# Integrated Product Development and Production Technology of Large Composite Plastic Products

KRISTO KARJUST

TALLINN 2008

THESIS ON MECHANICAL AND INSTRUMENTAL ENGINEERING E41

# Integrated Product Development and Production Technology of Large Composite Plastic Products

KRISTO KARJUST

TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Mechanical Engineering
Department of Machinery

**Dissertation was accepted for the defense of the degree of Doctor of Philosophy in Engineering on May 21, 2008**

**Supervisor:** Rein Küttner, Prof., Faculty of Mechanical Engineering, Tallinn University of Technology

**Opponents:** Veijo Kauppinen, Prof. Emeritus, Helsinki University of Technology, Finland

Renno Veinthal, Prof., Tallinn University of Technology, Estonia

Martin Eerme, Prof., Tallinn University of Technology, Estonia

Defense of the thesis: June 26, 2008

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

ISSN 1406-4758
ISBN 978-9985-59-809-2

MASINA- JA APARAADIEHITUS E41

# Suuregabariidiliste komposiidist plastdetailide integreetitud tootearenduse metoodika ja valmistustehnoloogiad

KRISTO KARJUST

# CONTENTS

# INTRODUCTION

Current trends in manufacturing engineering activities show the direction spreading from system-level to multiple-system-level design, for instance, from product-level optimality to optimality for the portfolio of products, from one SME to a network of cooperating SMEs, etc.

In the production and product development phase advanced CAD/CAE/CAM tools are becoming increasingly used in companies. The computer-based methods are used to support engineering decision making processes. They allow the integrated use of information about different aspects, such as geometry of product, manufacturing processes, available resources, pricing, supplier data etc. The computer simulations of product and process performance are carried out. Any undesirable conditions are modified, and the simulation is performed again. The simulations enable to optimize the product and manufacturing processes.

Progress in design search and optimization (DSO) has continued steadily in past forty years, and by now, a formidable range of optimization methods is available to the engineers. In general, design optimization may be defined as the search for a set of inputs that minimizes (or maximizes) objective function under given constraints. The objective function may be expressed as cost, product lead time, product efficiency, return on investment, and/or any combination of the product performance parameters. It is subject to constraints in accordance with given relationships among variables and parameters and constraints of manufacturing system parameters and resources. These functions may be represented by simple expressions, complex computer simulations, or large-scale experimental facilities.

The request to reduce the development time has challenged to design simultaneously multiple products, which have lead to collaborative optimization in the engineering research community. There are several approaches to collaborative optimization. [Ravindran, 1987; Gu, 2000; Fujita, 2001; Deen, 2003]. The main problems are: to decompose initial complex design tasks and identify links between different engineering decisions, to reach coordination between different tasks, and to allow an individual design task to be conducted autonomously.

In the competitive environment the development of new products and their manufacturing processes has become a focal point of attention for many companies. Much of the motivation for the work comes from effort to integrate computer-based product development, technological process planning and manufacturing resource planning activities, and to take full advantage of the concurrent manner accomplished optimal engineering decision tasks.

There are several approaches proposed for collaborative optimization multi-disciplinary engineering design problems [Fujita, 2001; Küttner, 2002; Küttner, 2004]. The main problem is to identify the key links among different engineering decisions, reach to the coordination between different engineering teams on a system level and let the individual design task to conduct separately.

Competitiveness of the company depends on its ability to produce a range of products which are continually updated and are based on effective use of resources.

This is a case of reusing designs as well as manufacturing and other resources for multiple product groups that share substantive portion of their structure [Gu, 2000; Nayak, 2000; PMMA/SME, 2001; Fujita, 2001; Halman, 2003].

In many industries (whirlpool, outdoor portable spa, aerospace, healthy treatment capsule, plastic boat, car body details building industries) the final product price and quality depends on the large composite plastic products. In those industries the large plastic parts are the firstly seen parts, what client can see and that's why they will determine the final product popularity and whole concept. It is very important the unique design and quality of large composite plastic parts. The quality depends on the molds quality, storage and handling conditions and manufacturing skills. It is very important to invest more money for better molds, high skilled workers and new benches and equipment. Then we can guarantee that the large composite plastic parts have the best quality and the final product could be successful. Also large parts needs more storage and handling spaces and it is very important to organize effectively the whole technology route depending on the manufacturing and lead times, production capacity and market requirements.

## ACKNOWLEDGEMENT

This work has been carried out at the Department of Machinery, Tallinn University of Technology. The research was financed by Ministry of Education and Research of Estonia (Grant T684) and by Estonian Science Foundation (Grants G5620 and ETF5883).

I would like to thank specially my supervisor, Prof. Rein Küttner, for his professional guidance and support.

I would also like to thank all my colleagues at Tallinn University of Technology and my special thanks belongs to Dr. Meelis Pohlak. Also this work hasn't been possible without the support of the Estonian company Wellspa OÜ, where have been carried out the main tests and research.

Finally, I would like to thank my wife Ave for the support and patience. I am also grateful to my relatives and friends for understanding and support.

Tallinn, 2008

Kristo Karjust

# SYMBOLS

| Symbol | Unit | Comment |
|---|---|---|
| $a_i$ | min | Time required to manufacture one unit of product |
| $a_{iw}$ | min | Time for workstation |
| $b_i$ | | Target variable |
| $B$ | mm | Sheet material width |
| $c_w$ | | Capacity of workstation |
| $C_i$ | EEK | Unit production cost |
| $cf_{j,i}$ | EEK | Cost of implementing the additional feature |
| $D$ | mm | Sheet material thickness |
| $D_r$ | mm | Reinforcement layer thickness |
| $\mathrm{d_i}^+$ | | Max deviational variable |
| $\mathrm{d_i}^-$ | | Min deviational variable |
| $d_{ik}^{max}$ | | Maximum demand for $p_i$ in the market segment k |
| $d_{ik}^{min}$ | | Minimum demand for $p_i$ in the market segment k |
| $E$ | min | Cooling time |
| $e$ | | Bias vector of the unit |
| $F_j$ | | Additional (specific) feature |
| $f$ | mm | Distance from the heater |
| $g$ | | The activation function of the unit |
| $G_i$ | | Goal of planning task |
| $G_c$ | | Geometric complexity |
| $h$ | mm | Wall thickness after forming |
| $h_{air}$ | $\mathrm{W/(m^2K)}$ | Convective heat transfer coefficient |
| $h_i$ | EEK | Cost to hold one unit of product |
| $h_{moulds}$ | $\mathrm{W/(m^2K)}$ | Heat transfer coefficient |
| $H$ | mm | Depth of draw |
| $i$ | | An index of derivative product |
| $I_i$ | | Indicator of product $p_i$ use in the family |
| $I_{i,t}$ | | Products in inventory |
| $Inv_i$ | EEK | Investment required for implementing product |
| $j$ | | An index of used future |
| $k$ | | Market segment type |
| $L$ | mm | Sheet material length |
| $l$ | | The input activation of the unit |
| $m$ | | Total number of product variants in product family |
| $m_{i,u}$ | | Amount of the material |
| $M_u$ | EEK | Cost of material $u$ |
| $N$ | | Batch size |
| $n$ | | Net input |
| $p_i$ | | Derivative product |
| $P$ | | Cooling point |

| | | |
|---|---|---|
| $P_c$ | % | Peroxide concentration in glass-fiber |
| $Q$ | | Surface quality |
| $r_i$ | EEK | Net profit |
| $s_i$ | EEK | Selling price |
| $S_{i,t}$ | | Sold products |
| $T$ | min | Manufacturing/purchasing lead time |
| $T_a$ | min | Time for putting/taking product into/from workbench; |
| $T_c$ | min | Cooling time |
| $T_h$ | ˚C | Heating temperature |
| $T_{moulds}$ | ˚C | Moulds temperature |
| $T_r$ | min | Reinforcement time |
| $T_{room}$ | ˚C | Room temperature |
| $T_{sheet}$ | ˚C | Sheet temperature |
| $T_t$ | min | Trimming time |
| $T_v$ | min | Vacuum forming time |
| $T_w$ | min | Bench working time |
| $T_{wf}$ | min | Finishing time |
| $T_{wr}$ | min | Rough working time |
| $u$ | | Material type |
| $v_i$ | | The output activation of the unit |
| $w$ | | Workstation type |
| $W_{j,i}$ | | Numeric weight |
| $x^p_i$ | | Design variable |
| $X_i$ | | Quantity of products produced during the period |
| $Z$ | | Heating zones |
| $\alpha$ | ˚C | Draft angle |
| $\mu_u$ | | Resource of material *u*; |
| $\gamma_{i,i}$ | | Coordination variable |

# ABBREVIATIONS

ABS – Acrylonitrile-Butadiene-Styrene
AP – Aggregate Planning
ANN – Artificial Neural Network
CAD – Computer Aided Design
CAE – Computer Aided Engineering
CAM – Computer Automated Manufacturing
CAPP – Computer Aided Process Planning
DFA – Design for Assembly
DFM – Design of Manufacture
DOE – Design of Experiments
DSO – Design Search and Optimization
ERP – Enterprise Resource Planning
FEA – Finite Element Analysis
FEM – Finite Element Method
GFR – Glass-Fiber Reinforcement
LCD – Liquid Crystal Display
LED – Light Emitting Diode
LPP – Linear Physical Programming
MRPII – Material Requirement Planning
PMMA – Polymethylmethacrylate
RSE – Response Surface Equation
SME – Small and Medium-Sized Enterprises

# 1 REVIEW OF LITERATURE

## 1.1 Overview of the Product Family Planning

A Product Family is considered as a set of products that share common features, the same structure, function(s) and manufacturing technology. It addresses a related market segment application. Features refer generally to the shape and function refers generally to the utilization intent of a product. A product family comprises a set of variables, features or components that remain constant from product to product [Zha, 2006]. In Figure 1.1 is showed that product family depends on the market needs and different market segment requirements. On the other hand it depends on the results what we get from the product family planning, technology planning and manufacturing planning stages.

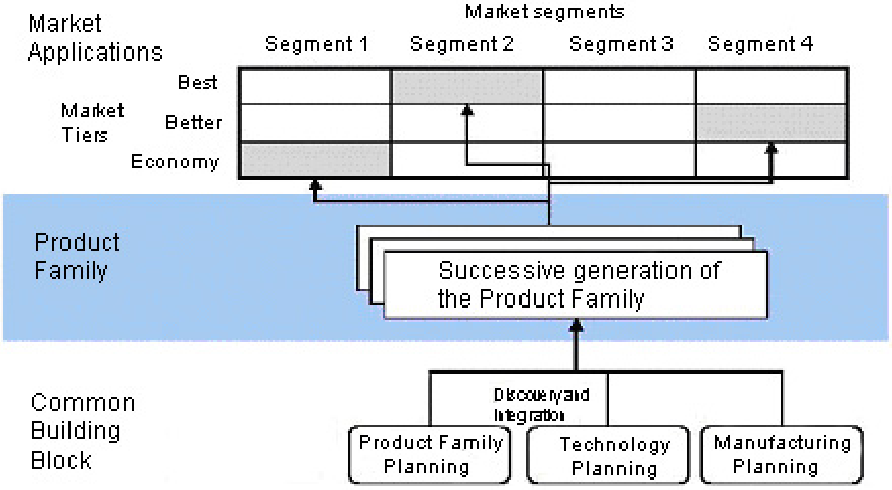


**Figure 1.1. Product family integration of market applications [Meyer, 1997].**

All three common building blocks are tightly related with each other and to the market needs, because optimal product family planning gives us inputs for product technology planning stages and on the manufacturing planning. In the same time technology planning affects product family planning and manufacturing planning. Generally they all affect each other and we could use one planning result as inputs on the other planning stage.

There are two basic approaches to product family design. The first is a top-down (proactive platform) approach where in a company strategically manages and develops a family of products based on a product platform and its derivatives. The second is a bottom-up (reactive redesign) approach where in a company redesigns or consolidates a group of distinct products to standardize components and improve economies of scale [Simpson, 2001; Ong, 2006; Salhieh, 2007].

The key to success in either approach is the product platform around which the product family is derived. A product platform can be either narrowly or broadly defined as:

- “a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched”;
- “a collection of the common elements, especially the underlying core technology, implemented across a range of products”;
- “the collection of assets [i.e., components, processes, knowledge, people and relationships] that are shared by a set of products”.

The prominent approach to platform-based product development is it top-down or bottom-up, is through the development of a Module-Based Product Family where in product family members are instantiated by adding, substituting, and/or removing one or more functional modules from the platform. An alternative approach is through the development of a Scale-Based Product Family where in one or more scaling variables are used to “stretch” or “shrink” the platform in one or more dimensions to satisfy a variety of market niches.

In the other hand the product family design process is tightly cooperated to issues of importance to the entire enterprise: product variety, product change, component standardization, product performance, manufacturability, and product development management. An effective platform for a product family can allow a variety of derivative products to be created more rapidly and easily (cost and time savings), with each product providing the features and functions desired by a particular market segment [Sundgren, 1999; Jiang, 2003].

Product family is generated through configuration design, in which a family of products can widely vary the selection and assembly of modules or pre-defined building blocks at different levels of abstraction so as to satisfy diverse customer requirements [Tseng, 1996; Tseng, 1998; Fujita, 1999]. The essence of configuration design is to synthesize product structures by determining what modules or building blocks are in the product and how they are configured to satisfy a set of requirements and constraints. There are many approaches to address module assembly and configuration design, such as assembly incidence matrix and genetic algorithms

The design of product families has been associated with the concept of product architecture, which defines the scheme by which the function of the product is allocated to physical components. Although the concept of product architecture is usually associated with a single product, it has been also written in the literature that a product family sharing a set of common components (or modules) can have an architecture that describes the mapping between functions provided by the products and the structure of these products [Sawhney, 1998; Ulrich, 2000; Martin, 2002; Salhieh, 2007]. As shown also in Figure 1.2, the product variety can be implemented at different levels within the product architecture. From the aspect of product design, component standardization through a modular architecture has clear advantages in the areas of cost, product performance and product development. Decomposing the problem into modules and defining how modules are related to one another creates the model of a design problem [Zha, 2001; Jefrey, 2001; Zha, 2002].

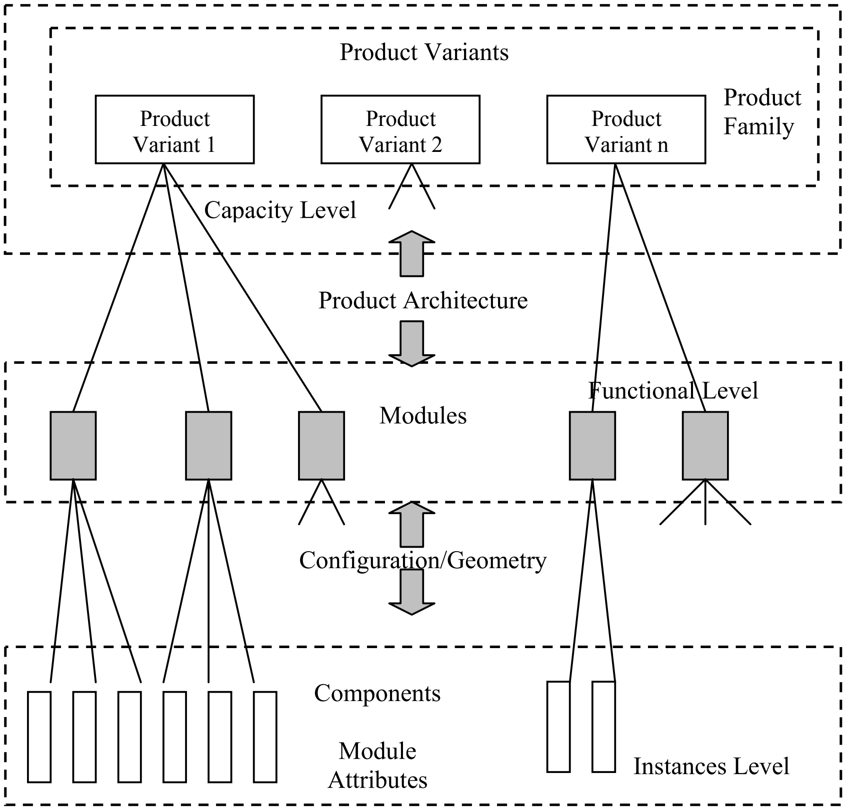


**Figure 1.2. Product families and modules [Zha, 2006]**

In figure 1.3 is brought out the generic information platform. The approach is to model a product family architecture, according to the semantics used in product development, prepared for the information needs of configuration [Muffatto, 2000; Meyer, 2002].

A product family architecture represents the conceptual structure and logical organization of product families from viewpoints of both customers and designers. A well-developed product family architecture can provide a generic architecture to capture and utilize commonality, within which each new product instantiates and extends so as to anchor future designs to a common product line structure. Thus, the modeling and design of product architectures is critical for mass customizing products to meet differentiated market niches and satisfy requirements on local content, component carry-over between generations, recyclables, and other strategic issues [Zha, 2006].

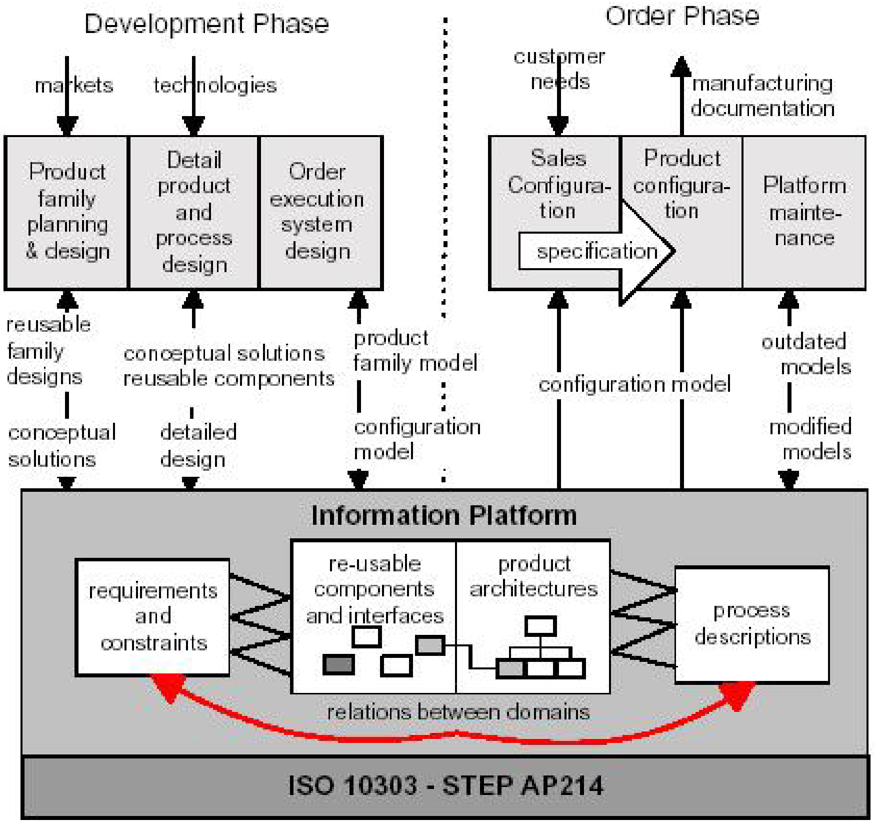


**Figure 1.3. Product family generic information platform [Sivard, 2000].**

The product family development task is quite hard, because of the product portfolio and their manufacturing system are not developed at the same time. We consider the “continuous improvement“ situation for both, the product family and their manufacturing system, aimed to enhance the efficiency of production, better satisfactions the market needs, and to estimate the bottlenecks in production. We assume that there is a stable production environment, and the required data for analytical modeling and optimization are available.

In that work we use bottom up approach (see paragraph 2), which implements family-based product design through re-design or modification of constituents of the product.

For optimizing existing product family we have to follow different constraints like market needs, production resources, production availability, product design parameters and functional/handling requirements [Erens, 1997; Hsiao, 2005; Galan, 2007; Bryan, 2007]. These tasks will affect each other, because from the design parameters we can get input parameters for product family optimal planning model and in the other hand results what we could get from the planning operation, affect the design parameters. For describing that situation is brought out Figure 1.4.

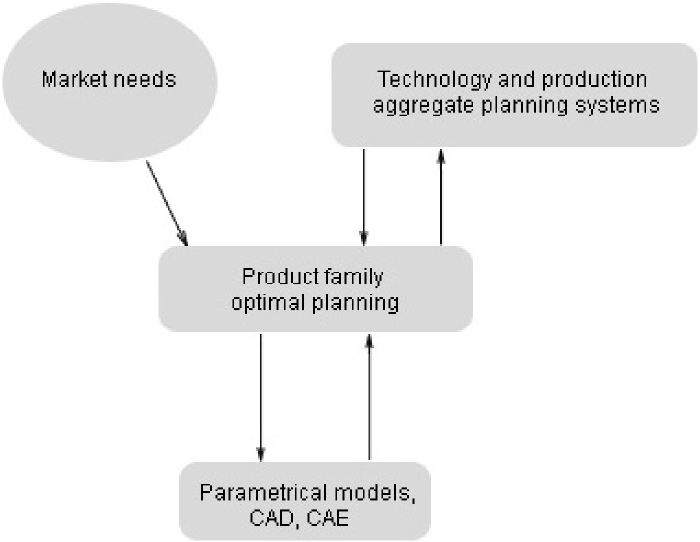


**Figure 1.4. Product family optimal planning scheme**

Generally we will try to investigate how to optimize the family of products and their manufacturing processes, in particular, to integrate computer-based product family planning, technological process planning and multi-period manufacturing resource planning activities for an enterprise or network of co-operating enterprises, and to take full advantage of the computer-based optimal engineering decision process. The basic approach of the "evolutionary product and process development" has been accepted, which involves re-engineering and evolutionary improvement of products and processes.

The major concern in optimal planning is the overwhelming complexity of tasks. Simplification is based on the decomposition of initial task. There are several reasons for the decomposition:

- The division of the initial task into smaller sub-tasks will lead to a better understanding of the whole problem;
- Breaking down the tasks between the subsystems may lead to the realization of design in different teams or functional units of enterprise; there may be some already existing models that can provide useful information.

## 1.2 Overview of the Plastic Forming Technologies

There are many different methods for forming plastics materials like injection molding, blow molding, extrusion, thermoforming (vacuum forming). We are mainly investigating the thermoforming processes, because our products consist of the large composite plastic parts, which is technologically and economically effective to form using thermoforming processes.

The commercial thermoforming is called vacuum forming, was not developed until the 1870s, when cellulose nitrate was first cut into thin sheets, Egyptians, Pacific natives, and American Inuit's formed naturally occurring tortoise sheet and tree bark or natural cellulose into bowls and boats long before then [Throne, 1996]. In the 1870s, cellulose sheet was formed using metal molds and steam as the heating and forming medium [Throne, 2002]. The earliest products were toys, baby rattles, mirror cases and hairbrush backs. In the early 1900s, piano keys were drape formed over captive wooden cores. The heating, bending, and shaping of plastic sheet were taught in high school industrial art courses in the late 1930s. The Second World War accelerated interest in thermoforming, with the demand for cast poly (methyl methacrylate) fighter/bomber windows, windscreens and gun closure. In the mid-1950s, thermoformed blister packages and food containers of polystyrene were found in most grocery stores. In 1962, approximately 77,000t of plastic was thermoformed in the United States. By 1998, approximately 2.9 million metric tons of plastic were thermoformed in North America [Mooney, 2002]. This is a sustained annual growth rate of about 10% over nearly four decades. An additional 4.55 million metric tons are thermoformed worldwide. The total world market is estimated to have a value of about US$ 35,000 million [Herman, 2003].

