of the cost profile of blow molding production plants, a factory cost breakdown will be elaborated focusing on the most important cost categories and cost drivers for production.
2) *What are the cost-saving potentials?*
   When having a complete overview and understanding of the different cost categories linked with blow molding production plants, it is possible to identify specific cost-saving potentials. Those cost-saving potentials will be described qualitatively.

3) *What impact has optimizing production time, energy and inventory on the total production cost?*
   Three relevant opportunities for cost-savings will be quantitatively evaluated to determine their impact on the total cost.
   a) *Optimizing production time:* Could we save costs when using machine uptime more optimally if also producing during the weekends?
   b) *Optimizing energy:* Could energy-reducing measurements reduce energy consumption and the corresponding cost?
   c) *Optimizing inventory:* What are the cost-saving opportunities of inventory optimization?

The research questions will be answered along the different chapters. Throughout this master dissertation, Nervia Plastics will be used as reference case for the application of the cost model and the improvement scenarios. Nervia Plastics is a representative Belgian blow molding production company located in Okegem and known for its experience in extrusion blow molding of polyethylene bottles. The company was established in 1965 and acquired in 2004 by French Groupe Millet-Marius and Mr. Stefaan Luca. Nervia Plastics will be used as source of input information and as a benchmark for the results. [6] Because of confidentiality, the quantitative input and result section related to this case will not be part of the public version of this Master thesis.

Chapter 2 introduces a theoretical framework based on literature research that will be used as guidance throughout the techno-economic evaluation. A lifecycle cost breakdown will be developed for the identification and categorization of the different costs related to blow molding production plants in Chapter 3. A lifecycle cost breakdown consists in general of five stages: planning, deployment, migration, operations and teardown. In Chapter 4, Nervia Plastics and the corresponding input data will be introduced. The implementation of the cost model in Java will be discussed in Chapter 5. This chapter also includes the application of the cost model on the current state of Nervia Plastics and a discussion of the obtained results. When performing the lifecycle cost breakdown on a blow molding production plant, different cost categories and cost drivers can be identified. In Chapter 6, cost-saving potentials are proposed and described qualitatively for the most important cost categories. First three improvement philosophies will be introduced followed by several improvement techniques to optimize different cost categories. In Chapter 7, three relevant opportunities for cost-savings will be quantitatively evaluated to determine their impact on the total cost. These three improvement scenarios deal with production time, energy and inventory optimization. Finally, Chapter 8 concludes this thesis and gives directions for future research.

2

Theoretical framework as guidance throughout the techno-economic evaluation

The aim of this thesis is to develop a techno-economic evaluation of blow molding production plants, hence performing a cost analysis taking into account technological as well as economic aspects. This chapter introduces a theoretical framework based on literature research that will be used as guidance throughout this techno-economic evaluation.

Wallace [7] defines techno-economic evaluation as a combination of process modeling and engineering design with economic evaluation, to provide both quantitatively and qualitatively understanding of the impacts of technology and research breakthroughs on the financial viability of a conversion strategy. Applying the techno-economic methodology on blow molding production plants, will give more insight into the corresponding cost profile and can be used as guidance when evaluating possible strategies.

According to Verbrugge et al. [5] a techno-economic evaluation for telecom deployment planning consists of four practical steps: scope, model, evaluate and refine. The general methodology, as shown in Figure 1, can also serve as a framework for other projects such as blow molding production plants. In the next sections, the different steps will be discussed more in detail.

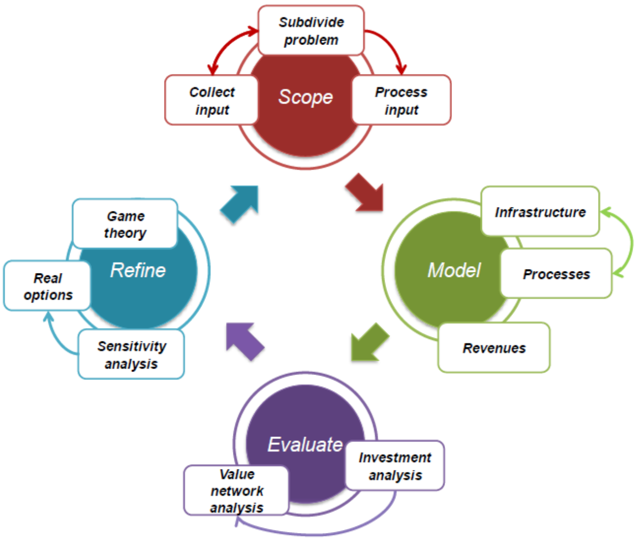

Figure 1 Detailed techno-economic methodology [5]

2.1 Scope

The initial scope phase consists of three important elements: the collection of the necessary input data, the subdivision of the problem and the processing of the input. First the required input information should be collected using different reliable sources. In this thesis the input data is collected through interviews with experts, press releases, papers from various authors and data originating from the examined blow molding production plant.

After gathering the input data, the information needs to be structured and aggregated. A cost breakdown using the lifecycle cost approach will help to identify and categorize the different costs. This will result in a complete overview of the different costs making it possible to focus on the most important cost categories. After subdividing the problem, the input information should be processed so it can be used to estimate the different cost categories.

A lifecycle cost breakdown can be used to categorize the different costs related to blow molding production plants taking into account the entire lifecycle. Verbrugge et al. [10] applied the lifecycle cost breakdown on a Fiber To The Home (FTTH) network. This can be represented using a tree structure with five different branches each representing a stage as shown in Figure 2.

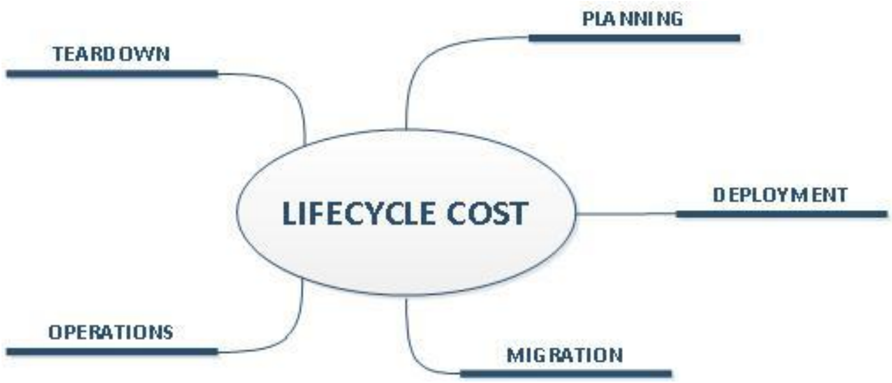

Figure 2 Lifecycle cost breakdown

The five different stages are:

1. **Planning:** In this phase cost categories linked with the initial start-up of the project are displayed. In a blow molding production plant, activities such as purchasing, long-term planning and manpower planning are part of the planning phase.
2. **Deployment:** The deployment phase consists of the activities needed to start the production e.g. the necessary equipment should be provided and the optimal layout of the production plant should be determined.
3. **Migration:** In the migration phase, the costs associated with a set-up for a new project or production are included. For example, at a blow molding production plant the migration phase includes costs associated with mold changeovers and start-ups.
4. **Operations:** In this phase all the costs concerning the day-to-day operations are displayed e.g. costs related to the manufacturing process, quality control, preventive maintenance, inventory and material handling.
5. **Teardown:** This phase represents the end-of-lifetime of a project including recycling, remanufacturing and disposal. In a blow molding production plant this will include the processing of faulty products, unused/unsold stock and outdated molds.

The lifecycle cost breakdown framework is used to get a complete overview of the different cost categories. This approach will be applied to blow molding production plants in Chapter 3.

2.2 Model

There exist different perspectives to model costs and revenues with a corresponding level of detail, which depends on the chosen modelling approach and the input information available.

In business environments, costs are often divided into capital expenditures (CapEx) and operational expenditures (OpEx). CapEx can be defined as [8] "*funds used by a company to acquire or upgrade physical assets such as property, industrial buildings and equipment. This type of layout is made by companies to maintain or increase the scope of their operations".* OpEx on the other hand can be defined as [8] *"a category of expenditure that a business incurs as a result of performing its normal business operations".*

Verbrugge et al. [5] propose a classification of different cost modelling methods based on the required level of detail: fractional, driver-based or dedicated dimensioning models.

2.2.1 Fractional models

In fractional models, components of costs are expressed in relation to other cost components. For example in blow molding production plants, the total overhead cost will be calculated as a percentage of the total production cost. Fractional modeling does not provide much information on the source of the cost or how it might evolve, hence it appropriate for those cost categories that are difficult to assess.

2.2.2 Driver-based models

Driver-based models consist of a function taking a limited amount of parameters (cost drivers) and calculating from this the cost of the component. For example when processing teardown material at a blow molding production plant, the amount of wasted raw material can be seen as a cost driver for the determination of the total teardown cost. The cost drivers represent a lot of information; therefore driver-based models are appropriate for important cost categories.

Cooper and Kaplan [11] propose Activity-Based Costing (ABC) as driver-based model. ABC is a method where the process of tracing costs is executed from resources to activities and then from activities to specific products. For each activity you have to determine cost drivers which are measures of the demand of an activity.

According to Asking and Gustavsson [12] an ABC analysis consists of five different steps. These steps will be explained using as example the purchase of raw materials

1. Identify and select activities by performing study visits and interviews e.g. the purchase of raw materials including preparing purchased orders.
2. Allocate costs to the selected activities including direct and indirect resources costs e.g. the resource cost is a labor cost needed to place the orders.

3. Select cost drivers that cause the need for activities to be performed e.g. demand of a certain product and the specifications of the product concerning raw materials.
4. Determine the activity measures to link the activity costs to the products that consume this activity e.g. number of purchased orders.
5. Perform the calculations and define the total cost of a product.

According to Kaplan and Anderson [13] ABC appears to be a great way to manage a company's limited resources in theory, but in practice time and cost demands of creating and maintaining an ABC model is a major barrier. ABC models also often fail to capture the complexity of actual operations. As the activity dictionary expands, the demands on the computer programs used to store and process data escalate. Another problem arises from the interview and survey process itself used to provide the input data. Data gathering is quite expensive and frequent updates are necessary to obtain accurate estimates of process, product and customer costs. When applying ABC for blow molding production plants, similar difficulties may occur.

Kaplan and Anderson [13] state that a Time-Driven Activity-Based Costing approach provides a solution to these problems. Managers directly estimate the resource demands imposed by each transaction, product or customer. For each group of resources, two parameters are required:

1. The cost per time unit of supplying the resource capacity e.g. the labor cost per hour.
2. The unit times of consumption of the resource capacity by products, services and customers e.g. the amount of hours spent on the preparation of the purchased orders for a certain product.

To derive the cost-driver rates, the two input variables should be multiplied e.g. multiplying the labor cost per hour with the amount of hours spent on the given activity. Time-driven ABC enables managers to report their costs on an ongoing basis in a way that reveals both the costs of business activities as well as the time spent on them. There are two factors that can cause cost-driver rates to change: changes in the price of the supplied resources or a shift in the efficiency of the activity.

Time-Driven Activity-Based Costing will be applied to specific cost categories such as the costs related to the manufacturing process, inventory and teardown.

2.2.3 Dedicated dimensioning models

Network dimensioning models take into account the equipment necessary to provide a given functionality while using the infrastructure as efficient as possible. Process dimensioning models or process-based models on the other hand, calculate costs by the frequent execution of a specific process. When dealing with operational processes such as mold changeovers or start-up, process-based models are more suitable because it is easy comprehensible to model those activities using flowcharts. A standard representation format of process-based models, Business Process Modelling and Notation (BPMN), will be examined more in detail.

BPMN is suitable when dimensioning and estimating the cost of executing operational processes where standardized tasks are frequently performed. According to the Object Management Group [14], a BPMN provides businesses with the capability of understanding their internal business procedures in a graphical notation while giving companies the ability to communicate in a standardized way.

BPMN defines a Business Process Diagram (BPD) which is based on a flowcharting technique tailored for creating graphical models of business operations. It consists of a set of graphical elements with four main categories [15]:

- Flow objects consisting of three building blocks: events, activities and gateways.
- Connecting objects combine flow objects using sequence flows, message flows and associations.
- Swimlane objects are used to organize and categorize activities including pools and lanes.
- Artifacts allow developers to include more information into the model such as data objects, groups and annotations.

In this thesis only flow and connecting objects will be used to represent the operational processes. A BPMN example of the start-up of blow molding production lines is shown in Figure 3.

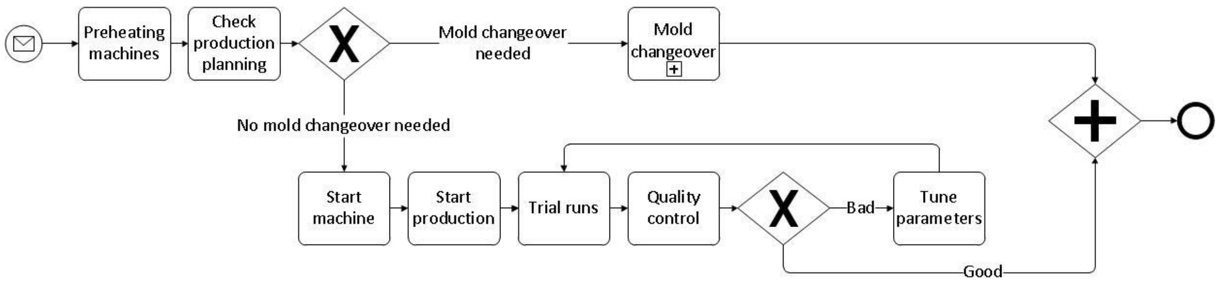

Figure 3 BPMN: Start-up of blow molding production lines

The different cost modelling methods e.g. fractional, driver-based and process-based models will be applied on blow molding production plants in Chapter 3.

2.3 Evaluate

When a cost and revenue model have been set up, it is possible to calculate the cash flows at each point in time. Based on this information, decisions about the business case can be made. Besides investigating the profitability of a single project, it is also important to consider the position of the project in the business landscape.

In this master dissertation the focus lies on the determination of a cost model of blow molding production plants without incorporating revenues. In Chapter 5, the implementation of the cost model in Java will be discussed. There are several costs that fluctuate over time such as energy prices and labor costs. To cope with these fluctuations, the class *TimeFunction* is used to determine costs over time. It should also be noted that investments such as the machine CapEx and the transport equipment will be depreciated over time using the straight-line depreciation method. [18]

$$Cost\ per\ hour = \frac{purchase\ price - residual\ value}{useful\ life\ (hours)}$$

Applying the cost model on a blow molding production plant, will help to gain insights into the cost profile. The cost model will be evaluated determining the total cost and the division into production and overhead cost. An overview of the cumulative cost categories and cost drivers will respectively lead to the identification of the most important cost categories and the most critical cost drivers. Having a complete overview and understanding of the different cost categories will make it possible to identify cost-saving potentials and propose improvement scenarios.

2.4 Refine

The last phase of the techno-economic methodology consists of refining the previous steps. Verbrugge et al. [5], discusses several techniques including sensitivity analysis. The current implementation of the business case does not provide any information considering risks and uncertainties. Sensitivity analysis can be used to answer questions related to the impact of variation of different input parameters.

According to Saltelli, a possible definition of sensitivity analysis is the following [16]: "*The study of how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input.*" An overview of the sensitivity analysis mechanism is shown in Figure 4. The input data and the cost model will be combined. At the end of the estimation step, 'best' parameter values as well as their errors are known. At that moment, it is possible to run a sensitivity analysis by propagating the uncertainty in the parameters through the model, all the way to the model output. [17]

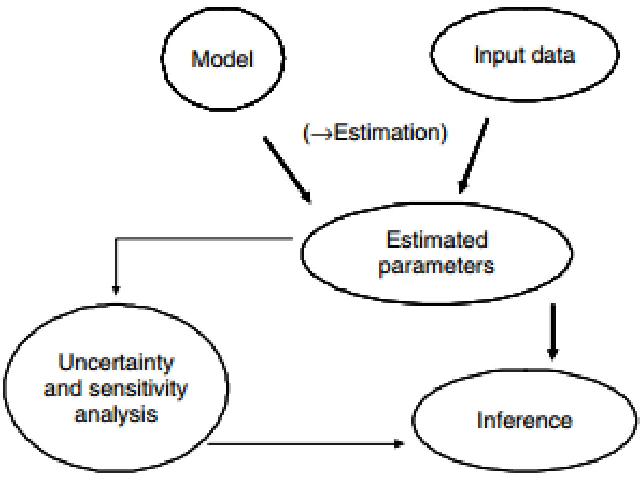

Figure 4 Overview of the sensitivity analysis mechanism [17]

The choice of a suitable sensitivity analysis technique depends on several considerations:

- The computational cost of running the model
- The number of input factors
- The features of the model (e.g. linearity)
- The consideration of interactions among the input parameters in the model
- The setting for the analysis and its audience

In this master dissertation, a sensitivity analysis will be incorporated in Chapter 5 when determining the overhead cost of the current situation.

2.5 Conclusion

A techno-economic evaluation consists of four main stages: scope, model, evaluate and refine. In the scope stage, a lifecycle cost breakdown can be used to identify and categorize different cost categories related to blow molding production plants. In the model stage, different cost modelling approaches can be applied to estimate the different costs e.g. fractional, driver-based and dedicated dimensioning models. In the third stage, the cost model and the obtained results should be evaluated. Finally, the refine stage includes sensitivity analysis to deal with uncertainties in the input parameters. The theoretical concepts introduced in this chapter will be applied on blow molding production plants throughout this master dissertation.

3

Lifecycle cost breakdown of a blow molding production plant

As discussed in Chapter 2, a lifecycle cost breakdown will be developed for the identification and categorization of the different costs related to blow molding production plants. In Figure 5, the factory cost breakdown of a blow molding production plant is shown using the lifecycle cost tree structure consisting of five stages: planning, deployment, migration, operations and teardown. In the next sections, the different stages will be discussed in detail. In this master dissertation, the focus lies on optimizing the production cost (indicated in blue). The remaining costs will be classified as overhead cost (indicated in green). The classification of these costs into production and overhead cost will be explained when assessing the specific cost categories.

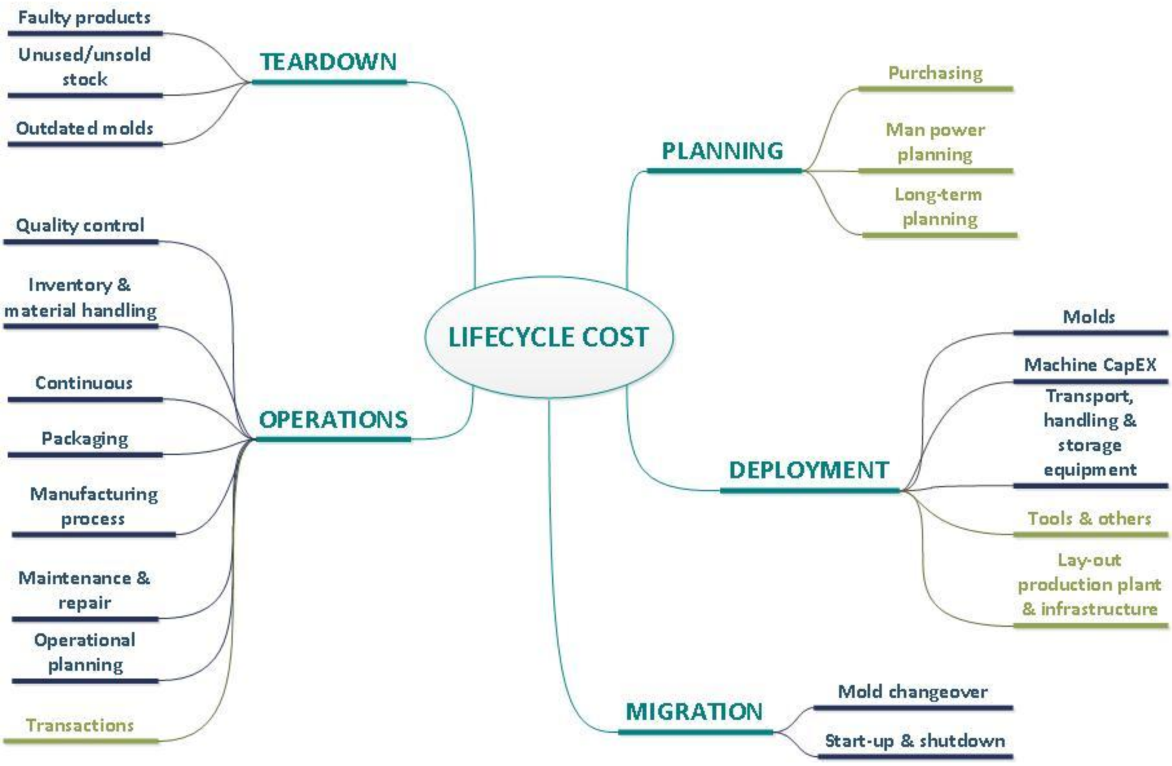

Figure 5 Lifecycle cost breakdown of a blow molding production plant

3.1 Planning phase including purchasing, manpower and long-term planning

The first phase of the lifecycle cost breakdown is the planning phase including cost categories such as purchasing, manpower planning and long-term planning (Figure 6). Those three main categories will be discussed more in detail in the remainder of this section.

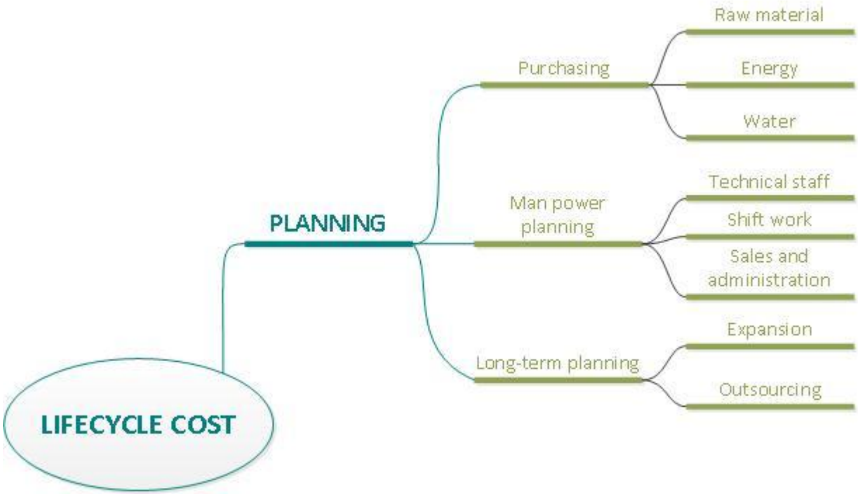

Figure 6 Lifecycle cost breakdown: Planning phase

3.1.1 Purchasing

The cost category related to purchasing consists of three main components: purchasing raw materials, energy and water.