Thermoforming uses heat, vacuum, and pressure to form plastic sheet material into a shape that is determined by a mold. Sheet stock is heated to a temperature at which the plastic softens, but that is below its melting point. Using vacuum or pressure, the plastic is then stretched to cover and duplicate the contours of a mold. Next the plastic is cooled so it retains its shape. Finally it is removed from the mold and trimmed as required to create a finished part. [Rubin, 1990]

Thermoforming is different from other processes because of the lower pressure that are required to thermoform. Both the mechanical and pneumatic pressures used in thermoforming are just slightly greater than atmospheric pressures. Hence the forming equipment and the molds can be made of less sturdy materials than are required for high-pressure plastic forming processes such as extrusion, injection-molding and even blow molding. Large parts can therefore be made using thermoforming without the capital cost of large molds and pressurizing machines.

A significant disadvantage of thermoforming versus the other processes is the much greater amount of scrap it generates. Because the parts are made from portions of a sheet, each part must be trimmed and the excess material recycled.

The designs of parts made by thermoforming are more limited than injection molding, because the plastic does not melt and flow into intricate shapes. Parts made by thermoforming are generally open structures with diameters of the openings greater than the diameter of the body. Parts with sharp bends and corners are difficult and parts with thick and thin walls, such as bosses and solid ribs, are generally not possible. Wall thickness control is also difficult and some areas inherently thinner than others, because of the uneven stretching of the material as it is pressed into the mold. [Strong, 2000]

Thermoforming is good for low to moderate volumes (up to approximately 100 000 units per year depending on the part). Injection molding is a better approach for very high volumes (100 000 per month) – particularly when unit cost need to be quite low.

Tooling for injection molding can cost ten times as much as thermoforming tooling, but thermoformed parts can cost several times as much as comparable injection molding components [Rubin, 1990]. The advantages and disadvantages of thermoforming is brought out in Table 1.1.

**Table 1.1. Thermoforming advantages and limitations**

Advantages

- Production parts can be run on relatively inexpensive aluminum or epoxy molds;
- The maximum mold pressure for vacuum forming is under 1 MPa. Mold pressures for pressure forming can be range from 2 MPa to 20 MPa and requires tooling accordingly;
- Properly molded parts exhibit no excessive molded-in stress;
- With pressure forming, detail very close to injection molding and much faster cycle times can be achieved;
- Very large relatively simple parts can be molded. Size up to 1 by 25 m are common;
- The cost of the part is low compared to other processes;
- Packaging can be thermoformed to thinner gauges than is possible with other processes;
- Parts can be molded, filled, decorated and capped or sealed in one continuous operation;
- Part design changes can be less costly due to less expensive tooling.

Limitations

- Details can be molded only on one side of the part without special matched tooling;
- Precise wall thicknesses are difficult to achieve and cannot be effectively varied within the part;

**Table 1.1. Thermoforming advantages and limitations - continuation**

| | |
|---|---|
| | • Wall thickness and part dimensions can vary from part to part;<br>• Labor cost are higher, because of trimming and detailing;<br>• Material costs are higher, because of extended sheet or film. |

## 1.2.1 Analyze of the Thermoforming Processes

The wide variety of parts made by thermoforming processes has led to the development of several modifications of the basic techniques to optimize the making of particular shapes and improve upon some of the inherent problems associated with thermoforming. These process modifications reflect changes in the type of mold and the method of forcing the plastic material into the mold. The techniques can be grouped into several major types which will each be considered separately.

*Straight vacuum forming/drape forming.* This is the simplest thermoforming technique and the one most commonly envisioned when thermoforming is discussed [Bourgin, 1995; Strong, 2000]. The plastic sheet is clamped in a frame and heated, then drawn over the mold either by pulling it over the mold and creating a seal to the frame, or by forcing the mold into the sheet and creating a seal. Then vacuum is applied through the mold, pulling the plastic tight to the mold surface. In this method, the top of the part (area of the mold that contacts the plastic first) tends to be thickest, and the sides and lower portions that stretch and contact the mold last, tend to be thinnest. In Figure 1.5 is brought out the different steps of straight vacuum forming process.

*Snap-Back Vacuum forming - Male Tool.* After the plastic sheet is heated, a vacuum box seals to the clamping frame. Vacuum applied through this box pre-stretches the material by pulling it into a "bubble". Bubble height is frequently controlled by an electric eye. When the plastic has been pre-stretched to the desired height, the mold enters the sheet and seals to the clamping frame. At that point vacuum is applied through the mold, and the vacuum box is allowed to vent to the atmosphere (or light pressure is applied in place of the vacuum). Very deep draws can be obtained with this system, and undesirable material thinning can be greatly minimized. In Figure 1.6 is brought out different steps of snap-back vacuum forming process.

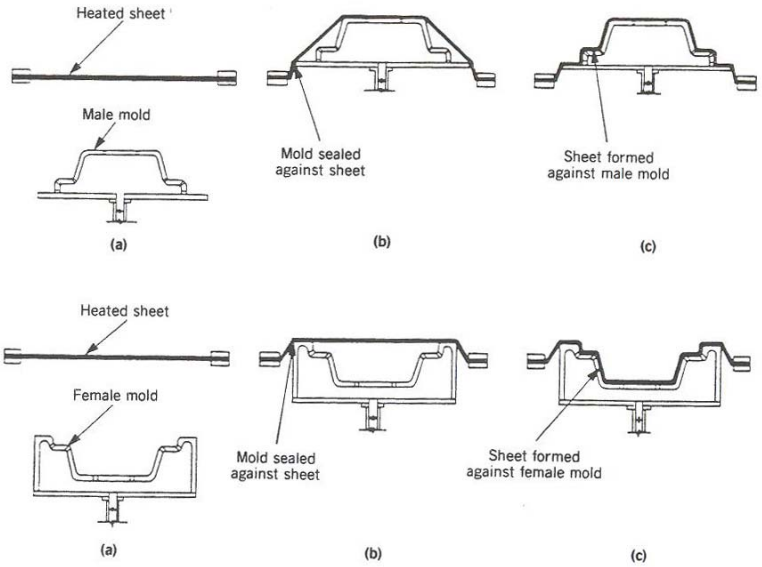


**Figure 1.5. Straight vacuum forming types**

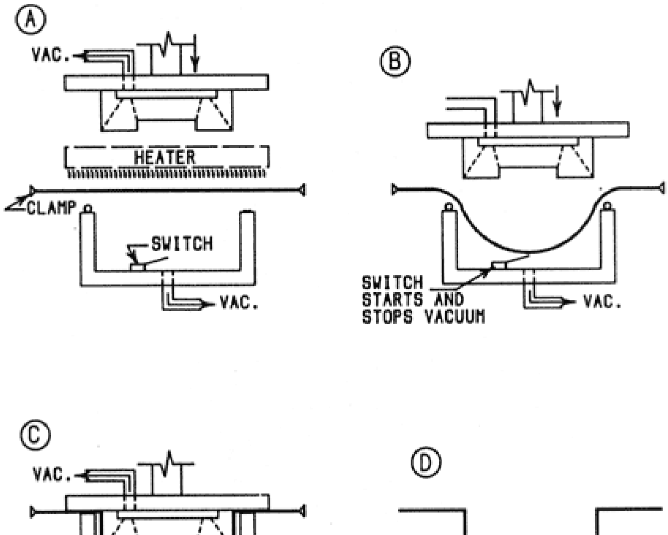


**Figure 1.6. Snap-back vacuum forming types [Rubin, 1990; Sawhney, 1998]**

*Billow Snap-Back Vacuum forming - Male Tool.* The heated plastic is clamped and sealed across a pressure box, then a bubble is blown "toward the tool" (see

Figure 1.7). Once the sheet has pre-stretched approximately 35 to 40%, the mold is forced into it while pressure behind the sheet remains constant. When the mold seals to the frame, vacuum is supplied through the mold. In some cases it may also be desirable to increase pressure in the pressure box at this point.

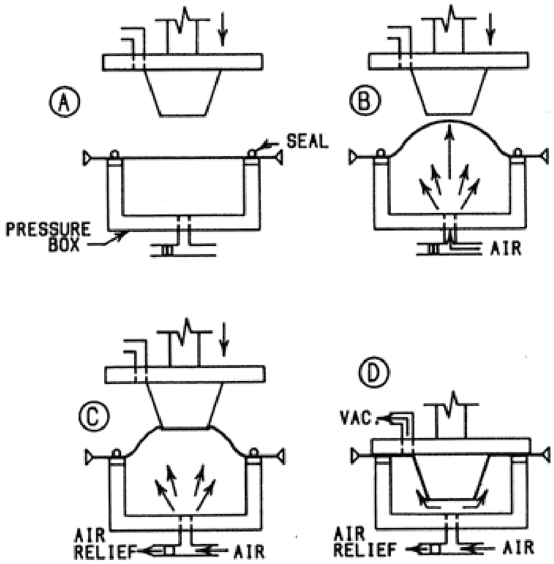


**Figure 1.7. Billow Snap-Back Vacuum forming steps [Strong, 2000; Sonic, 2005]**

*Straight Vacuum forming - Female Tool.* The heated plastic is clamped and sealed to the mold rim. Vacuum is then applied through the mold, causing atmospheric pressure to push the sheet down into the mold (see Figure 1.8). As the plastic contacts the mold it cools. Areas of the sheet reaching the mold last are generally the thinnest.

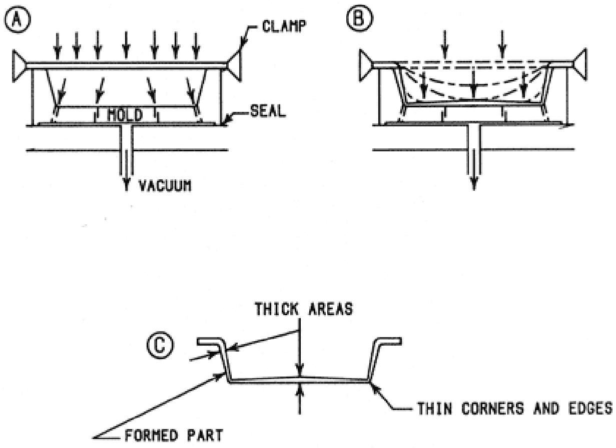
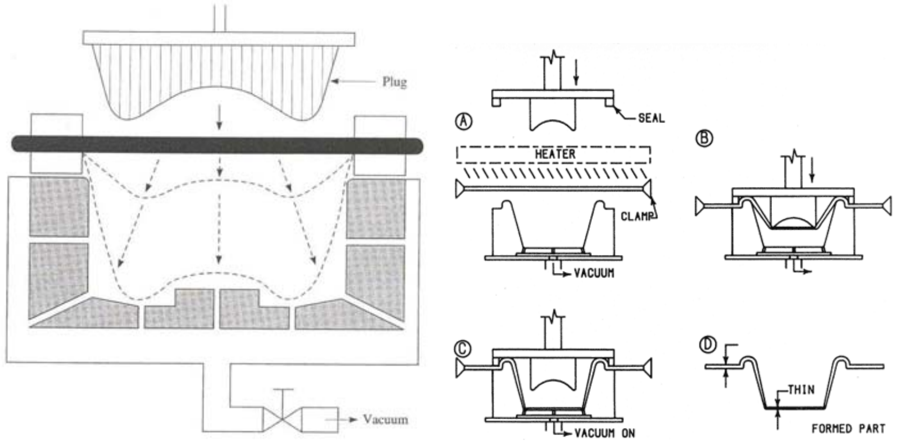


**Figure 1.8. Billow Snap-Back Vacuum forming steps**

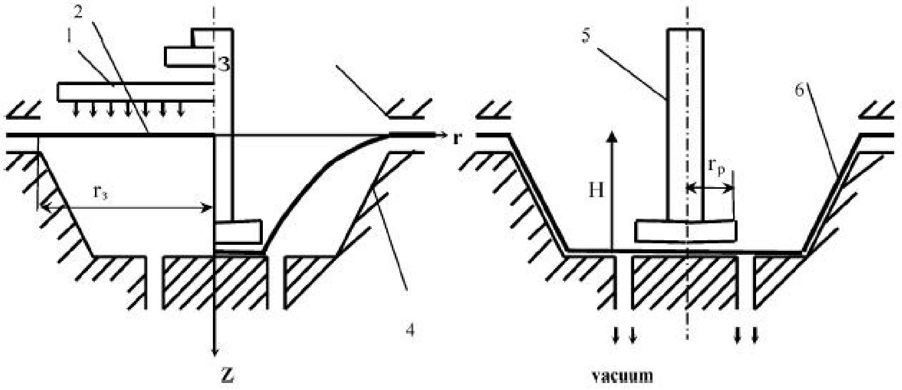
*Plug Assist Vacuum forming - Female Tool.* After the plastic sheet is heated and sealed across the mold cavity, a plug shaped roughly like the mold cavity (but smaller) is plunged into the plastic sheet, pre-stretching the material (see Figure 1.9). When the plug platen has reached its closed position, a vacuum is drawn through the mold to complete the formation of the sheet. Wall thickness can be varied by changing the shape of the plug. Areas of the plug touching the sheet first create thicker areas due to the chilling effect. Consequently, plug design is a critical determining factor in the geometry of the finished part being produced.



**(a)** **(b)**

**Figure 1.9 Plug assist forming (a) and steps (b) [Strong, 2000; Sonic, 2005]**

*Plug Assist Pressure Forming - Female Tool.* Plug assist pressure forming is similar to plug assist vacuum forming, except that as the plug enters the sheet, air under the sheet is vented to the atmosphere. When the plug completes its stroke and seals the mold, air pressure is applied from the plug side (see Figure 1.10, where 1-heater, 2-sheet prior to forming, 3-clamp frame, 4-mold, 5-plug, 6-deformed sheet). Plug temperatures are also important. By using the proper combination of plug design, plug temperature, and forming pressure, finished part wall thickness consistency can be greatly increased.



(a) (b)

**Figure 1.10. Plug Assist Vacuum forming, (a) heater and (b) vacuum forming [Hosseini, 2006]**

*Billow Plug Assist Vacuum/Pressure Forming - Female Tool.* After the plastic sheet is heated and sealed across the female cavity, air is introduced into the mold cavity and blows upward toward the plug, forming a bubble that pre-stretches the material evenly (see Figure 1.11). Height of this bubble is frequently controlled by an electric eye. A plug, shaped roughly to the contour of the cavity, plunges into the bubble. When the plug has reached its lowest position, a vacuum is drawn on the mold side to complete the formation of the sheet. In some instances, pressure forming air, supplied through the plug, is also used in this process [Wiesche, 2004].

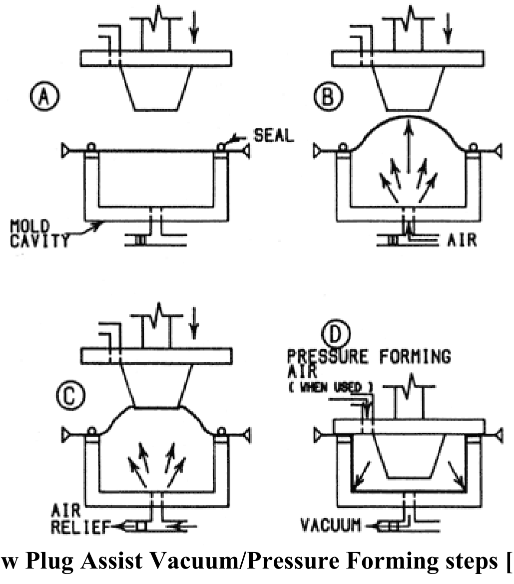


**Figure 1.11. Billow Plug Assist Vacuum/Pressure Forming steps [Sonic, 2005]**

For analyzing different thermoforming processes we have to consider different advantages and disadvantages of the processes. For better understanding is brought out a Table 1.2.

**Table 1.2. Advantages and disadvantages of thermoforming processes**

| Process | Advantages | Disadvantages |
|---|---|---|
| Straight vacuum forming | Easiest and commonly envisioned method | Can't mold longer distances |
| | The side against the mold has fine detail or close tolerances | Wall thicknesses are inherent |
| | Low machine cost | |
| Pressure forming | Mold cycles are faster | Higher forcing pressure |
| | Lower forming temperature | Limited to about 1 atm. |
| | Greater dimensional control | |
| | More strain free parts | |
| Plug-Assist forming | Better wall thickness in deep draws | Plug is necessary |
| | | More energy for heating the plug |
| Reverse draw forming | Better wall thickness in deep draws | Higher machine cost |
| | | Longer mold cycle |

[Rubin, 1990; Strong, 2000; Warby, 2003; Sonic, 2005; Hosseini, 2006]

We are using right now for testing straight vacuum forming bench, because of the lower machine cost, better temperature and mould control and simplicity. That bench have 400 W heaters (see also Paragraph 3.1.1.1 Temperature Variations in Thermoforming) with one top heating layer. Mould maximal parameters which fits to that bench are: 2330 x 2330 x 1200 mm. That bench allows us better control over the part thickness and to form deeper shapes.

## 1.3 The Objectives and Tasks

### 1.3.1 Objectives

The objective of the doctoral thesis is to develop and modify integrated product development and optimal planning of production technology methods and models of large composite plastic products.

### 1.3.2 Tasks

For achieving the described objective, we have to solve some tasks. The tasks are as follows:

- To analyze the state of the art in the field of the large composite plastic products;
- To develop the product family for large composite plastic parts, depending on the proposed product platform and different constraints like functional and handling requirements; requirements for products geometry, structure, product materials and parameters etc.;
- To develop the technology planning model, which results are based on maximization of total profit and subject for workstation time capacities and material availability constraints in the optimal selection of technology route;
- Experimental study – the investigation of the thermoforming process parameters to the quality and manufacturing time of the products. To optimize the reinforcement ply thickness depending on the maximum deformations and stresses;
- To implement the manufacturing resource planning model to the proposed scheme of the large composite plastic parts;
- To integrate proposed three subtasks: product family planning, technology planning and aggregate planning of the manufacturing resources so that they would support complex optimizing incurred in the whole life cycle of the product.

# 2 THE PRODUCT FAMILY PLANNING

Product definition and planning are the critical starting points in the development of any new product.

The product plan helps to resolve the design issues related to the markets, the types of the products and the resources of the company. A product plan is generally prepared on an annual basis; it should be reviewed and updated at least quarterly. Market conditions will change, new opportunities will be identified, and a new product technology will emerge - all having a potential impact on the product plan. These opportunities need to be evaluated and the product plan changed if needed.

Cost efficiencies, technological leverage and market power can be achieved when companies redirect their thinking and resources from single products to families of products built upon robust product platforms.

First, what do we mean by a "product family?" A product family is a set of products that share a common structure, function(s), and technology and address a related set of market applications. Derivative Products are specific instantiations of a product family, which possess unique features and functions as compared to other members in the family.

Product family planning will try to satisfy the range of functional requirements of products. By using standardized and pre-tested modules, the accumulated learning and experience will reduce resources and make higher performance [Meyer, 1997; Sivard, 2000; Fujita, 2001]. The product family design helps to resolve issues related to the markets, the types of the products and the resources of the company.

It is proposed, that a complex engineering design task of product family could be decomposed into three design sub-tasks: product family design, manufacturing technology design and multi-period manufacturing resource planning. We proposed that each of these sub-tasks could be represented in the form of a general goal-seeking system, based on the general optimization approach [Mesarovic, 1970; Mesarovic, 1989]. We represented each engineering design task $S : B \rightarrow L$ explicitly with a planning component (goal-seeking component [Mesarovic, 1989]) *P* and *a* (functional) design component *D* (Figure 2.1).

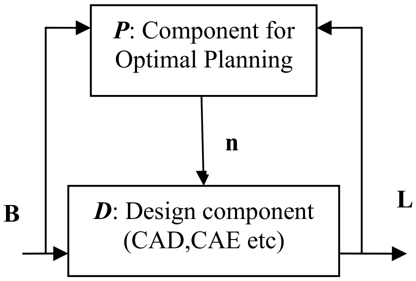


**Figure 2.1. Decomposition of a design task**

In Figure 2.1 *P* represents the planning component, with object $N = \{n\}$, is denoting the domain of choices which *P* has. The task *S* is now represented in terms of two mappings *P* and *D*:

$$P : B \times L \rightarrow N$$
$$D : N \times B \rightarrow L. \tag{2.1}$$

N is an "internal input"; as distinct from *B* and *L*, which are the true input/output objects of *S*. Object $n \in N$ specifies a parameterized family of products (input-output data *B* and *L* of design tasks for product family) in the sense that to every $n \in N$ corresponds a subset $S_m \subset B \times L$, such that

$$(b,l) \in S_m \leftrightarrow (n,b,l) \in D \tag{2.2}$$

For specifying planning activities of *P* we must define an objective function *G*: $G : N \times B \times L \rightarrow V$, and develop a decision strategy which is used to select *n*, where *V* is a vector-valued objective function of corresponding design task.

Relations *D* and *P* must be consistent with the system *S*, i.e., they must satisfy the condition:

$$(b,l) \in S \leftrightarrow (\exists n)[(n,b,l) \in P \text{ and } (b,l,n) \in D]. \tag{2.3}$$

In the following are described planning components for each of the defined design sub-tasks, which are brought out in Paragraph 2.1, 3 and 4).

## 2.1 Development of the Product Family

It is recommended to split the product family design process into two layers: a product family planning layer, and the layer for optimization (for each fixed combination of functional features) the design parameters of derivative products (product attributes optimization task). Under the introduction of these two layers, the product family design process is a hierarchical system of mixed-integer programming model for family planning and a constrained nonlinear programming model for product attribute optimization tasks [Mesarovic, 1989; Zhu, 2000].

The objective of the product family development is to create the desired variety of products in a family economically, to manage the costs of product variety considering product development approaches that reduce complexity and better leverage investments in product design and manufacturing. In fact, the product family is planned so that a number of derivative products and their production volumes are efficiently created from the common family structure and market data. The parametrical models are used as instruments to link the planning tasks with the CAD (Unigraphics) and CAE (ANSYS) systems. Figure 2.2 shows examples of the derivative members of a product family.

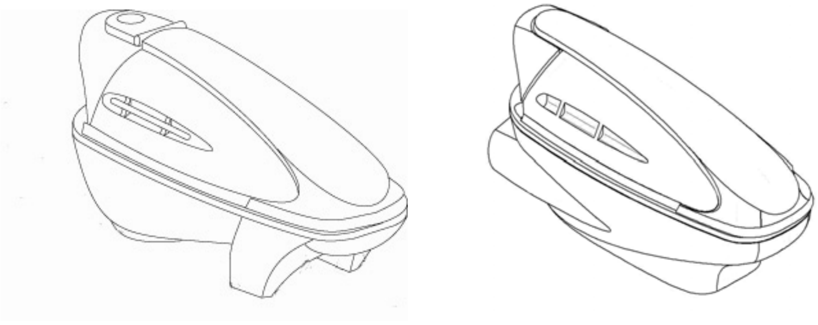


**Figure 2.2. Examples of the derivative products**

Each derivative product $p_i \in P$ is associated with the vector of design variables $x^{p}_{i}$. In Table 2.1 is brought out example of main design parameters.

**Table 2.1. Main design parameters**

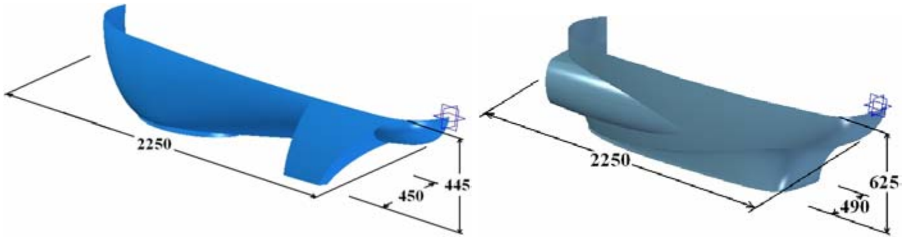
| Design parameter | Value |
|---|---|
| Weight | 120…160 kg |
| Height | 1050/2200…1250/2300(open hood) mm |
| Length | 2200 mm |
| Width | 900 mm |
| Max. current | 15A, 25A |
| Power | 3500 W |
| Water pressure | 2 - 4 bar |
| Water inlet | ½” |
| Water drain | 40 mm |
| Capsule color | white |

Product $P_i$ is composed of a series of modules and parts corresponding to the set of features $F_i$, which are determined in the product family planning phase. Simplified examples of these functions are showed in Table 2.2. The common basic structures of modules and/or parts in Table 2.2 are representing the commonality and similarity pattern of features and design parameters for corresponding derivative products.

**Table 2.2. The use of basic functional features for four products $p_1$, $p_2$, $p_3$ and $p_4$**

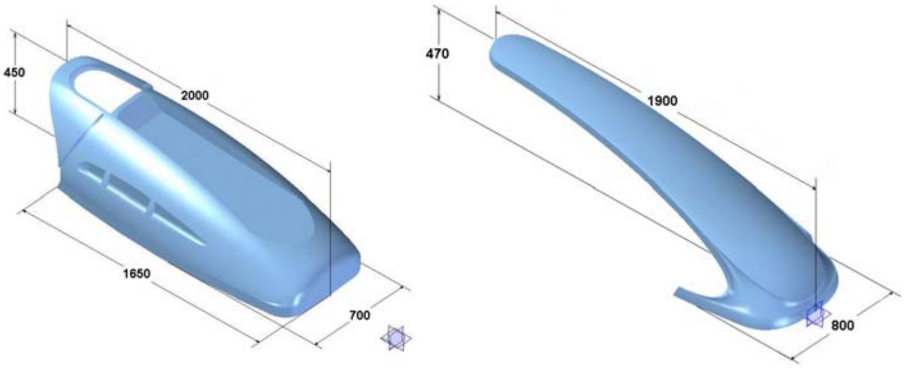
| Features | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Translucent shell | 1 | 1 | 1 | 1 |
| Far infrared heat | 1 | 1 | 1 | 1 |
| Vibratory massage bed | 1 | 1 | 1 | 1 |
| ------------------------------ | ---------- | ---------- | ---------- | ---------- |
| Touch-button control panel | 1 | 1 | 1 | 1 |
| 5.6” LCD color display | 1 | 1 | 1 | 0 |
| 10 pre-set programs (+1 custom) | 1 | 1 | 1 | 0 |
| Steam (direct plumbing) | 1 | 1 | 0 | 0 |
| Steam (no plumbing) | 0 | 0 | 1 | 1 |
| Vichy shower | 1 | 1 | 0 | 0 |
| Hand held shower system | 1 | 1 | 0 | 0 |
| Underbody shower | 0 | 1 | 0 | 0 |
| Foot massage shower | 1 | 1 | 0 | 0 |
| Misting system | 1 | 1 | 0 | 0 |
| Vitamin/mineral product diffusion system | 1 | 1 | 0 | 0 |
| 200l hydrotherapy bath | 1 | 0 | 0 | 0 |
| Underwater LED lights | 1 | 0 | 0 | 0 |
| Massage function diverter | 1 | 0 | 0 | 0 |
| Automatic disinfection system | 1 | 0 | 0 | 0 |
| ------------------------------ | ---------- | ---------- | ---------- | ---------- |

The design variables and structure of modules for basic product variants are the main interfaces of product family planning task for the design and analyze systems CAD and CAE. The parametrical models of modules are used as instruments to link planning tasks with the CAD and CAE systems. In Figure 2.3 are brought out simplified examples of the main parametrical side panel models (in Figure 2.3.a type 1 and Figure 2.3.b type 2). In Figure 2.4.a. is brought out Polycarbonate translucent shell and in Figure 2.4.b. ABS hood cover. Same parts which have brought out in Figures 2.3 and 2.4 have brought out also in generic structure of product family in Figure 2.5.



(a) (b)

**Figure 2.3. Parametrical 3D CAD model of the side panels**



(a) (b)

**Figure 2.4. Parametrical 3D CAD model of the Polycarbonate and ABS parts**

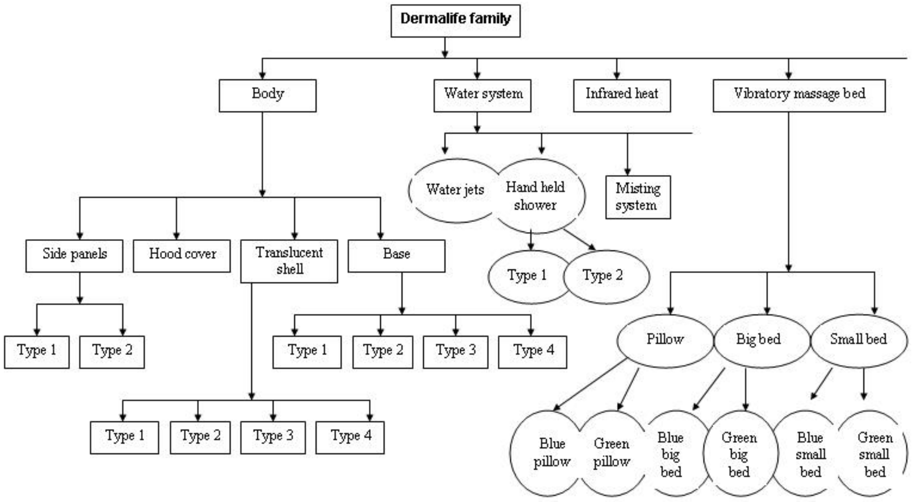


**Figure 2.5. A generic structure of the product family**

The product family *P* could be represented by some generic structure from which a stream of related product variants can be developed and produced [Karjust, 2006 a]. That structure is brought out in Figure 2.5, where are also showed some different modules, which are made in factory (rectangular shapes) and modules, which are brought in form the suppliers (circular shapes). There are also brought out a general variation of different products.

Development of entire product family *P* in most cases requires more investments and development time than developing a single product. This implies that family – based development may not be appropriate for all products and market conditions and requires a careful planning of product family.

## 2.2 Optimal Planning of Product Family

To determine optimal planning volumes of a product family and a module combination, we have developed a model that maximizes the net profit minus investment costs and is subject to upper and lower bounds of demand on the market and to the capacity constraints imposed on workstations and materials [Küttner, 2006 a; Küttner, 2006 b]. The following optimal planning task can be stated.

Next, a list of different variables is composed, which are used in the following models of planning tasks:

- $i$ - an index of derivative product $p_i$, $i = 1 \ldots m$, where m represent the total number of product variants in product family:
- $a_i$ - time required to manufacture (assembly)/purchase one unit of product $p_i$ (or a component);
- $a_{iw}$ - the same for workstation (or technology line) $w$, $w = 1 \ldots k$, where $k$ denotes the number of workstations;
- $c_w$ - capacity of workstation (or technology line) $w$ in units, consistent with those used to define $a_{iw}$;
- $m_{i,u}$ - amount of the material (and purchased components) of type $u$, needed for product $p_i$;
- $r_i$, $s_i$, $h_i$ - net profit, selling price and cost to hold one unit of product $p_i$;
- $C_i$ - unit production cost (excluding inventory costs) of product $p_i$;
- $M_u$, $\mu_u$ - cost and resource of material $u$;
- $Inv_i$ - investment required for implementing product $p_i$ (estimate costs related to the implementation of an appropriate product);
- $X_i$ - quantity of products pi produced during the period analyzed;
- $I_i - \left[\begin{array}{l} 1 \quad \text{in the case of } X_i > 0 \\ 0 \quad \text{in the case of } X_i = 0 \end{array}\right.$ - indicator of product $p_i$ use in the family.

The combinations of products pi and additional (specific) features $F_j$ required by different customers of market segments are represented by the integer indicators:

- $F_{j,i} - \begin{cases} 1 & \text{in the case of the use of feature } j \text{ in product } p_i \\ 0 & \text{in the case of no use of feature } j \text{ in product } p_i \end{cases}$;
- $cf_{j,i}$ - cost of implementing the additional feature j for product $p_i$.

Each market segment has its own customer preferences of additional product features which are represented by $d_{ik}^{max}(F_{j,i})$, $d_{ik}^{min}(F_{j,i})$ - maximum and minimum demand for $p_i$ in the market segment k (as the function of $F_{j,i}$)

For the given $a_{i,w}$, $m_{i,u}$, $r_i$, $cf_{j,i}$ find the volumes of production $X_i$ and use of additional features $F_{j,i}$ that maximize profit $C$ and minimize the manufacturing/purchasing lead time $T$ for the total product family.

$$\textbf{Max } C = \sum_{i=1}^{i=m} \sum_{j=1}^{j=k} (r_i \times X_i - I_i \times Inv_i - F_{j,i} \times cf_{j,i}) \tag{2.4}$$

$$\textbf{Min } T = \sum_{i=1}^{m} a_i * X_i \tag{2.5}$$

Subject to:

1. $d_{i,k}^{\min}(F_{j,i}) \le X_{i,k} \le d_{i,k}^{\max}(F_{j,i})$ for all product variants $i$ and market segments $k$;
2. $\sum_{i=1}^{m} a_{iw} * X_i \le c_w$ for all workstations $w$;
3. $\sum_{i=1}^{m} m_{i,u} \times X_i \le \mu_u$ for all materials $u$;
4. $X_i \ge 0$, $F_{j,i} \in \{0,1\}$ for all $i,j$.

Based on this planning step, a product concept for a family is selected. To solve the given problem we used an integer programming tool. The example of some results of optimal product family planning is represented in Table 2.3 and Table 2.4. Those two tables are different because one input parameter (in that case maximal production volume) was different.

For testing the optimization model we changed different critical input parameters like production volumes, critical investments etc. They were also constraints in our calculations. In spite of the different input parameters we could see the effective set, that profit is maximal, when first and second product is produced and optimal is to add additional function for only the second product, because then we could sell more units.

**Table 2.3. Optimization results**

| Parameters | $p_1$ | $p_2$ | $p_3$ | $p_4$ | Description |
|---|---|---|---|---|---|
| $X_1, X_2, X_3, X_4$ | 30 | 63 | 0 | 0 | Production volumes |
| $I_1, I_2, I_3, I_4$ | 1 | 1 | 0 | 0 | Indicators |
| $F_{1,i}$ | 0 | 1 | 0 | 0 | Additional function-1 |
| $F_{2,i}$ | 0 | 0 | 0 | 0 | Additional function-2 |
| $F_{3,i}$ | 0 | 1 | 0 | 0 | Additional function-3 |
| $F_{4,i}$ | 0 | 0 | 0 | 0 | Additional function-4 |

**Table 2.4. Optimization results**

| Parameters | $p_1$ | $p_2$ | $p_3$ | $p_4$ | Description |
|---|---|---|---|---|---|
| $X_1, X_2, X_3, X_4$ | 30 | 65 | 25 | 0 | Production volumes |
| $I_1, I_2, I_3, I_4$ | 1 | 1 | 1 | 0 | Indicators |
| $F_{1,i}$ | 0 | 1 | 0 | 0 | Additional function-1 |
| $F_{2,i}$ | 0 | 0 | 0 | 0 | Additional function-2 |
| $F_{3,i}$ | 0 | 1 | 0 | 0 | Additional function-3 |
| $F_{4,i}$ | 0 | 0 | 0 | 0 | Additional function-4 |

Using our optimization model there was found out new additional functions depending on the market needs; required investments for each function; possible market growth when function is added to the old product; and production cost for each product. After that we could see the direction where to invest and what modifications and changes are profitable to do. We could reduce the delivery time and lead time. Because of those results we developed these two additional functions and right now the selling numbers shows that the direction was right.

Other important parameter to know is the production capacity and how it depends on the profit in different markets. In Figure 2.6 are represented the results of the simulation of maximizing the profit (brought out profit and production capacity) in international and local market. International market is North- and South-America, Australia, Asia, West- and South-Europe. Local market is Baltic States, East-Europe, Scandinavia and Russia. In different markets are many parameters different like the product demands in different market segments, possible growth for adding the additional functions, transportation and marketing cost etc.

Using the simulation model we could see that depending on our constraints and variables the profit are growing till 120 units, then it will stay similar. It is because of that, the production cost and material cost is getting higher. In the local market graph is the profit negative, when we produce 10 units, because the marketing cost is very high, when the units' number is so small. In local and International market the profit goes lower when production capacity is 80, because there is effective to produce beside first product also 25 second ones, but in second products the profit is smaller, but material cost is higher and that's why the whole month profit goes down.

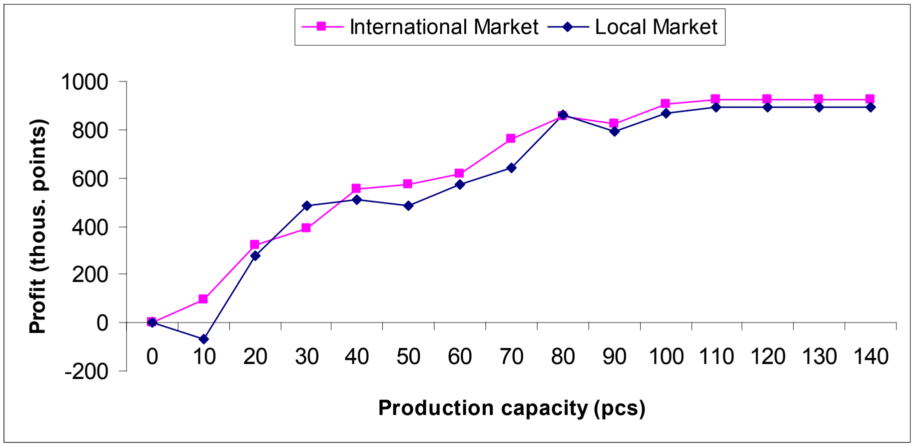


**Figure 2.6. Profit depending on the month production capacity**

## 2.3 Conclusions of the Chapter

1. The products in family of large composite plastic parts has been modified, depending on the different constraints like functional and handling requirements, requirements for products geometry, structure, product materials and different parameters.
2. Different calculation models were used for finding out optimal size of the production capacity, optimal size of different products and sub-products.
3. Using the calculation models the optimal new additional functions, depending on the market needs; required investments for each function; possible market growth when function is added to the old product; and production cost for each product has been found out. Generally we found out that when we try to maximize the profit, then the constraint is monthly production capacity. In the other hand the profit is maximal when new additional functions (first and third) are developed for second product not any other ones. But in spite of that, when we decreased the whole production capacity to 80 units, then the most effective was to add only first additional function to second product.
4. Using the simulation model, our constraints and variables the profit is growing till 120 units and it will stay similar, because the production cost and material cost is getting higher.
5. The solved practical examples demonstrate that the proposed approach and models are valid and effective, and that it can generate the best solutions, if the initial global planning problem models are appropriately represented. The efficiency of use the proposed approach is increasing with the

increasing the complexity of the initial planning problem, since human experts cannot precisely deal with complicated problems. This situation is obvious when we are shifting our concern from the planning the manufacturing of a single product to the manufacturing of product families.

6. Finally for the conclusion of this chapter we could say that using the calculation model we can analyze the optimal batch of the production capacities and decide which new functions are useful to develop and add to the products and which are not.

# 3 THE TECHNOLOGY PLANNING

## 3.1 The Product Family Manufacturing Process Planning

We define manufacturing planning as the process of identifying a manufacturing operation plan, which defines either a complete or partial order in which the manufacturing tasks can be performed.

Generation and selection of manufacturing (operation) plans for a product family is a problem of great practical importance with many significant cost implications. It is known that many feasible operation sequences exist, but some are more desirable than others, according to the utility criteria, such as quality, throughput, cost, need for special tools (incl. jigs or fixtures), etc. The planning problem encompasses generation of feasible manufacturing plans, evaluation of different feasible solutions and selection of the optimal plan(s).

Modeling of the manufacturing process planning tasks is generating a set of correct and complete precedence graphs of operations rather than generating fully specified operation sequence. The word “complete” refers to the generation of a set of precedence graphs from which all possible manufacturing sequences can be derived. The word “correct” implies that all of these sequences are feasible, i.e. they satisfy all manufacturing constraints.

The technology planning model results in the optimal selection of technology operation sequences for the manufacturing of the product family, based on the maximization of the total profit and minimization of the manufacturing time or other process performance criteria and are subject to all constraints of operation establishment (operation necessity and operation precedence), workstation time capacities, material availability, etc. The input data for manufacturing technology planning are derived from the product family planning and manufacturing resource planning tasks.

For finding out optimal technology route we have to cut down the structure of the technology process into different process segments, meaning that we have to solve different sub systems, like finding out the optimal vacuum forming technology, the technology for post-forming operations (trimming, drilling the slots and cut-outs into the part, decoration, printing etc), strengthening (reinforcing) and assembly. An example of a generalized structure of the manufacturing plan for a product family is represented in Figure 3.1 [Ravindran, 1987].

In Figure 3.1 $Op_{1,1}$ represents reverse draw forming with two heaters; $Op_{1,2}$ represents straight vacuum forming; $Op_{2,1}$ represents automatic trimming with saws; $Op_{2,2}$ represents automatic trimming with 5-axis NC routers; $Op_{2,3}$ represents manual trimming with saws; $Op_{3,1}$ represents manual reinforcement; $Op_{3,2}$ represents automatic reinforcement; $Op_{4,1}$ represents sub-assembling; $Op_{5,1}$ represents assembling.

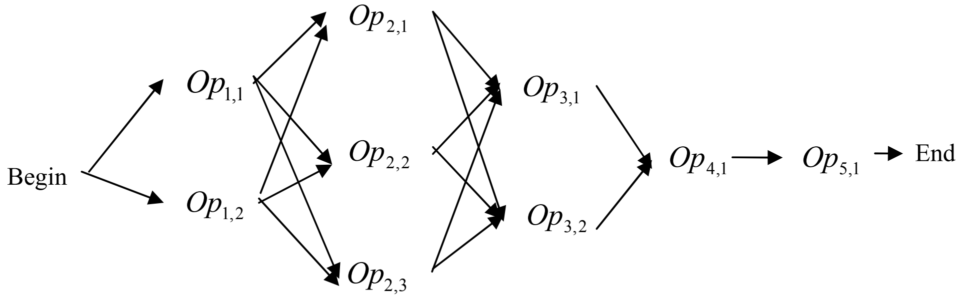


**Figure 3.1. Generalized structure of the manufacturing plan for a product family**

Based on the Figure 3.1 we define an indicator of the use of the technological operation (workstation) $j$ for product $p_i$ as follows:

$$Op_{j,i} = \begin{bmatrix} 1 & \text{operation } j \text{ is used for product variant } i \\ 0 & \text{operation } j \text{ is not used for product variant } i \end{bmatrix} \tag{3.1}$$

Precedence conditions could be described by technological constraints (in following the precedence conditions are specified implicitly by describing the system of constraints) in the form

$$(Op_{11} \vee Op_{12}) \rightarrow (Op_{21} \vee Op_{22} \vee Op_{23}) \rightarrow (Op_{31} \vee Op_{32}) \rightarrow Op_{41} \rightarrow Op_{51} \tag{3.2}$$

For each operation group the condition of necessity of operations is given in the form *IF* (Operation $Op_{j,i}$ is needed) *THEN* $Op_{j,i} = 1$ *ELSE* $Op_{j,i} = 0$.

Choosing among different design alternatives of operations involves detailed analysis, of existing knowledge and experience. A key factor in the selection process is representation of the knowledge in a way that operation selection and design becomes a computer supported process.

The necessity of operation is defined by logical conditions of work pieces and features of work pieces (or features of products for assembly operations). The task is to find a sequence of operations that would give a maximum profit and minimize the manufacturing time and is subject to capacity constraints to the use of technologies (workstations) and materials. We can give the following formulation of the task (definitions of the variables are brought out in Paragraph 2.2):

$$\textbf{Max} \quad \sum_{i=1}^{i=m} \sum_{u=1}^{n} X_i \times (r_i - C_i - m_{i,u} \times M_u) \tag{3.3}$$

$$\textbf{Min T} = \sum_{i=1}^{m} a_i * X_i \tag{3.4}$$

Subject to

1. $\sum_{i=1}^{m} a_{iw} * X_i \le c_w$ for all workstations w;

2. $\sum_{i=1}^{m} m_{i,u} \times X_i \le \mu_u$ for all material u;

3. $Op_{1,1} + Op_{1,2} = Op_{2,1} + Op_{2,2} + Op_{2,3} = Op_{3,1} + Op_{3,2} = Op_{4,1} = Op_{5,1} = 1$ (see Figure 3.1)

4. $X_i \ge 0$; $Op_{i,j}$ and $F_{j,i} \in \{0,1\}$ for all i,j.

Depending on the different operations there are also different formulations for the manufacturing times $a_i$. For instance the manufacturing time for vacuum forming and glass-fiber reinforcement are brought out in Formula 3.5 and for trimming in Formula 3.6.

$$\textbf{Min } \mathbf{T} = \sum_{i=1}^{m} (T_a + T_w + T_c) * X_i \tag{3.5}$$

$$\textbf{Min } \mathbf{T} = \sum_{i=1}^{m} (T_a + T_{wr} + T_{wf}) * X_i \tag{3.6}$$

Where :

- $T_a$ is time for putting/taking product into/from workbench;
- $T_w$ is working time;
- $T_c$ is cooling time;
- $T_{wr}$ is rough working time;
- $T_{wf}$ is finishing time.

There were made also the results analyze for each technology manufacturing time. The regression models for most significant parameters are shown below (definitions of the variables are same as brought out also in Paragraph 3.1.2).

Vacuum forming time:

$$T_v = -97.166 - 0.004L + 0.051B + 0.017H - 1.086G_c + \\ + 2.953D - 5.181T_h - 1.207T_{room} + 7.059Z + 3.185P + 1.817f \tag{3.7}$$

Glass-fiber reinforcement time:

$$T_r = -382.557 + 0.076L + 0.222B + 0.102H - 0.910D_r - \\ - 1.385P_c + 0.110T_{room} - 2.461G_c \tag{3.8}$$

Trimming time:

$$T_t = 48.794 - 0.024L + 0.007B + 0.002H + 16.735G_c \tag{3.9}$$

Where :

- $L$ is sheet material length;
- $B$ is sheet material width;

- $H$ is depth of draw;
- $G_c$ is geometric complexity;
- $D$ is sheet material thickness;
- $T_h$ is heating temperature;
- $T_{room}$ is room temperature;
- $Z$ is heating zone;
- $P$ is cooling point;
- $f$ is distance from the heater;
- $D_r$ is reinforcement layer thickness;
- $P_c$ is peroxide concentration in glass-fiber reinforcement.

Based on proposed models the technology planning is a combinatorial 0-1 integer programming problem. The results (in simplified form) of technology planning optimization task represent the list of operations used to manufacture the proposed family together with the data of use the resources. For better understanding is brought out Table 3.1.

**Table 3.1. Technology planning optimization results**

| $Op_{1,1}$ | $Op_{1,2}$ | $Op_{2,1}$ | $Op_{2,2}$ | $Op_{2,3}$ | $Op_{3,1}$ | $Op_{3,2}$ | $Op_{4,1}$ | $Op_{5,1}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |

Generally we managed to find out the optimal batch of technologies which maximizes the profit, minimizes the production times and production costs. In spite of that we have found out the optimal batch, it will takes quite a lot time to follow that direction, because right now we are using other cutting technology and developing the new optimal technology need very big investments.