3.1.1.1 Purchasing raw materials

In the case of blow molding production plants, the raw material consists mainly of transparent plastic and color additives. The raw material cost per unit volume is based on the purchase price, while also taking into account the order and transportation costs. The raw material cost will be included in Section 3.4.3 about the manufacturing process. The negotiation costs linked with purchasing raw materials are included in the overhead cost.

In addition, it should be noted that packaging materials need to be purchased as well. The packaging material cost will be taken into account in Section 3.4.4 where as the negotiation costs will be included in the overhead cost.

3.1.1.2 Purchasing energy

Energy prices change when consuming energy during the day, night or weekend. When determining the energy cost, the fluctuation of the energy price over time needs to be taken into account. The negotiation costs linked with purchasing energy are included in the overhead cost. The energy cost will be taken into account in Section 3.4.3 and 3.4.5.

3.1.1.3 Purchasing water

Blow molding production plants consume water e.g. for the cooling of the molds. The water is mostly used in a closed water circuit. The water cost will be included in Section 3.4.3 and 3.4.5. The negotiation costs linked with purchasing water are included in the overhead cost.

3.1.2 Manpower and long-term planning

The costs associated with manpower and long-term planning can be calculated by multiplying the amount of hours spent on the planning with the labor cost per hour. Manpower planning consists of establishing a schedule for the people working in sales and administration, the employees working in shifts and the technical staff. Long-term planning deals with decisions about expansions, outsourcing and others. The cost related to manpower and long-term planning will be included in the general overhead cost.

3.2 Deployment phase incorporating activities corresponding to the start of production

The second stage of the lifecycle cost breakdown is the deployment phase consisting of the activities needed to start the production. The different components of the deployment phase for blow molding production plants are shown in Figure 7 and will be discussed in this section.

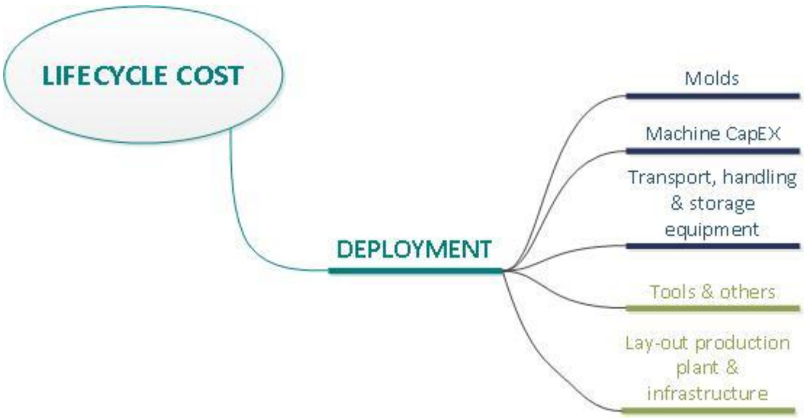

Figure 7 Lifecycle cost breakdown: Deployment phase

3.2.1 Molds: design and production

In blow molding production plants, the design and production of the different molds is an important cost category. For the design of molds several costs need to be determined: a labor cost, a production cost and a sampling cost to check if the molds give the right end result. If the amount of hours spent on the design of the mold (H_{MP}), the labor cost per hour (C_{MP}), the production cost (C_{MOP}) and the sampling cost (C_s) are given; it is possible to determine the mold cost (MO):

$$MO = H_{MP}.C_{MP} + C_{MOP} + C_s$$

The mold cost can be depreciated using the straight-line depreciation method resulting in a mold cost per hour. In straight-line depreciation, the same depreciation is charged over the entire useful life. [18]

$$Mold\ cost\ per\ hour: C_M = \frac{MO - residual\ value}{useful\ life\ (hours)}$$

The usage costs of the molds will be included in Section 3.4.3 about the manufacturing process.

3.2.2 Machine CapEx

The capital expenditures of the blow molding machines and the cooling system are also depreciated using the straight-line depreciation method. [18]

$$Machine\ cost\ per\ hour: C_{MA} = \frac{purchase\ price - residual\ value}{useful\ life\ (hours)}$$

The machine CapEx needed for the manufacturing process as well as for the cooling are taken into account in the corresponding sections.

3.2.3 Transport, handling and storage equipment

Every production plant needs transport (TEQ), handling (HEQ) and storage (SEQ) equipment such as forklift trucks, racks, conveyors, etc. The costs related to the purchase of these equipments can be depreciated using the straight-line depreciation method. [18]

$$Equipment\ cost\ per\ hour: C_{TEQ}\ or\ C_{HEQ}\ or\ C_{SEQ} = \frac{purchase\ price - residual\ value}{useful\ life\ (hours)}$$

The costs of the transport, handling and storage equipment are taken into account in Section 3.4.2 about inventory and material handling.

3.2.4 Tools and others

This cost category includes tools and other equipment needed for a normal production day, such as the tools needed when changing a mold. As the tool cost cannot be allocated to one specific production line or process, this will be included in the overhead cost.

3.2.5 Layout production plant and infrastructure

The cost associated with the layout of the blow molding production plant and the necessary infrastructure can also not be allocated to one specific production line or process, therefore it will be included in the overhead cost as well.

3.3 Migration phase including costs associated with a set-up of a new project

The migration phase includes costs associated with a set-up of a new project. In the case of blow molding production plants, the migration phase consists of mold changeovers, start-ups and shutdowns of the blow molding machines (Figure 8)

Figure 8 Lifecycle cost breakdown: Migration phase

3.3.1 Mold changeover

The cost of a mold changeover can be represented and calculated using a BPMN model. The different steps that are necessary in order to achieve a successful mold changeover are shown in Figure 9.

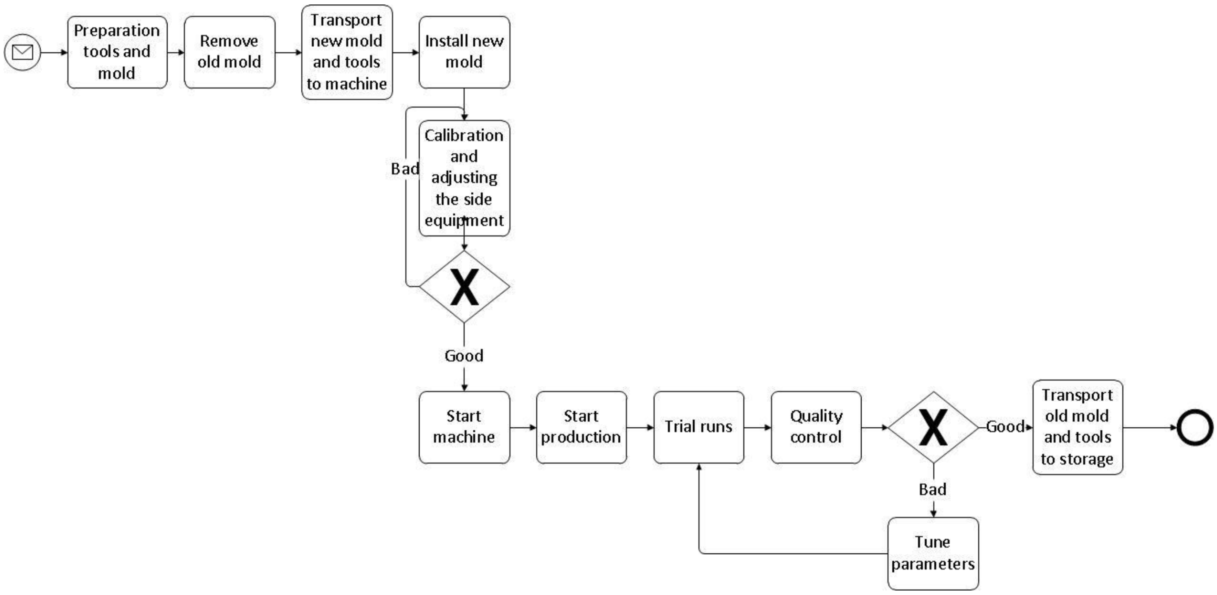

Figure 9 BPMN: Mold changeover

3.3.2 Start-up and shutdown

The costs related to a start-up of a blow molding machine can be calculated using a BPMN model as shown in Figure 10. If there is a mold changeover needed during the start-up of the blow molding production line, the BPMN model in Figure 9 should be incorporated. In addition, a shutdown consists of switching off the machines which usually requires less effort.

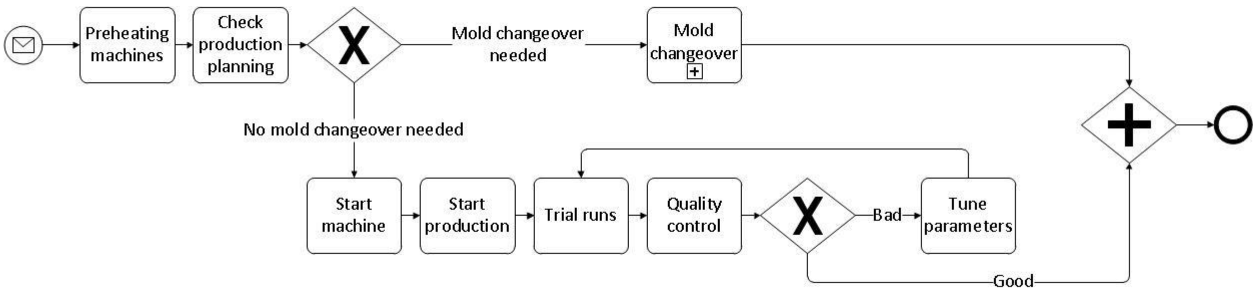

Figure 10 BPMN: Start-up

3.4 Operations phase concerning the costs related to day-to-day operations

In the operation phase all the costs concerning day-to-day operations are displayed. The different components of the operation phase for blow molding production plants are shown in Figure 7 and will be discussed more in detail in this section.

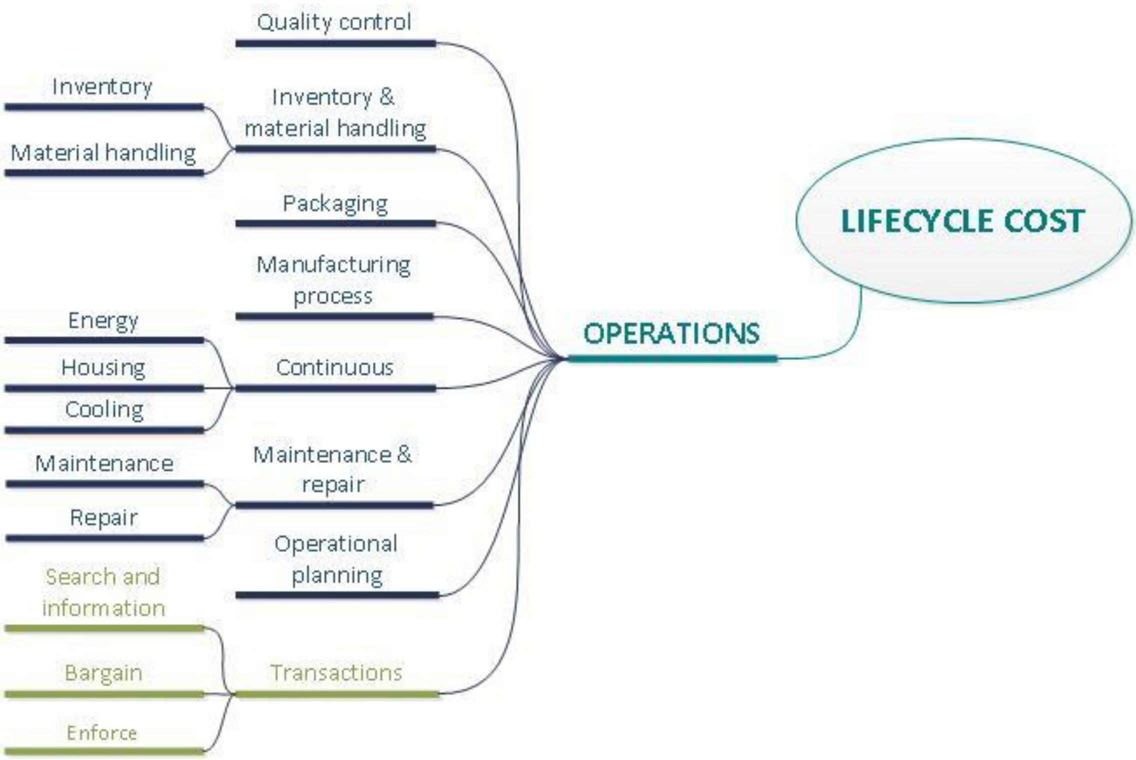

Figure 11 Lifecycle cost breakdown: Operation phase

3.4.1 Quality control

In general, the quality control cost can be divided into four components: a prevention, an appraisal, an internal failure and an external failure cost: [19]

- **Prevention cost** includes actions to prevent defects from occurring such as training. The prevention cost will be part of the overhead cost.
- **Appraisal cost** includes the costs related to inspection and testing in order to ensure that the products conform to quality standards. The appraisal cost can be calculated taking into account a labor and quality material cost.
- **Internal failure cost** includes all additional production-related costs such as rework. The internal failure cost will be included in Section 3.5 about teardown.
- **External failure cost** is the cost incurred when quality failures enter the market resulting in lost sales. The external failure cost will be included in the overhead cost. [19]

Extra quality controls related to mold changeovers and start-ups are taken into account when dealing with these topics.

3.4.2 Inventory and material handling

3.4.2.1 Inventory

In a blow molding production plant, the inventory consists of raw materials as well as finished products. The inventory cost is composed of an ordering, a carrying and a stock out cost. [20]

- **Ordering costs** include the ordering process and an inbound logistic cost.
- **Carrying costs** take into account aspects such as storage space, inventory service and inventory risk.
- **Stock out costs** are determined by the incurred cost in case of a shortage.

According to Timme et al. the total cost of holding inventory can be calculated using a division into an inventory non-capital carrying cost and an inventory capital charge. [22]

- **Inventory non-capital carrying cost** includes warehousing, obsolescence, pilferage, damage, insurance, taxes, administration and others.
- **Inventory capital charge** represents the cost of capital which is the opportunity cost of investing in an asset relative to the expected return on assets of a similar risk.

On average, the total inventory carrying cost amounts to 25% of inventory with a contribution of the non-capital carrying cost of 10% and the contribution of the cost of capital of 15%. [22]

REM Associates [23] state that the standard "rule of thumb" for the inventory carrying cost is 25% of the inventory value on hand. According to Richardson [24], the inventory carrying cost rate could be placed between 25 – 55% consisting of several components:

Table 1 Overview inventory carrying cost rate

Inventory carrying cost rate	
Cost of money	6% - 12%
Taxes	2% - 6%
Insurance	1% - 3%
Deterioration & Pilferage	3% - 6%
Obsolescence	6% - 12%
Clerical & Inventory control	3% - 6%
Warehouse expenses	2% - 5%
Physical handling	2% - 5%
TOTAL	**25% - 55%**

The cost of money represents the cost to secure financing. Besides the cost of money, the goods also have to be taxed and insured. Raw materials and finished products can deteriorate, get damaged or even be stolen. Besides deterioration and pilferage, also obsolescence of finished products and raw materials can occur. Clerical and inventory control includes the administration cost of data entry and bookkeeping. Warehouse expenses include the ground, the building and the maintenance of the building. Related to inventory is also the physical handling in order to move the goods to and from the storage space.

3.4.2.2 Material handling

The material handling process consists of three components: inbound, outbound and in factory. The cost associated with material handling is constituted of a labor cost and a transport and handling equipment cost. If the labor hours (H_{MP}), the used equipment hours (H_{EQ}), the labor cost per hour

(C_{MP}) and the transport (C_{TEQ}) and handling (C_{HEQ}) equipment cost per hour are known; it is possible to calculate the material handling cost (MH):

$$MH = \sum_{\substack{Inbound,Outbound,\\ In\ factory}} (H_{MP}.C_{MP}) + H_{EQ}.(C_{TEQ} + C_{HEQ})$$

3.4.3 Manufacturing process

The manufacturing process cost includes all the cost components related to the blow molding production itself consisting of several production lines. For every production line the labor, mold, machine CapEx, raw material, energy and water cost should be determined. The raw material cost per production line is calculated by multiplying the consumed volume of raw material (V_{RM}), the cost of raw material per unit volume (C_{RM}) and a waste coefficient (W_{RM}). The labor cost can be calculated when the labor hours (H_{MP}) and the labor cost per hour (C_{MP}) are known. The costs related to the machine CapEx and molds can be calculated when the hours of manufacturing (H_M) and the depreciation cost per hour for respectively the machine CapEx (C_{MA}) and mold (C_M) are known. The energy and water cost can be calculated if the machine hours (H_M), the consumption per hour of energy (E_c) and water (W_c) and the cost per consumption unit of energy (C_E) and water (C_W) are given. The summation of all those costs related to the different production lines, results in the manufacturing process cost (MAP).

$$MAP = \sum_{Production\ lines} V_{RM}.C_{RM}.W_{RM} + (H_{MP}.C_{MP}) + H_M.(C_M + C_{MA} + E_c.C_E + W_c.C_W)$$

3.4.4 Packaging

After the manufacturing process, the finished products need to be packaged. The packaging process can be performed manually or by using a packaging machine. The packaging material cost is calculated by multiplying the consumed volume of packaging material (V_p), the cost of packaging material per unit volume (C_p) and a waste coefficient (W_p). When the labor hours (H_{MP}), the labor cost per hour (C_{MP}), the machine hours (H_{PM}), the machine cost per hour (C_{PM}) and the packaging material cost are determined; the total packaging cost (PA) can be estimated:

$$PA = H_{MP}.C_{MP} + H_{PM}.C_{PM} + V_p.C_p.W_p$$

3.4.5 Continuous

The continuous cost category consists of three components: cooling, housing and energy.

3.4.5.1 Cooling

The mold cooling system consumes water and energy. If the operating hours of the cooling system (H_C) and the consumption rates of both water (consumption per hour W_C and cost per unit consumption C_W) and energy (consumption per hour E_C and cost per unit consumption C_E) are known; it is possible to calculate the cooling cost (CC):

$$CC = H_C\ .(W_C\ .C_W + E_C\ .C_E)$$

3.4.5.2 *Housing*

Every production plant needs a location which can be rented or owned; hence a rent or loan should be taken into account. If the amount of square meters as well as the price per square meter is given, the cost of production and storage space can be calculated.

3.4.5.3 *Energy*

A part of the energy is fixed such as lighting, ventilation, etc. Another part of the energy consists of the variable energy consumption by the different production lines and the cooling system. The variable energy consumption depends on the production quantity and will be included in Section 3.4.3 and 3.4.5.1. The fixed energy consumption will be taken into account when calculating the overhead cost.

3.4.6 Maintenance and repair

This cost category consists of two components: maintenance and repair.

3.4.6.1 *Maintenance*

In blow molding production plants, the cost of maintenance can be represented and calculated using a BPMN model. The different steps of the BPMN model are shown in Figure 12.

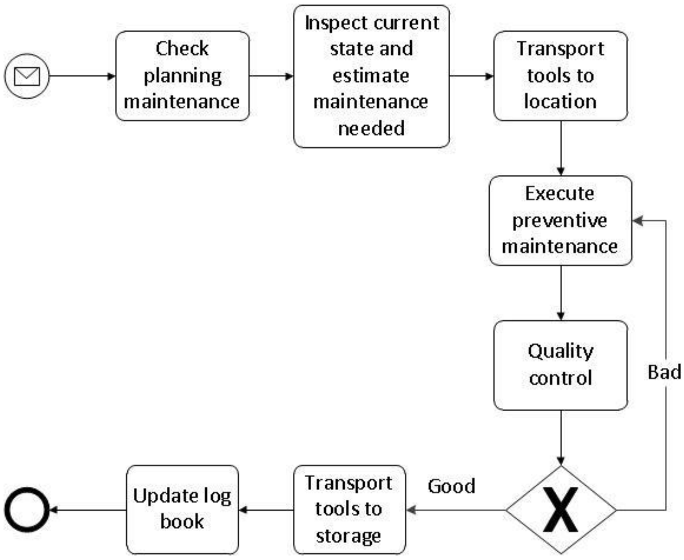

Figure 12 BPMN: Maintenance

3.4.6.2 *Repair*

The cost related to repair activities in a blow molding production plant can be calculated using a BPMN model as shown in Figure 13.

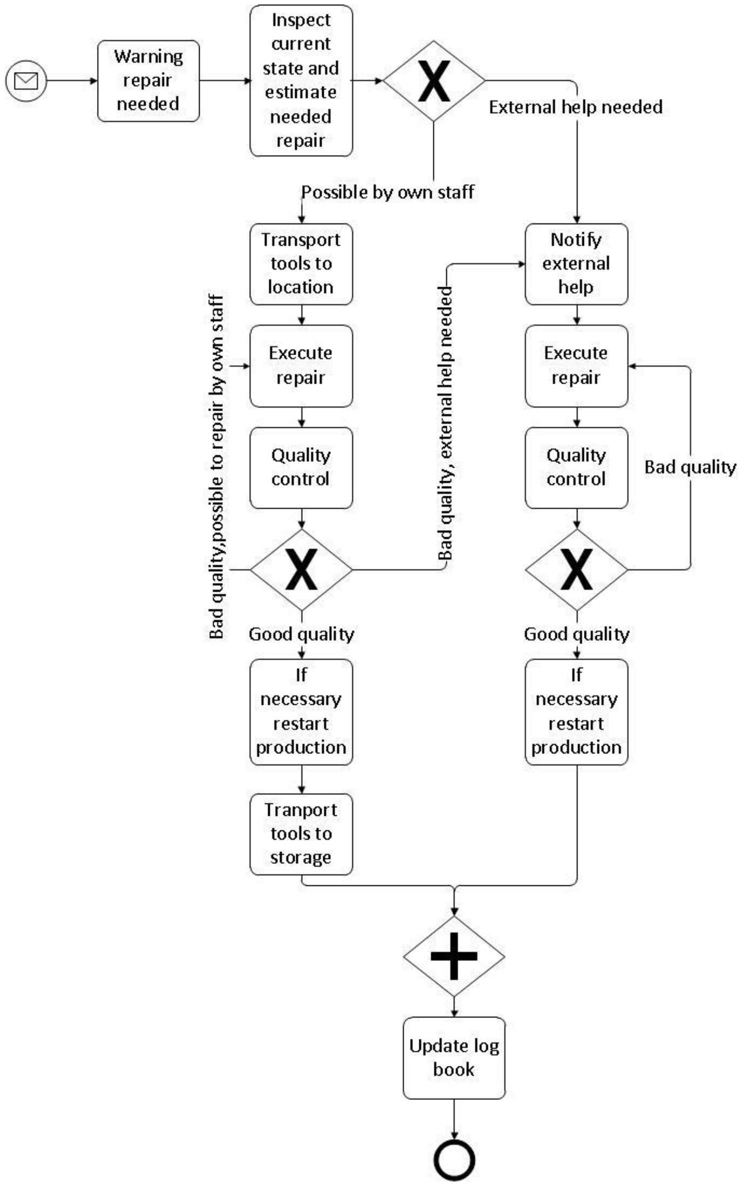

Figure 13 BPMN: Repair

3.4.7 Operational planning

The operational planning consists of two main components: production scheduling and maintenance planning. The operational planning cost (OP) can be calculated when taking into account the hours spent on operational planning (H_{MP}) and the labor cost per hour (C_{MP}).

$$OP = H_{MP}.C_{MP}$$

To evaluate the impact of automating the operational planning process, the amount of labor hours saved by introducing an automated system should be determined as well as the cost of developing and maintaining the system.

3.4.8 Transactions

The transaction cost consists of three components: search and information, bargain and enforce. [30] The transaction cost can be determined by multiplying the labor hours spent on these activities with the labor cost per hour. This master dissertation focuses on the production cost; therefore the transaction cost is seen as an administration cost which will be included in the overhead cost.

3.5 Teardown phase representing the end-of-lifetime of a project

The teardown phase represents the end-of-lifetime of a project including remanufacturing, recycling and disposal. The different aspects of the teardown phase of a blow molding production plant are shown in Figure 14.

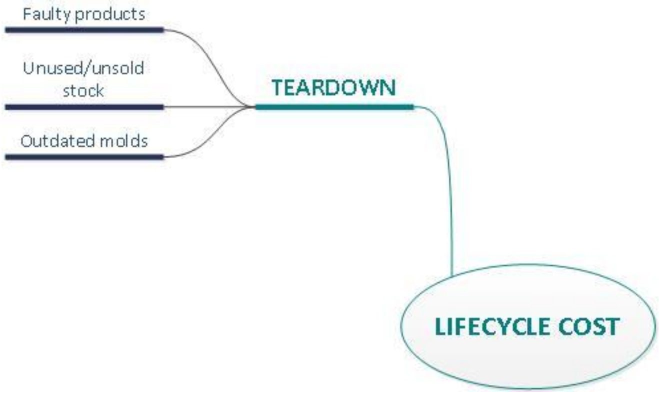

Figure 14 Lifecycle cost breakdown: Teardown phase

3.5.1 Faulty products, unused/unsold stock and outdated molds

There are three options for the faulty products, unused/unsold stock and outdated molds:

- **Rework** means that an adjustment has to be made in order to sell the product afterwards.
- **Recycling** a product implies that the material of the faulty product will be used as raw material for a new product.
- **Disposal** includes the collecting of the faulty products and arranging removal as waste.

The probability of each of these activities can respectively presented by α, β and γ. If the costs of rework (C_{RW}), recycling (C_{RC}) and disposal (C_D) are known as well as the volume of teardown materials (V_{TD}), the labor hours spent on teardown (H_{MP}) and the labor cost per hour (C_{MP}), it is possible to calculate the teardown cost:

$$TD = V_{TD}.(\alpha.C_{RW} + \beta.C_{RC} + \gamma.C_D) + H_{MP}.C_{MP}$$

3.6 Different approaches to estimate an accurate overhead cost rate

The total cost associated with a blow molding production plant can be divided into a production and an overhead cost. The overhead cost will be estimated using a fractional cost modelling method; multiplying a chosen overhead cost rate with the production cost. It should be noted that the overhead cost rate will be different for every production plant. Direct expenses such as labor and material cost are those that go directly towards producing a profit-making product. Overhead is a way of measuring indirect expenses such as long-term planning cost, infrastructure cost, prevention costs, utilities, etc. The overhead cost rate is the resulting ratio of indirect versus direct expenses. When comparing the overhead cost rate of your company with typical overhead rates of the industry, it is possible to estimate your competitive advantage.

The Government Contractor Industry Survey [25] gives an idea about the overhead rates. Overhead pools are developed to allocate certain management and support types of indirect costs. The reason for setting up different overhead pools differs between companies, but is mostly related to location, functional requirements or customer requirements. Bedsworth et al. [28] evaluated an examination of 25 industries showing that the overhead rates range from 13 to 50 %, with an average around 25 %.

According to Miller and Vollmann [26] high manufacturing overhead has a dramatic effect on profit and competitiveness. Overhead costs as a percentage of overall manufacturing costs have been rising steadily for more than 100 years. Overhead costs grow in percentage as direct labor costs fall due to automation, but overhead costs also grow in real terms because of the increased support costs associated with maintaining and running automated equipment. Across the spectrum of U.S. industry, manufacturing overhead averages 35 % of production costs. The critical step in controlling overhead costs lies in developing a model that relates these costs to the forces behind them. According to Banker et al. [27] overhead costs are driven not by production volume but by transactions resulting from production complexity.

In this master dissertation, the overhead cost includes:

- Negotiation costs linked with purchasing raw and packaging materials, energy and water.
- Costs related to manpower and long-term planning.
- Costs of tools and others.
- Costs related to the layout and infrastructure of the production plant.
- Costs related to prevention and external failure.
- Fixed energy cost such as lighting, ventilation and heating of the building.
- Transaction costs including activities related to search and information, bargain and enforce.

A survey report of the North American Plastics Industry of 2013 [29], investigated the average overhead rates of the participating companies. The average overhead rate of companies in the plastics industry having less than $12.8 million quartile sales amounted to 25.7 %.

3.7 Conclusion

In this chapter the lifecycle cost breakdown of a blow molding production plant was introduced. The factory cost breakdown using the lifecycle cost tree structure consists of five stages: planning, deployment, migration, operations and teardown. The estimation of the cost components corresponding to the five stages can be performed using driver-based, process-based or fractional cost modelling methods. The different cost categories were also classified into production or overhead cost.

The lifecycle cost breakdown provides an overview of all costs related to blow molding production plants and will be used throughout this master dissertation. In Chapter 4, the case of Nervia Plastics as a representative Belgian blow molding production company will be introduced. The input data will be discussed using the lifecycle cost tree structure. The implementation of the cost model in Chapter 5 as well as the determination of cost-saving potentials in Chapter 6 will also be based upon the lifecycle cost breakdown.

4
Introduction to the case of Nervia Plastics

This chapter introduces the case of Nervia Plastics. Nervia Plastics can be seen as a representative Belgian blow molding production company that will be used throughout this master dissertation for the application of the cost model and the improvement scenarios. In the first section general information about Nervia Plastics is given, followed by an explanation of its blow molding production process and its factory value chain. In Section 4.3, an overview of the input information is given based upon the lifecycle cost breakdown introduced in Chapter 3.

4.1 Introduction and general information about Nervia Plastics

Nervia Plastics is a company located in Okegem and for many years known for its experience in extrusion blow molding of polyethylene bottles. The company was established in 1965 and acquired in 2004 by French Groupe Millet-Marius and Mr. Stefaan Luca. Nervia Plastics is a supplier of plastic bottles with a wide range of standard bottles as well as custom build bottles. They can produce really diverse bottles from 40 ml up to 5 l. [6]

Throughout this thesis the case of Nervia Plastics will be used as reference. It will be used as source of input information and as a benchmark for the results. The cost model as well as the improvement scenarios will be applied on the case of Nervia Plastics.

4.2 Discussing the blow molding production process

There are different types of blow molding techniques such as extrusion blow molding, injection blow molding and stretch blow molding. At Nervia Plastics, extrusion blow molding is used.

The extrusion blow molding production process starts with mixing the white plastic with a certain color additive and melting it into a liquid plastic. A parison (hollow tube) is formed using an extruder screw that transports the melted plastic into a die head. The pre-form or parison is then brought into a mold where hot air is blown in to form the shape of the mold cavity. Afterwards the mold is cooled down and the final shape is set using water circulation in the mold. The mold halves open and the bottle is removed from the mold. The excess plastic around the bottle (flash) is eliminated and the bottle undergoes leak testing. An overview of the extrusion blow molding process can be found in Figure 15.

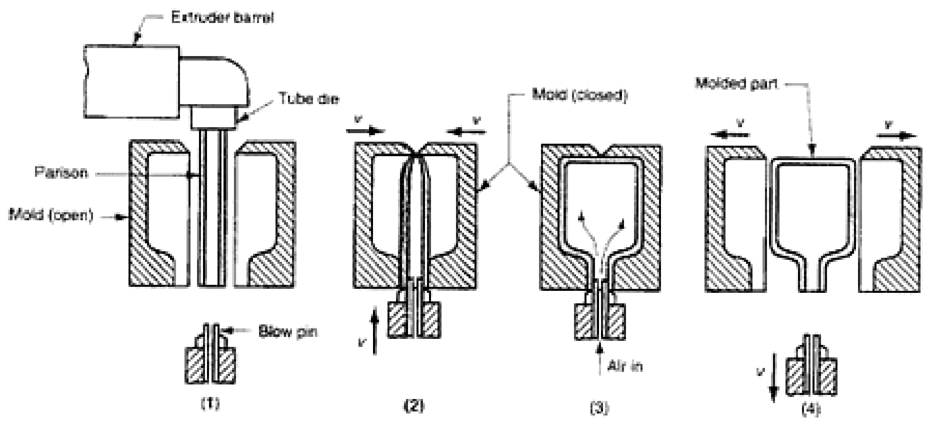

Figure 15 Extrusion blow molding technique [34]

The extrusion blow molding technique is a very fast process allowing high volumes to be produced. Disadvantages are that there is some waste present, the wall thickness can be uneven and it is difficult to achieve low tolerances.

At Nervia Plastics the extrusion blow molding technique is used, but for the completeness the two other main blow molding techniques will be discussed briefly: injection and stretch blow molding.

The injection blow molding technique consists in general of four steps as shown in Figure 16: (1) a parison is injection molded around a blowing rod; (2) the injection mold is opened and the parison is transformed to a blow mold; (3) the parison is inflated to the final shape and (4) the blow mold is opened and the blown product is removed.

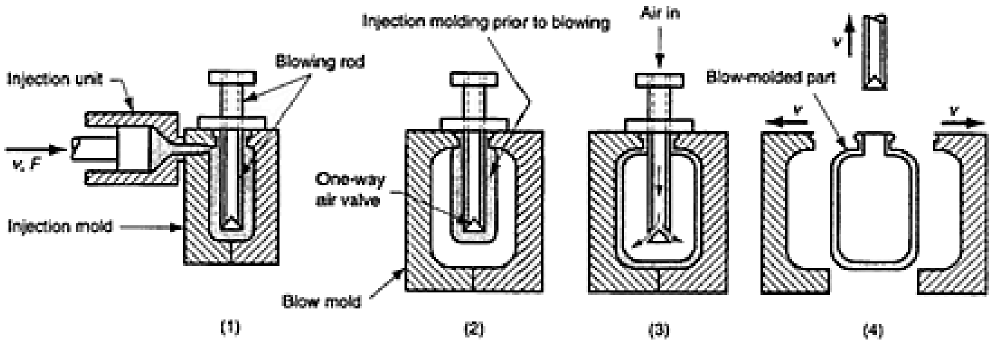

Figure 16 Injection blow molding technique [34]

The stretch blow molding technique consists in general of three steps as shown in Figure 17: (1) injection molding of the parison; (2) stretching of the parison and (3) the blowing of the parison.

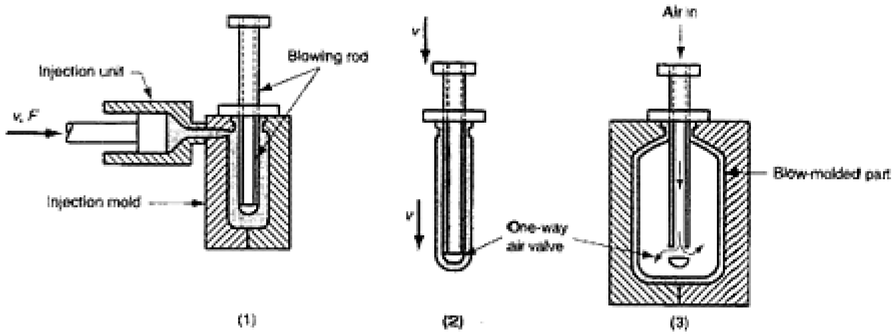

Figure 17 Stretch blow molding technique [34]

The complete factory value chain of Nervia Plastics is shown in Figure 18. Besides the blow molding process, it also includes activities such as mold changeovers, receiving raw materials, quality controls, packaging, storage and shipping to the customers.

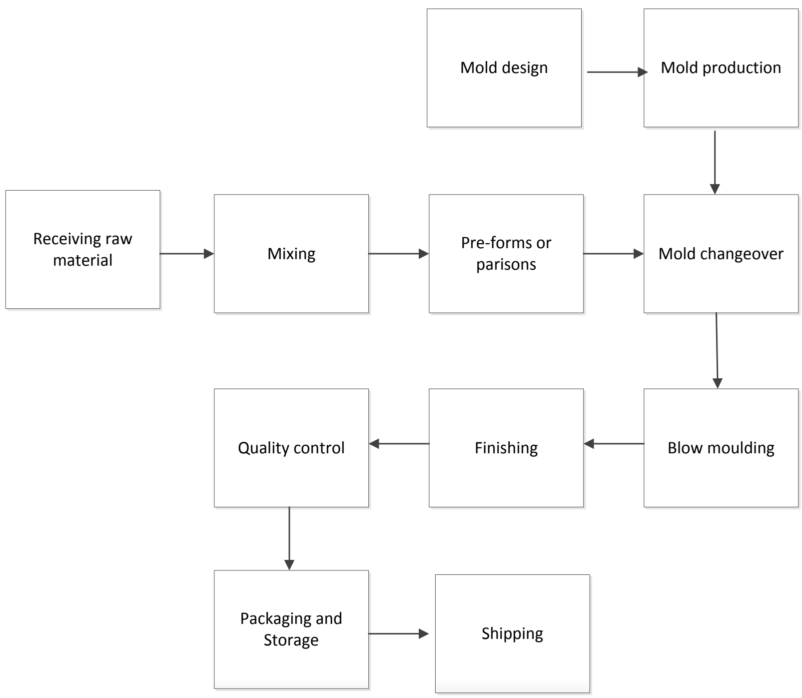

Figure 18 Nervia Plastics: Factory Value Chain

4.3 Overview of the input data

This section is confidential.

4.4 Conclusion

Nervia Plastics is a representative Belgian blow molding production company known for its experience in extrusion blow molding of polyethylene bottles. This chapter introduced the case of Nervia Plastics, discussing its factory value chain and giving an overview of the available input data. Nervia Plastics will be used as reference case to validate the cost model (Chapter 5) and the three improvement scenarios (Chapter 7)

5

Implementation of the cost model and discussion of the obtained results

In Chapter 3, the lifecycle cost breakdown for blow molding production plants was introduced giving an overview of the different cost categories. The costs associated with those cost categories can be calculated using fractional, driver- and process-based cost models. This chapter introduces the implementation of the cost model in Java based on the lifecycle cost breakdown (Section 5.1). The expected output results of this cost model will be discussed in Section **Fout! Verwijzingsbron niet gevonden.**. The cost model will be applied on the current situation of Nervia Plastics and the obtained results will be discussed in Section 5.3.

5.1 Implementation of the cost model in Java

The cost model is based upon the lifecycle cost breakdown as proposed in Chapter 3. The cost model has been implemented in Java in combination with the BEMES-tool (Business, Modeling and Simulation tool). [37] The BEMES-tool is used for those costs that can be calculated using a BPMN model. An overview of the class structure as implemented in Java can be found in Figure 19.

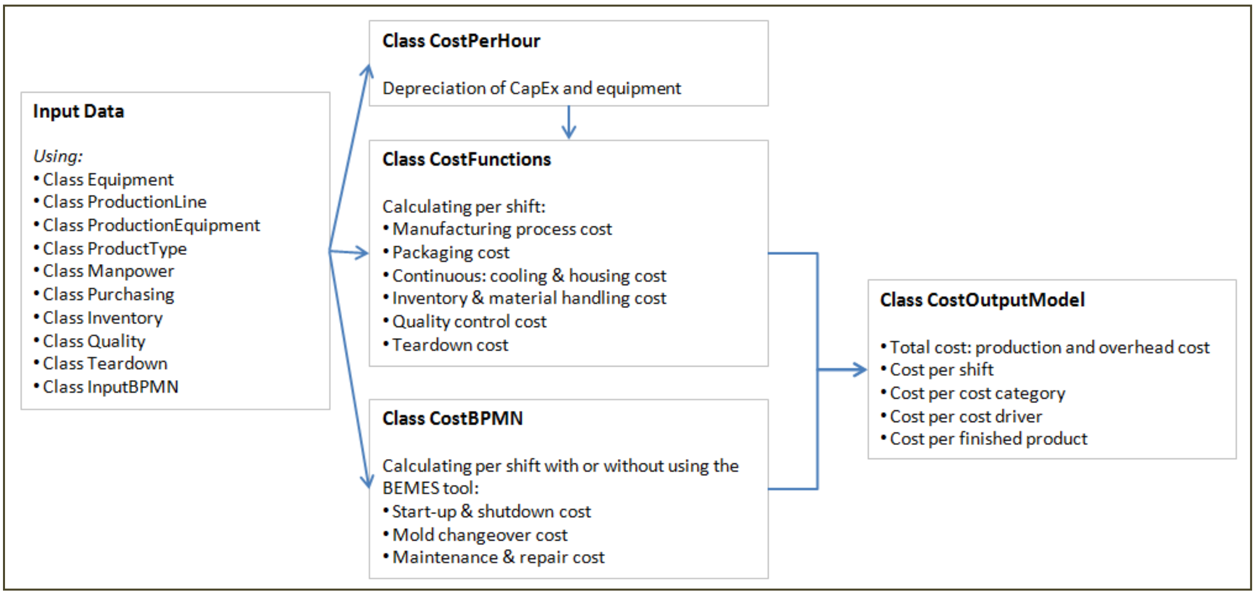

Figure 19 Overview of the cost model as implemented in Java

Throughout the master dissertation, the used time unit is 1 shift consisting of 8 hours. To cope with the shift system a new *TimeFunction* is introduced having as parameters: the first shift, the last shift and values corresponding with the early, late, night shift during the week as well as during the weekend. This function will set up a repeated stream of values starting from the first shift until the last shift, providing the model on every moment with the right value corresponding with the current shift.

In order to include the input data into the cost model, several classes are present each representing a certain category of input elements. For example the class *ProductionLine* can be used if a new production line needs to be included in the cost model. In the class *CostPerHour*, different functions are designed to cope with depreciations using the given input data such as the depreciation of a blow molding machine. The class *CostFunctions* consists of several cost functions to calculate different cost categories (manufacturing process, packaging, inventory and material handling, housing, cooling, quality control and teardown) using driver-based cost models. This class will use information from the provided input data and the class *CostPerHour*. In the class *CostBPMN*, the cost of start-ups, shutdowns, mold changeovers, maintenances and repairs can be calculated per shift using general estimates (without using the BEMES-tool). It is also possible to calculate those costs more in detail when linking the cost model with the corresponding BPMN model using the BEMES-tool. This class will use the provided input data to calculate the different costs. The class *CostOutputModel* combines the results obtained by the class *CostFunctions* and the class *CostBPMN*. This class will provide information about the total cost, the cost per shift, the cost per cost category, the cost per cost driver and the cost per finished product.

It is important that the calculation of the cost profile of a blow molding production plant using Java can be done in a reasonable time. In Figure 20, the execution time of the Java program is shown per number of weeks included in the cost model for 16 production lines. In Figure 21, the execution time for different numbers of production lines included in the cost model during 4 weeks is shown. The execution time was determined using an Apple MacBook Pro (Processor: 36 Hz Intel Core i7, Memory: 16 GB 1600 MHZ DDR3). The execution time increases when the number of weeks or production lines included in the cost model increases. When calculating the cost model for 4 weeks and 16 production lines, the execution time amounts 3.3 seconds which is a reasonable time. The increase of the execution time can be attributed to the cumulative *TimeFunctions* included in the cost model.

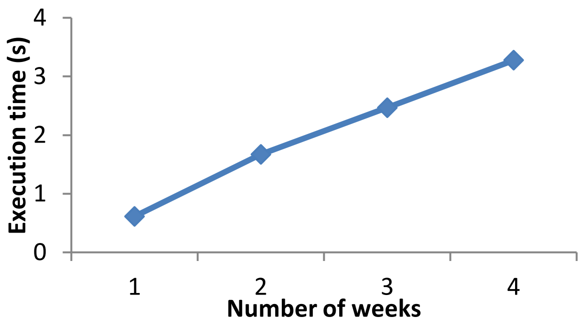

Figure 20 Execution time per number of weeks for 16 production lines

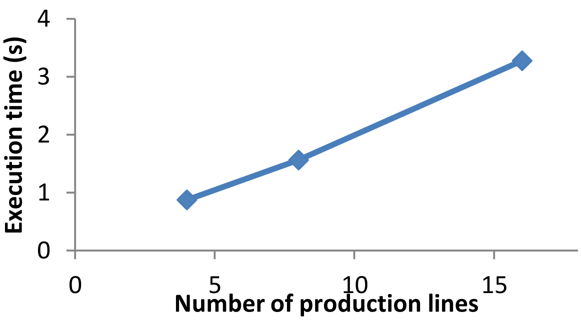

Figure 21 Execution time per number of production lines for 4 weeks

Applying the cost model on blow molding production plants will help to gain insights in the corresponding cost profile. In Section 5.3, the cost model will be applied on the current state of Nervia Plastics. When having a complete overview and understanding of the different cost categories linked with blow molding production plants, it is possible to identify several cost-saving potentials (Chapter 6) and to propose some improvement scenarios (Chapter 7).