### 3.1.1 Optimal Thermoforming Technology

The first process in the technology route is vacuum forming. Vacuum forming (thermoforming) uses heat, vacuum, or pressure to form plastic sheet material into a shape that is determined by a mould (Figure 3.2). Sheet stock is heated to a temperature at which the plastic softens (but below its melting point). Using vacuum or pressure, the plastic is then stretched to duplicate the contours of a mould. Next, the plastic is cooled, by what it retains its shape. Finally, it is removed from the mould and trimmed as required to create a final product. Thermoforming is good for low to moderate volumes (up to approximately 100 000 units per year) because, for example, tooling for injection molding can cost ten times as much as thermoforming tooling.

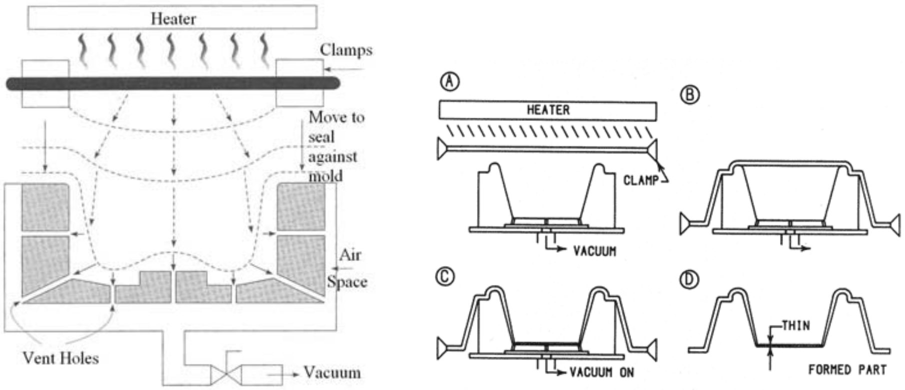


**Figure 3.2. Straight vacuum forming technique [Strong, 2000; Sala, 2002]**

In the thermoforming process, the knowledge and the experience of engineers (process personnel) is of great importance. Geometrical complexity, depth of draw, level of surface detail required, ribbing, fillets, stress concentration, shrinkage, expansion, and undercuts are all factors that must be carefully considered when creating component design and design of the vacuum forming operation [Jacobs, 2003; Karamanou, 2006; Stanley, 2006; Tam, 2007]. The example of the typical components for thermoforming is given in Figure 3.3 (Geometric complexity). The different parts have been divided into three separate types: simple parts (there are parts with simple geometry), medium complex parts (there are parts with medium complex geometry), complex parts (there are parts with complex geometry parameters like angle, ribbing, fillets and different radiuses.

The inherent variability of the formation of the bubble and timing of the thermoforming operation make thermoforming more variable than other plastic molding operations. Successful control of the thermoforming operation can best be accomplished by standardizing the critical parameters associated with the process. These parameters include: sheet properties, heating conditions, and forming operations.

The most important sheet property to control and standardize is the thickness. Variations in thickness over the sheet should be kept under 5%. The experimental analyzes of the thermoforming thinning process is brought out in Paragraph 3.2. A key property that should be controlled from sheet is the melt index. If one sheet has a lower melt index than another, the amount of heat to achieve the same formability will be higher in the sheet with the lower melt index. Sheet material thickness is also affected by different parameters like: mould wall angle and radiuses, depth of draw. Also sheet material physical and chemical properties; mould and room temperature; heating temperature and heating points; vacuum holes diameter, number and positions in mold; cooling points and cooling time. Other variables that might change from sheet to sheet and could affect thermoforming cycles include: density, regrind content and molecular orientation.

Simple parts: code 1

Parts with medium complexity: code 2

Complex parts: code 3

**Figure 3.3. Typical thermoforming parts**

The processing behavior of ABS/PMMA plastics, Polycarbonate and acrylic Plexiglas is largely predictable from their chemical nature, in particular their amorphous nature and the some what unpleasant degradation products. The quality of formed parts is seriously affected by the moisture absorbing ability of the material. The materials known as hygroscopic, if not pre-dried prior to forming, could have moisture blisters which will pit the surface of the sheet, resulting in a rejection of the part. For instance ABS is able to absorb up to 0.3 % moisture in 24 hours. In Figure 3.4 and Figure 3.5 are brought out the samples of wet ABS material sheet after thermoforming. For technology side the moisture is very difficult, because it comes up only after the forming process. Before forming it is very hard to see the moisture in the sheet material. In some cases the moisture comes up with bubbles (as brought out in Figure 3.4) in other cases with hollows (as brought out in Figure 3.5).

The same issues are with Polycarbonate material sheet, what we also used in the tests, according to that work (see Figure 3.6). To overcome this problem it is therefore sometimes necessary for hygroscopic materials to be pre – dried in an oven before thermoforming. The drying temperature and duration of drying time depends on the material structure and thickness [Rubin, 1990; Strong, 2000].

**Figure 3.4. Surface defects – the ABS was wet before thermoforming**

**(a)** **(b)**

**Figure 3.5. ABS sheet was wet before thermoforming (a) and zoom in picture (b)**

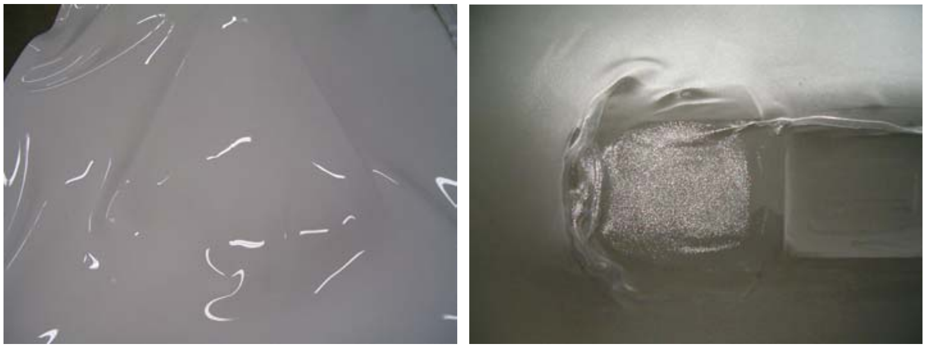
**Figure 3.6. Surface defects – the polycarbonate was wet before thermoforming**

Successful design of the thermoforming operation can best be accomplished by controlling the critical parameters associated with the process. These parameters include: sheet properties, heating conditions, and parameters of the forming operations [Smith, 1996].

The other important parameter for changing the quality of formed part is thermoforming temperature. Generally the ABS parts forming temperature is in range 160-170 °C and Polycarbonate 180-230 °C ,when room temperature is 22 °C. The heating zones and temperature variations in thermoforming are analyzed in Paragraph 3.1.2. There could be many issues, when forming temperature is higher than 210 °C, then the material will flow and the result is brought out in Figure 3.7. Vacuum couldn't throw the material correctly to the mold, that's why came out so called waves. Also when material is over heated there could be the similar bubbles as brought out in Figure 3.4 and Figure 3.5.

**Figure 3.7. The ABS plastic part is too warm and vacuum doesn't work correctly**

The other problem is that thermoformed material is not enough warm and forming process doesn’t last to the end. That means that details are molded partly [Fang, 2006; Fang, 2007; Karjust, 2007 a]. For better introduction is brought out Figure 3.8. It happened because of the problem in the bench and material cooling started before thermoforming process. The other reason could be that mold moved too slowly and sheet could cool down or the plastic sheet is not connected properly to the table. Then material could come out from the connecting table.



**(a)** **(b)**

**Figure 3.8. The ABS plastic (a) and Polycarbonate (b) sheet was cold**

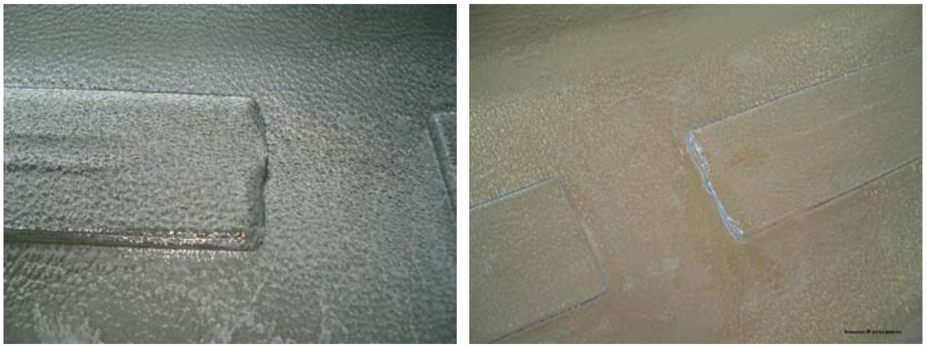
Generally in molding process there are many difficult areas what has to be considered while developing and thermoforming the part:

- Recommended wall thickness/length of flow:
  - minimum 0,75 for 50 mm distance;
  - maximum 9,375 for 1050 mm distance;
  - ideal 3,125 for 400 mm distance.
- Allowable wall thickness variation, % of nominal wall: 5;
- Radius requirements: outside – minimum 0,005, inside – minimum 0,02 maximum 60% of wall (see also Figure 3.9);
- Reinforcing ribs: maximum thickness 70%;
- Solid pegs and bosses: maximum thickness 70%;
- Draft angles: outside – minimum ¼°, ideal 1°; inside – minimum ¼°, ideal 1° (see also Figure 3.10).

(a) (b)

**Figure 3.9. Critical corner radius (a) and wall thickness (b) in ABS part**

In Figure 3.10 are brought out defects in polycarbonate parts depending on the critical product design in the wall edge areas. In the Figure 3.10.a. is brought out the critical wall radius and angle, which caused the material flow over the wall. In the Figure 3.10.b. is brought out the same critical parameters, which caused the wall hollows in the edge of Polycarbonate part.



(a) (b)

**Figure 3.10. Critical outside radius - bubble (a) and hollow (b) of the wall**

(a) (b)

**Figure 3.11. Critical outside angle –wall defect (a) and material stretching (b)**

Beside the outside radius it is also critical the wall angle in thermoforming process. When the angle is smaller than minimal one, then there could be different defects like brought out in Figure 3.11. In Figure 3.11.a. is seen that the wall is not properly formed and there is one bubble. In Figure 3.11.b. is seen that the wall is formed properly, but the material is stretched and structure is changed. Beside the critical angle and radius parameters we have to consider also the mold air channels, their diameters and amount in the wall edge. Also very important is to connect the sheet properly with the clamp frames. If the connection is weak then during the molding process the material will come loose and molds partly, as brought out in Figure 3.12.

(a) (b)

**Figure 3.12. Sheet connected weakly (a) and caused the material waves (b)**

For the conclusion it is brought out Table 3.2, where is summarized the main problems and possible causes in thermoforming processes.

**Table 3.2. Thermoforming troubleshooting guide**

| Description of Problem | Possible Causes | Possible Corrective Action |
|---|---|---|
| **Bubbles in formed part** | Excessive moisture | Pre-dry sheet<br>Heat sheet on both sides |
| | Heating sheet too rapidly | Lower heater temperature<br>Increase distance between heaters and sheet |
| | Uneven sheet heating | Check heater output<br>Use pattern heating |
| **Crazed or brittle parts** | Mold cooling | Increase mold temperature |
| | Overheated part | Remove part from mold as soon as it is stable |
| | Incompatible mold lubricant | Change mold lubricant |
| **Incomplete forming of part, poor detail** | Sheet too cold | Increase heating time<br>Increase heating temperature |
| | Cold clamping frame | Preheat clamping frame |
| | Insufficient vacuum | Check for vacuum holes<br>Add vacuum holes |
| | Poor mold design | Add vacuum holes<br>Check for good seal between clamp frame and vacuum box |
| | Part draw ratio too large | Check vac. system for leaks |
| **Poor surface finish** | Mold surface too rough | Draw-polish mold |
| | Draft angle too shallow | Increase draft angle |
| | Mold mark-off | Use silicone or powdered mold lubricant sparingly |
| | Dirty sheet or mold | Clean sheet or mold |
| | Scratched sheet | Polish sheet |
| | Mold too hot | Decrease mold temperature |
| | Mold too cold | Increase mold temperature |
| **Poor wall thickness distribution and excessive thinning** | Uneven heating | Check uniformity of heater<br>Use screening to control heating<br>Check for drafts in heating stat. |
| | Cold mold | Increase mold temperature<br>Check for uniform mold heating |
| | Sheet pulls from rails | Air-cool rails prior to heating<br>Increase rail tooth bite |
| | Sheet slips from frame | Adjust frame alignment<br>Increase frame clamp pressure |
| | Excessive thickness variation in sheet gauge | Check sheet gauge |
| **Corners too thin in deep draw** | Uncontrolled material distribution | Consider other techniques such as billow-up, plug assist. Etc. |
| | Sheet too thin | Use heaver gauge sheet |
| | Sheet temp. too high at corners | Use screening to control heating |
| | Drape speed too fast | Reduce drape speed |

The moulds are one of the most important elements of the forming cycle. One of the main advantages of vacuum forming is that the significantly lower pressures compared to, for example, the injection molding process. As result, the vacuum formed tools can be produced economically from the wide range of materials to suit different prototype and production requirements. The prime function of a mould is to enable the machine operator to produce the necessary quantity of duplicate parts before degradation.

Selection of the best suited mould material depends largely on the severity and length of service required. If only a few parts are required, using fairly low temperature plastics, wood or plaster could be used. However, if the quantity requirements and material temperatures are higher then ideally an aluminum based resin or aluminum mould would be recommended.

For vacuum forming, it is necessary to accept the significant thinning in the sheet material accompanying the process [Sala, 2002]. This thinning is a natural consequence of the deformation conditions. For vacuum forming, elastic strains are negligible; therefore, constancy of the volume can be assumed. The thinning process is described in the Paragraph 3.2.

### 3.1.2 Temperature Variations in Thermoforming

The forming temperature of the sheet is one of the most critical processing parameters, and can be influenced greatly by the type of thermoforming equipment used. For example, heater efficiency, distance of sheet from the heaters, and uniformity of heat distribution can impact how the part forms. In most of the thermoforming machines, the heating step if performed using an infrared oven constituted of long waves infrared emitters (3-5 μm spectral bandwidth). Depending of the thermoforming bench there could be upper and lower rows of infrared emitters. The number of emitter rows and emitter power influence the length of time the part is heated. Beside the emitter power the thickness of the laminate also affect the sheet temperature. For analyzing the suitable vacuum forming process, the heating zone and plastic sheet temperature variations should be also calculated. The temperature and working time for each heating zone depends on the part, material structure, geometry complexity and different parameters. That means that in the technology planning and product development phase we have to consider the heating zones and temperatures on it [Monteix, 2001; Schmidt, 2003; Bendada, 2005]. For instance the wrong temperature and product design can cause many different problems like bubbles in the top of the material, because the temperature was too high; partly molded parts, because of the complex design and low temperature; cracks in the molded parts, because of the complex design and low temperature when removing the mold and etc.

The temperature-dependency of the specific heat is significant in the vicinity of the melting range. Its effect on the heat equation within the sheet is therefore of major importance for thermoforming because this melting range is reached during reheating [Wiesche, 2004; Ploteau, 2007]. The temperature differences on the acrylic Plexiglas sheet are shown in Figure 3.13. We also measured temperatures in polycarbonate and ABS/PMMA sheets. Normal forming temperatures in sheet surface for the ABS/PMMA is (166±1)˚C, Polycarbonate (191±1)˚C and acrylic Plexiglas (231±1)˚C in reliability 95%. For measuring the temperatures we used foil sensors. The different positions of sensors are shown in figure 3.14.

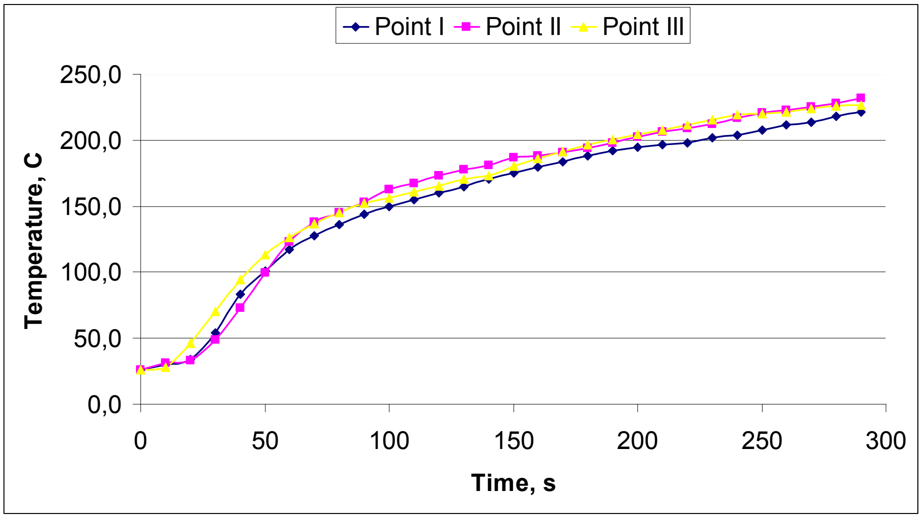


**Figure 3.13. Sheet temperature in concrete points**

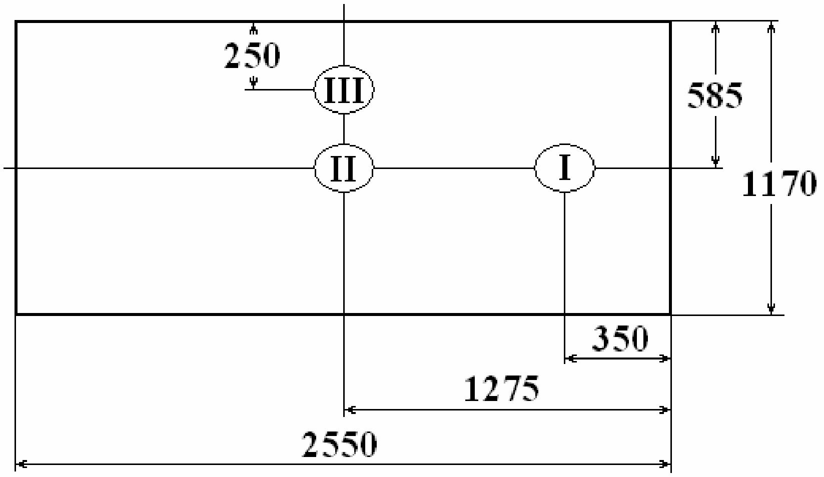


**Figure 3.14. Foil sensor positions in sheet material**

Using the foil sensors we could measure the temperature dependence of the time in different points of the plastic sheet. The average temperatures and parameters of the experimental tests with different materials are brought out in Table 3.3. Those parameters are used in the ANN training for optimizing the vacuum forming process. The ANN modeling and optimization are brought out in Paragraph 3.1.3.

**Table 3.3. Thermal process parameters**

| Description/Parameter | ABS/PMMA | Polycarbonate | Acrylic |
|---|---|---|---|
| Temperature of room $T_{room}$ | 26˚C | 24˚C | 26˚C |
| Temperature of sheet $T_{sheet}$ (forming) | 166˚C | 191˚C | 231˚C |
| Temperature of moulds $T_{moulds}$ (forming) | 34˚C | 33˚C | 34˚C |
| Temperature of infrared heaters $T_{heaters}$ | 321˚C | 290˚C | 328˚C |
| Convective heat transfer coefficient $h_{air}$ (air) | 5 W/(m$^2$K) | | |
| Heat transfer coefficient $h_{moulds}$ (moulds) | 1000 W/(m$^2$K) | | |

For experimental analysis we have to consider beside the sheet temperature also the infrared emitters temperatures. The product with four independent zones and with controlled temperature was used, the heater temperature variation were between 290-340˚C. For better understanding in Figure 3.15 is brought out introductive infrared emitters in vacuum forming bench and in Figure 3.16 different heating zones. In Figure 3.17 is brought out temperature variations depending on different zones and materials.

The infrared emitter temperatures and actual sheet temperatures are different in different materials, because of the material properties, mould geometry, parameters, air and mould temperature. In our experimental tests the infrared heaters were 20 cm above the plastic sheet and the temperatures of the heaters and the temperatures of the plastic sheet were different. We could see that difference also in Figure 3.13 and 3.17.

**Figure 3.15. Infrared emitters in thermoforming bench**

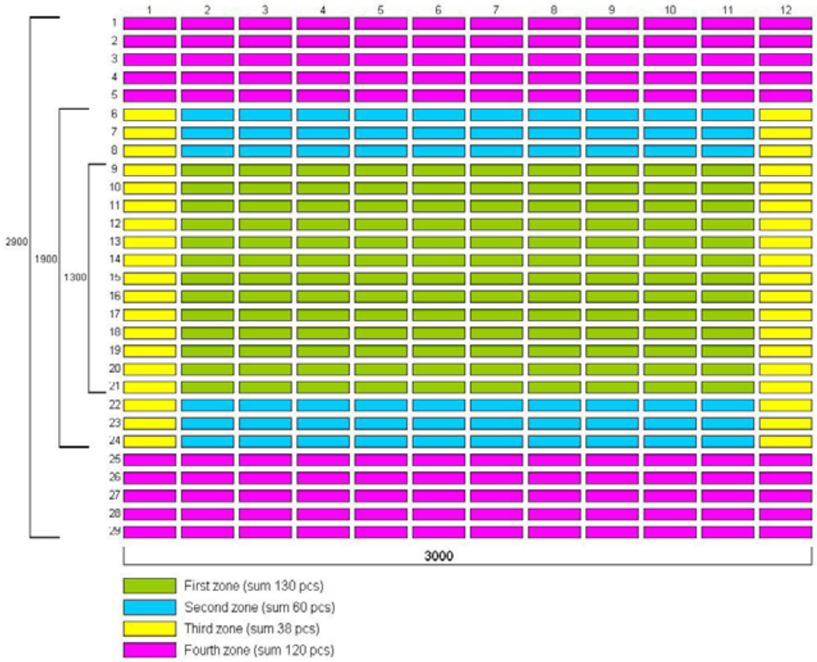


**Figure 3.16. Heating zones in vacuum forming bench**

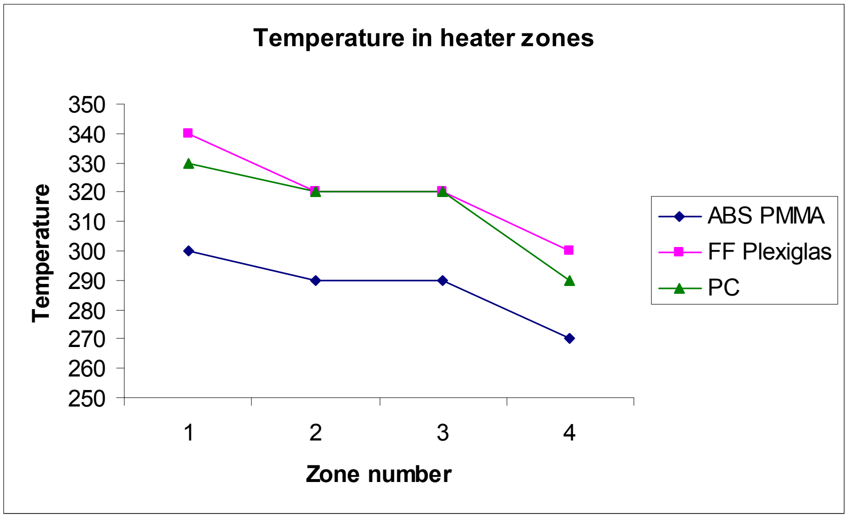


**Figure 3.17. Temperature differences in heating zones**

For optimizing the thermoforming process it is important to know the sheet forming temperature and also the time for cooling plastic sheet down. The cooling process depends on the cooling points (air ventilators) positions, numbers and power. As minimal the cooling time is the better it is, but we have to consider also the sheet material properties and physical parameters to avoid the cracks after intensive cooling. We made different experimental tests for finding out the cooling time in different materials and positions of the plastic sheet. In Figure 3.18 is brought out the temperature drop down dependence of time in acrylic Plexiglas. The sensor was in the centre of plastic sheet, which is brought out in Figure 3.14. The cooling points and time is used for ANN training and thermoforming optimization in Paragraph 3.1.3.