5.2 Expected output results when applying the cost model

In Section 5.1 the cost model as implemented in Java was discussed. This cost model can be used to provide an overview of the costs related to blow molding production plants. When providing the cost model with the necessary input data, several output results can be expected as shown in Figure 22.

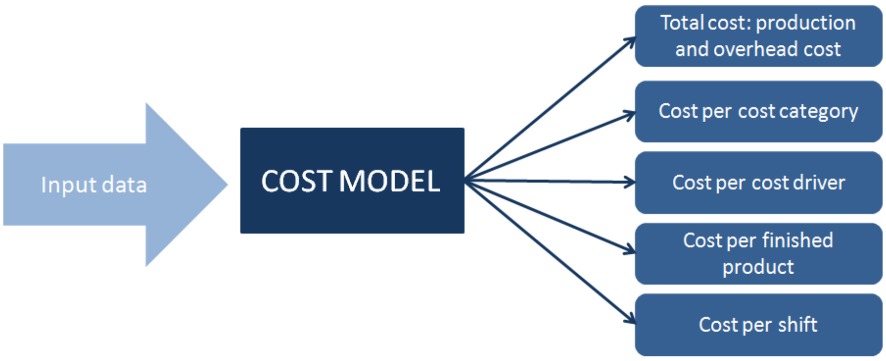

Figure 22 Overview of the output results when applying the cost model on a set of input data

The total cumulative cost over the examined period can be calculated highlighting the difference between production and overhead cost as discussed in Chapter 3. The total cost per shift can be examined as well as the division of the cost in different cost categories. Besides the division of the costs per cost category, it also possible to determine the division of the costs per cost driver. The used cost drivers are energy, CapEx, manpower and raw, packaging and teardown material. When having the total cumulative cost and the number of finished products, it is possible to calculate the cost per finished product. In Section 5.3, the cost model will be applied on the current situation of Nervia Plastics and the obtained results will be discussed.

5.3 Application of the cost model on the case of Nervia Plastics

This section is confidential.

5.4 Generic results

The cost model was applied on the current situation of Nervia Plastics i.e. a representative Belgian blow molding production company that is known for its experience in extrusion blow molding of polyethylene bottles. This provided insights in the distribution of the total cost into the different cost categories. The manufacturing process cost is the major cost category accounting for around 60% of the total cost. In particular, the raw material costs associated with the manufacturing process are significant. The second most important production cost category concerns packaging (10%), followed by the inventory and material handling cost (5%). In addition to the production cost, there is an overhead cost accounting for 20% of the total cost.

When determining the different cost drivers, the raw material cost accounts for more than 50% of the total cost. When optimizing the consumption of white plastics and color additives, big cost savings could result. As a consequence, the cost per finished product is greatly influenced by the bottle type requiring a specific amount of raw materials. The second most important cost driver is the labor cost accounting for 10% of the total cost. The remaining cost drivers i.e. packaging material, energy, equipment, CapEx and teardown material cost represent each less than 5% of the total cost.

Benchmark: literature

According to Kent [71], the energy cost for blow molding production plants has traditionally been between 4 to 5% of the total cost, but this is increasing rapidly with rising energy prices. At Nervia Plastics the energy cost contributes around 2% to the total cost. The difference can possibly be caused by the fact that during the examined period most of the time 5 l bottles were produced requesting more raw materials hence raising the total cost. Therefore the energy cost has a lower contribution to the total cost.

Merki and Kuhmann (EUROMAP) [38] provide a cost overview for an example of an injection molded closure using high-density polyethylene which is the same raw material as the bottles of Nervia Plastics. The comparison between the EUROMAP example and Nervia Plastics is shown in Figure 23.

It should be noted that at Nervia Plastics extrusion blow molding is used instead of injection blow molding, but both techniques show similarities as explained in Chapter 4. When comparing the obtained results of Nervia Plastics to the example of EUROMAP, it can be concluded that the magnitude and importance of the different cost driver categories are similar.

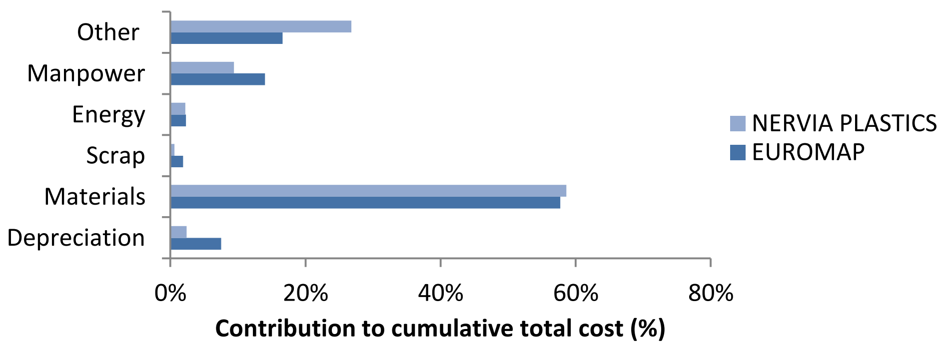

Figure 23 Comparison Nervia Plastics with EUROMAP: Closure - injection blow molding

According to the Canadian Industry Statistics concerning plastic bottle manufacturing, the three most important cost categories are: cost of materials and supplies, production worker wages and cost of energy, water and vehicle fuel. The manufacturing costs in the plastic bottle manufacturing industry are dominated by the costs of materials and supplies as can be seen in Figure 24. The industry is therefore vulnerable for fluctuations in the raw material prices. [39]

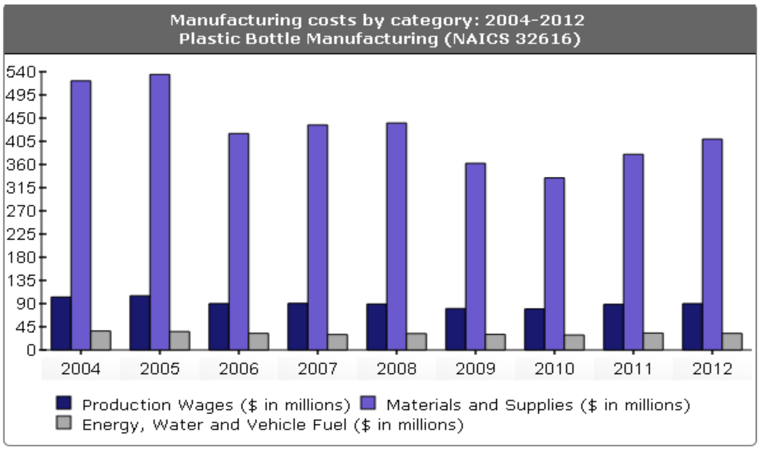

Figure 24 Canadian Industry Statistics: Overview of the plastic bottle manufacturing costs [39]

When comparing the results of the Canadian Industry Statistics with the obtained results of the case of Nervia Plastics (Figure 25), it can be concluded that the cost of raw materials is by far the most important cost category, followed by the cost related to manpower.

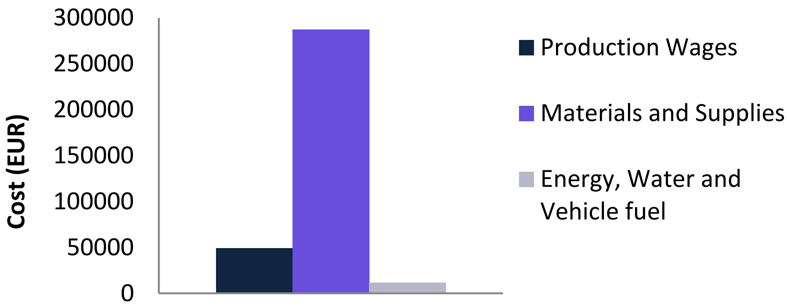

Figure 25 Comparison of the production wages, materials & supplies and energy, water & vehicle fuel cost at Nervia Plastics

5.5 Conclusion

The cost model of blow molding production plants was based on the lifecycle cost breakdown and has been implemented in Java in combination with the BEMES-tool for those costs that can be calculated using a BPMN model. When the necessary input data is provided, the cost model can generate several output results such as the total cumulative cost, the cost per shift, the cost per cost category, the cost per cost driver and the cost per finished product. The application of the cost model on the case of Nervia Plastics, gave insights in the cost profile of a blow molding production plant providing an answer on the first research question. The most important production cost categories are the manufacturing process cost, the packaging cost and the cost related to inventory and material handling. Raw material consumption is the largest cost driver for blow molding production plants followed by manpower. Literature confirmed the magnitude and importance of the cost categories and drivers.

When having a complete overview and understanding of the different cost categories linked with blow molding production plants, it is possible to identify specific cost-saving potentials. In Chapter 6, several cost-saving potentials will be described qualitatively. In Chapter 7, the focus lies on three promising improvement areas of blow molding production plants which will be quantitatively evaluated. The scenario about production time will determine the impact of producing 7 days per week (also during weekends) instead of 5 days per week. The second scenario about energy will investigate energy-reducing measurements, aiming at determining the impact on the total energy consumption and cost. The last scenario will discuss inventory optimization opportunities and how those will impact the total inventory cost.

6

Qualitative description of cost-saving potentials

When applying the cost model on blow molding production plants, different cost categories and cost drivers were identified providing an answer on the first research question. The second research question deals with possible cost-saving potentials. In this chapter, cost-saving potentials are proposed and described qualitatively for the most important cost categories. There are three important improvement philosophies that are widely adapted in the industry: Operational Excellence, Lean Manufacturing System and Going Green. These philosophies will be introduced in Section 6.1. Several improvement techniques introduced by the three philosophies can be used to optimize different production cost categories as will be discussed in Section 6.2.

6.1 Introduction to important improvement philosophies

In this section three important improvement philosophies will be introduced: Operational Excellence, Lean methodology and Going Green. Operational Excellence focuses on the competitiveness of the production process, aiming at finding the best cooperation between people, processes and assets. The Lean methodology strives to deliver the best quality at the lowest cost with the shortest lead time while taking the desires of its customers into account. The last improvement philosophy, Going Green, focuses on sustainability. These are currently the most important improvement strategies that are widely adapted in many industries in order to improve the production efficiency.

6.1.1 Operational excellence

Every company strives to obtain operational excellence by aiming at finding the best cooperation between people, processes and assets. To obtain operational excellence, several steps should be followed [42][41]:

1) Clarify the business model and sources of competitive advantage.
2) Install a philosophy of passion for operational improvement.
3) Design the processes and the production system to become competitive.
4) Disaggregate the journey into a sequence of digestible pieces driven by real change.
5) Align the organization with objectives and reinforce with superior execution.

The most important barriers to obtain operational excellence are: the inability to rapidly adapt business processes to changes, ineffective or inadequate IT systems and lack of accurate and timely information. Those barriers should be taken into account when installing an Operational Excellence philosophy. [42]

6.1.2 Lean Manufacturing Methodology

The Lean manufacturing methodology is currently one of the most applied improvement philosophies in manufacturing companies. This methodology is based on the Toyota Production System introduced by Kiichiro Toyoda, Taiichi Ohno and Shigeo Shingo (1949-1975). With the increasing competition among the different car suppliers, the aim of Toyota was to excel in cars with limited financial means while fighting bureaucracy by pushing problem-solving downward in the organization. In order to achieve this, Toyota introduced interchangeable parts and flexible assembly lines. They hired highly skilled workers while focusing on excellent quality. The methodology is brought to North America through Ohno and Shingo's books and launched as "Lean" by Womack & Jones in 1995. [70]

Lean is a manufacturing philosophy which shortens the time between customer order and product shipment by eliminating waste. Its main objective is to offer the best quality at the lowest cost with the shortest lead time. Figure 26 shows the basic principles of the Toyota Production System. The two pillars introduce the concepts of Just In Time (JIT) meaning "the right part should be at the right time in the right amount" and Jidoka meaning "built-in quality". It is important to have a culture of continuous improvement with flexible, capable and highly motivated people. Operational stability is the foundation being achieved using techniques such as Total Productive Maintenance, Standardized Work, Heijunka (Level Production) and Value Chain. [43]

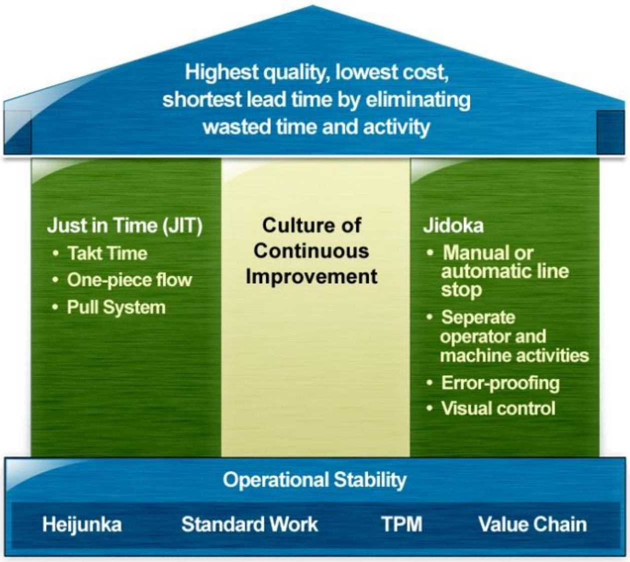

Figure 26 General overview of the Lean Manufacturing Methodology [43]

Lean manufacturing is a systematic approach to identify and eliminate waste through continuous improvement by flowing the product at pull of the customer in pursuit of perfection. Three elements should be eliminated [42]:

- Muda i.e. the elimination of non-value adding activities.
- Mura i.e. the elimination of variation in production planning, workloads and targets.
- Muri i.e. the elimination of overburdening of people and machines.

When a company wants to become a Lean company, it should apply the following five steps:

STEP 1: Define value for the customer

The first step in becoming a Lean company consists of defining value for the customer. Value means the amount of money the customer is willing to pay for the product or service which is solely determined by the customer.

STEP 2: Identify the value stream and eliminate waste in it

A value stream map includes all steps that produce value for the customer. In Chapter 4, the factory value chain of Nervia Plastics is given. When having a value stream map, it is possible to identify and eliminate waste along the value stream. There are eight types of waste as shown in Figure 27: defects, overproduction, waiting, non-utilized talent, transportation, inventory, motion and extra-processing.

Figure 27 Lean Manufacturing Methodology: Eight types of waste [44]

STEP 3: Make the product flow

A synchronous chain has to be installed where each person has a balanced amount of work and work is moved down the line synchronously. Every person is empowered to stop the production process. The pace of production should match the pace of sales.

STEP 4: Let the customer pull

When introducing a pull system, the product is pulled through the manufacturing process at the rate of customer demand. At the end of the process, there are finished goods that need to be replenished through a linked series of tactical buffers. Pull systems limit the Work In Progress (WIP).

STEP 5: Strive for perfection every day

It is important to continuously improve the production process. The company should create a non-blaming culture where problems are recognized as opportunities and emphasis should lie on finding solutions. The biggest challenges are learning to see and eliminate waste and sustaining the change.

There are different tools supporting the Lean implementation such as SMED, Kanban and 5S. Different techniques associated with the Lean manufacturing methodology will be elaborated in Section 6.2.

6.1.3 Going Green

A growing trend in industry is focusing on sustainability. Sustainability is about taking responsibility to continue to guarantee a better quality of life for people while respecting the environment. Corporate social responsibility is an integral part of the objective of many companies to improve the lives of consumers now and for future generations. To achieve this objective, innovation and sustainable use of resources is crucial.

A method used to assess the sustainability of a product, is performing a Life Cycle Assessment (LCA). According to the United States Environment Protection Agency [45], LCA is a technique to assess environmental aspects and potential impacts associated with a product, process or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases.
- Evaluating the potential environmental impacts associated with the identified inputs and releases.
- Interpreting the results so as to make a more informed decision.

Every company should strive to minimize the ecological footprint in every aspect of a product's life cycle. In Figure 28, a general product life cycle is shown with the material (M) and energy (E) inputs and the waste (W) output from product, process or distribution.[46]

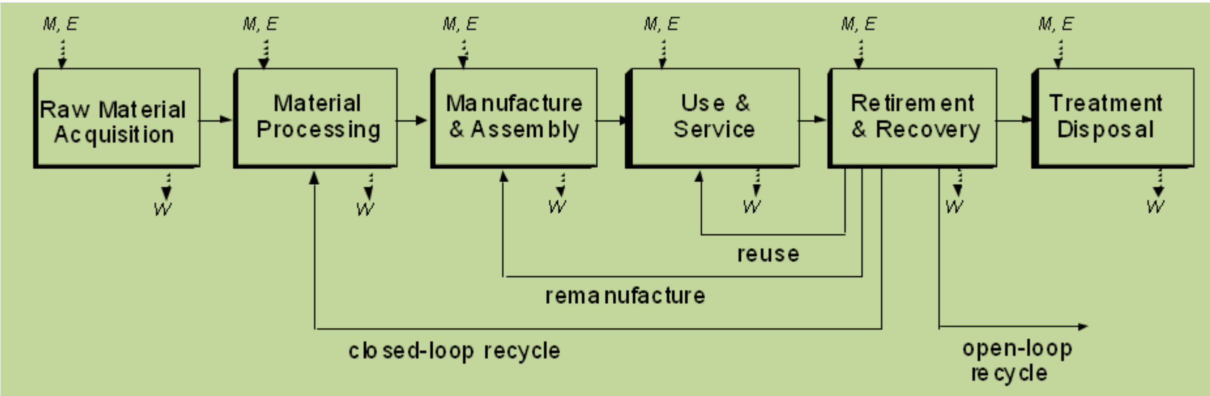

Figure 28 Going Green: Product Life Cycle [46]

6.2 Improvement methods to optimize different production cost categories

In the previous section three improvement philosophies were introduced: Operational Excellence, Lean manufacturing and Going Green. In this section possible improvement methods for the different production cost categories are discussed based upon the lifecycle cost breakdown of Chapter 3. For every cost category indicated in dark blue (Figure 29), a corresponding improvement technique will be discussed in cyclical order.

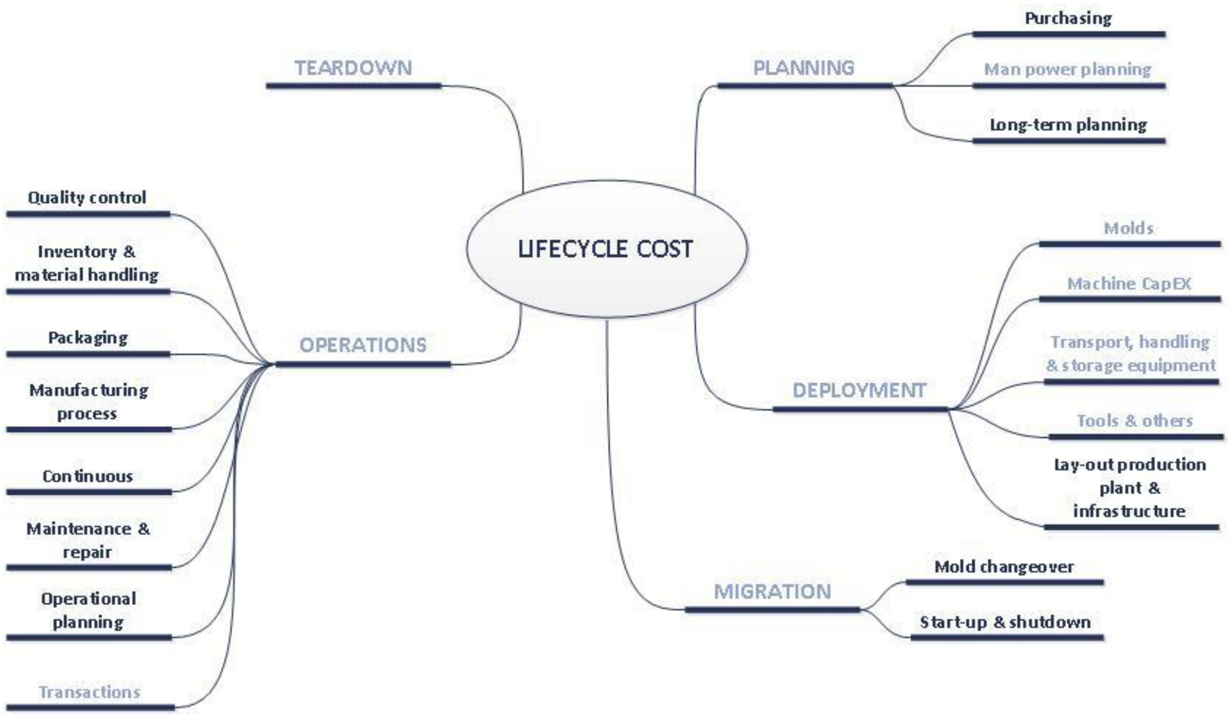

Figure 29 Cost-saving potentials: Lifecycle cost breakdown

6.2.1 Purchasing

Purchasing refers to a business or organization attempting to acquire goods or services to accomplish the goals of its enterprise. Purchasing can have a significant effect on an organization's total profit. The success of a purchasing function depends on competent buyers and a purchasing manager. In order to improve the purchasing activity, it is necessary to employ systematic purchasing methods, implement technological advances, and hire capable and qualified buyers and an intelligent purchasing manager. [47]

Roland Berger [48] performed a Purchasing Excellence Study introducing a Purchasing Excellence Performance Cube to assess companies' purchasing performances. They identified seven key findings:

1) Purchasing excellence supports profitable growth strategies for companies.
2) Purchasing excellence enterprises treat the purchasing function as a true business partner.
3) Sustainability – economic, ecological and social – is a key part of the purchasing strategies of purchasing excellence enterprises.
4) The purchasing function assesses the different financing options and is largely responsible for managing investments.
5) Risk management – suppliers, raw materials and utilities – is considered a top-priority ongoing task in purchasing.
6) Interdisciplinary and cross-functional activities place new demands on purchasing – intercultural, linguistic and technical skills are increasing.
7) Employees are better qualified and purchasing has become more professional – the number of buyers with relevant degrees is increasing.