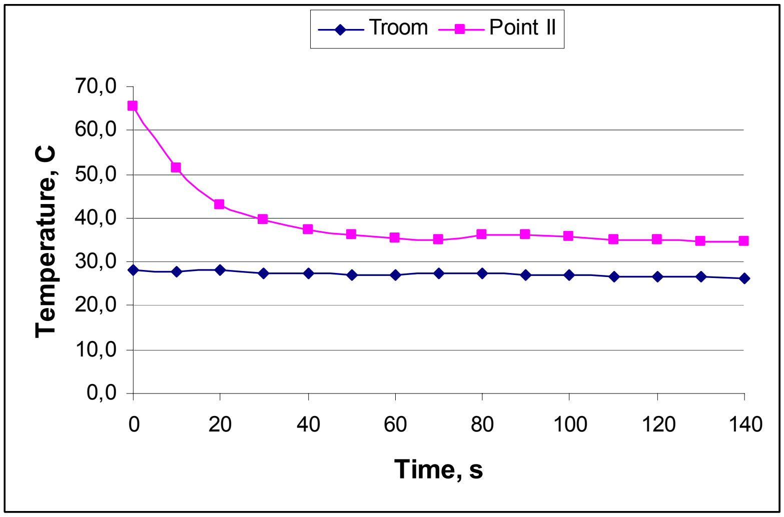


**Figure 3.18. Cooling temperature and time variations**

### 3.1.3 Technology Route ANN Modeling and Optimization

Artificial Neural Network is used for modeling the decisions of technology planning processes for each operation. ANN copes well with incomplete data and imprecise inputs. In Figure 3.19 is brought out the neural networks structure. A neural network approach and MatLab Neural Network Toolbox is used to determine a set of initial relationships process parameters and performance indicators and classification information for vacuum forming of high volume plastic parts (see also Figure 2.3, 2.4 and 2.5). Neural networks approach can be trained to solve problems that are difficult for conventional computers or human beings. The preliminary validation test of the system has indicated that the system can determine a set of initial process parameters for vacuum forming quickly from which good quality formed parts can be produced without relaying on experienced forming personnel.

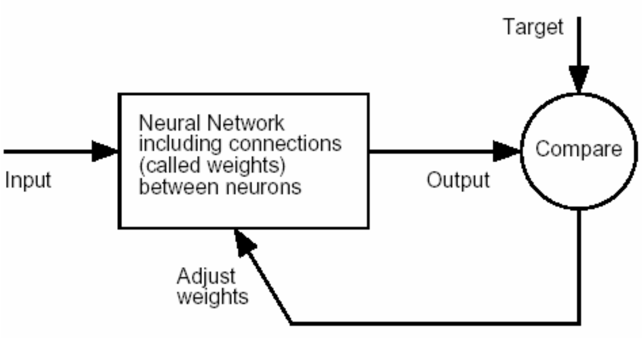


**Figure 3.19. Neural network structure[Matlab, 2007]**

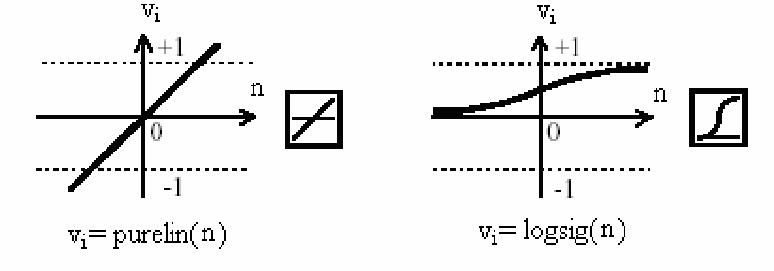
A non-linear input-output mapping is accepted for modeling. A model of neural network can have several layers like Multiple Layers of Neurons. In the other words Neural Networks are composed of nodes (neurons) connected by directed links. Each link has a numeric weight matrix $W_{j,i}$ , a input vector $l$, the bias vector e and an output vector $v_i$. A mathematical model for a neuron could be represented as:

$$v_i = g(\sum_{j=0}^{n} W_{j,i} \cdot l + e), \qquad (3.10)$$

Where:

- $v_i$ is the output activation of the unit $l$;
- $e$ is the bias vector;
- $g$ is the activation function of the unit (the sigmoid and linear functions are used as activation functions).

For transfer functions the linear transfer function (see Figure 3.20.a.) and sigmoid transfer functions (see Figure 3.20.b) are used, where $n$ is a net input. The log-sigmoid transfer function takes the input, which may have any value between plus and minus infinity, and squashes the output into the range 0 to 1. The log-sigmoid transfer function is used to model the discrete–valued functions which are used to represent classification information.



**(a)** **(b)**

**Figure 3.20. Linear transfer function (a) and Log-Sigmoid transfer function (b)**

For modeling the multi-layer model was selected, which is brought out in Figure 3.21. The maximum number of layers is two and depending on the optimized tasks the functions are linear or log-sigmoid.

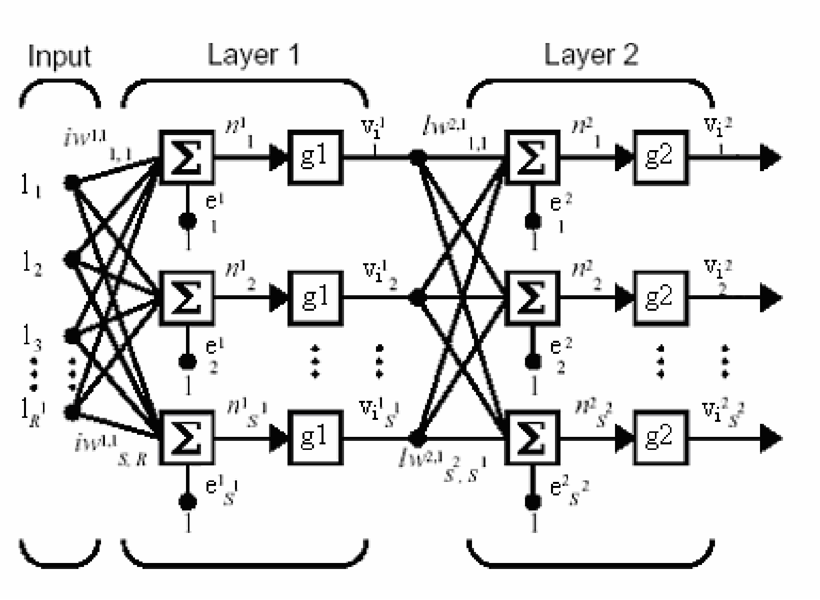


**Figure 3.21. Multi-layer model for ANN modeling [Matlab, 2007]**

The "classical" measure of the network performance (error) is the sum of squared errors. Different ANN training algorithms were investigated: a multilayer feed forward networks with one hidden layer, the Sigmoid (for hidden layer) and linear activation functions (for output layer). Back-propagation and the Levenberg-Marquart approximation algorithms were selected as more suitable. The use of the artificial feed-forward neural networks and Radial Basis Function Network is proposed [Rojas, 1996; Haykin, 1999; Kawabe, 2006; Kang, 2007]. The attempt is made to tackle the problem in a practical and integrative way.

To solve the different sub systems the selection parameters for each technology have to be determined. Table 3.4 shows short list of the parameters and their values or ranges for vacuum forming processes. Those parameters were used also in the ANN training.

Using the selection parameters down (Table 3.4), the ANN trained for each technology (like vacuum forming processes, acrylic trimming technologies and reinforcement) was used. For illustrating of the point the Table 3.5 is presented. There are three variations: {0 - Not usable, 1- Reverse draw forming with two heaters, 2- Straight vacuum forming} for finding out optimal vacuum forming technology.

**Table 3.4. Selection parameters for vacuum forming processes**

| Parameter and mark | Description |
|---|---|
| Dimensions (L and B): | L x B; 280x430,680x760 mm up to 2000x1000 mm |
| Max depth of draw (H): | H; 183, 220, 300 mm up to 800 mm |
| Max material thickness (D): | D; 3.2 mm, 4 mm, 6 mm, 7 mm |
| Undercuts (UC): | yes/no |
| … | … |
| Draft angle ($\alpha$): | $\alpha$; $\alpha > 5^\circ$ |
| Surface quality (Q): | low, medium, high |
| Batch size (N): | N; $1 <= N <= 10000$ ($0<= \log N<= 4$) |
| … | … |
| Wall thickness after forming (h): | h; $0.7 < h < 3$ mm |
| Heating temperature ($T_h$): | $T_h$; $180^\circ C <= T_h <= 220^\circ C$ |
| Cooling time (E): | C; $3 < C < 7$ min |
| Heating zones (Z): | Z; $1 < Z < 4$ |
| Cooling points (P): | P; $2 <= P <= 5$ |

**Table 3.5. Vacuum forming training mode**

| Sample | Vacuum forming | Geom | Log (nP) | Dim | Thick | SQ | PT | UC | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 2 | 1 | 0 | 2 | 1 | 2 | 2 |
| 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 1 |
| … | … | … | … | … | … | … | … | … | … |
| 20 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 |

Where:

- *Geom* is the geometric complexity;
- *Log(nP)* is the number of parts;
- *Dim* is the dimension of vacuum forming bench table;
- *Thick* is maximal material thickness;
- *SQ* is surface quality;
- *PT* is part texture;
- *UC* is undercuts;
- *I* is investments.

The acceptability of model was estimated by the accuracy of model on training data (it was accepted that training goal, the total error estimate must be less than 0.000001). In that task a mathematical model for a neuron could be represented as:

$$v_i = g_2(w_{2,1} \cdot g_1(w_{1,1} \cdot l + e_1) + e_2), \tag{3.11}$$

Where:

- $v_i$ is the output activation of the unit $l$;
- $W$ is a numeric weight;
- $e$ is the bias vector;
- $g$ is the activation function of the unit (there was used two log-sigmoid functions as activation functions).

The proposed models have the following parameters:

$$v_i = g_2\left(\begin{bmatrix} -3.47 \\ -14.03 \\ -23.99 \\ 38.57 \\ 33.60 \\ -1.18 \end{bmatrix} g_1\left(\begin{bmatrix} -2.26 & -5.04 & . & . & . & . & -1.86 & -2.02 \\ -15.52 & 6.17 & . & . & . & . & 4.28 & -11.81 \\ 2.39 & 6.93 & . & . & . & . & 4.55 & -0.82 \\ -6.84 & 3.69 & . & . & . & . & -0.56 & 1.33 \\ 0.60 & 2.72 & . & . & . & . & 10.69 & -11.30 \\ 0.09 & 0.40 & . & . & . & . & -5.23 & 8.32 \end{bmatrix} l + \begin{bmatrix} -26.37 \\ -4.90 \\ -5.50 \\ 12.02 \\ 6.48 \\ -6.55 \end{bmatrix}\right) + (-26.99)\right) \tag{3.12}$$

In Figure 3.22 is brought out the training curve, which got using the system MatLAB. The training curve shows the reduction in error over several epoch of training for selection of reverse draw vacuum forming or straight forming.

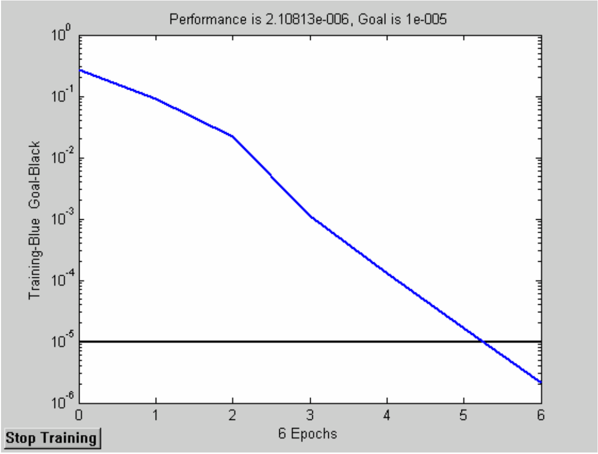


**Figure 3.22. Training curve showing the reduction in error over several epoch of training for selection of reverse draw vacuum forming or straight forming**

Thermoformed parts are trimmed in several ways: with matched shearing dies, steel rule cutting dies, saws, routers, hand knives, and 3- and 5-axis NC routers. The type of equipment best suited depends largely on the type of cut, size of the part, draw ratio, thickness of material and the production quantity required. They are also factors to consider when determining the cost of such equipment. Below some of the more popular methods adopted are listed.

The trimming tasks has four different possibilities {0 – Not usable, 1 – manual trimming with saws, 2 – automatic trimming with saws, 3 – automatic trimming with 5-axis NC routers}. For finding out the optimal trimming method, different processes have to be analyzed and possible defects determined. The ANN was trained using different parameters. For illustrating the training mode the Table 3.6 is brought out.

**Table 3.6. Trimming training mode**

| Sample | Trimming | Geom | Log (nP) | Dim | I | SQ | t | Lr |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 2 |
| 2 | 2 | 3 | 1 | 3 | 0 | 1 | 3 | 2 |
| … | … | … | … | … | … | … | … | … |
| 40 | 2 | 2 | 2 | 3 | 0 | 1 | 2 | 1 |

Where:

- *Geom* is the geometric complexity;
- *Log(nP)* is the number of parts;
- *Dim* is the dimension of vacuum forming bench table;
- *I* is investments cost;
- *SQ* is surface quality;
- *t* is machining time;
- $L_r$ is labor requirement.

In the trimming optimization task a mathematical model for a neuron could be represented as:

$$v_i = g_2(w_{2,1} \cdot g_1(w_{1,1} \cdot l + e_1) + e_2), \tag{3.13}$$

Where:

- $v_i$ is the output activation of the unit $l$;
- $W$ is a numeric weight;
- $e$ is the bias vector;
- $g$ is the activation function of the unit (log-sigmoid transfer function in first layer and linear functions in second layer are used).

The proposed models have the following parameters:

$$v_i = g_2 \cdot \left( \begin{bmatrix} 0.146 \\ -0.003 \\ -0.005 \\ -0.001 \\ 3.210 \\ -0.048 \end{bmatrix} \cdot g_1 \cdot \left( \begin{bmatrix} -0.06 & 0.09 & . & . & . & . & 0.23 & -5.79 \\ -2.25 & -3.39 & . & . & . & . & -1.19 & -5.84 \\ 3.31 & -2.64 & . & . & . & . & 4.17 & 0.15 \\ -0.00 & 5.38 & . & . & . & . & 1.37 & -2.06 \\ 0.00 & 7.55 & . & . & . & . & 0.00 & -0.86 \\ -2.35 & 3.85 & . & . & . & . & 0.20 & 1.38 \end{bmatrix} \cdot l + \begin{bmatrix} 2.44 \\ 15.18 \\ -3.96 \\ -10.62 \\ -15.03 \\ 5.85 \end{bmatrix} \right) + (0.04) \right) \tag{3.14}$$

The analysis resulted in optimal input parameters for the neural networks tasks. In Figure 3.23 is brought out the training curve showing the reduction in error over several epoch of training for selection of trimming methods.

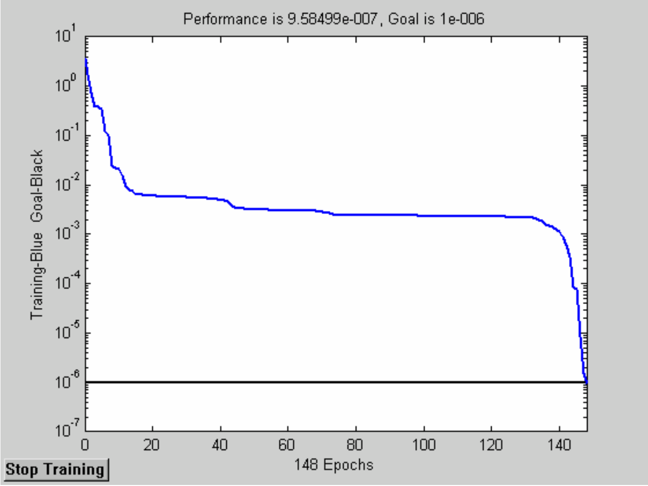


**Figure 3.23. Training curve showing the reduction in error over several epoch of training for selection of trimming methods**

Reinforcement tasks have two choices: {yes, no}; in case of "yes" the manual or automatic reinforcement can be used. In order to obtain sufficient training data for the neural networks used for optimization tasks later, the series of finite element analysis, to simulate and optimize the reinforcement ply thickness, were performed.

The following formulation of the task can be given. Find the feasible operation sequences for a product family that gives us: maximum profit and minimize the manufacturing time; and is subject to the following constraints:

- capacity constraints for all workstations;
- use of materials;
- use of technologies.

The results of the technology planning optimization task, represent the list of operations used to manufacture the proposed family together with the data of the used resources.

Applying above mentioned methodology, it is possible to find out the optimal set of technologies, maximizing the profits, minimizing the production time and costs. The validation test of the proposed approach has indicated that the system can determine a set of optimal process parameters for vacuum forming and post-forming operations quickly. As a result, good quality parts can be produced without relaying on experienced forming personnel.

## 3.2 Optimization of the Vacuum Forming Thinning Process

Each derivative product ( $p_i \in P$ ) of product family is associated with the vector of design parameters ($x^p_j$). To start the design process concurrently, the coordinator has to propose the initial "guesses" for vector ($x^p_o$) and distribute parameters between different tasks. The objective of the coordinator is to improve these estimations iteratively ( $j = 0,1 \ldots n$).

Adding constraints and focus on constraints satisfaction is one of the major approach for coordinating design sub-systems [Zhu, 2000]. The process of adding and processing constraints, for instance, in the form of manufacturability constraints, is traditional for engineering design practice. The constraint-based reasoning approach changes the design process from one of selecting the best alternatives to one aimed at rejecting alternatives that would not meet the specified constraints.

For optimization it is necessary to establish appropriate models of system performance, cost, profit, etc for examining product family feasibility and optimality. Rather than directly linking CAD, CAE and process planning tasks with numerical optimization tools, the basic approach involves the design performance attribute propagation through the response surface equations (RSE). That will define the variation of key responses of product family with respect to the design parameters of interest. The key approach was to base the generation of the RSE on a classical design of experiments (DOE) approach.

In Figure 3.24 and Figure 3.25 is brought out possible response surface. They were prepared using finite element analysis (software: ANSYS) of a large composite plastic product family.

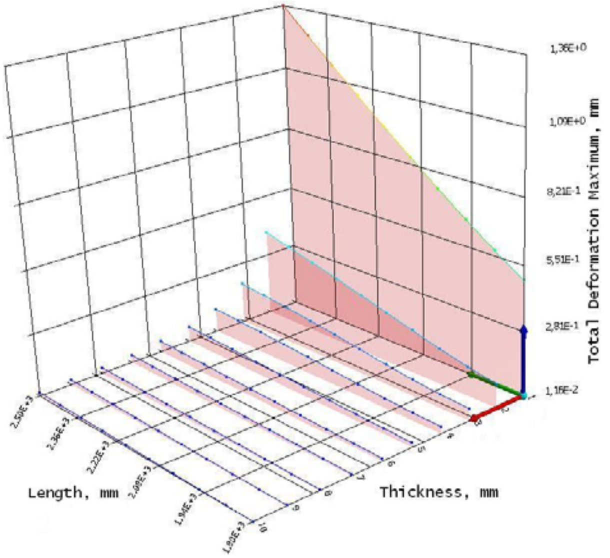


**Figure 3.24. Response surfaces used in the optimization**

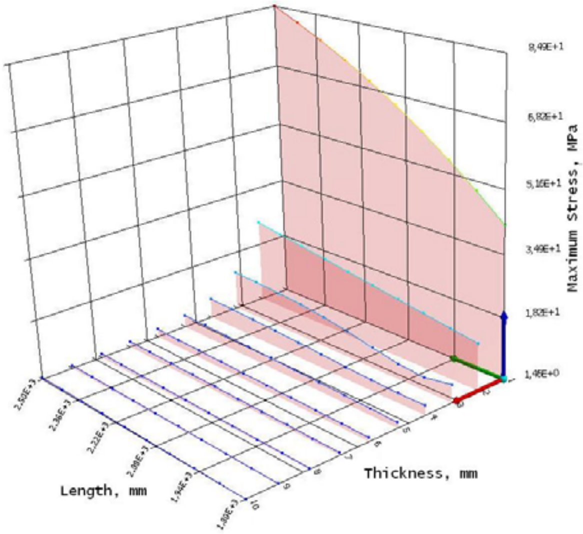


**Figure 3.25. Response surfaces used in the optimization**

In product family modeling phase, general guidelines for product structural calculations and optimization are defined [Küttner, 2006 a; Karjust, 2006 b]. Later, in design of derivative products for the product family, the nonlinear optimization is used and the detailed description of the product is established. For modeling and structural analysis of derivative products CAE (ANSYS) and CAD (Unigraphics) systems are used.

It is important to emphasize that the design of new product is tightly integrated with technological aspects and production technology route. For example, the bathtub is produced in two stages – in the first stage the shell is produced by vacuum forming, and in the second stage the shell is strengthened by adding glass-fiber-epoxy layer on the one side. And also the optimal wall thickness distribution for a vacuum forming part affects the product design and production technology route [Crawford, 1982; Wang, 1999; Takano, 2004; Abadi, 2006; Huang, 2007].

In that work we produced the glass-fiber epoxy reinforcement layer for bathtub using the spraying and rolling technique. In our calculations we used constant concentration for peroxide 0,8%, the epoxy resin 64,1% and glass-fiber 35,1%.

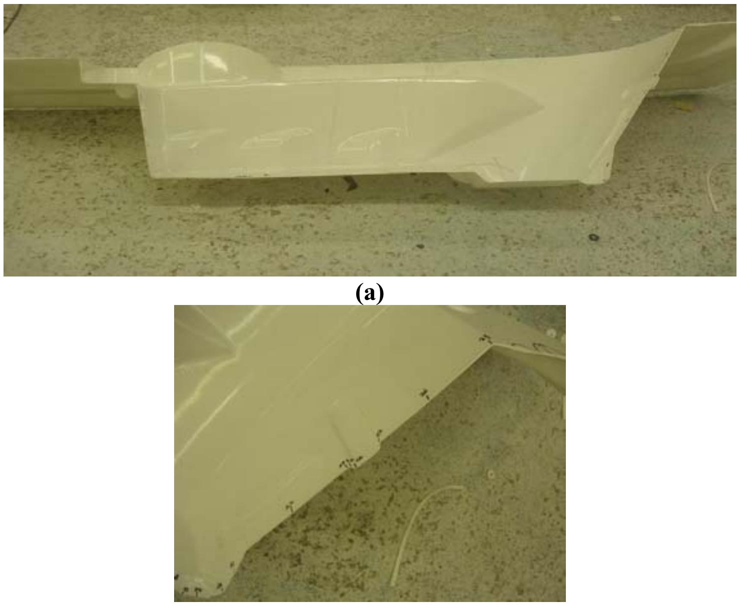
We have analyzed the vacuum forming part thinning process with different materials like ABS PMMA white 2000BM 1516, polycarbonate ICE (UV) clear and acrylic FF0013 Plexiglas. In the study we mainly concentrate on the acrylic FF0013 Plexiglas, which is formed at the sheet temperature 220-230˚C, heating time was 6 min and cooling time was 2 min. In the Figure 3.26 is brought out the sample vacuum formed part (a) and testing equipment (b).

The final shell thickness in different areas may differ significantly in the vacuum forming process, so this has to be taken into account in structural analysis of the product [Song, 2000; Sala, 2002; Cho, 2006].