Energy, water, raw and packaging materials need to be purchased in order to start the blow molding production process. As stated in Chapter 5, the raw material cost accounts for more than 50% of the total cost of blow molding production. The purchasing activity has an important impact on the raw material prices. Hence, installing a strategy of purchasing excellence can help blow molding production plants to control their production cost and to get one step closer in obtaining Operational Excellence.

6.2.2 Long-term planning

In an increasingly competitive international environment, production costs must continuously be monitored closely. It is important to develop a strategy on the long-term in order to ensure that the blow molding production plant remains competitive. Long-term planning includes several corporate decisions such as possible investments in new machinery or determining the optimal production time. The context of corporate decision making can be characterized by a framework that includes multiple actors at different levels and in various types of domestic and international spheres as shown in Figure 30. [67]

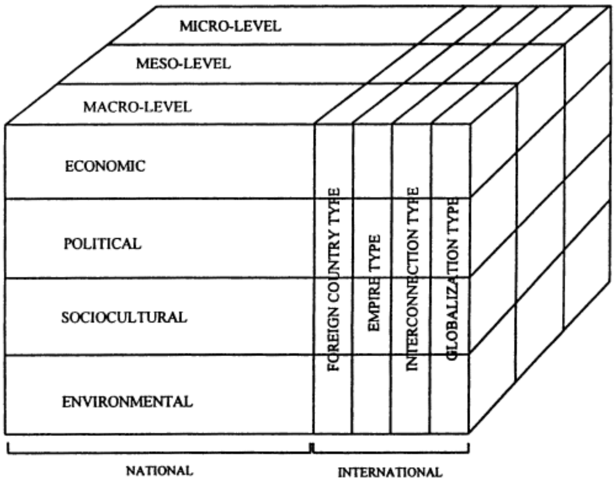

Figure 30 Conceptual framework of corporate decision making [67]

According to Enderle et al. [67] every corporate decision is accompanied with a corporate responsibility. Regarding corporate responsibility, four realms can be identified: the economic, political, socio-cultural and environmental. The distinction between the micro-, meso- and macro-level of acting highlights the decisive, qualitative differences between persons, organizations and systems. With regard to international relations, four types can be identified: foreign, empire, interconnection and globalization.

Corporate decision making is future-related and deeply exposed to uncertainty and change. It can be analyzed as a three-step process: (1) strategic positioning, (2) resource commitments and (3) assessment. In formulating strategy, responsibilities are translated into objectives. The firm commits to its strategic plans when resources are allocated to specific activities. In the post-commitment phase, there is the necessity of measuring the efficiency that results from the committed resources. Appropriate measurements permit comparability across realms of responsibility, embrace all phases of business planning and performance, and incorporate long-term effects. [67]

In the case of blow molding production plants, it is an interesting exercise to determine the impact of production time. Producing seven days per week (also during weekends) instead of five days per week, will affect several factors such as the capacity utilization, labor cost, energy cost, inventory cost, start-up and shutdown cost. The impact of production time on blow molding production plants will be further elaborated in Section 7.1.

6.2.3 Layout production plant and infrastructure

An important part of the production cost is attributed to material handling which is affected by the layout of facilities. A good layout of the production plant provides a smooth flow of people and materials while increasing the productivity. The aim of facility planning is improving the material handling process, maximizing the speed for quick customer feedback, providing safety and job satisfaction, introducing flexibility and utilizing effectively the amount of available people, equipment, space and energy. [42]

For blow molding production plants, the design of the production plant is important to ensure a smooth flow of raw materials to the blow molding machines and of the finished products to the warehouse. Also the design of the outside area should be adapted to the amount of trucks that need to be (un)loaded in order to reduce the number of traffic jams. As discussed in the Lean manufacturing methodology, unnecessary movements of products and materials should be eliminated. Several techniques exist such as Flow Process Chart, String Diagram and Travel Chart [49] that can assist in the development of an optimal design.

When dealing with the layout of a production plant, the plant capacity and the grade of flexibility should be determined. When an increase of capacity is required, the plant can opt to procure more blow molding production lines or to increase the production time as will be discussed in Section 7.1.

Besides the determination of the capacity of the production plant, the necessary grade of flexibility should be decided. Flexibility means the ability to respond to change. The amount of production flexibility depends on the internal and external uncertainties and the available buffers such as physical stock, spare capacity and spare lead times. There are two flexibility principles that are important to take into account [42]:

1) A small amount of flexibility appropriately used yields most of the benefits of total flexibility.
2) Adding flexibility to chain plants and products together is the most efficient.

For every individual production plant, it is possible to design a flexibility plan. When purchasing new blow molding production lines, the flexibility needs to be taken into account e.g. the product types a particular blow molding machine can produce.

Operations management is crucial to realize the benefits of a good design. In this respect, the socio-technical design was introduced by Eric Trist, Tavistock Institute in 1950 [68]. The socio-technical design consists of a technical system including machinery, procedures and physical arrangements and a social system including people and their attitudes, values, behavioral styles and relationships. Eric Trist made a list with rules how to build and manage the integration of both the social and the technical system.

6.2.4 Mold changeover and start-up

The start-up of a blow molding production plant and the execution of a mold changeover can be seen as set-up operations. Set-up is defined as the preparation and after-adjustment before and after a product lot is processed. When the set-up time can be reduced, it is possible to produce more. Other benefits are the reduced inventory level, the increased flexibility, the increased bottleneck capacity and the reduced costs. A technique used for set-up time reduction is Single-Minute Exchange of Die (SMED) that is part of the Lean methodology. [49]

In the SMED technique, two different types of set-up operations are identified:

- **Internal setup** which can only be performed when the machine is stopped.
- **External setup** which can be conducted while the machine is operating.

The SMED procedure consists of four conceptual stages and three improvement steps in order to reduce the set-up time to a minimum. In every conceptual stage several practical techniques can be applied to help executing the different improvement steps. [50]

The different stages and improvement steps are:

- **Preliminary stage:** This is the initial state where internal and external set-up conditions are not distinguished.
- **Step 1:** This improvement step involves separating internal and external set-up leading to the first stage called the separated stage.
- **Step 2:** During this improvement step, the internal set-up activities should be converted as best as possible to external set-up activities leading to the second stage called the transferred stage.
- **Step 3:** This last improvement step involves the streamlining of all aspects of the set-up operation leading to the final stage called the improved stage.

The aim of the different improvement steps is clearly shown in Figure 31.

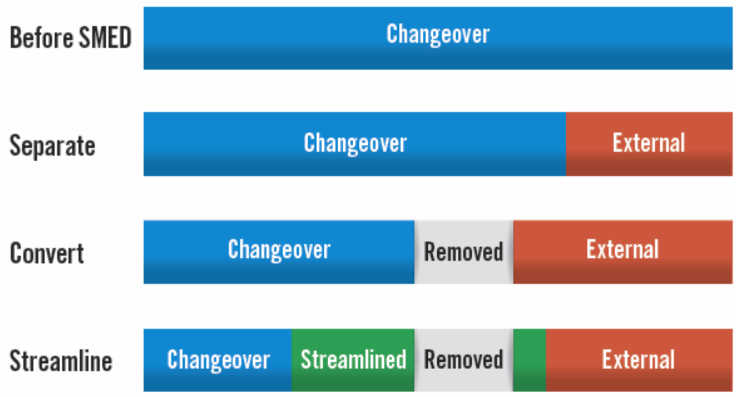

Figure 31 SMED: Conceptual stages and improvement steps [50]

The SMED technique can be used to optimize for example mold changeovers and start-ups at blow molding production plants. This technique has been applied on a mold changeover at Nervia Plastics resulting in a possible 35% reduction of the mold changeover duration. The complete study and corresponding results can be found in Appendix A.

6.2.5 Operational planning

In many companies the operational planning is still executed manually using Excel, but it is possible to automate the scheduling of the different products on the different machines using a variety of algorithms, heuristics and software packages. Scheduling means planning of different jobs over time on different resources taking into account the capacity of these resources and possible extra constraints concerning due dates, release dates, changeover times, etc. In a blow molding production plant, a schedule needs to be drawn determining which product type will be produced using a specified blow molding machine during a certain shift. The scheduling of start-ups, mold changeovers and maintenances should be performed for every production line.

In practice, the scheduling activity consists of four steps [52]:

1) **Machine loading:** Assigning tasks to the different machines.
2) **Sequencing:** Placing the tasks on one machine in a specified sequence.
3) **Dispatching:** Spreading the detailed planning to the operators.
4) **Execution feedback:** Monitoring the implementation to make adjustments possible.

To solve this kind of optimization problems, several methods exist. Exact methods will find an optimal solution using a mathematical model, but in practice this will need a lot of calculation time and memory for complex systems. Heuristics on the other hand, find very quickly a solution using a sequence of many small improvements of an existing solution until a local optimum is reached. Disadvantage is that the solution can be of bad quality. The final method consists of meta-heuristics using the method of heuristics, but adding specific steps to escape from the local optima to improve the solution. In this respect, meta-heuristics will give the best time-quality trade-off when scheduling complex systems. Possible meta-heuristic methods are iterated local search, evolutionary algorithms, GRASP, simulated annealing and tabu search. [53]

When automating the operational planning in blow molding production plants, the labor cost can be reduced because less time needs to be spent on this task. An automatically determined schedule will be computed more accurately and quickly than a manual schedule.

6.2.6 Maintenance and repair

In a production plant maintenance and repair are crucial in order to keep producing and delivering good quality. This section focuses on maintenance and corresponding improvement techniques in order to increase the benefits of maintenance.

There are different types of maintenance: preventive (usage triggered maintenance), predictive (condition triggered maintenance) and corrective maintenance (failure triggered maintenance). Currently there is a trend from corrective maintenance towards preventive and predictive maintenance. In practice, when dealing with maintenance, the risk of failure should be estimated and evaluated. Risk can be defined as the probability of failure times the consequences of failure. Risk assessments can be performed qualitatively or quantitatively. The result of a qualitative risk assessment is often shown as a **risk matrix** where one axis shows the probability of occurrence and the other axis shows the consequences given a relative risk value as shown in Figure 32.

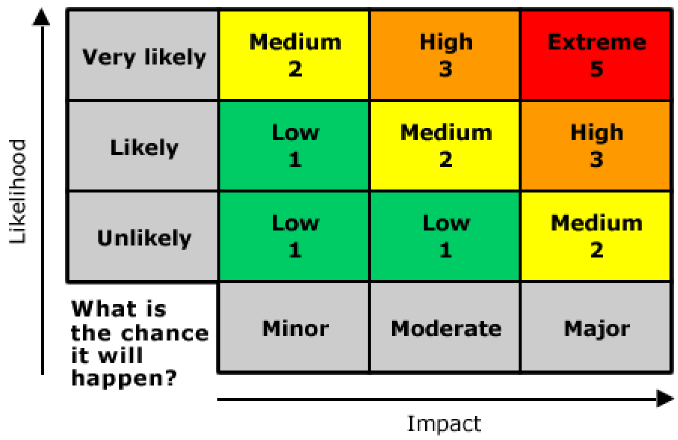

Figure 32 Risk Matrix [54]

Risk-based maintenance (RBM) is a quantitative approach for preventive maintenance planning based on a risk assessment with the aim of minimizing the probability of system failure. The risk-based maintenance methodology consists of three main modules [55]:

1) **Risk estimation** consisting of risk identification and estimation.
2) **Risk evaluation** consisting of risk aversion and risk acceptance analysis.
3) **Maintenance planning** considering the risk factors.

Another risk assessment tool is the **Hazard & Operability Analysis** (HAZOP) which is a structured and systematic technique for system examination and risk management. HAZOP is often used for identifying potential hazards and operability problems. It is based on a theory assuming that risk events are caused by deviations from design or operating intentions. The identification of deviations is achieved by a questioning process using predetermined guide words such as more, less, early, later, other than, before, after, part of, etc. [56]

A HAZOP analysis is a qualitative brainstorming technique consisting of four phases [56]:

1) **Definition phase:** A cross-functional team determines the scope of the required risk assessment project.
2) **Preparation phase:** Identifying and locating necessary data, project management preparations and agreeing on HAZOP guide words.
3) **Examination phase:** Identifying deviations by applying the guide words, identifying consequences and possible measures and agreeing on actions.

After the examination phase a report of the study needs to be made and the implemented actions will need follow-up.

In blow molding production plants, it is important to continuously perform maintenances in order to maintain the high quality standards and to avoid breakdowns of the blow molding machines. For example air leaks in a poorly maintained plant can account for 30 to 50% of the compressed air consumption. [69] Therefore a maintenance planning should be made using an appropriate risk evaluation technique.

6.2.7 Continuous: Energy

Energy efficiency forms an integrated and important aspect of the overall evaluation of investment opportunities fitting into the improvement philosophy of Going Green. The most important driving forces for improved energy efficiency are financially and organizational related e.g. a cost reduction due to lowered energy use, possible direct fiscal subsidies, rising energy pricing, investment subsidies for technology, future external pressures and enhancing the competitiveness. [57]

Two main ways of reducing energy costs are [57]:

- **Supply side management** such as investing in new electricity production and negotiating lower prices with suppliers.
- **Demand side management** including energy-efficient technologies, load management, energy conversion and encouraging more energy-efficient behavior.

According to Hermann and Thiede [58] energy consumption is a major aspect in the context of increasingly important economic relevance of originally environmentally driven issues in production companies. Main objective is to maximize energy efficiency; optimizing the ratio of the production output to the energy input. Energy consumption is highly dynamic depending on the production process and the actual state of the machines. Machines consist of several energy consuming components which generate a specific energy profile.

It is important to foster energy efficiency on different layers of the production plant [58]:

- **Production process and machines:** minimizing energy requirements in standby, decreasing energy consumption when operating, increasing the output rate with the same or lower energy input and efficient shutdown.
- **Production system:** avoiding processes without value creation or further processing of bad quality, avoiding peaks of energy consumption and employing opportunities of time and location shifting.
- **Technical building services:** increasing resource productivity and avoiding unnecessary demand and system losses.

Improving the energy efficiency of blow molding production plants requires the full understanding of the energy usage. It is also crucial to analyze the energy supply contracts. The blow molding production process consists of several steps that can be optimized when installing energy-reducing measurements. This will be further discussed in the second improvement scenario about energy in Section 7.2.

6.2.8 Manufacturing process

There are two types of manufacturing process strategies: push and pull. Push systems schedule the release of work based on information from outside the system e.g. the forecasted demand. Pull systems authorize the release of work based on information from inside the system e.g. the system status. Push systems do not limit the Work In Progress (WIP) in the system in contrary to pull systems that establish a limit on the WIP. Installing a pull system in a production plant will lead to reduced costs because there will be no more WIP explosions and the average WIP level will be reduced. [60]

According to the Lean methodology, a manufacturing company should install a pull system. To implement a pull system, there can be opted for different strategies such as Kanban, CONWIP and POLCA. [60]

When implementing a **Kanban** strategy, Kanban squares are designed limiting the amount of WIP in front of each workstation. When implementing a Kanban system, a (limited) number of finished parts will be available at the end of the production line. The finished goods will be replenished through a linked series of tactical buffers. Kanban is suited for high-volume, low-mix repetitive manufacturing environments. [60]

A Kanban is an approval to have a full container of a determined quantity of a specific product. There are two sequential processes (supplying and customer process) with an intermediate buffer called a supermarket. A withdrawal Kanban is a transport authorization to transport a full container to the customer. When a container has left the supermarket, a production Kanban is send to the production process to make a new container. This is also shown in Figure 33. [60]

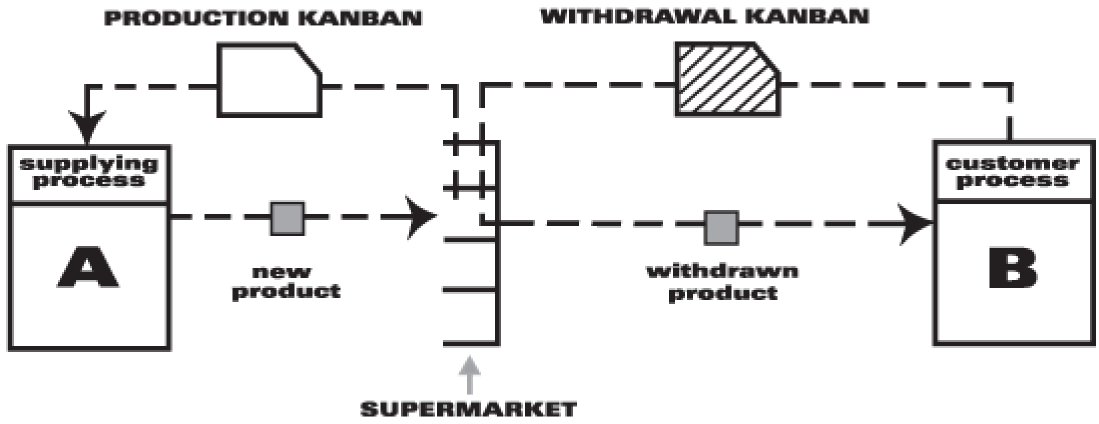

Figure 33 Kanban system [65]

CONWIP is an abbreviation of ‘Constant WIP’. CONWIP is a capacity signal which limits the total amount of orders present in the production system. Whenever an order is finished, and thus the WIP level is decreased by one, the system gets a signal to release a new order in the production system. This strategy is suited for low-volume, high-mix environments with a limited amount of different routings. The next job to release is selected from the work backlog which is often based on a Manufacturing Resources Planning (MRP) schedule. [60]

POLCA (Paired-cell Overlapping Loops of Cards with Authorization) is a pull system specifically designed for low-volume, high-mix environments with many different routings. POLCA cards are used for every pair of workstations that are consecutive in any routing. [60]

Pull systems have several advantages over push systems; hence it is interesting for blow molding production plants to implement a pull strategy. In blow molding production plants, the manufacturing process cost accounts for 60% of the total cost. The most appropriate strategy to implement a pull system in a blow molding production plant is Kanban because Kanban is mostly used for high volume, low-mix repetitive manufacturing environments.

6.2.9 Packaging

The second most important production cost category is packaging representing around 10% of the total cost. The labor cost accounts for almost 50% of the packaging cost. Work study and the corresponding techniques try to improve the methods of packaging and material handling. Work study is defined as the systematic examination of methods so as to improve the effective use of resources and to set up standards of performance for the activities being carried out. Work study exists of two elements: method study and work measurement. Method study is "the systematic recording and critical examination of ways of doing things in order to make improvements" and work measurement can be described as "the application of techniques designed to establish the time for a qualified worker to carry out a task at a defined rate of working". [62]

Method study focuses on eliminating unnecessary movements and reveals shortcomings of design, materials and methods. Work measurement on the other hand is a method to eliminate ineffective times. [49]

A method study always needs to be performed before a work measurement. Method engineering can be performed on different levels:

1. **Analysis of processes** where a process is a series of operations performed to manufacture a product. Different techniques can be used to analyze processes such as Operations Process Chart, Flow Process Chart, Flow Diagram, String Diagram, Travel Chart, PQ analysis, Value Stream Mapping and layout planning. [49]
2. **Analysis of operations** focuses more on the specific operations using techniques as multi-activity diagram, man/machine diagram, SMED, line balancing and ergonomics. [49]
3. **Analysis of motions** is the most low-level where specific motions are studied in detail. To perform this analysis, techniques such as two-hands analysis, the principles of motion economy and workplace layout can be used. [49]

After performing a work study, the most efficient work process can be defined and implemented called the standardized work method. Standardized work aims to maintain the productivity, quality and safety at high levels. For every task a standard time should be determined stating the average time it takes to execute the task. [42]

Labor cost accounts for almost 10% of the total cost in blow molding production plants. When applying work study techniques, new improved methods can be installed reducing the labor hours needed to perform certain tasks. The analysis of the mold changeover performed at Nervia Plastics consisted of a combination of the SMED technique and work study techniques. The different activities executed by the operator were recorded in order to improve the work process (see Appendix A).

6.2.10 Inventory

Inventory is the third most important cost category representing more than 5% of the total cost. When a lot of inventory is present, other problems can be hidden underneath the surface such as long set-up times, rework, poor housekeeping, machine breakdowns, delay in deliveries, etc. By systematically decreasing the inventory level, the different problems will be discovered and can be tackled. [49]

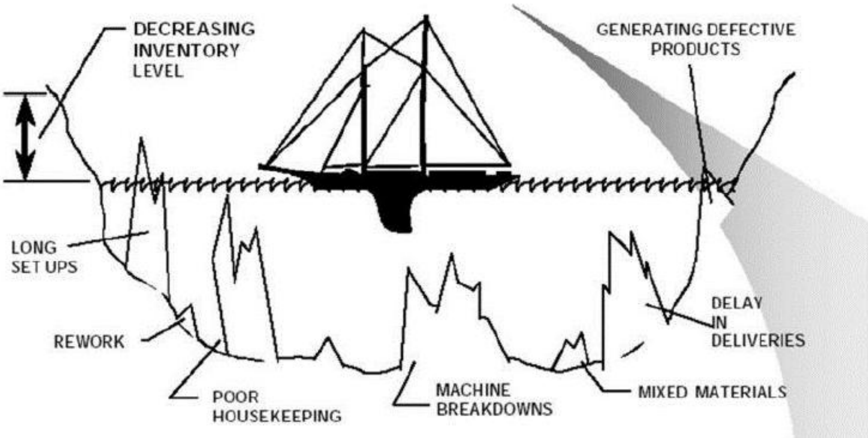

Figure 34 Illustration of problems covered by a high inventory level [49]

The inventory cost consists of an ordering, carrying and stock out cost component as discussed in Section 3.4.2.1. It is important to define the most optimal inventory level so as to minimize the total inventory cost. One of the most important models used to solve this problem is the Economic Order Quantity (EOQ) model. This model determines the optimal order quantity and reorder point taking into account the inventory holding cost, the replenishment cost, the replenishment lead time, the demand, etc. To deal with a variable demand, a safety stock can be provided. The third improvement scenario will discuss inventory optimization techniques more in detail (Section 7.3).

6.2.11 Quality control

Most companies strive everyday to deliver the best quality while trying to minimize the total amount of teardown. In this section, different techniques being part of the Lean methodology are discussed in order to improve the quality.

One of the pillars of the Lean methodology is **Jidoka**, also called built-in quality. This quality principle became known as autonomation or automation with a human touch. There are four steps involved in Jidoka: discover an abnormality, stop the process, fix the problem immediately and investigate and correct the root cause. Jidoka is about building quality into a process rather than inspecting for it at the end of the process. It is important that every employee has the authority and responsibility to stop the production when finding a problem, but also to train everyone in problem solving. [42]

A very useful technique used in many companies is **visual management**. Visual management means the ability to understand the status of a production area in less than five minutes by simple observation without using computers or speaking to anyone. When implementing visual management methods, it is possible to save a lot of time. **5S** is an example of a visual management method identifying the location for tools, components and work in progress. When something is not in its allocated place, action can be taken. [42] The 5S stands for:

1. **Sort:** keep only what you need.
2. **Set in order:** a place for everything and everything in its place.
3. **Shine:** cleaning and looking for ways to keep clean and organized.
4. **Standardize:** maintaining and monitoring the first three categories.
5. **Sustain:** sticking to the rules.

For example in blow molding production plants, the 5S strategy can be applied on the tool box of mold changeovers. This would reduce the total searching time and would decrease the duration of the mold changeover.

Another method called **Six Sigma** is often used in combination with the Lean manufacturing methodology. Six Sigma is a measure of quality that strives for near perfection. It is a disciplined and data-driven approach and methodology for eliminating defects in any process. It drives the quality toward six standard deviations between the mean and the nearest specification limit. Lean Six Sigma is based on the DMAIC-cycle: Define, Measure, Analyze, Improve and Control as shown in Figure 35. [44]

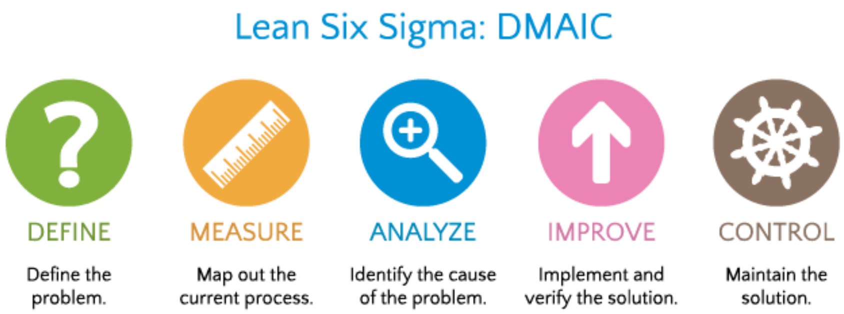

Figure 35 Lean Six Sigma: DMAIC [44]

6.3 Conclusion

After having a complete overview and understanding of the different cost categories linked with blow molding production plants, it was possible to identify several cost-saving potentials. There are three important improvement philosophies widely adapted in industry: Operational Excellence, Lean Manufacturing System and Going Green. Several improvement techniques introduced by the three philosophies can be used to optimize different production cost categories such as mold changeovers, the operational planning, the manufacturing process, etc. All the cost-saving potentials described in this chapter prove that there exist promising techniques to optimize minor and major cost categories. Three cost-saving potentials dealing with production time, energy and inventory optimization will be further examined in Chapter 7.

7

Analysis of three improvement scenarios: production time, energy and inventory optimization

The cost model as explained in Chapter 5, revealed the most important cost categories i.e. the manufacturing process cost, the packaging cost and the cost related to inventory and material handling. Raw material consumption is the largest cost driver for blow molding production plants. The other main cost drivers are amongst others manpower and energy consumption. In Chapter 6, several cost-saving potentials dealing with the optimization of different cost categories were discussed qualitatively. In this chapter three relevant opportunities for cost savings will be quantitatively evaluated to determine their impact on the total cost. These opportunities focus on production time, energy and inventory.

The first scenario deals with optimizing production time: could we save costs when using machine uptime more optimally by also producing during weekends? The manufacturing process cost can possibly be reduced when adjusting the production time. The impact of production time on machine utilization will be examined as well as the impact on manpower, energy, start-up and inventory costs.

Energy consumption of blow molding production plants will only gain more significance due to ever increasing energy prices. The second improvement scenario deals with optimizing the energy consumption proposing energy-reducing measurements so as to decrease the total energy cost.

Raw and packaging materials play a central role in the total cost profile of blow molding production plants. In addition, the inventory and material handling cost is the third most important production cost category. In the scenario about inventory, the costs related to the purchase of raw and packaging materials will be examined as well as other inventory optimization opportunities to determine the optimal supply strategy.

For every scenario the impact on the total cost profile of blow molding production plants will be discussed. The three improvement scenarios will be applied on the case of Nervia Plastics.

7.1 Scenario 1: Optimizing production time

The first improvement scenario concerning production time deals with the following question: could we save costs when using machine uptime more optimally if also producing during the weekends? When determining the impact of producing seven days per week (also during weekends) instead of five days per week, several factors should be taken into account as shown in Figure 36. These factors will be discussed more in detail in the following sections.

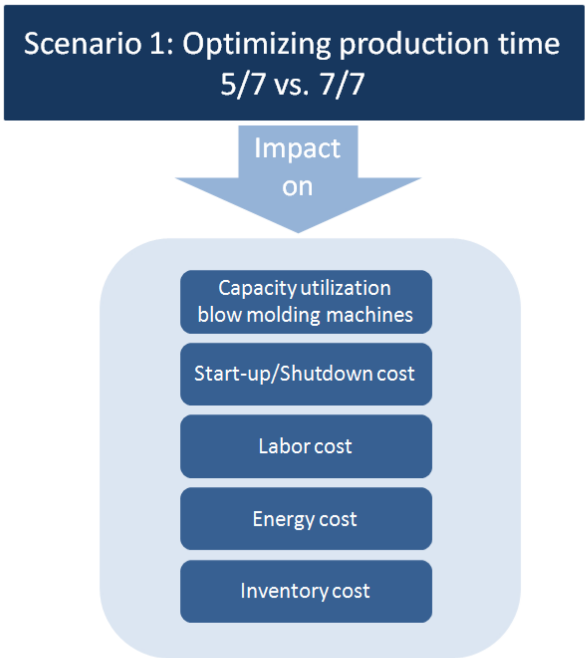

Figure 36 Overview of Scenario 1: Optimizing production time

To determine the cost impact of including weekends in the production time, two scenarios need to be compared: a scenario where there is only production during the week and a scenario where the blow molding production plant is producing continuously. The impact of both scenarios on the cost profile can be investigated using the cost model as discussed in Chapter 5. The improvement scenario about production time will be applied on the case of Nervia Plastics (Section 7.1.6).

7.1.1 Capacity utilization of blow molding machines

The machine utilization will be higher when producing continuously due to an increase of production time. Since the blow molding machines can produce more products, there will probably be fewer machines needed. Of course when utilization is higher, more maintenance is needed. It is important to schedule this during the most expensive energy hours or the less expensive technician labor hours. Another possibility is to schedule maintenances during mold changeovers, but the drawback is that it is more difficult to keep track of.

7.1.2 Start-up and shutdown cost

When you are producing continuously instead of five days per week, no start-up is necessary on Monday mornings nor shutdowns on Saturday mornings. The costs related to start-ups and shutdowns will be avoided. The valuable production hours that are lost when performing a start-up or shutdown can also be utilized when producing continuously.

The start-up includes heating of the blow molding machines, extra quality controls, tuning of the different parameters, etc. During start-up, the likelihood to encounter small problems that need to be cured is higher than during continuous production. Hence avoiding start-ups could reduce the number of production problems as well as the number of customer complaints due to products of inferior quality.

7.1.3 Labor cost

In blow molding production plants, the labor cost accounts for almost 10% of the total cost. The labor cost during weekends will be higher due to the higher personnel cost per hour. When working in shifts, a premium percentage depending on the type of shift will be accounted for as shown in Table 2. When working during the weekend, the labor cost will increase with 50%. There are special work regimes available for weekend work. It is possible to make use of a team of employees that work every weekend during two shifts of 12 hours.

Table 2 Difference in labor cost per shift

Labor	Early/Late shift	Night shift	Weekend shift
Shift premium	+ 10%	+ 20%	+ 50%

7.1.4 Energy cost

Labor costs are rising when producing during the weekend, but on the other hand the energy price will decrease. Energy prices fluctuate depending on the type of shift. The energy price per kWh was estimated using historical data from Belpex [36] based on week six of 2014 (2/2/2014 until 8/2/2014) as shown in Table 3. The energy price during the weekend shifts is remarkably lower than during the week.

Table 3 Difference in energy cost per shift

Energy	Shift type	Energy price (EUR/kWh)
Week	Early shift	0,0504
	Late shift	0,0497
	Night shift	0,0324
Weekend	Early shift	0,0260
	Late shift	0,0352
	Night shift	0,0280

7.1.5 Inventory cost

Increasing the production time, will also affect the inventory level of the finished products. It is unlikely that trucks will come by during the weekends to transport the finished products to the customer. Hence the inventory of finished products will be higher during the weekend and necessary storage space needs to be available. When including weekends in the production time, it is possible to produce more products influencing the amount of raw materials that need to be available. This will impact the inventory management strategy as will be explained in Section 7.3.

7.1.6 Application on the case of Nervia Plastics

This section is confidential.

7.2 Scenario 2: Optimizing energy consumption

Energy consumption of blow molding production plants will only gain more significance due to ever increasing energy prices. The most compelling reason for the plastics industry to implement energy-reducing measurements is that wasting energy costs money. Energy costs can be controlled and often reduced by implementing measures that do not require significant investments. [69]

In this section, energy-reducing measurements are investigated determining the impact on the total energy consumption and cost of blow molding production plants. The different aspects related to the scenario about optimizing energy consumption are shown in Figure 37.

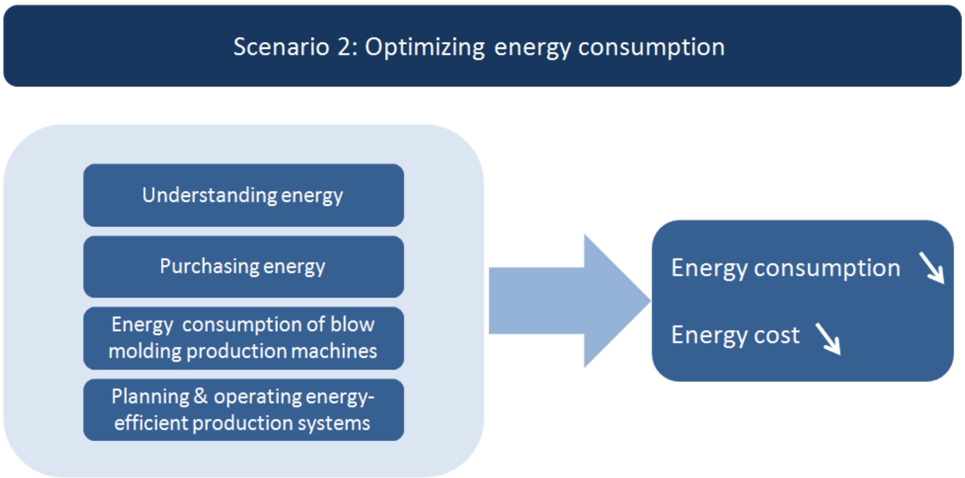

Figure 37 Overview Scenario 2: Optimizing energy consumption

Improving the energy-efficiency of blow molding production plants requires full understanding of the energy usage. It is also crucial to understand the energy bill to become energy aware. For every step of the blow molding production process, several possible energy-reducing measurements will be discussed. In a blow molding production plant, also side equipments such as the cooling and compressed air supply system consume energy and need to be made as energy-efficient as possible. Besides the assets of blow molding production plants, this scenario will also discuss a method for planning and operating energy-efficient production systems. At last, this improvement scenario will be applied on the case of Nervia Plastics.

7.2.1 Understanding energy

It is important to understand the basics of the energy usage before it is possible to reduce the energy consumption and corresponding cost. The upcoming questions will help to obtain an overview of the energy usage of a blow molding production plant. [71]

1) When is the blow molding production plant using energy?
2) Why is the blow molding production plant using energy?

3) Where is the blow molding production plant using energy?
4) How much energy is the blow molding production plant using?

Plastics processing involves cycles of energy demand, therefore it is important to understand when energy is being used and the difference between productive and standby energy. The demand plotted versus time will give valuable information on the energy consumption. Most organizations will have a base load which will be present even when there is no production (e.g. energy spent on heating, lighting, etc.). The energy corresponding to the base load will be included in the overhead cost. It is important to minimize the waste of energy through standby losses. In Figure 38, a demand graph is shown indicating the base load energy consumption. In the beginning there is no production, afterwards a start-up takes place and production occurs until the shutdown. [71]

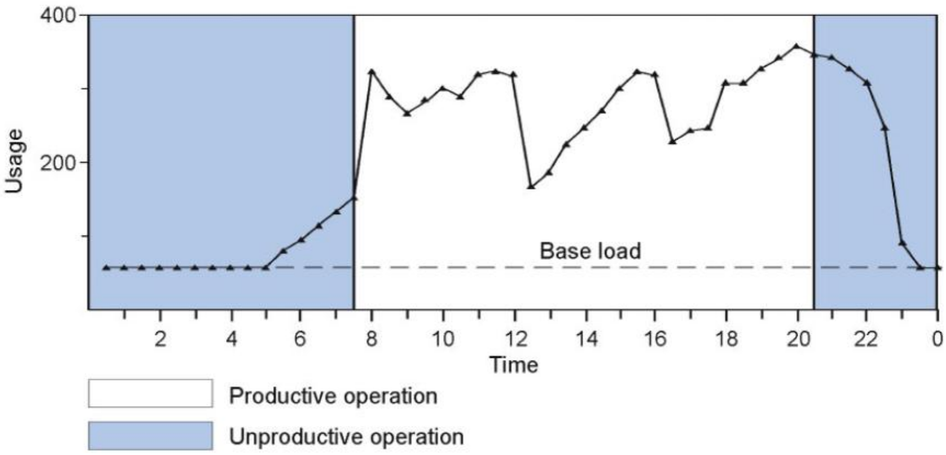

Figure 38 Demand graph: determination base load [71]

Energy consumption of a blow molding production plant does not solely depend on the production volume, but also other factors influence the energy consumption such as an increase in scrap levels, poor maintenance, poor quality of raw materials, climate changes, etc. It is important to known how much energy is used in every component of the blow molding production plant. Installing sub-meters will help to get further information on the areas of high energy use. [71]

A site survey [71] will help to gain an overview of the site energy use and is a key starting point for energy savings. A site survey not only considers the blow molding machines, but also the building and the side equipment such as conveyors and palletizers. Buildings-related energy is an easy area to make energy savings because changes do not impact the production. Many processes generate excess heat and it is worth investigating if this can be used for other purposes, such as space heating on colder days. [69]

To benchmark a plant's performance, the Specific Energy Consumption (SEC) is used. [83] SEC is a measure of the energy used for every unit of throughput of polymer (kWh/kg). For extrusion blow molding, the Specific Energy Consumption varies from 'typical' values of 1.5 - 2.0 kWh/kg up to 'high' values of greater than 3.0 kWh/kg. [71]

7.2.2 Purchasing energy

When having an overview of the energy usage in a blow molding production plant, it is possible to compare the energy consumption with the total energy cost. Understanding the energy bill will help to become energy aware. The electricity bill is usually made up of a basic price per unit of energy (EUR/kWh) and costs related to four key factors [69]:

1) **Maximum Power Requirement (MPR):** The maximum current a site can draw at the supply voltage without tripping the main circuit breakers. If the MPR is exceeded, the supplier will charge a penalty cost as well as a cost for upgrading the supply system.
2) **Power factor:** It is a measure of how efficiently electrical power is consumed. The lower the power factor, the higher the energy cost. The reactive power charge on the electricity bill is used for companies that do not demonstrate efficient use of their energy.
3) **Load factor:** Utility regulations allow energy suppliers to apply a demand charge that reflects the proportionate investment in power generation capacity needed to meet customers maximum load requirements or peak demand. The demand charge, unlike the energy charge, is a fixed cost.
4) **Maximum demand:** Maximum demand is the highest average value of any thirty-minute period.

When purchasing energy, it is important to negotiate the lowest energy price as possible with energy suppliers taking into account the maximum power requirement, the power factor, the load factor and the maximum demand.

7.2.3 Energy consumption of blow molding production machines

There are many blow molding machine functions that influence the energy usage. Identifying these will provide opportunities to reduce the energy consumption and to increase profits. The 5 stages of an extrusion blow molding production process are shown in Figure 39. Energy consumption in every stage will be discussed and some general remarks about capital equipment selection will be made.

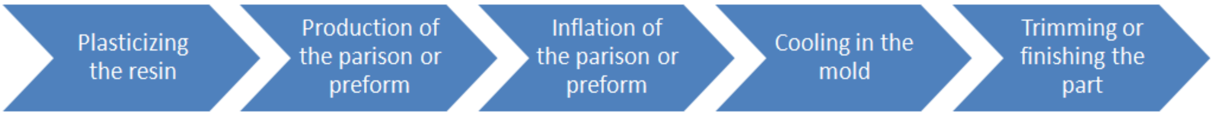

Figure 39 The five stages of a blow molding production process

STAGE 1: Plasticizing the resin

The polymer is fed from an overhead hopper into the extrusion unit where it is plasticized by a combination of mechanical shear of the extruder screw and electrical heat. To maintain the control of the polymer temperature, there is often a water-cooling circuit supplemented by external cooling fans present. The process should be optimized to ensure that the polymer leaves the die in the correct state and in the most efficient time possible. [69]

Processing of hygroscopic polymers and repeatable processing of non-hygroscopic polymers requires drying. If a polymer is not dried, any moisture present will be converted to steam during processing and will create surface marks or even weaken the molding. Drying is a hidden cost, but consumes quite a lot of energy. It is necessary to determine the required time and temperature for drying. Good storage of raw materials will reduce their moisture content. [71]

STAGE 2: Production of the parison or preform

The major component of energy consumption of a blow molding machine is the extruder area which typically uses 40% of the energy. Controlling the wall thickness ensures that the container weight is optimized and the extruder capacity is not wasted. Controlling the parison length ensures that the polymer is not extruded unnecessarily. [83]

STAGE 3: Inflation of the parison or preform using compressed air

The mold unit has two functions: shaping the product and extracting heat from the product. High pressure expands the polymer quickly to the shape of the mold. Hydraulic cylinders are present to close the mold and keep it closed against the blowing pressure. The most appropriate compressed air pressure must be determined. [71]

Compressed air is a convenient and often essential utility, but it is very expensive to produce. In fact, most of the energy used to compress air is turned into heat and then lost. In order to minimize the energy consumption of the compressed air supply system, the air demand should be minimized and the supply of compressed air should be optimized. To expand the parison, compressed air at around 40 bar is used for PET bottles. Economic use is dependent on three factors [69]:

1) Selecting the correct type and size of compressors to match the anticipated levels of use.
2) Operating at the appropriate pressure for optimum production.
3) Rigorous maintenance procedures to minimize leaks.

Reducing the air demand can be achieved by removing the supply of air when compressed air is not required. The pressure levels, air intake conditions and control of the compressor should be checked to improve efficiency. It is important to keep the air intake as cold as possible e.g. with a 3°C reduction on the air intake the power consumption falls with 1%. Ducting to allow fresh air intake rather than air from the compressor could reduce the intake temperature by 15°C and reduce energy usage with 5%. Good maintenance is essential to high-efficiency. Air leaks in a poorly maintained plant can account for 30 – 50% of the compressed air consumption. [69]

STAGE 4: Cooling of the mold

The cooling system provides a controlled supply of chilled water that flows through the mold and cools the product. Cooling capacity is the rate-determining factor of the blow molding production process. Good contact between the cooling water and mold channels is essential. The cooling rate depends on the heat transfer rate from the cooling media to the mold and from the mold to the product. Water has a higher heat transfer rate than air; therefore air bubbles could possibly reduce the cooling efficiency of the water. [71]

A reliable and consistent source of cooling water is essential for fast and repeatable plastics processing. The cooling system uses approximately 11% of all the energy consumed in a blow molding manufacturing plant. All the energy that is put into the polymer during processing must be removed again to produce a finished product at room temperature. It is important to decide the maximum water temperature needed for cooling. A 1°C rise of the cooling water results in a 3% reduction in the chillers power. When the ambient temperature falls 1°C below the temperature of the returning water, free cooling is possible. Before going to the chiller, the water is automatically diverted through the free cooler that pre-cools the water reducing the load on the chiller and the energy consumed by the compressors. The lower the ambient temperature, the greater the free cooling effect. [69]

STAGE 5: Trimming or finishing the part

After ejection of the part from the mold, the part needs to be trimmed i.e. the flash needs to be removed. The finished product should be designed as to minimize the unnecessary material waste.

It is important to set correct process parameters and to control those continuously. Just enough energy should be used for every stage of the process. Throughout the process the possibility should be examined to reduce the heating time, the cooling time and other cycle stages to save energy.

Capital equipment selection

The most simple and easy way to permanently improve the energy-efficiency of a blow molding production plant is purchasing energy-efficient capital equipment. The total cost of ownership of the equipment (i.e. the initial cost and the operating cost) need to be taken into account when selecting the capital equipment. [71]

Until recently, the majority of blow molding machines used a hydraulic unit. The hydraulic drive provides the power to various motions of the mold, the extruder screw and the die head. Pumps are required to generate the hydraulic pressure even when no motion is required and auxiliary chillers are needed to cool the hydraulic oil. Hence hydraulic machines consume energy even when idle. All-electrical machines do not use energy during breaks in the production cycle. Currently an all-electrical machine is the most energy-efficient solution with potential energy saves between 30 to 40% compared to hydraulic machines. This system eliminates energy loss in the electro/hydraulic interface and improves accuracy and cycle times. [69]

Approximately two-third of the energy costs in plastics processing is the result of electric motor usage. In many cases, motors are overlooked when considering energy usage. The motors in the main processing equipment such as compounders and extruders are obvious but the majority of motors are 'hidden' in other equipment such as compressors, pumps and fans. [71]

High-efficiency motors (HEM) have a small cost premium which is easily offset by the energy cost savings resulting from their use. HEM achieves efficiency levels up to 3% more than conventional motors. The speed of conventional motors is fixed; therefore hydraulic pumps are driven at a constant speed even though the demand varies continuously during the process cycle. Fitting a Variable Speed Drive (VSD) to the motor will meet the varying demand. This will significantly reduce the energy costs. [71]

7.2.4 Methodology for planning and operating energy-efficient production systems

Weinert et al. [73] proposed the EnergyBlocks methodology (Figure 40) for accurate prediction of the energy consumption. In order to design energy-efficient systems, the consumption of the whole process chain has to be taken into account. Scheduling assigns products and processes to available production equipment and influences the energy consumption behavior of the whole system. By integrating energy-efficiency into scheduling, a reduction of energy costs can be expected. Scheduling heavy energy consumers at low-cost electricity hours could greatly reduce the energy cost.