**(a)** **(b)**

**Figure 3.26. The sample vacuum formed part (a) and testing bench (b)**

For vacuum forming, it is necessary to accept the significant thinning in the sheet material accompanying the process. This thinning is a natural consequence of the deformation conditions. Elastic strains are negligible; therefore, constancy of the volume can be assumed. The thickness variations are potentially large for a part. Therefore, it is often important to control the thickness variations in order to meet functional requirements of the part. The values of thinning of the plastic sheet in the forming operations can be determined from experience, special tests or simulations. During that work there have been made the experimental test for analyzing the wall thickness reduction in certain materials. One testing part is brought out in Figure 3.27.a. and zoom in part Figure 3.27.b.



**(a)**

**(b)**

**Figure 3.27. Thickness reduction testing part (a) and zoom in part (b)**

After the experimental test we could analyze the wall thickness reduction in acrylic FF0013 Plexiglas. The results are brought out in Figure 3.28.

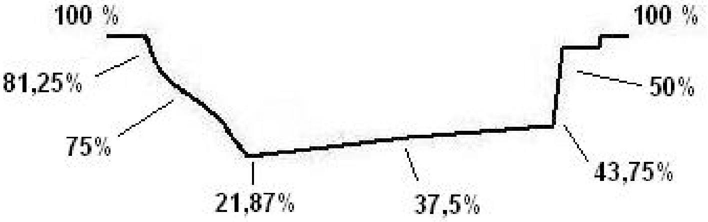


**Figure 3.28. Wall thickness reduction in a 3.2 mm thick FF0013 Plexiglas**

When considering the optimal wall thickness of the thermoformed part, it should be obviously different in different areas of the bathtub. In the current study 12 critical areas (nodes) of the bathtub were considered. Figure 3.29 show the diagram of the deformations in the sheet, where acrylic sheet was without the glass-fiber reinforcement layer - in the first task there were analyzed only the acrylic part. Different nodes (A-E) represent the critical nodes in bottom surface of the part, which is also brought out in Figure 3.26. The critical nodes are in bottom surface, because there is the material thickness lowest one and the deformation biggest one. Figure 3.30 shows the diagram indicating deformation - reinforcement thickness relationship in some critical nodes (areas) – in the second task there were analyzed the acrylic part with the glass-fiber layer. The critical nodes are in same positions as in Figure 3.29. The diagram is illustrating the selection of reinforcement ply thickness depending on maximum allowable deformations.

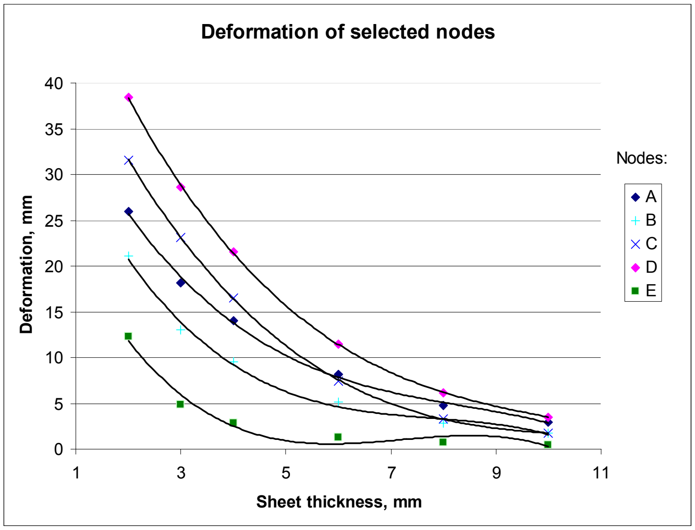


**Figure 3.29. Deformation of the part w/o the glass-fiber reinforcement**

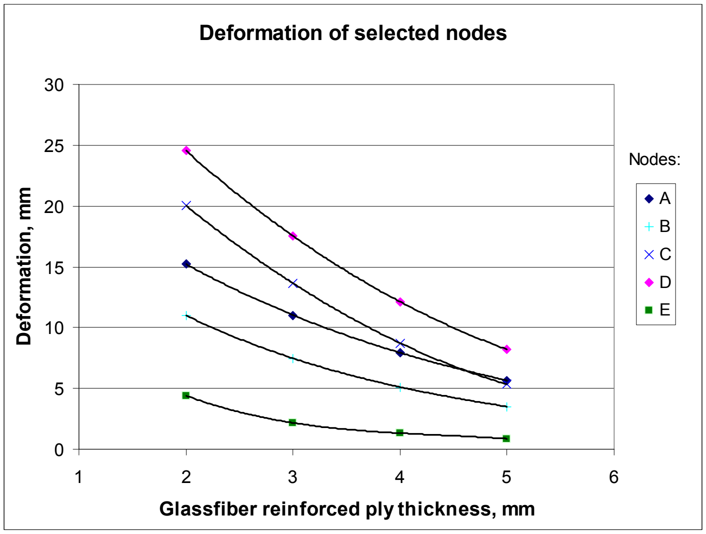


**Figure 3.30. Deformation of the part with the glass-fiber reinforcement**

For optimizing the thickness we have to consider the deformations and stresses in plastic sheet material and glass-fiber epoxy reinforcement [Belingardi, 2002; Kornmann, 2005]. For understanding the glass fiber and acrylite FF0013 Plexiglas tensile strength we made different tensile tests. In Figure 3.31 is brought out the glass-fiber epoxy reinforcement tensile strength, which is (95,0±0,2)MPa in reliability 95%. In Figure 3.32 is brought out the acrylite FF0013 Plexiglas tensile strength, which is (60,0±0,2)MPa in reliability 95%.

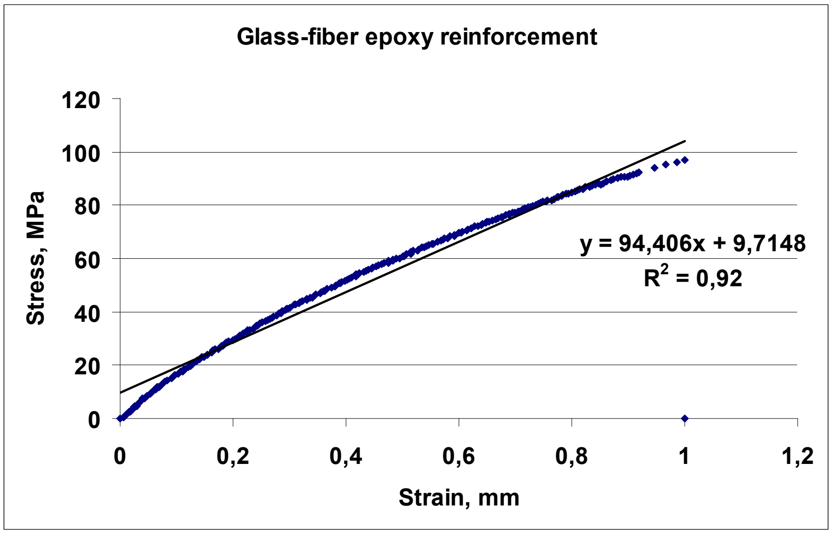


**Figure 3.31. Glass-fiber epoxy reinforcement tensile strength**

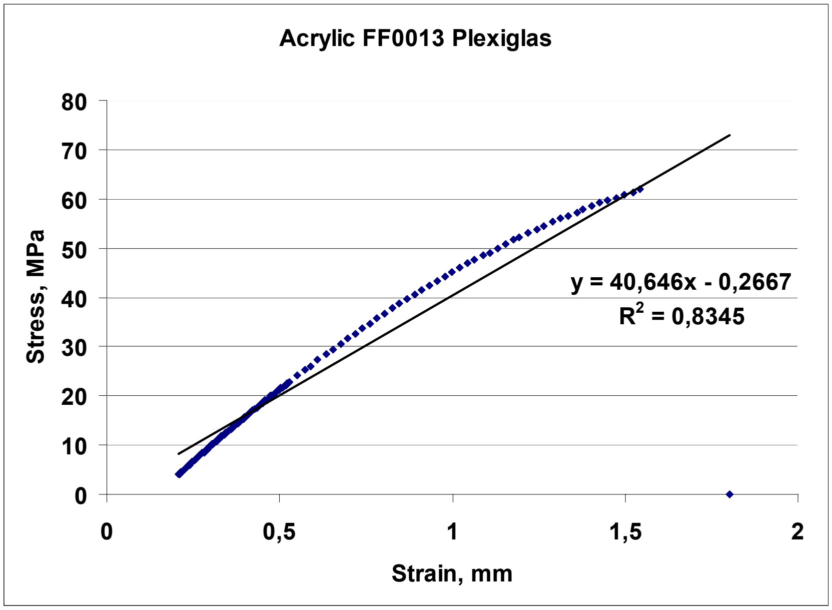


**Figure 3.32. Acrylite FF0013 Plexiglas tensile strength**

Figure 3.33 shows the deformation plot (in millimeters) of the composite structure. Figure 3.34 shows the equivalent stress plot for the loaded model, which indicates the stress concentrators and is used to optimize the part and glass-fiber reinforcement wall thickness in the given areas [Fereshteh-Saniee, 2005; Wrobel, 2006].

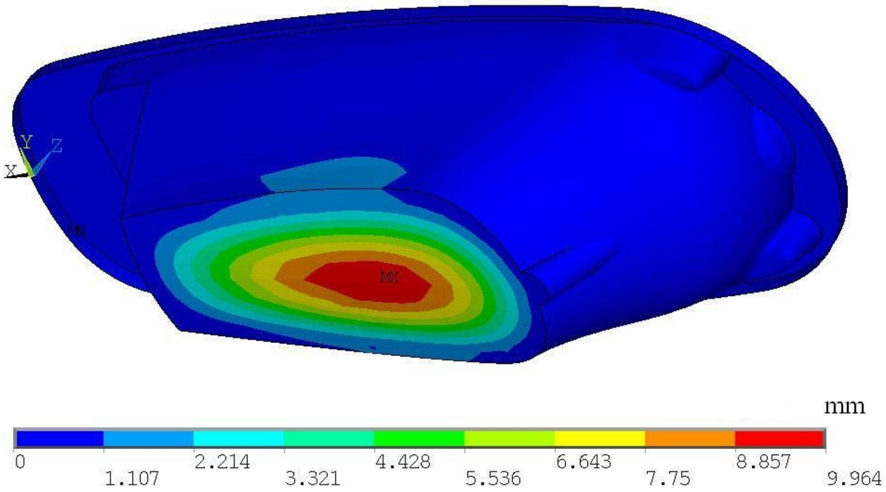


**Figure 3.33. Deformation plot**

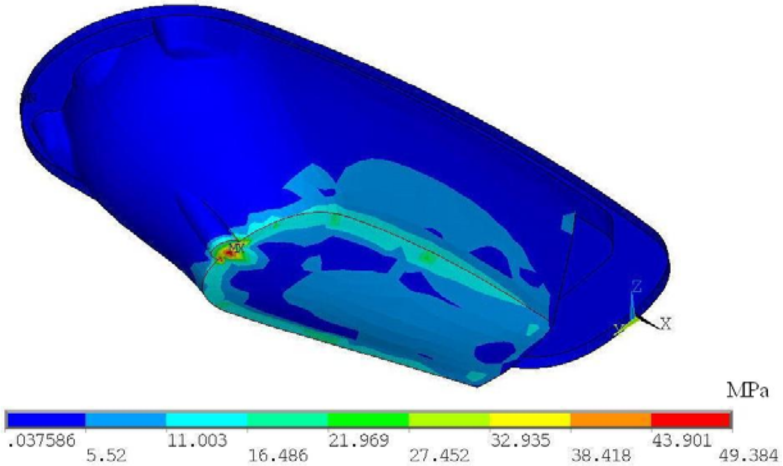


**Figure 3.34. Equivalent stress plot**

In the current study, for design exploration and for the surrogate design model (to provide estimate for the strengthening layer thickness-structural response relationship), the Neural Network meta-modeling technique was used. The optimization is then performed using the surrogate design model. Finally, the FEA simulation with optimal thickness values is performed to verify the prediction accuracy of a surrogate model. Thus, the time of the optimization was shortened considerably. [Karjust, 2007 b].

### 3.2.1 Optimization Results and Analyses

There was developed a surrogate model consisting of finite element method (FEM) and artificial neural network (ANN) to find out the optimal wall thickness distribution for a vacuum forming and glass- fiber reinforced part.

In Figure 3.33 is brought out the results of the experimental test, made with the acrylic FF0013 Plexiglas, which sheet thickness was 3.2 mm, before thermoforming. The thermoforming temperature and heating parameters are showed in Paragraph 3.1.1.1. When to compare the Figure 3.28 and Figure 3.35, there could see that the thickness of the acrylic depends on the distance from the 0 level (top level of the thermoformed part) and also the mold parameters and constraints. For instance when the distance from 0 levels is 340 mm, then the glass-fiber reinforcement and acrylic thickness is increased to 5.0 mm, because of the equivalent stress concentrate and the radius if the bath bottom and side face. When the distance is 390 mm, then whole thickness is again smaller – now 4.0 mm, because of the different position in the bath model and smaller stress values. Generally the Figure 3.35 represents us the cutting line of the bath model. We just cut it as showed in Figure 3.27.a. and analyzed the different thicknesses, before the optimization.

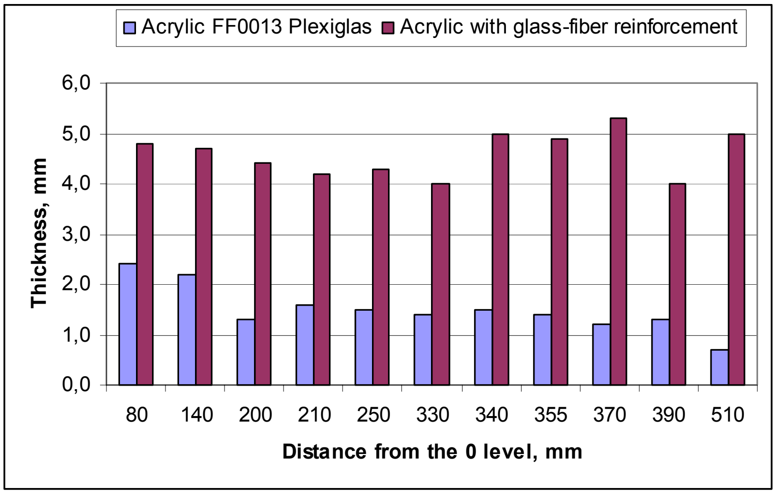


**Figure 3.35. Thinning in a 3.2 mm thick acrylic and the glass-fiber reinforcement.**

Because of the acrylic thickness variations the glass-fiber reinforcement (GFR) layer thickness is also different. The optimal GFR layer depends on the acrylic sheet thickness, deformation, material strains and equivalent stress plots [Torres, 2000]. In Figure 3.36 is brought out the equivalent stress plot and in Figure 3.37 the thickness distribution after optimization of the composite structure, using the surrogate design model. In optimization the wall thickness was varied between 2…5 mm. The constraints for maximum equivalent stress on each layer and the total deformation were also defined and the volume of added glass-fiber reinforcement layer was minimized.

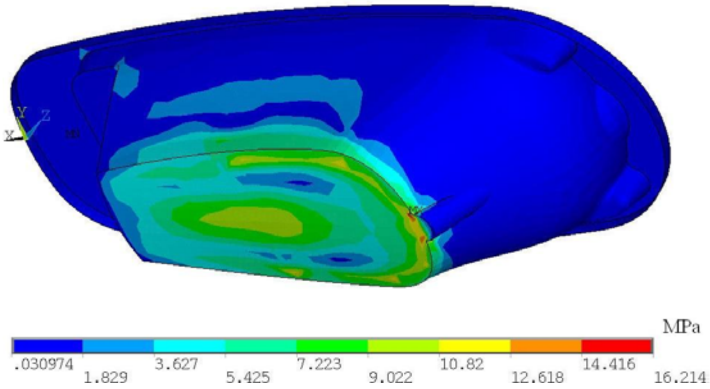


**Figure 3.36. The stress plot after optimization of the composite structure**

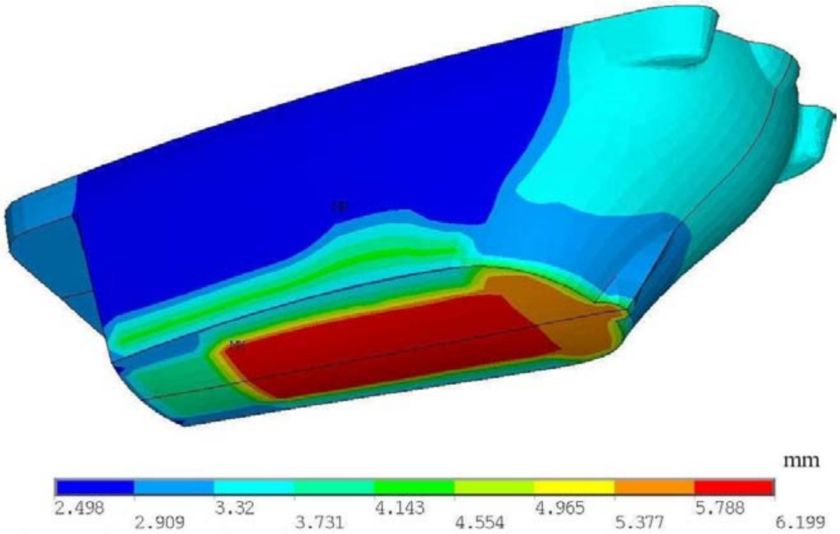


**Figure 3.37. The thickness plot after optimization of the composite structure**

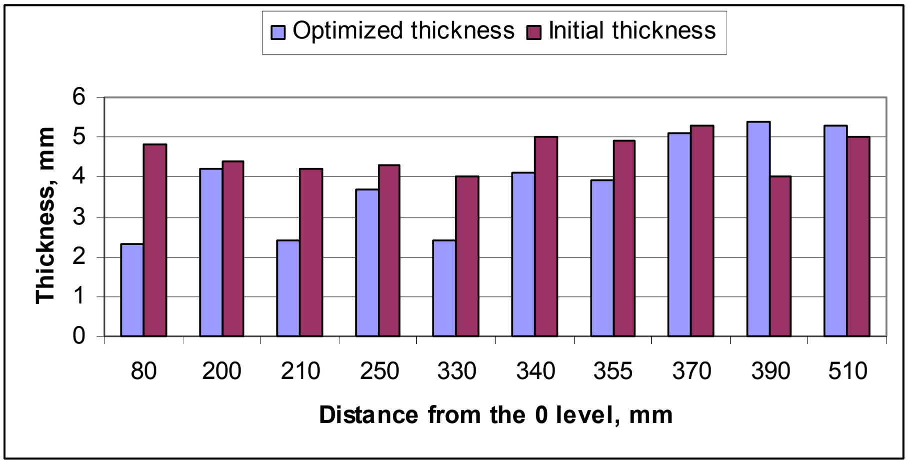


**Figure 3.38. Comparison between the initial and optimized part thicknesses**

Figure 3.38 shows the total thickness of structure after optimization, which result was to minimize the glass-fiber reinforcement layer volume and material cost. Here we can see that in some areas we actually don't need such amount of acrylic and glass-fiber reinforcement thickness, because of the lower stress values and concentrators as was expected in the past. The different positions of the node points are because of the different stress values and location in the actual bath model, brought out in Figure 3.27. Figure 3.38 represents us the similar cutting line of the bath model as brought out in Figure 3.35, but there is also added the optimized thickness values in different node points of the bath model.

## 3.3 Conclusions of the Chapter

1. The computer-based product design was integrated with the process planning. For optimal selection of technology, the corresponding optimization model was proposed. The optimization model controls and analyzes the calculated technology planning route, the optimal vacuum forming process, post-forming operations, strengthening (reinforcing) and assembling operations.
2. Using the technology optimization model there found out the optimal batch of technologies which maximizes the profit, minimizes the production times and production costs.
3. A neural network approach and Matlab neural network toolbox is used to determine a set of initial relationships process parameters and performance indicators for technology route optimization. The acceptability of model was estimated by the accuracy of model on training data (it was accepted that training goal, the total error estimate must be less than 0.000001). The optimal vacuum forming technology is reverse draw forming with two heaters, because of the higher productivity and minimal plastic sheet thickness variations.
4. The design of the new products is tightly integrated with manufacturing aspects. In the current chapter the Neural Network meta-modeling technique was used for finding out the optimal thickness of the glass-fiber reinforcement layer. The optimization of the plastic sheet and its strengthening layer thickness was performed using the surrogate design model, which consists of finite element method (FEM) and artificial neural network (ANN). Variations in thickness over the sheet should be kept under 5%. The optimal thickness of the glass-fiber reinforcement layer and plastic sheet is between 2,3 – 5,1 mm.
5. The other important parameter for changing the quality of formed part is thermoforming temperature. From the experimental tests and analyses the optimal forming temperatures in sheet surface for the ABS/PMMA is in range 160-170˚C, Polycarbonate 180-230˚C and acrylic Plexiglas 210-235˚C, depending on the conditions of the experimental bench, room and mould temperatures.
6. The most of the above described methods are now under development and industrial testing. To facilitate these developments, it is important to provide effective techniques and computer tools to integrate an increasing number of disciplines into design system in which the human ingenuity combines with the power of computers in making design decisions.

# 4 THE AGGREGATE PLANNING OF MRP

The objective of manufacturing resource planning (MRP) tasks is to plan the volumes of products produced $X_{i,t}$ sold $S_{i,t}$ and hold as inventory $I_{i,t}$ for given time periods $T_{t,t}=1...tl$. The problem is called multi-period aggregate planning (AP) [Hopp, 2001; Küttner, 2004]. Input for that task can be obtained from the technology planning and product family planning tasks.

The model of AP maximizes the overall profit and minimizes the manufacturing time, considering available resources and demand for multiple products subject to upper and lower bounds on the sales and capacity constraints. We can give the following formulation of the task (definitions of the variables are brought out in Paragraph 2.2):

$$\textbf{Max} \sum_{t=1}^{tl}\sum_{i=1}^{m} s_i * S_{it} - C_i * X_{it} - h_i * (I_{it} + X_{it}/2) \quad \text{net profit} \qquad (4.1)$$

$$\textbf{Min } \mathbf{T} = \sum_{i=1}^{m} a_i * X_i \quad \text{manufacturing time} \qquad (4.2)$$

Subject to:

1. $d_{it}^{\min} \le S_{it} \le d_{it}^{\max}$ for all i,t – demand;

2. $\sum_{i=1}^{m} a_{iwt} * X_{it} \le c_{wt}$ for all w,t - capacity of workstation w;

3. $I_{it} = I_{it-1} + X_{it} - S_{it}$ for all i,t - inventory balance;

4. $I_{it} \ge s_{it}$, for all $i = 1, m, t = 0.tl$ requirements for safety stock;

$X_{i,t}, S_{i,t}, I_{i,t} \ge 0$ for all i,t. - non-negativity.

The basic formulation contains capacity constraints for the workstations, but in some situations also other resources, such as people, raw materials, transport device capacity, allowed maximum for inventory (capacity of store (ware) houses), may be important determinants [Fujita, 2001].

To solve the manufacturing planning problem the integer programming software was used. The example of the results of AP task like the volumes of production, selling and holding parts are represented in Table 4.1.

**Table 4.1. Manufacturing resource planning result**

| | Time period t=1 | | | | Time period t=i | | | | Time period t=tl | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $p_1$ | $p_2$ | $p_3$ | $p_4$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ | $p_1$ | $p_2$ | $p_3$ | $p_4$ |
| $X_{i,t}$ | 14 | 0 | 14 | 2 | 14 | 0 | 16 | 4 | 14 | 0 | 14 | 4 |
| $S_{i,t}$ | 15 | 1 | 16 | 4 | 16 | 1 | 16 | 4 | 15 | 1 | 16 | 4 |
| $I_{i,t}$ | 3 | 2 | 2 | 0 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| $I_{i,0}$ | 4 | 3 | 4 | 2 | - | - | - | - | - | - | - | - |

## 4.1 Coordination of Subtasks

We suppose that the initial task is to be decomposed because of its complexity. As the result of decomposition, for example in this study, three planning subsystems $P_1$, $P_2$, and $P_3$, corresponding to product family planning, technological process planning and multi-period manufacturing resource planning, are introduced in Figure 4.1.