In order to integrate the energy-efficiency criteria in the production planning, a detailed prediction of the energy consumption is necessary. Each type of equipment has various operating states (EnergyBlocks) that exhibit different energy consumption patterns that can be identified in its power profile. A production process can therefore be described as a sequence of EnergyBlocks. During production planning and scheduling, it is possible to assign processes to machines according to the energy consumption and duration per task taking into account external parameters such as volatile energy price and availability. [73]

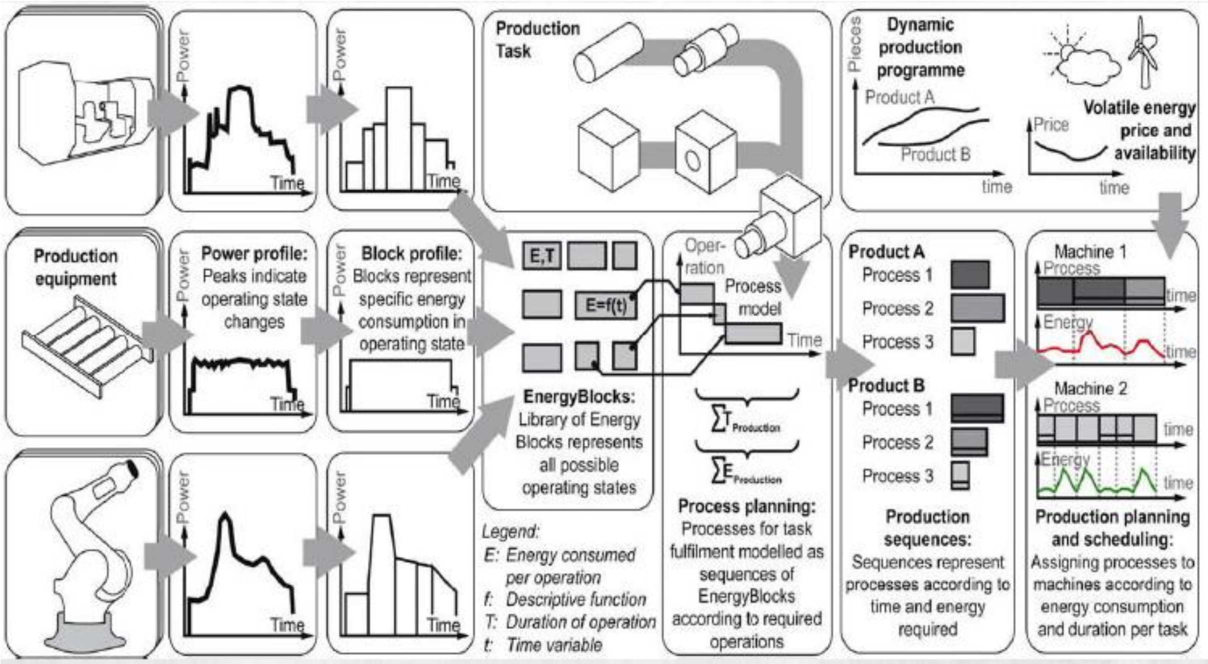

Figure 40 EnergyBlocks methodology [73]

7.2.5 Application on the case of Nervia Plastics

This section is confidential.

7.3 Scenario 3: Optimizing inventory

Raw and packaging materials play a central role in the total cost profile of blow molding production plants. In addition, the inventory and material handling cost is the third most important production cost category. There are several reasons to keep inventory such as to maintain the independence of operations, to meet variation in product demand and to allow flexibility in production scheduling. [80]

The applied inventory management depends on the type of demand: deterministic or stochastic. There are multiple reasons why companies keep inventory resulting in different inventory types [60]:

- **Cycle stock** is the result of the difference between the ordering and the processing batch. This stock will be calculated when dealing with a deterministic demand.
- **Safety stock** is the buffer for demand and supply uncertainty. The safety stock will be discussed when dealing with a stochastic demand.
- **Pipeline or in-transit inventory** corresponds to the goods in transit between supply chain stages.
- **Seasonal inventory** is stock to cope with periodic demand and/or supply.
- **Congestion stock** is the result of items sharing resources with limited capacity.
- **Hedging stock** refers to the speculative stock for price increases and/or supply shortages.

If inventory is present in a company, an associated inventory holding cost needs to be determined as explained in Section 3.4.2.1. The standard "rule of thumb" for inventory carrying cost is 25% of inventory value on hand. [24]

Installing an appropriate supply management strategy will already result in a more optimal sourcing process. The determination of the cycle and safety stock will respectively be discussed in the sections about deterministic and stochastic demand. Besides the cycle and safety stock, a production plant should continuously monitor the Work In Progress. In addition, a production plant should determine an appropriate storage policy. The different topics related to the optimization of inventory are shown in Figure 41. The scenario about the inventory optimization will be applied on the case of Nervia Plastics.

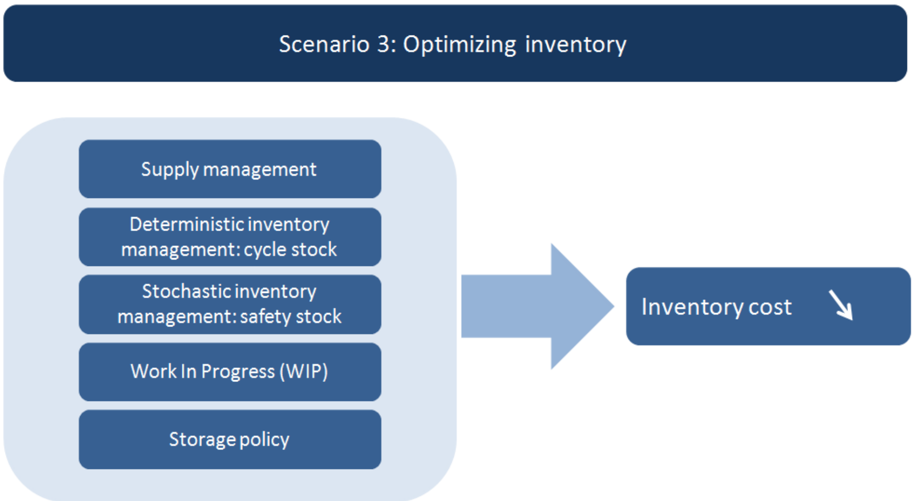

Figure 41 Overview Scenario 3: Optimizing inventory

7.3.1 Supply management

Sourcing is the set of business processes required to purchase goods and services. Effective sourcing can have several benefits such as better economies of scale if orders are aggregated, more efficient procurement transactions, better coordination with the suppliers, etc. Before selecting suppliers, a firm must decide its sourcing strategy. The company needs to determine which activities to perform in-house and which to outsource. The production plant also has to decide how many suppliers it needs and the capabilities those suppliers need to have. Suppliers can have similar or complementary capabilities such as replenishment lead time, on-time performance, supply flexibility, supply quality, exchange rates, transportation costs, information coordination capability, etc. [77]

The sourcing process includes several steps [77]:

1) **Supplier scoring and assessment:** The supplier performance should be compared on the basis of the supplier's impact on the total cost.
2) **Supplier selection and contract negotiation:** The selection of the supplier can be achieved through competitive bids, reverse auctions and direct negotiations. In a contract, the parameters are specified in which the buyer places orders and the supplier fulfills them.
3) **Design collaboration:** Collaborating with suppliers can result in reduced costs, improved quality and decreased time to market.
4) **Procurement:** This is the process in which the supplier sends products in response to orders placed by the buyer while trying to minimize the overall cost.
5) **Sourcing planning and analysis:** A firm should periodically analyze its procurement spending and supplier performance and use this analysis as an input for future sourcing decisions.

7.3.2 Deterministic inventory management: determining the cycle stock

The cycle inventory is the average inventory in the supply chain because a supply chain stage produces or purchases in lots that are larger than those demanded by the customer. A lower cycle inventory is better because the average flow time, the working capital requirements and the inventory holding costs are lower. When determining the inventory management strategy for deterministic demands, the Economic Order Quantity (EOQ) model is used. [60]

The EOQ model considers the trade-off between ordering and storage cost in choosing the appropriate replenishment quantity. When having a larger order quantity, the ordering frequency will be reduced and hence the ordering cost will be lower, but the cost of holding the inventory will be higher. On the other hand, having a smaller order quantity will reduce the average inventory level resulting in a lower holding cost, but the ordering cost will be higher due to more frequent ordering. The main foal of the EOQ model is minimizing the cost by determining an optimal order quantity. [74]

The EOQ model takes several assumptions into account [60]:

- Production is instantaneous.
- Delivery is immediate.
- Backlogging is not allowed.
- Item cost is known and fixed.
- Order preparation cost is known and fixed.
- Single product is considered.
- Demand is deterministic and constant.

The EOQ model determines the optimal order quantity (Q^*), the optimal reorder interval (T^*) and the total annual cost (TAC) in function of the order quantity (Q). [60] [74]

$$Q^* = \sqrt{\frac{2.D.S}{H}} \; and \; T^* = \sqrt{\frac{2.S}{D.H}}$$

$$TAC(Q) = C.D + \left(\frac{D}{Q}\right).S + \left(\frac{Q}{2}\right).H$$

With:

- Q: order lot size or production batch size (Q/2 is the cycle inventory)
- D: demand per unit time
- S: fixed ordering cost
- C: material cost
- H: holding cost (H= hC with h the cost of holding 1 EUR in inventory for one year)

The total cost is relatively stable around the EOQ; therefore it is often better to order a more convenient lot size close to the EOQ. There exist many variants on the standard EOQ model depending on which of the assumptions are no longer valid.

Because transportation cost is a significant contributor to the fixed cost per order, ways of aggregating multiple product orders need to be investigated. The fixed ordering and transportation costs can be spread across products, retailers or suppliers. In practice, the fixed cost is dependent at least partly on the variety associated with an order of multiple products [81]:

- A portion of the cost is related to transportation and independent on the variety of the product order.
- A portion of the cost is related to loading and receiving and therefore dependent on the variety of the product order.

Complete aggregation is effective if the product specific fixed ordering cost is a small fraction of the joint fixed ordering cost.

So far, the optimized lot sizes are determined only taking into account the buyer costs. Joint optimization of buyer and supplier costs will lead to an optimal lot size different from the buyer's local optimum. The supplier can offer a lot-size based quantity discount to the buyer as an incentive to order in lots that minimize joint total costs. [60]

7.3.3 Stochastic inventory management: determining the safety stock

Forecasts are always wrong; therefore safety inventory is installed to cope with the variable demand. Safety inventory is inventory carried for the purpose of satisfying demand that exceeds the amount forecasted in a given period. Average inventory is therefore cycle inventory added with the safety inventory (and the in-transit inventory). There is a fundamental trade-off: raising the level of safety inventory provides higher levels of product availability and customer service. But raising the inventory level also raises the level of average inventory and therefore increases holding costs and average flow time. The level of safety stock depends on the replenishment policy, demand and supply uncertainty and the objective (e.g. cycle service level or fill rate). There are two types of replenishment policy: continuous and periodic review. In a continuous review, the order size is fixed but the timing fluctuates. In a periodic review the order size differs, but the time of ordering is always the same. The demand during the uncertainty period needs to be estimated. The uncertainty period consists of a lead time and a review time. [60]

The demand during the uncertainty period can be estimated using the normal distribution. If the demand per period has mean D and standard deviation σ_D and the lead time has mean L and standard deviation σ_L, than the demand during the uncertainty period (DDUP) utilizing continuous review can be estimated as: [60] [82]

$$\sigma_{DDUP} = \sqrt{L\sigma_D^2 + D^2\sigma_L^2}$$

There can be different objectives such as minimizing the total cost or guaranteeing product availability to the customers. There are two types of customer service measurements [60]:

1) **Cycle Service Level** (CSL) is the fraction of replenishment cycles without stock-out i.e. the probability that a stock-out is avoided. The safety stock (SS) can be determined as followed:

$$SS = Z\ \sigma_{DDUP}$$

   Z is the safety factor which can be determined as the CSL'th percentile of the standard normal distribution.

2) **Fill Rate** (fr) is the fraction of demand filled from product available in inventory. Fill rate takes into account the magnitude of stock-outs.

$$fr = 1 - \frac{ESRC}{Q}\ and\ ESRC = \sigma_{DDUP}E(Z)$$

$$SS = Z\ \sigma_{DDUP}$$

   With:

   ESRC: Expected Shortage per Replenishment Cycle
   Q: Order quantity per replenishment
   E(Z): Standard normal loss function

The total annual cost (TAC) can now be extended with a cost term corresponding with the safety stock.

$$TAC(Q) = C.D + \left(\frac{D}{Q}\right).S + \left(\frac{Q}{2}\right).H + SS.H$$

It is possible to reduce the safety stock by reducing the demand and supply uncertainty, reducing the supplier lead time and safety stock aggregation. Reducing the demand uncertainty can be achieved when introducing better forecasts, collecting and using the available information better and applying demand management. The supply uncertainty can be reduced by building better relationships with suppliers and sharing the benefits of financial gains. Safety stock aggregation means that the stock is aggregated in a single central warehouse which reduces the stock level. Disadvantages are that this can lead to an increase in response time to the customer and an increase in transportation cost to the customer. [60]

7.3.4 Work In Progress

Not only the stock of raw materials and finished goods need to be taken into account, but also the Work In Progress (WIP). The WIP can be defined as the inventory between the start and the end of a routing. The WIP can be determined using Little's law if the throughput (TH) and the flow time (FT) are known [79]:

$$WIP = TH\ x\ FT$$

The throughput is the average quantity of good parts produced per unit and the flow time is the time between the release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing.

The critical or ideal WIP is the WIP level in which a line having no congestion would achieve maximum throughput with minimum flow time. This can be represented as [78]:

$$WIP_0 = r_b T_0$$

With r_b the bottleneck rate and T_0 the raw process time.

If the WIP cost is significant, the determination of the optimal WIP level could influence the total inventory cost. Reducing the WIP level can be achieved by installing a pull system as explained in Section 6.2.8.

7.3.5 Storage Policy

Besides the determination of the optimal order quantity and reorder point, it is also important to determine what type of storage policy is appropriate to install in the production plant. A storage policy decides how to allocate various storage locations to a number of products and has effect on the material handling associated with inventory. In general, there are three different storage policies that can be implemented [42]:

1. **Dedicated storage**: every product has a fixed number of storage locations.
2. **Randomized storage**: each unit is stored in any available location.
3. **Class-based storage**: groups of products have a dedicated storage area, but the products inside a group are random located.

The 'active' units that cause a lot of traffic should be placed in the most convenient locations i.e. having the smallest distance to the in/out point.

7.3.6 Application on the case of Nervia Plastics

This section is confidential.

7.4 Conclusion

In this chapter, three improvement scenarios about production time, energy and inventory were discussed.

The first improvement scenario dealt with optimizing the production time, examining the impact on the cost when producing seven days per week instead of five days. The capacity utilization of the blow molding machines increases resulting in fewer machines needed. When producing continuously, the start-up and shutdown costs can be eliminated. The energy cost decreases because the energy prices during weekends are lower than during the week. In contrary, the labor cost increases due to higher shift premiums during the weekend. Another consequence of producing continuously is the increase of the inventory level; hence more storage space needs to be available. In the case of Nervia Plastics, the total cost per finished product when producing continuously, increases with 2% relative to the situation when production only takes place during the week. When producing continuously, 25% of the production lines became redundant which results in a remarkable CapEx investment saving. Whenever a company needs to increase its capacity, it needs to consider the option of changing the production time instead of acquiring new blow molding production machines.

Optimizing energy consumption was discussed in the second improvement scenario. Improving the energy-efficiency of blow molding production plants requires the full understanding of the energy usage. Also understanding the energy bill is crucial. The energy bill is made up of a basic price per unit of energy and costs related to four key factors: maximum power requirement, power factor, load factor and maximum demand. The blow molding production process consists of five stages. Just enough energy should be used for every stage of the process. When devising energy-reducing measurements, it is important to include side equipments such as the cooling system and compressed air supply system. Purchasing energy-efficient capital equipment is a simple and easy way to permanently improve the energy-efficiency of a blow molding production plant e.g. installing an all-electrical machine instead of hydraulic blow molding machines. Developing a method for planning and operating energy-efficient production systems such as the EnergyBlocks methodology also contributes to lower energy consumption. Four energy-reducing measurements were theoretically applied on Nervia Plastics, resulting in a reduction of the energy consumption of 37%.

The third improvement scenario discussed inventory optimization. There are different reasons why companies keep inventory resulting in different inventory types of which cycle and safety stock are the most common. For deterministic demands, the Economic Order Quantity (EOQ) model is used to determine the cycle stock including the optimal order quantity and reorder interval. When dealing with stochastic demand, the level of safety stock needs to be determined. When applying the EOQ and safety stock model on the case of Nervia Plastics, a potential gain of 77% for the inventory holding cost is possible. This indicates that it is worthwhile to design an appropriate inventory replenishment model in order to reduce the inventory holding cost.

8
Conclusion and future work

Blow molding production plants, as part of the plastic material converting stage, form a significant portion of the plastics industry. In Europe, the plastics industry consists of more than 60,000 companies giving direct employment to 1,450,000 people. In recent decades, the industry in western countries has felt the effects of deindustrialization and ever increasing globalization. The high labor costs and energy prices are the principal challenges for Belgium. In an increasingly competitive international environment, production costs must continuously and closely be monitored in order to ensure that they are kept under control. The aim of this master dissertation was developing a techno-economic evaluation of blow molding production plants; performing a cost analysis taking into account technological as well as economic aspects, in order to identify the most important cost categories and propose measures for cost reduction.

8.1 Summary and conclusion

By performing a techno-economic evaluation of blow molding production plants, this thesis aimed at gaining insights in the corresponding cost profile. The applied techno-economic evaluation consists of four practical steps: scope, model, evaluate and refine. In the scope phase, a factory cost breakdown was developed in order to get an overview of the cost profile of blow molding production plants. This factory cost breakdown was used for the identification and categorization of the different costs while focusing on the most important cost categories and drivers for production. In the model phase, several cost modelling techniques were applied: fractional, driver-based and dedicated dimensioning models. Activity-Based Costing as driver-based model and Business Process Modelling and Notation as process-based model were used throughout this master dissertation. The third phase consisted of the evaluation of the cost model as well the incorporation of costs over time. In the refine stage, sensitivity analysis was applied to deal with uncertainties in the input parameters.

Three research questions were formulated and used as guidance throughout the master dissertation. Answers were provided along the different chapters:

1) **How can the different costs be divided into categories and what drives these costs?**

For blow molding production plants, a customized lifecycle cost tree structure was designed consisting of five stages: planning, deployment, migration, operations and teardown. The planning phase consists of cost categories such as purchasing, manpower and long-term planning. The second stage of the lifecycle cost breakdown is the deployment phase consisting of activities needed to start the production such as molds and machine CapEx. The migration phase includes mold changeovers, start-ups and shutdowns. The operation phase contains several sub-categories i.e. quality control, inventory and material handling, manufacturing process, packaging, maintenance and repair, operational planning and transactions. The teardown phase deals with remanufacturing, recycling and disposal of faulty products, unused/unsold stock and outdated molds. The different cost categories were classified into production and overhead cost depending on the type of relationship that exists with the finished products. The magnitude of the different cost components was estimated using driver-based, process-based or fractional cost modelling methods.

This cost model of blow molding production plants has been implemented in Java. Several classes are available to include the input data. The cost model also contains a class consisting of functions to cope with depreciations. Another class calculates different cost categories (manufacturing and packaging process, inventory and material handling, housing, cooling, quality control and teardown) using driver-based cost models. A complementary class calculates the cost of start-ups, shutdowns, mold changeovers, maintenances and repairs using general estimates or by linking the cost model with the corresponding BPMN model using the BEMES-tool. The results obtained by the previous classes are combined in a class providing the output results (e.g. the total cumulative cost, the cost per shift, the cost per cost category, the cost per cost driver and the cost per finished product).

The cost model was applied on the current situation of Nervia Plastics i.e. a representative Belgian blow molding production company that is known for its experience in extrusion blow molding of polyethylene bottles. This provided insights in the distribution of the total cost into the different cost categories. The manufacturing process cost is the major cost category accounting for around 60% of the total cost. This manufacturing process cost consists of a machine CapEx, raw material, energy and labor cost, thus all directly related to the manufacturing process. In particular, the raw material costs associated with the manufacturing process are significant. The manufacturing process cost per finished product depends on the shift type. The differences occur because of changes in energy price and labor cost per shift. During night and weekend shifts, the labor cost increases while the energy cost decreases. The second most important production cost category concerns packaging (10%), followed by the inventory and material handling cost (5%). The labor cost accounts for almost 50% of the total packaging cost. In addition to the production cost, there is an overhead cost accounting for 20% of the total cost. The overhead cost includes the transaction costs, the negotiation costs related to purchasing, the manpower and long-term planning costs, the cost of the layout of the production plant and infrastructure, the tooling cost and the fixed energy cost.

When determining the different cost drivers, the raw material cost accounts for more than 50% of the total cost. When optimizing the consumption of white plastics and color additives, big cost savings could result. As a consequence, the cost per finished product is greatly influenced by the bottle type. The second most important cost driver is the labor cost accounting for 10% of the total cost. The remaining cost drivers i.e. packaging material, energy, equipment and CapEx cost represent each less than 5% of the total cost.

The results obtained by applying the cost model on the current situation of Nervia Plastics were compared with literature. Literature confirmed the magnitude and importance of the cost categories and drivers.

2) What are the cost-saving potentials?

After having a complete overview and understanding of the different cost categories linked with blow molding production plants, it was possible to identify cost-saving potentials. There are three important improvement philosophies that are widely adapted in the industry: Operational Excellence, Lean Manufacturing System and Going Green. The focus of Operational Excellence lies on the competitiveness of the production process, aiming at finding the best cooperation of people, processes and assets. The Lean methodology strives to deliver the best quality at the lowest cost with the shortest lead time. The last improvement philosophy, Going Green, focuses on sustainability.