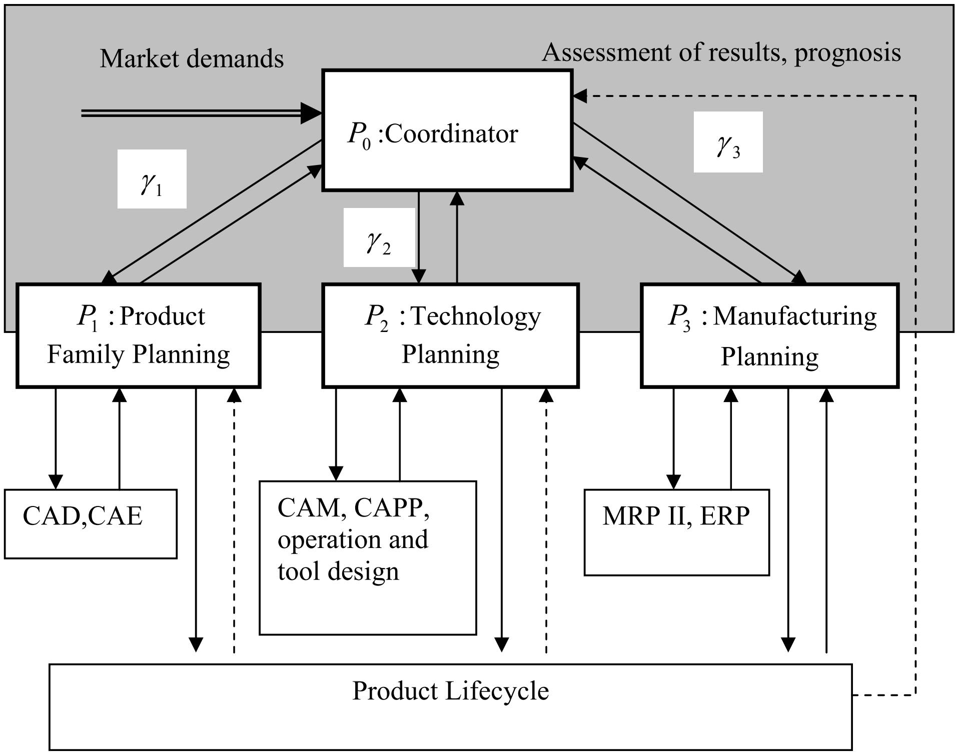


**Figure. 4.1.** Two-level scheme of product family production planning.

We suppose that each planning task $P_i$, is concerned with the decision problem related to its own planning task that has its own goal $G_i$. If there were no coordination among $P_i$, the overall optimum could not be achieved because the component subsystems are pursuing their goals without paying attention to interactions. Consequently, a coordinator $P_o$ has to be introduced in order to coordinate the activities of the lower level decision subsystems $P_1$, $P_2$, $P_3$. The task of the coordinator is to choose the suitable coordination variables $\gamma_{i,i}=1,2,3$ such that the planning activities on the lower level subsystems would yield a result consistent with the requirements of optimality for the overall task.

The proposed optimal planning tasks are related to the analysis or design tasks (systems CAD, CAE, CAM, ERP, etc.). Those systems take the planning results, the variables and parameters as inputs and return the responses for upper level planning systems as outputs.

The main problem is the question of equivalence between the initial optimal design task and the tasks represented by the decomposition schemes. To coordinate and to eliminate step-by-step possible discrepancies between the tasks, the supervisory subsystem provides [Mesarovic, 1970; Mesarovic, 1989; Zhu, 2000; Küttner, 2002]:

- the prognosis of “auxiliary planning variables” representing the initial "guesses" of parameters for tasks, typical and recommendable solutions, etc.;
- additional constraints that represent the convergence restrictions on possible solutions;
- objective functions for the subtasks.

Consistent system design can then be accomplished with minimum communication, i.e., maximum efficiency, avoiding costly iterations later in the process. The process for initial "guesses" for auxiliary planning variables aims at minimizing the gap between what higher-level elements “want” and what lower-level elements “can”.

The process of adding additional constraints, for instance, in the form of “Design for Manufacture” (DFM), “Design for Assembly” (DFA) is traditional for concurrent engineering design practice and is not described here.

To measure performance, evaluate decisions and coordinate the objective functions of subtasks, optimization with multi-objectives is proposed as a general framework. For different tasks, different objective functions that represent some hierarchy of objectives could be used. Two methods for handling multiple criteria were investigated:

- Goal programming approach [Ravindran, 1987; Galan, 2007];
- (Linear) Physical optimization approach [Messac, 1996].

Goal programming [Ravindran, 1987] is a technique primarily used to find a compromised solution, which will simultaneously satisfy a number of design goals.

In addition to initial planning tasks (Paragraph 2), (Paragraph 3) and (Paragraph 4), the general goal programming model can be expressed as follows:

$$\textbf{Min}\ Z = \sum_{i=1}^{m} (w_i^+ d_i^+ + w_i^- d_i^-) \tag{4.3}$$

Subject to:

1. $\sum_{j=1}^{n} a_{ij} x_j + d_i^- - d_i^+ = b_i$ for all $i$
2. $x_j, d_i^-, d_i^+ \geq 0$ for all i and j

In goal programming, the objective function minimizes the weighted sum of deviational variables $d_i^+$, $d_i^-$. The system of constraints represents (in addition to (2.1), (3.1) and (4.1)) the goal constraints, relating the decision variables ($x_j$) to the targets ($b_i$). If the relative weights ($w_i^+$ and $w_s^-$) and targets ($b_i$) can be specified by the coordinating system, the model of linear programming could be used. Unfortunately, it is difficult in practical cases to determine values of the weights. In reality, goals are usually incompatible and an iteration process is needed.

A defining characteristic of the physical optimization approach is the availability of information regarding the physical meaning of the objectives. The Linear Physical Programming (LPP) paradigm [Messac, 1996] is characterized by the following example used in our study: assume that we wish to (i) maximize the profit (r), and (ii) minimize the manufacturing time (T). We assume that a coordinating subsystem knows significantly more than the fact that the coordinator wants to maximize the profit and minimize the manufacturing time. Instead of attempting to find correct weights, the coordinator, for example, expresses the following preference levels:

Ideal profit: > 306000 (EEK for time period)
Desirable: 306000-305000
Tolerable: 305000-304000
Undesirable: 304000-303000
Unacceptable: <303000.

Ideal time: <1295 hours
Desirable: 1295-1300
Tolerable: 1300 1305
Undesirable: 1305-1310
Unacceptable: >1310

## 4.2 Conclusions of the Chapter

1. The large composite plastic parts manufacturing resources planning task has been optimized. There was created a model of aggregate planning, which maximizes the overall profit and minimizes the manufacturing time.
2. There was investigated how to optimize the family of products and their manufacturing process, in particularly to integrate computer-based product

family planning, technological process planning and manufacturing resource planning activities, and to take full advantage of the in a concurrent manner accomplished optimal engineering decision process.

3. For each sub-problem is formulated different optimization model. It is assumed that optimization is generally best suited in the incremental improvement of existing production, when the required data are available for analytical modeling and optimization.

# 5 CONCLUSION

The main conclusions of the current thesis are as follows:

1. The products in family of large composite plastic parts has been modified, depending on the different constraints like functional and handling requirements, requirements for products geometry, structure, product materials and different parameters.
2. Different calculation models were used for finding out optimal size of the production capacity, different products and sub-products. Using the calculation models the optimal new additional functions, depending on the market needs; required investments for each function; and production cost for each product has been found out. Generally when we try to maximize the profit, then the constraint is monthly production capacity. In the other hand the profit is maximal when new additional functions (first and third) are developed for second product not any other ones.
3. The computer-based product design was integrated with the process planning. A neural network approach and Matlab neural network toolbox is used to determine a set of initial relationships process parameters and performance indicators for technology route optimization. The acceptability of model was estimated by the accuracy of model on training data (it was accepted that training goal, the total error estimate must be less than 0.000001). For optimal selection of technology, the corresponding optimization model was developed. The optimization model controls and analyzes the calculated technology planning route, the optimal vacuum forming process, post-forming operations, strengthening (reinforcing) and assembling operations. Using the technology optimization model, there found out the optimal batch of technologies which maximizes the profit, minimizes the production times and production costs.
4. The design of the new products is tightly integrated with manufacturing aspects. The Neural Network meta-modeling technique was used for finding out the optimal thickness of the glass-fiber reinforcement layer. The optimization of the plastic sheet and its strengthening layer thickness was performed using the surrogate design model, which consists of finite element method (FEM) and artificial neural network (ANN). Variations in thickness over the sheet should be kept under 5%. The optimal thickness of the glass-fiber reinforcement layer and plastic sheet is between 2,3 – 5,1 mm.
5. The large composite plastic parts manufacturing resources planning task has been optimized. Was created a model of aggregate planning, which maximizes the overall profit and minimizes the manufacturing time.
6. There was optimized the family of products and their manufacturing process, in particularly there was integrate the computer-based product family planning, technological process planning and manufacturing

resource planning activities. For each sub-problem is formulated different optimization model.

7. The most of the above described methods are now under development and industrial testing. To facilitate these developments, it is important to provide effective techniques and computer tools to integrate an increasing number of disciplines into design system in which the human ingenuity combines with the power of computers in making design decisions.

The main topics for the future research are as follows:

1. Simulations of ABS plastics and Polycarbonate vacuum molding processes depending on the material differences and mold parameter variations, using different FEM software.
2. Optimization of the reinforcement layer drying time depending on the large composite plastic parts parameters, reinforcement layer resin and glass-fiber concentrations.
3. Analyzing the glass-fiber reinforcement layer tackiness to the large composite plastic parts, depending on the different parameters.
4. Development of the integration optimization models for the large composite products and their product families.

# REFERENCES

Abadi, M.T., Daghyani, H.R., Fariborz, S. 2006. Finite element analysis of thermoplastic composite plates in forming temperature. Composites Science and Technology, vol. 66, Issue 2, pp. 306-313.

Belingardi, G., Vadori, R. 2002. Low velocity impact tests of laminate glass-fiber-epoxy matrix composite material plates. International Journal of Impact Engineering, vol. 27, Issue 2, pp. 213-229.

Bendada, A., Erchiqui, F., Kipping, A. 2005. Understanding heat transfer mechanisms during the cooling phase of blow molding using infrared thermography. NDT & E International, vol.38, Issue 6, pp. 433-441.

Bourgin, P., Cormeau, I., Saint-Matin, T. 1995. A first step towards the modelling of the thermoforming of plastic sheets.Journal of Materials Processing Technology, vol. 54, Issues 1-4, pp. 1-11.

Bryan, A., Ko, J., Hu, S.J., Koren, Y. 2007. Co-Evolution of Product Families and Assembly Systems. CIRP Annals - Manufacturing Technology, vol. 56, Issue 1, pp. 41-44.

Cho, C., Kwahk, S.-Y., Kim, W.-J., Choi, J.-K. 2006. Thermo-viscoelastic-plastic deformation of huge products in thermal process. Journal of Achievements in Materials and Manufacturing Engineering, vol. 17, Issues 1-2, pp. 233-236.

Crawford, R.J., Lui, S.K.L. 1982. Prediction of wall thickness distribution in thermoformed mouldings. European Polymer Journal, vol.18, Issue 8, pp. 699-705.

Deen, S.M. 2003. Agent-Based manufacturing. Springer Verlag, Berlin, Heidelberg, NY, pp. 326.

Erens, F., Verhulst, K. 1997. Architectures for product families Computers in Industry, vol. 33, Issues 2-3, pp. 165-178.

Fang, Q.Z., Wang, T.J., Li, H.M. 2006. Large tensile deformation behavior of PC/ABS alloy. Polymer, vol. 47, Issue 14, pp. 5174-5181.

Fang, Q.Z., Wang, T.J., Li, H.M. 2007. Overload effect on the fatique crack propagation of PC/ABS alloy. Polymer, vol.48, Issue 22, pp. 6691- 6706.

Fereshteh-Saniee, F., Majzoobi, G.H., Bahrami, M. 2005. An experimental study on the behavior of glass–epoxy composite at low strain rates. Journal of Materials Processing Technology, Issues162-163, pp. 39-45.

Fujita, K., Sakaguchi, H., Akagi, S. 1999. Product variety deployment and its optimization under modular architecture and module commonalization, in: Proceedings of the 1999 ASME Design Engineering Technical Conferences, Paper No. DETC99/DFM-8923, ASME.

Fujita, K., Yoshida H., 2001. Product Variety Optimization : Simultaneous Optimization of Module Combination and Module attributes, Proceding of DETC'01, ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pennsylvania, pp. 14.

Galan, R., Racero, J., Eguia, I., Garcia, J.M. 2007. A systematic approach for product families formation in Reconfigurable Manufacturing Systems. Robotics and Computer-Integrated Manufacturing, vol. 23, Issue 5, pp. 489-502.

Gu, X., Renaud, J.E. 2000. Decision Based Collaborative Optimization. 8th ASCE Speciality Conference on Probabilistic Machanics and Structural Reliability. PMC2000-217. Indiana, pp.6.

Halman, I. M., Hofer, A. P., Vuuren W. 2003. Platform-driven Developemnt of Product Families:Linking Theory with Practice. Journal. Prouct Innovation Management, vol. 20, pp 149-162.

Haykin, S. 1999. Neural Networks. A comprehensive Foundation. 2nd ed. Prentice Hall, New Jersey.

Herman, M. F. 2003. Encyclopedia of Polymer Science and Technology. Part 2, 3rd Edition. Volumes 5-8. pp.3112

Hopp, W.J., Spearman, M.L. 2001. Factory Physics. Foundation of Manufacturing Management. McGraw Hill Publishing Companies Inc., pp. 698.

Hosseini, H., Berdyshev, V.B., Mehrabani-Zeinabad, A., 2006. A solution for warpage in polymeric products by plug-assisted thermoforming. European Polymer Journal, vol. 42, Issue 8, pp. 1836-1843.

Hsiao, S.-W., Liu, E. 2005. A structural component-based approach for designing product family. Computers in Industry, vol. 56, Issue 1, pp. 13-28.

Huang, G.-Q., Huang, H.-X. 2007. Optimizing parison thickness for extrusion blow molding by hybrid method. Journal of Materials Processing Technology, vol. 182, Issues 1-3, pp. 512-518.

Jacobs, O., Dalock, W. and Demenus, H. 2003. Shear cutting of thermoplastic foils. Polymer Testing, vol. 22, Issue 5, pp. 579-587

Jiang, Z. H., Yan, J. Q. 2003. Research and development on constraint-based product family design and assembly simulation. Journal of Materials Processing Technology, vol. 139, Issues 1-3, pp. 257-262.

Jefrey, B.D., Gonzalez-Zugasti, J.P., Otto, K.N. 2001. Modular product architecture, Design Studies, vol. 22, Issue 5, pp. 409–424.

Kang, Y., Chang, C.-W., Huang, Y., Hsu, C.-L., Nieh, I.-F. 2007. Modification of a neural network utilizing hybrid filters for the compensation of thermal deformation in machine tools. International Journal of Machine Tools and Manufacture, vol. 47, Issue 2, pp. 376-387.

Karamanou, M., Warby, M.K. and Whiteman, J.R. 2006. Computational modelling of thermoforming processes in the case of finite viscoelastic materials. Computer Methods in Applied Mechanics and Engineering, vol. 195, Issues 37-40, 15 pp. 5220-5238

Karjust, K., Küttner, R. 2006 a. Aggregate planning of hydro spa equipment product family. 5th International DAAAM Baltic Conference, Tallinn, Estonia. pp.197-202.

Karjust, K., Küttner, R. 2006 b. Integrated product development and manufacturing planning for product families with application to hydro spa equipment . 1st Nordic Conference on Product Lifecycle Management – NordPLM, Göteborg, Sweden. pp. 187-198.

Karjust, K., Küttner, R., Pohlak, M. 2007 a. Technology design of composite parts. Journal of Achievements in Materials and Manufacturing Engineering, vol. 22, Issue 2, pp. 23-26.

Karjust, K., Küttner, R., Pohlak, M. 2007 b. The design and production technology of large composite plastic products. Proceedings of the Estonian Academy of Sciences, Engineering, vol. 13, Issue 2, pp. 117-128.

Kawabe, H., Tsukiyama, N., Yoshida, K. 2006. Active vibration damping based on neural network theory. Journal of Materials Science and Engineering: A, vol. 442, Issues 1-2, pp. 547-550.

Kim, J.-Y., Wong, V., Eng, T.-Y. 2005. Product variety strategy for improving new product development proficiencies. Technovation, vol. 25, Issue 9, pp. 1001-1015.

Kornmann, X., Rees, M., Thomann, Y., Necola, A., Barbezat, M., Thomann, R. 2005. Epoxy-layered silicate nanocomposites as matrix in glass fibre-reinforced composites. Composites Science and Technology, vol. 65, Issue 14, pp. 2259-2268.

Küttner, R. 2002. A Framework for Collaborative Product and Production Developemnt System, Proceeding 3th International DAAAM Conference Industrial Engineering – Nchalleges to SME, Tallinn, Estonia. pp 34-37.

Küttner, R., Kurg, J. 2004. Optimal Planning of Technological Flow Lines. Proceedings 4th International DAAAM Conference "Industrial Engineering – Innovation as competitive Edge for SME", Tallinn, Estonia, pp 51-54.

Küttner, R., Karjust, K. 2006 a. Coordination of complex tasks of engineering product and manufacturing process optimization. In Proc. of Estonian Academy of Sciences. Engineering. Tallinn, vol. 12, Issues 13-1, pp. 163-175.

Küttner, R., Karjust, K., Pohlak, M. 2006 b. Integrated optimal planning of product family and manufacturing technology of its components. 4th International Conference on Manufacturing Research, Liverpool, United Kingdom. pp. 55-60.

Matlab - Matlab Version 7 Help. Neural Network Toolbox (29.12.2007)

Martin, MV., Ishii, K. 2002. Design for variety: Developing standardized and modularized product platform architectures. Research in Engineering Design, vol.13, pp. 213–35.

Mesarovic, M.D., Macko, D., Takahara, Y. 1970. Theory of Hierarchical Multilevel Systems. Vo 68 in "Mathematics in Science and Engineering". Academic Press, New York and London, pp. 285.

Mesarovic, M. D., Takahara, Y. 1989. Abstract System Theory. Lecture Notes in Control and Information Sciences, 116. Ed. by M. Thoma and A. Wyner. Springer Verlag. Berlin, Heidelberg, pp. 439.

Messac, A., Gupta, S.M., Akbulut, B. 1996. Linear Physical Programming: A new Approach to multiple Objective Optimization. Transactions on Operational Research, vol. 8, pp. 39-59.

Meyer M. H., Lehnerd A. P. 1997.The power of product platforms. Building value and cost leadership. The Free Press, New York, NY.

Meyer, H. M., Dalal, D. 2002. Managing platform architectures and manufacturing processes for nonassembled products. Journal of Product Innovation Management, vol. 19, Issue 4, pp. 277-293.

Mooney, P. J. 2002. Understanding the Thermoforming Packaging Business, Plastics Custom Research Services, Advance, N.C.

Monteix, S., Schmidt, F., Maoult, Y. L., Yedder, R. B., Diraddo, R. W. and Laroche, D. 2001. Experimental study and numerical simulation of preform or sheet exposed to infrared radiative heating. Journal of Materials Processing Technology, vol. 119, Issues 1-3, pp. 90-97.

Muffatto, M., Roveda, M. 2000. Developing product platforms: analysis of the development process. Technovation, vol. 20, Issue 11, pp. 617-630.

Nayak, R., Chen, W., Simpson, T.W. 2000. A Variation- based Methodology for Product Family Design. Proceedings of DEC'00, ASME 2000, DETC00/DAC-14264.

Ong, S.K., Xu, Q.L., Nee, A.Y.C. 2006. Design Reuse Methodology for Product Family Design. CIRP Annals - Manufacturing Technology, vol. 55, Issue 1, pp. 161-164.

PMMA/SME. 2001. Plastics Molding & Manufacturing Tech Trends 2000-2001. Plastics Molders & Manufacturers Association of the Society of Manufacturing Engineers, pp. 21

Ploteau, J.P., Glouannec, P. and Noel, H. 2007. Conception of thermoelectric flux meters for infrared radiation measurements in industrial furnaces. Applied Thermal Engineering, vol. 27, Issues 2-3, pp. 674-681

Ravindran, A., Phillips, D., Solberg, J. 1987. Operation Research Principles and Practice, 2.edition. John Wiley&Sons, New York, pp. 637.

Rojas, R. 1996. Neural Networks: A systematic introduction. Springer Verlag, Berlin.

Rubin, I. I. 1990. Handbook of plastic materials and technology. Robinson Plastics Corporation, New York.

Sala, G., Landro, L., Cassago, D. 2002. A numerical and experimental approach to optimise sheet stamping technologies: polymers thermoforming. Journal of Materials & Design, vol. 23, Issue 1, pp. 21-39.

Salhieh, Sa'Ed M., 2007 A methodology to redesign heterogeneous product portfolios as homogeneous product families. Computer-Aided Design, vol. 39, Issue 12, pp. 1065-107.

Sawhney, MS. 1998. Leveraged high-variety strategies: From portfolio thinking to platform thinking. Journal of the Academy of Marketing Science, vol. 26, Issue 1, pp. 54–61.

Schmidt, F. M., Maoult, Y. Le and Monteix, S. 2003. Modelling of infrared heating of thermoplastic sheet used in thermoforming process. Journal of Materials Processing Technology, vol. 143-144, 20, pp. 225-231

Simpson, T.W., Maier, J.R.A., Mistree, F. 2001. Product platform design: method and application, Research In Engineering Design, vol. 13, pp. 2– 22.

Sivard G. 2000. A generic information platform for product families. Stockholm. pp. 212.

Smith, F.C., Moloney, L.D., Matthews, F.L., Hodges, J. 1996. Fabrication of woven carbon fibre/polycarbonate repair patches. Composites Part A: Applied Science and Manufacturing, vol. 27, Issue 11, pp. 1089-1095.

Song, Y. H., Zhang, K. F., Wang, Z. R., Diao, F. X. 2000. 3-D FEM analysis of the temperature field and the thermal stress for plastics thermalforming. Journal of Materials Processing Technology, vol. 97, Issues 1-3, pp. 35-43.

Sonic – [WWW] htpp://www.sonic.net/~ewest/academy/ (3.12.2005).

Stanley, W.F. and Mallon, P.J. 2006. Intraply shear characterisation of a fibre reinforced thermoplastic composite. Composites Part A: Applied Science and Manufacturing, vol. 37, Issue 6, pp. 939-948

Strong, A.B. 2000. Plastics materials and processing. Second Edition. Prentice Hall, New Jersey, pp. 811.

Sundgren, N. 1999. Introducing interface management in new product family development. Journal of Product Innovation Management, vol. 16, Issue 1, pp. 40-51.

Takano, N., Zako, M., Fujitsu, R., Nishiyabu, K. 2004. Study on large deformation characteristics of knitted fabric reinforced thermoplastic composites at forming temperature by digital image-based strain measurement technique. Composites Science and Technology, vol. 64, Issues 13-14, pp. 2153-2163.