Improvement techniques introduced by the three philosophies can be used to optimize different production cost categories.

- *Purchasing* has a significant impact on the total production cost, hence it is useful for blow molding production companies to apply the seven key findings of the Purchasing Excellence Survey.
- *The layout of the production plant and infrastructure* is important in order to create a smooth flow of people and materials while increasing the productivity. Every blow molding production plant should decide which layout structure fits the production plant the most. Besides the layout of the production plant, also the plant capacity and the grade of flexibility need to be determined.
- *Mold changeovers, start-ups and shutdowns* can be seen as set-up operations. A technique used for set-up time reduction is Single Minute Exchange of Die (SMED) consisting of three improvement steps: separating internal and external set-up, converting internal set-up to external set-up activities and streamlining all aspects of the set-up operation.
- *The operational planning* can be optimized by automating the scheduling of the different products on the different machines using a variety of algorithms, heuristics and software packages. An automatically determined schedule will be computed more quickly and optimally than a manual schedule.
- *Maintenance and repair* are crucial in order to keep producing and delivering good quality. The risk of failure should be estimated using qualitative or quantitative risk assessments such as the risk matrix, risk-based maintenance method (RBM), and hazard and operability analysis (HAZOP).
- *The manufacturing process* cost accounts for almost 60% of the total cost. Installing a pull system in blow molding production plants can lead to reduced costs due to lower average Work In Progress level, reduced flow time variability, shorter lead times and improved quality. A pull system can be implemented by installing a Kanban, constant Work In Progress (CONWIP) or Paired-cell Overlapping Loops of Cards with Authorization (POLCA) strategy.

- *Packaging* takes up a significant portion of the labor cost of blow molding production plants. Executing a time and method study would allow to eliminate unnecessary movements, to reveal shortcomings of design, materials and methods, and to eliminate ineffective times.
- *Quality control* is important in order to deliver the best quality to the customer. Several improvement techniques exist in order to reduce the probability of errors such as Jidoka, visual management, 5S and Six Sigma.

All the cost-saving potentials described above prove that there exist promising techniques to optimize minor and major cost categories. Three important cost-saving potentials about production time, energy and inventory optimization will be discussed more in detail when dealing with the third research question.

3) **What impact has optimizing production time, energy and inventory on the total production cost?**

The cost model revealed the most important cost categories of blow molding production plants i.e. the manufacturing process cost, the packaging cost and the cost related to inventory and material handling. Raw and packaging material consumption is the largest cost driver for blow molding production plants. Other main cost drivers are manpower and energy consumption. Three relevant opportunities for cost savings are quantitatively evaluated to determine their impact on the total cost. These opportunities focus on production time, energy and inventory.

Scenario 1: Optimizing production time
Could we save costs when using machine uptime more optimally if also producing during the weekends?

When determining the impact of producing seven days per week instead of five days, several cost factors need to be taken into account. The available production time increases significantly as weekends and the duration of start-up and shutdown can be added to the valuable production time. The capacity utilization is higher resulting in fewer machines needed in order to produce the same amount of finished products. As a result fewer machine CapEx needs to be provided. Having no start-ups also reduces the number of production problems as well as the number of customer complaints due to products of inferior quality. The energy cost decreases because energy prices are lower during the weekends. On the other hand, the labor cost increases with 50% during the weekend. Producing during weekends also implies an increase of the inventory level; hence more storage space is required.

In the case of Nervia Plastics, the total cost per finished product when producing continuously increases with 2% relative to the situation when production only takes place during the week. When producing continuously, 25 % of the production lines became redundant which results in a remarkable CapEx investment saving. An increase of 2% of the cost per finished product is not significant. Hence, delicate balancing is necessary for every blow molding production plant in order to determine if producing continuously is economically more attractive than purchasing new blow molding machines when an increase of capacity is necessary.

Scenario 2: Optimizing energy

Could energy-reducing measurements reduce energy consumption and the corresponding cost?

Energy consumption as cost driver for blow molding production plants will only gain more significance due to ever increasing energy prices. In order to reduce the energy cost, full understanding of the energy consumption of the blow molding production plant is necessary. Energy consumption of a blow molding production plant does not solely depend on the production volume, but also other factors influence the energy consumption such as an increase in scrap levels, poor maintenance, poor quality of raw materials, climate changes, etc. Understanding the energy bill is crucial to become energy aware. The energy bill is usually made up of a basic price per unit of energy and costs related to four key factors: maximum power requirement, power factor load factor and maximum demand. A popular measure to benchmark a plant's performance is the Specific Energy Consumption (SEC) determining the energy used for every unit of throughput of polymer (kWh/kg).

Several blow molding machine functions influence the energy usage. Blow molding machines account for about 50% of the overall energy consumption. For every stage of the blow molding process, energy-reducing measurements were devised. It is important to set correct process parameters and to control those continuously. Just enough energy should be used for every stage of the process. Side equipment such as the cooling system should be taken into account when optimizing energy consumption. A 1°C rise of the cooling water results in a 3% reduction in the chillers power. When the ambient temperature falls 1°C below the temperature of the returning water, free cooling is possible. Almost 21% of the total energy consumption is contributed by the compressed air supply system. Air leaks in a poorly maintained plant can account for 30 – 50% of the compressed air consumption; hence good maintenance is crucial. Ducting to allow fresh air intake rather than air from the compressor could reduce the intake temperature by 15°C and reduce energy usage with 5%.

Purchasing energy-efficient capital equipment is a simple and easy way to permanently improve the energy-efficiency of a blow molding production plant. Installing an all-electrical machine is the most energy-efficient solution with potential energy saves between 30 to 40% compared to hydraulic machines. Approximately two-third of the energy costs in plastics processing is the result of electric motor usage. High-efficiency motors (HEM) achieve efficiency levels up to 3% more than conventional motors. Developing a method for planning and operating energy-efficient production systems such as the EnergyBlocks methodology also contributes to lower energy consumption. Implementing the suggested energy-reducing measurements, led to a theoretically energy consumption reduction of 37% in the case of Nervia Plastics.

Scenario 3: Optimizing inventory

What are the cost-saving opportunities of inventory optimization?

Raw and packaging materials play a central role in the total cost profile of blow molding production plants. In addition, the inventory and material handling cost is the third most important production cost category. Hence it is worth examining several inventory optimization opportunities to determine the optimal inventory strategy. Installing an appropriate supply management strategy will already result in a more optimal sourcing process.

Companies keep inventory for several reasons resulting in different inventory types such as cycle and safety stock. Cycle stock is the result of the difference between the ordering and the processing batch. The Economic Order Quantity (EOQ) model provides a framework to determine the cycle stock, the optimal order quantity and the reorder interval when dealing with deterministic demand. If the demand is stochastic, an appropriate level of safety stock needs to be determined to cope with the variable demand. The level of safety stock depends on the replenishment policy, demand and supply uncertainty and the objective (e.g. cycle service level or fill rate). Besides the cycle and safety stock, a production plant should continuously monitor the Work In Progress. Reducing the Work In Progress is possible by implementing a pull strategy.

When applying the EOQ and safety stock model on the case of Nervia Plastics, a potential theoretical gain of 77% for the inventory holding cost was possible. This indicates that it is worthwhile to design an appropriate inventory replenishment model in order to reduce the inventory holding cost.

8.2 Future work

This master dissertation gives an overview of the cost profile of blow molding production plants while focusing on the main cost categories and drivers. Several cost-saving potentials were introduced briefly and three improvement scenarios were examined quantitatively.

The application of the cost model on multiple blow molding production plants instead of only Nervia Plastics, would lead to a more accurate result. It would also be interesting to apply the suggested improvement measures in reality in order to assess their actual impact on the total production cost.

In this master dissertation the improvement scenarios about optimizing production time, energy and inventory were studied separately. It would be worthwhile to examine the cumulative impact when combining these various optimization scenarios. For instance, energy-efficient planning could be incorporated into the scenario of production time. When producing continuously, it might be interesting to schedule heavy energy consumers at low-electricity hours. In contrary, mold changeovers should be planned when the energy price is high. Another example is combining the production time and inventory scenario in order to determine the optimal inventory replenishment strategy as a function of the available production time.

The focus of this master dissertation lied on blow molding production plants. However the lifecycle cost breakdown and the corresponding cost model can be applied to other companies where production takes place in batches. Examples of batch processes can be found in the food industry (e.g. an industrial bakery), in the chemical industry (e.g. batch reactors) and even in the textile industry (e.g. fashion collections). For those companies, the lifecycle cost breakdown and the cost model should be adjusted and expanded.

The lifecycle cost breakdown, as introduced in Chapter 3, will need to be adjusted to the new production processes. It is possible that some cost categories will no longer be applicable such as packaging in the chemical industry. Packaging may become unimportant when transport of chemicals occurs directly using pipelines. On the other hand new cost categories, such as marketing activities, can be added to the lifecycle cost breakdown. A third option is an increase or decrease of the magnitude of certain cost categories. Hence the division of the cost categories in production and overhead cost can vary. For example transaction costs can become more important; therefore being included in the production cost.

Besides the lifecycle cost breakdown, the cost model implemented in Java needs to be adapted to the new production processes. In the cost model an adjustment of the input data format can be required. For example when dealing with the scheduling of chemical batches where the reactants leave jointly the tank instead of continuously. In addition, when a product is assigned to multiple production lines, instead of a single production line in blow molding production plants, the various combinations and interactions should be incorporated into the cost model e.g. the routing of a clothing piece in the textile industry. It is also possible that the implementation of the different cost functions needs to be adapted, for example calculating the quality control cost per product type instead of per production line. Furthermore, production processes that are using other set-up operations than mold changeovers will require an adjustment of the foreseen BPMN models. These are just a few examples of possible adjustments, but multiple adjustments are possible.

Although most cost functions can be applied directly to several production companies, some changes will be required as stated above. The cost model implemented in Java allows to add, adjust and remove cost functions or to adapt cost functions to a new input format.

References

[1] EuPc and PlasticsEurope. (2014, November). The Plastics Industry: A strategic partner for economic recovery and sustainable growth in Europe - Manifesto on the competitiveness of the plastics industry. Available at www.plasticseurope.org

[2] PlasticsEurope. (2015, January). Plastics – the Facts 2014/2015: An analysis of European plastics production, demand and waste data. Available at www.plasticseurope.org

[3] Robert, B., & Dresse, L. (2005). Industry in Belgium: past developments and challenges for the future. Economic Review of the National Bank of Belgium,3(2005), 7-44.

[4] American Chamber of Commerce in Belgium. Belgium's energy challenges. Available at www.amcham.be [Accessed on 5/4/2015]

[5] Verbrugge, S., Casier, K., Van Ooteghem, J., & Lannoo, B. (2009). White Paper: Practical steps in techno-economic evaluation of network deployment planning. UGent/IBBT: Gent, Belgium, 45.

[6] Nervia Plastics. About us. Available at www.nerviaplastics.be [Accessed on 10/5/2014]

[7] Wallace, B. (2011, July). Techno-economic Analysis and Life Cycle Cost. Available at www.bioenergy.psu.edu

[8] Investopedia, Available at http://www.investopedia.com [Accessed on 1/22/2015]

[9] Porter, M. E. (2008). Competitive advantage: Creating and sustaining superior performance. Simon and Schuster.

[10] Verbrugge, S., Casier, K., Lannoo, B., Van Ooteghem, J., Meersman, R., Colle, D., & Demeester, P. (2008, June). FTTH deployment and its impact on network maintenance and repair costs. In Transparent Optical Networks, 2008. ICTON 2008. 10th Anniversary International Conference on (Vol. 3, pp. 2-5). IEEE.

[11] Cooper, R., & Kaplan, R. S. (1988). Measure costs right: make the right decisions. Harvard business review, 66(5), 96-103.

[12] Asking, P., & Gustavsson, S. (2011). Cost breakdown analysis-A study of the product costs in the kitchen appliances at IKEA of Sweden.

[13] Kaplan, R. S., & Anderson, S. R. (2003). Time-driven activity-based costing. Available at SSRN 485443.

[14] Object Management Group: Business Process Model and Notation (BPMN), Available at http://www.bpmn.org/ [Accessed on 11/12/2014]

[15] White S.A., IBM Corporation, (2004). Introduction to BPMN. Available at www.omg.org

[16] Saltelli, A. (2002). Sensitivity analysis for importance assessment. Risk Analysis, 22(3), 579-590.

[17] Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., & Tarantola, S. (2008). Global sensitivity analysis: the primer. John Wiley & Sons.

[18] Accounting Simplified. Accounting for Fixed Assets: Straight Line Depreciation Method. Available at www.accounting-simplified.com [Accessed on 12/5/2014]

[19] Williams, J. R., Haka, S. F., Bettner, M. S., & Carcello, J. V. (2005). Financial and managerial accounting. China Machine Press.

[20] Vermorel, E. Inventory costs (ordering costs, carrying costs). Definition and formula. Lokad. Available at www.lokad.com [Accessed on 11/20/2014]

[21] Harding M.L. (2002). Calculating the total cost of ownership for items which are inventoried. National Property Management Association, Volume 14, Issue 2
[22] Timme, S. G., & Williams-Timme, C. (2003). The real cost of holding inventory. Supply chain management review, V.7, No. 4 (July/Aug. 2003), P. 30-37: ILL.2003
[23] REM Associates. Methodology of calculating inventory carrying costs. Available at www.remassoc.com [Accessed on 11/20/2014]
[24] Richardson, H. (1995). Transportation & Distribution, "Control Your Costs then Cut Them"
[25] Hackeman C. (2001). Government Contractor Industry Survey: The Pulse of a Vital Industry. Grant Thornton. Available at www.grantthornoton.com
[26] Miller, J. G., & Vollmann, T. E. (1985). The hidden factory. Harvard business review, 63(5), 142-150.
[27] Banker, R. D., Potter, G., & Schroeder, R. G. (1995). An empirical analysis of manufacturing overhead cost drivers. Journal of Accounting and Economics,19(1), 115-137.
[28] Bedsworth, W., Gregory, A. G., & Howard, D. (2008). Non-profit overhead costs: Breaking the vicious cycle of misleading reporting, unrealistic expectations, and pressure to conform. Bridgespan Group. Available at www.bridgespan.org
[29] Plante Moran (2013). North American Plastics Industry Study – 2013 Survey Report. Available at www.plantemoran.com
[30] Williamson, O. E. (1981). The economics of organization: The transaction cost approach. American journal of sociology, 548-577.
[31] Encyclopaedia Britannica, Inc. Extrusion Blow Molding (cutaway view). Available at http://kids.britannica.com [Accessed on 3/10/2015]
[32] Delta Engineering. Mail conversation on 3/16/2015
[33] Peeters S., Account manager at Jones Lang LaSalle. Mail conversation on 3/11/2015
[34] Conaplat. Type of PET Blow Molding. Available at http://www.conaplat.com.ar [Accessed on 3/15/2015]
[35] Rayapack, Available at www.rayapack.be [Accessed on 2/10/2015]
[36] Belpex. (2014). Spotmarket data 2014. Available at www.belpex.be
[37] Casier, K., Van der Wee, M., & Verbrugge, S. (2014, July). Cost evaluation of innovative offers using detailed equipment, process and network modeling languages. In Transparent Optical Networks (ICTON), 2014 16th International Conference on (pp. 1-4). IEEE.
[38] Merki, B., Kuhmann, T., European Plastics and Rubber Machinery (2011, October). Energy efficiency: Plastics and Rubber Machines Well Placed, Available at www.euromap-wmd.info
[39] Canadian Industry Statistics (CIS) (2013, March). Plastic Bottle Manufacturing (NAICS 32616): Manufacturing costs, Available at https://www.ic.gc.ca
[40] Brandau, O. (2013). Six Common-Sense Tips: Optimize Resin Management in Extrusion Blow Molding. Plastics Technology, 59(1), 23-25.
[41] Manenti P. (2012). In Pursuit of Operational Excellence: Accelerating Business Change Through Next-Generation ERP. IDC Manufacturing Insights.
[42] Van Landeghem, H. (2014). Master Course Industrial Engineering and Operations Research: Design of Manufacturing and Service Operations. University of Ghent.
[43] TBM Consulting Group. Our Roots – Lean: The history of Lean. Available at www.tbmcg.co.uk [Accessed on 11/10/2014]

[44] GoLeanSixSigma. The basics of Lean Six Sigma. Available at www.goleansixsigma.com [Accessed on 11/10/2014]
[45] United States Environment Protection Agency. (2006). Life Cycle Assessment (LCA). Available at www.epa.gov
[46] Lepech, M. Life Cycle Assessment: A scientific way to look at Going Green. Stanford University. Available at web.stanford.edu [Accessed on 3/15/2015]
[47] P&G. Purchasing. Available at www.pg.com [Accessed on 11/10/2014]
[48] Roland Berger Strategy Consultants, (2011). Purchasing Excellence Study: Purchasing trends and benchmarks 2011. Available at www.rolandberger.com
[49] Limère V. (2014). Master Course of Industrial Engineering and Operations Research: Time and Method study. University of Ghent.
[50] Shingo, S. (1985). A revolution in manufacturing: the SMED system. Productivity Press.
[51] Vorne. Single-Minute Exchange of Dies. Available at www.perfectproduction.com [Accessed on 12/5/2014]
[52] Van den Broecke F., Vansteenwegen P. (2012). Master Course Industrial Engineering and Operations Research: Inleiding tot bedrijfs- en productiebeheer. University of Ghent.
[53] Sidharta G. (2014). Master Course Industrial Engineering and Operations Research: Heuristics and Search Methods. University of Ghent.
[54] Austrac. (2011). Risk assessment: Risk matrix and risk score. Available at www.austrac.gov.au
[55] Khan, F. I., & Haddara, M. M. (2003). Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning.Journal of Loss Prevention in the Process Industries, 16(6), 561-573.
[56] PQRI Risk Management Training Guides. Hazard & Operability Analysis. Available at www.pqri.org [Accessed on 11/25/2014]
[57] De Groot, H. L., Verhoef, E. T., & Nijkamp, P. (2001). Energy saving by firms: decision-making, barriers and policies. Energy Economics, 23(6), 717-740.
[58] Thollander, P., Backlund, S., Trianni, A., & Cagno, E. (2013). Beyond barriers–A case study on driving forces for improved energy efficiency in the foundry industries in Finland, France, Germany, Italy, Poland, Spain, and Sweden. Applied Energy, 111, 636-643.
[59] Herrmann, C., & Thiede, S. (2009). Process chain simulation to foster energy efficiency in manufacturing. CIRP Journal of Manufacturing Science and Technology, 1(4), 221-229.
[60] Raa B. (2015). Master Course Industrial Engineering and Operations Research: Supply Chain Engineering. University of Ghent.
[61] Marchwinski, C., & Shook, J. (Eds.). (2003). Lean lexicon: a graphical glossary for lean thinkers. Lean Enterprise Institute.
[62] Kanawaty, G. (1992). Introduction to work study. International Labour Organization.
[63] BITS Pilani. Chapter 12: materials handling. Available at www.bits-pilani.ac.in [Accessed on 11/26/2014]
[64] Leachman, (2009). Notes on economic lot scheduling and economic rotation cycles. Available at www.ieor.berkeley.edu
[65] Lean manufacturing tools. Lean manufacturing tools, principles and implementation. Available at www.leanmanufacturingtools.org [Accessed on 11/15/2014]
[66] iSixSigma. What is Six Sigma? Available at www.isixsigma.com [Accessed on 11/15/2014]

[67] Enderle, G., & Tavis, L. A. (1998). A balanced concept of the firm and the measurement of its long-term planning and performance. Journal of Business Ethics, 17(11), 1129-1144.
[68] Trist, E. L. (1978). On socio-technical systems. Sociotechnical systems: A sourcebook. San Diego, CA.: University Associates.
[69] euRECIPE. (2006). European Best Practice Guide: Low Energy Plastics Processing. Available at ec.europa.eu
[70] Womack, J. P., & Jones, D. T. (1996). Beyond Toyota: how to root out waste and pursue perfection. Harvard business review, 74(5), 140.
[71] Kent R. (2005). Energy-efficiency in plastics processing: practical worksheets for industry. Tangram Technology Ltd. Available at www.tangram.co.uk
[72] The Society of the Plastics Industry Inc. & U.S. Department of Energy. (2011). Improving Energy-efficiency at U.S. Plastics Manufacturing Plants. Available at energy.gov
[73] Weinert, N., Chiotellis, S., & Seliger, G. (2011). Methodology for planning and operating energy-efficient production systems. CIRP Annals-Manufacturing Technology, 60(1), 41-44.
[74] Schwarz, L. B. (2008). The economic order-quantity (EOQ) model. In Building Intuition (pp. 135-154). Springer US.
[75] Lowe, T. J., & Schwarz, L. B. (1983). Parameter estimation for the EOQ lot-size model: Minimax and expected value choices. Naval Research Logistics Quarterly, 30(2), 367-376.
[76] Li, X., & Wang, Q. (2007). Coordination mechanisms of supply chain systems. European journal of operational research, 179(1), 1-16.
[77] UT Dallas. Chapter 13: Sourcing and Contracts, Available at www.utdallas.edu [Accessed on 4/20/2015]
[78] Sapcharoenkul, M., Anussornnitisarn, P., & Sooksmarn, S. (2012). Root Cause Analysis Using Internal Benchmarking. In Knowledge and Learning: Global Empowerment; Proceedings of the Management, Knowledge and Learning International Conference 2012 (pp. 1029-1037). International School for Social and Business Studies, Celje, Slovenia.
[79] Hopp, W. J., & Spearman, M. L. (2011). Factory physics. Waveland Press.
[80] Leenders, M. R., Fearon, H. E., Flynn, A., & Johnson, P. F. (2001). Purchasing and supply management. McGraw-Hill College.
[81] Chopra, S., & Meindl, P. (2007). Supply chain management. Strategy, planning & operation (pp. 265-275). Gabler.
[82] Peterson, R., & Silver, E. A. (1979). Decision systems for inventory management and production planning (pp. 799-799). New York: Wiley.
[83] Schepp, C., Tabrizi, M., Tucker T., Nicol, J., English, B. & Kent R. (2006). Plastics industry energy best practice guidebook. Focus on Energy.
[84] International Chamber of Commerce. The Incoterms rules. Available at www.iccwbo.org [Accessed on 5/7/2015]