Tam, K.W. and Chan, K.W. 2007. Thermoforming mould design using a reverse engineering approach.Robotics and Computer-Integrated Manufacturing, vol. 23, Issue 3,pp. 305-314

Throne, J. L. 1996. Technology of Thermoforming. Hanser Publishers, Munich.

Throne, J. L. 2002. Soc. Plast. Engrs. Annual Tech. Conf., Tech Papers, vol. 60, Issue 3, pp. 4089–4095.

Torres, F. G. and Bush, S. F. 2000. Sheet extrusion and thermoforming of discrete long glass fibre reinforced polypropylene. Composites Part A: Applied Science and Manufacturing, vol 31, Issue 12, pp 1289-1294

Tseng, M.M., Jiao, J.X. 1996. Design for mass customization, CIRP Annals, vol. 45, Issue 1, pp. 153–156.

Tseng, M.M., Jiao, J.X. 1998. Product family modeling for mass customization, Computers in Industry, vol. 35, Issues 3–4, pp. 495–498.

Ulrich, KT., Eppinger, SD. 2000. Product design and development. New York: Mc Graw-Hill.

Wang, S., Makinouchi, A,. Tosa, T., Kidokoro, K., Okamoto, M., Kotaka, T., Nakagawa, T., 1999. Numerical simulation of acrylonitrile-butadiene-styrene material's vacuum forming process. Journal of Materials Processing Technology, vol. 91, Issues 1-3, pp. 219-225.

Wanga, Y. D., Shen, W. and Ghenniwab, H. 2003. WebBlow: a Web/agent-based multidisciplinary design optimization environment. Computers in Industry, vol. 52, pp. 17-28.

Warby, M. K., Whiteman, J. R., Jiang, W. -G., Warwick, P., Wright, T. 2003. Finite element simulation of thermoforming processes for polymer sheets. Mathematics and Computers in Simulation, vol. 61, Issues 3-6, pp. 209-218.

Wiesche, S., 2004. Industrial thermoforming simulation of automotive fuel tanks. Applied Thermal Engineering, vol. 24, Issue 16, pp. 2391-2409.

Wrobel, G., Pawlak, S. 2006. Ultrasonic evaluation of the fibre content in glass/epoxy composites. Journal of Achievements in Materials and Manufacturing Engineering, vol.18, Issues 1-2, pp. 187-190.

Zha, X.F., Du, H. 2001. Mechanical systems and assemblies modeling using knowledge intensive petri net formalisms, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, vol. 15, Issue 2, pp. 145–171.

Zha, X.F., Lu, W.F. 2002. Knowledge support for customer-based design for mass customization, AID'02, Kluwer Academic Press, pp. 407–429.

Zha, X.F., Sriram, R.D. 2006. Platform-based product design and development: A knowledge-intensive support approach. Knowledge-Based Systems, vol. 19, Issue 7, pp. 524-543.

Zhu, L., Kazmer, D. 2000. A Performance-based representation of constraint-based reasoning and decision-based design. DETC'2000/DTM-14556 Proceedings of 12th International Conference on Design theory and Methodology, Design Engineering Technical Conferences. Baltimore, Maryland, pp. 10.

# LIST OF PUBLICATIONS

The main results of the research have been published in several journal papers and presented in different conferences. The research papers published in international peer-reviewed journals are as follows:

1. Küttner, R., Karjust, K. 2006. Coordination of complex tasks of engineering product and manufacturing process optimization. Proceedings of the Estonian Academy of Sciences, Engineering, vol.12, Issue 13-1, pp. 163-175.
2. Karjust, K., Küttner, R., Pohlak, M. 2007. Technology design of composite parts. Journal of Achievements in Materials and Manufacturing Engineering, vol. 22, Issue 2, pp. 23-26.
3. Karjust, K., Küttner, R., Pohlak, M. 2007. The design and production technology of large composite plastic products. Proceedings of the Estonian Academy of Sciences, Engineering, vol. 13, Issue 2, pp. 117-128.

The conference papers are as follows:

1. Karjust, K., Küttner, R. 2006. Integrated product development and manufacturing planning for product families with application to hydro spa equipment. 1st Nordic Conference on Product Lifecycle Management – NordPLM, Göteborg, Sweden, pp. 187-198.
2. Karjust, K., Küttner, R. 2006. Aggregate planning of hydro spa equipment product family. 5th International DAAAM Baltic Conference, Tallinn, Estonia, pp. 197-202.
3. Küttner, R., Karjust, K., Pohlak, M. 2006. Integrated optimal planning of product family and manufacturing technology of its components. 4th International Conference on Manufacturing Research, Liverpool, United Kingdom, pp. 55-60.
4. Karjust, K., Küttner, R., Pohlak, M. 2008. The production technology considerations of large composite parts. Proceedings of the 6th international conference of DAAAM Baltic industrial engineering, Tallinn, Estonia, pp. 251-256.

# ABSTRACT

The speed of developing and delivering products and also product platform, what satisfies the whole range of customer and market needs, are the primary drivers of today's business decisions. Today's manufacturers must become leaner, smarter, and faster than their domestic and foreign competitors. Competitiveness of the company depends on its ability to produce a range of products which are continually updated. This is a case of reusing designs as well as manufacturing and other resources for multiple product groups that share substantive portion of their structure.

The objective of the study is to investigate how to optimize the family of products and their manufacturing processes, in particularly to integrate computer-based product family planning, technological process planning and manufacturing resource planning activities. The main problem is to identify how to link between different engineering decisions and let the individual design tasks to conduct separately in concurrent manner. Models of the proposed subtasks are integrated so that they would support the complex optimizing life cycle of the product. For each considered sub-problem, a multi-criteria optimization task is formulated together with the hierarchical coordination of strategy.

The development of the product family depends on the market segments, functional requirements, production capabilities and is related to the manufacturing planning, manufacturing requirements for product families. There has been developed the optimization model for optimal planning volumes of product family.

In the current thesis optimal design of the manufacturing technology processes of large composite plastic products has been studied. One of the key problems are how to integrate computer-based product design and planning of the technology process. There has been investigated the optimization of manufacturing technology processes of the large composite plastic products.

For optimal selection of technology the corresponding optimization model has been proposed. Model has based on maximization of total profit, where constraints are the workstation time capacities, material availability and optimal technology structure. The technology optimization model controls and analyzes the calculated technology planning route, the optimal vacuum forming processes, the technology of post-forming operations (like trimming, drilling the of slots and cut-outs), strengthening and assembling operations.

In the current thesis the Neural Network meta-modeling technique has been used. The optimization of the plastic sheet and its strengthening layer thickness has been performed using the surrogate design model. The Finite Element Analysis simulation has performed with optimal thickness values to verify the prediction accuracy of a surrogate model. The product family of the large composite plastic products together with the derivate products and their production technologies has modified using proposed methodology. The most of the methods described in this thesis are now under development and industrial testing.

The (aggregate) planning of manufacturing resources has been used to make decision about product portfolio and volumes of production in the given time periods, determine the possibilities to meet the customer requirements and market needs.

**Keywords**: Computer supported cooperative optimization, manufacturing resource planning, product family planning, technological process planning, large composite plastic products, and artificial neural networks.

# KOKKUVÕTE

Raalprojekteerimise erinevate süsteemide (CAD/CAM/CAE süsteemide) kasutamine tootmise ja tootearenduse faasis on muutunud ettevõtetes igapäevaseks. Arvuti kasutusel põhinevad projekteerimismeetodid toetavad projekteerijat parimate ja aega vähem nõudvate lahendite leidmisel, arvestades erinevaid aspekte, nagu toote geomeetria, tehnoloogilised võimalused, ressursside olemasolu, toote tootmise maksumus, investeeringute vajadus, allhankijate ja ostutoodete kasutamise otstarbekus jne. Üha enam minnakse üle üksik toote projekteerimiselt sarnaste toodete pere projekteerimisele. Ettevõtte võimaluste ja ressursside arvestamiselt ettevõtete koostöövõrgu võimaluste arvestamisele, mis omakorda võimaldab tegeleda järjest keerukamate ja ressursimahukamate ülesannetega. Arvutite võimsuse kasvuga on lisandunud samaaegse multidistsiplinaarse optimaalse projekteerimise kasutamise võimalused.

Erinevates tööstusharudes nagu lennunduses, paaditööstuses, välibasseinide ja mullivannide ehituses, massaaziseadmete valmistamises, auto keredetailide tootmises on tähtsal kohal suuregabariidiliste plastdetailide tootearendus- ja tootmistehnoloogiad. Antud valdkondades määravad lõpptoote disaini, omadused ja funktsionaalsuse just suurel määral erinevad suuregabariidilised plastdetailid. Sellepärast on vajalik, et need tooted oleks kvaliteetsed, unikaalse disainiga ning vastupidavad. Plastdetailide kvaliteedi määravad ära vormide kvaliteet, ladustuse ja pakkimise tingimused, töötlemistehnoloogiad ja oskused. Oluline on investeerida uutesse vormidesse, töötlemismeetoditesse ning oskustöölistesse, samuti suurendada tootlikkust, vähendada töötlemis-ja tootearendusaegasid ning effektiivistada kogu suuregabariidiliste plastdetailide tootmistehnoloogia tsüklit terve tootepere ülatuses.

Antud doktoritöö on jagatud kolme suurde ossa, kus erinevaid osi vaadatakse üksikult ning ka üksteisega koos, moodustades tervikpildi. Antud töös käsitletakse metoodikat tootepere, tootmistehnoloogia ja tootmise optimaalseks planeerimiseks suuregabariidiliste plastdetailide korral. Optimaalse projekteerimise ülesanne on esitatud kahetasandilisena ja sisaldab koordinaatorit ning madalamal tasemel erinevaid optimaalse planeerimise ülesandeid. Planeerimisülesanded on esitatud mitmekriteriaalse optimaalse planeerimise ülesannetena. Koordinaator “juhib” erienvaid planeerimisülesandeid siduvate parameetrite väärtuste prognoosimise, täiendavate tõkete püstitamise ja sihifunktsioonide parameetrite täpsustamise teel.

Töö sissejuhatavas osas vaadeldakse erinevaid vaakumvormimise meetodeid ning püütakse analüüsida erinevate meetodite eeliseid ja puudusi. Läbivaks vaatenurgaks on suuregabariidiliste plastdetailide optimaalsed töötlemise meetodid. Lisaks antakse ülevaade tooteperedest ning nõuetest tootepere planeerimisel. Vaadatakse lähemalt erinevaid tootepere planeerimise mudeleid ning sõltuvust tootepere planeerimise, tehnoloogia planeerimise ja tootmise ressursside planeerimise vahel.

Töö esimeses osas käsitletakse lähemalt tootepere planeerimist ning olemasoleva tootepere täiustamist/modifitseerimist, sõltuvalt erinevatest piirangutest nagu turu nõuded, nõuded toote kasutusele ja funktsionaalsusele, toote geomeetriale, struktuurile ja kasutatavatele materjalidele. Töö käigus loodi erinevad arvutusmudelid leidmaks optimaalseid tootmismahtusid toodete ja alamtoodete jaoks. Lisaks püüti luua antud osas ka arvutusmudel leidmaks optimaalseid uusi funktsioone, mida antud tooteperele lisada sõltuvalt turu nõuetest, investeeringutest uutesse funktsioonidesse, turu kasvust, kui uus funktsioon on tootele lisatud ja toote maksumusest.

Töö teises osas vaadatakse lähemalt suuregabariidiliste plastdetailide tehnoloogia optimaalset planeerimist. Püütakse projekteerida koos tootepere, derivaattooted ja nende valmistamise tehnoloogiad. Samas optimeeritakse erinevaid alamsüsteeme nagu vaakumvormimise ja lõikamise tehnoloogiad ning tugevdamise ja koostamise operatsioonid. Iga üksiku alamtehnoloogia protsessi planeerimissüsteemi modelleerimiseks kasutatakse närvivõrke, metoodika realiseerimiseks on kasutatud MS Exceli ja MatLAB'i keskkonda. Lisaks püütakse optimeerida suuregabariidiliste plastdetailide tugevdamise osas klaaskiud tugevduskihi paksust, kasutades reaalsete katsete tulemusi, närvivõrkude tehnoloogiat ning lõplike elementide meetodit (FEM).

Töö kolmandas ja ühtlasi viimases osas püütakse lähemalt analüüsida tootmise planeerimist suuregabariidiliste plastdetailde korral. Loodud optimeerimismudel püüab leida maksmaalse kasumi minimaalsete töötlemisaegade korral. Samas püüti ühendada ühtseks tervikuks kolm planeerimise ülesannet: tootepere, tootmistehnoloogia ja tootmise optimaalse planeerimise oma. Metoodika on realiseeritud MS Exceli keskkonnas ja selle kasutamist on kirjeldatud tervisekapslite tootepere projekteerimise näitel.

Töö põhilised järeldused on toodud alljärgnevalt:

1. Uuriti erinevaid vaakumvormimise meetodeid ning toodi välja nende põhilised eelised ja puudused.
2. Täiustati suuregabariidiliste komposiidist plastdetailide tooteperet ning loodi optimeerimismudel leidmaks effektiivseimad lisatavad uued funkstioonid/omadused. Simulatsiooni tulemusena leiti, et antud andmetega on optimaalseim lisada kaks uut funkstiooni/omadust teisele tootele.
3. Loodi arvutusmudel optimaalsete tootmismahtude leidmiseks erinevate tootegruppide kohta.
4. Kasutades tehnoloogia optimeerimise mudelit leiti optimaalne valmistustehnoloogiate kogum üle terve tootepere, mis maksimeerib kasumi, minimeerib töötlemisajad ja töötlemise maksumuse. Leiti, et antud juhul on effektiivseim kasutada vaakumvormimist ühe soojendusplaadiga jne.
5. Optimeeriti suuregabariidiliste komposiidist plastdetailide valmistustehnoloogiaid ja nende alamsüsteeme kasutades närvivõrke, MS Excel ja MatLAB keskkonda.

6. Plastist lehe ja klaaskiud tugevduskihi optimeerimisel leiti, et antud mudeli korral on optimaalne tugevduskihi paksus piirides 3 - 4 mm ja akrüüli ning tugevduskihi kogupaksus 2,3 – 5,1 mm.
7. Tootmise planeerimise optimeerimisel loodi mudel, mis maksimeerib kasumi ja minimeerib töötlemisajad.
8. Uuriti kuidas optimeerida tooteperet ning nende tootmisprotsesse, lisaks integreetiti arvutil põhinev tootepere planeerimine, tootmistehnoloogia ja tootmise planeerimisega.

Edaspidised uurimise suunad antud teemaga seoses on järgmised:

1. Suuregabariidiliste komposiidist plastdetailide vaakumvormimise protsessi simuleerimine sõltuvalt materjalide erinevusest ning vormi parameetrite variatsioonidest.
2. Klaaskiud tugevduskihi kuivamisaja optimeerimine sõltuvalt tugevduskihi kontsentratsioonist ning tugevdava detaili parameetritest.
3. klaaskiud tugevduse nakkuvuse analüüsimine suuregabariidiliste komposiidist plastdetailide pinnal.

# Elulookirjeldus

1. Isikuandmed

| | |
|---|---|
| Ees- ja perekonnanimi | Kristo Karjust |
| Sünniaeg ja –koht | 22.10.1979, Ambla |
| Kodakondsus | Eesti |

2. Kontaktandmed

| | |
|---|---|
| Aadress | Ehitajate tee 111-48, Tallinn |
| Telefon | +372 620 3254 |
| E-posti aadress | kristo@staff.ttu.ee |

3. Hariduskäik

| Õppeasutus (nimetus lõpetamise ajal) | Lõpetamise aeg | Haridus (eriala/kraad) |
|---|---|---|
| Tallinna Tehnikaülikool | 2004 | Tööstustehnika ja juhtimine/Tehnikateaduste magistrikraad |
| Tallinna Tehnikaülikool | 2002 | Tootmistehnika/ Bakalaureuse kraad (Cum Laude) |
| Nõo Reaalgümnaasium | 1998 | Keskharidus |
| Aravete Keskkool | 1995 | Põhiharidus |

4. Keelteoskus (alg-, kesk- või kõrgtase)

| Keel | Tase |
|---|---|
| Eesti | Kõrgtase |
| Inglise | Kesktase |
| Vene | Kesktase |

5. Täiendusõpe

| Õppimise aeg | Täiendusõppe läbiviija nimetus |
|---|---|
| 17.02-18.02.2005 | Business Grain, koolitus „Kvaliteedijuhtimissüsteemi ISO 9001:2000 siseaudiitori koolitus“ |

6. Teenistuskäik

| Töötamise aeg | Tööandja nimetus | Ametikoht |
|---|---|---|
| 2000-2003 | VMK Tarkvara OÜ | Müügiinsener |
| 2002-2003 | Tallinna Tehnikaülikool | Insener |
| 2003-2004 | Tallinna Tehnikaülikool | Insener (projektijuht) |
| 2004-2005 | Wellspa OÜ | Tootejuht |
| 2005-... | Wellspa OÜ | Tootmisjuht |
| 2004-... | Tallinna Tehnikaülikool | Assistent |

7. Teadustegevus

Publikatsioonid:

Karjust, K., Papstel, J., Pohlak, M. 2004. Knowledge based system of the surface finishing processes. 4th International DAAAM Conference. Tallinn, pp. 131-133.

Pohlak, M., Küttner, R., Majak, J., Karjust, K., Sutt, A.2004. Experimental study of incremental forming of sheet metal products. 4th International DAAAM Conference. Tallinn, pp. 145-148.

Pohlak, M., Küttner, R., Majak, J., Karjust, K., Sutt, A.2004. Simulation of incremental forming of sheet metal products. 4th International DAAAM Conference. Tallinn, pp. 149-151.

Sutt, A., Küttner, R., Pohlak, M., Karjust, K. 2004. Development of the experimental integrated design environment for progressive cutting dies. 4th International DAAAM Conference. Tallinn, pp. 161-164.

Küttner, R., Karjust, K. 2006. Coordination of complex tasks of engineering product and manufacturing process optimization. Proceedings of the Estonian Academy of Sciences, Engineering, vol.12, Issue 13-1, pp. 163-175.

Karjust, K., Küttner, R. 2006. Integrated product development and manufacturing planning for product families with application to hydro spa equipment . 1st Nordic Conference on Product Lifecycle Management – NordPLM, Göteborg, Sweden, pp. 187-198.

Karjust, K., Küttner, R. 2006. Aggregate planning of hydro spa equipment product family. 5th International DAAAM Baltic Conference, Tallinn, Estonia, pp. 197-202.

Küttner, R., Karjust, K., Pohlak, M. 2006. Integrated optimal planning of product family and manufacturing technology of its components. 4th International Conference on Manufacturing Research, Liverpool, United Kingdom, pp. 55-60.

Karjust, K., Küttner, R., Pohlak, M. 2007. Technology design of composite parts. Journal of Achievements in Materials and Manufacturing Engineering, vol. 22, Issue 2, pp. 23-26.

Karjust, K., Küttner, R., Pohlak, M. 2007. The design and production technology of large composite plastic products. Proceedings of the Estonian Academy of Sciences, Engineering, vol. 13, Issue 2, pp. 117-128.

Karjust, K., Küttner, R., Pohlak, M. 2008. The production technology considerations of large composite parts. Proceedings of the 6th international conference of DAAAM Baltic industrial engineering, Tallinn, Estonia, pp. 251-256.

8. Kaitstud lõputööd

Lõputöö teema "Tugitalla tehnoloogia", 2002

Lõputöö teema "Teadmuste juhtimine pinna puhastöötluse meetodite korral", 2004

9. Teadustöö põhisuunad

Suuregabariidiliste plastdetailide integreetitud tootearenduse metoodika ja valmistustehnoloogiad, vaakumvormimine

# Curriculum Vitae

1. Personal data

| | |
|---|---|
| Name | Kristo Karjust |
| Date and place of birth | 22.10.1979, Ambla |
| Citizenship | Estonian |

2. Contact information

| | |
|---|---|
| Address | Ehitajate tee 111-48, Tallinn |
| Phone | +372 620 3254 |
| E-mail | kristo@staff.ttu.ee |

3. Education

| Educational institution | Graduation year | Education (field of study/degree) |
|---|---|---|
| Tallinn University of Technology | 2004 | Industrial Engineering and Management/MSc |
| Tallinn University of Technology | 2002 | Production Technology/ BSc (Cum Laude) |
| Nõo High School of Science | 1998 | Secondary education |
| Aravete High School | 1995 | Comprehensive education |

4. Language competence/skills (fluent, average, basic skills)

| Language | Level |
|---|---|
| Estonian | Basic skills |
| English | Average skills |
| Russian | Average skills |

5. Special Courses

| Period | Educational or other organization |
|---|---|
| 17.02-18.02.2005 | Business Grain, course „ Quality management system ISO9001:2000 inside auditor course “ |

## 6. Professional Employment

| Period | Organization | Position |
|---|---|---|
| 2000-2003 | VMK Tarkvara OÜ | Sales Engineer |
| 2002-2003 | Tallinn University of Technology | Engineer |
| 2003-2004 | Tallinn University of Technology | Engineer (Project Manager) |
| 2004-2005 | Wellspa OÜ | Product Manager |
| 2005-... | Wellspa OÜ | Production Manager |
| 2004-... | Tallinn University of Technology | Assistant |

## 7. Scientific Work

Publications:

Karjust, K., Papstel, J., Pohlak, M. 2004. Knowledge based system of the surface finishing processes. 4th International DAAAM Conference. Tallinn, pp. 131-133.

Pohlak, M., Küttner, R., Majak, J., Karjust, K., Sutt, A.2004. Experimental study of incremental forming of sheet metal products. 4th International DAAAM Conference. Tallinn, pp. 145-148.

Pohlak, M., Küttner, R., Majak, J., Karjust, K., Sutt, A.2004. Simulation of incremental forming of sheet metal products. 4th International DAAAM Conference. Tallinn, pp. 149-151.

Sutt, A., Küttner, R., Pohlak, M., Karjust, K. 2004. Development of the experimental integrated design environment for progressive cutting dies. 4th International DAAAM Conference. Tallinn, pp. 161-164.

Küttner, R., Karjust, K. 2006. Coordination of complex tasks of engineering product and manufacturing process optimization. Proceedings of the Estonian Academy of Sciences, Engineering, vol.12, Issue 13-1, pp. 163-175.

Karjust, K., Küttner, R. 2006. Integrated product development and manufacturing planning for product families with application to hydro spa equipment . 1st Nordic Conference on Product Lifecycle Management – NordPLM, Göteborg, Sweden, pp. 187-198.

Karjust, K., Küttner, R. 2006. Aggregate planning of hydro spa equipment product family. 5th International DAAAM Baltic Conference, Tallinn, Estonia, pp. 197-202.

Küttner, R., Karjust, K., Pohlak, M. 2006. Integrated optimal planning of product family and manufacturing technology of its components. 4th International Conference on Manufacturing Research, Liverpool, United Kingdom, pp. 55-60.

Karjust, K., Küttner, R., Pohlak, M. 2007. Technology design of composite parts. Journal of Achievements in Materials and Manufacturing Engineering, vol. 22, Issue 2, pp. 23-26.

Karjust, K., Küttner, R., Pohlak, M. 2007. The design and production technology of large composite plastic products. Proceedings of the Estonian Academy of Sciences, Engineering, vol. 13, Issue 2, pp. 117-128.

Karjust, K., Küttner, R., Pohlak, M. 2008. The production technology considerations of large composite parts. Proceedings of the 6th international conference of DAAAM Baltic industrial engineering, Tallinn, Estonia, pp. 251-256.

8. Defended Theses

Theses theme "Support footing technology", 2002

Theses theme "Knowledge management of the surface finishing processes", 2004

9. Main areas of scientific work/current research topics

Integrated product development and production technology of large composite plastic products, thermoforming technologies