Bachelor Degree Project

UNIVERSITY OF SKÖVDE

A CHECKLIST FOR PLASTIC PRODUCT DESIGN

Preventing Pitfalls in a Design Process and Premature Failures of Plastic Products

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Assurance of Originality and Referencing

This thesis has been submitted 2014-06-25 by Johanna Kaartinen to University of Skövde as a Bachelor Degree Project in Integrated Product Development at the School of Technology and Society.

I certify that all material in this Bachelor Degree Project, which is not my own work has been identified and that no material is included, for which a degree has previously been conferred on me.

Johanna Kaartinen

Abstract

Designing an injection molded plastic part requires optimizing the part with respect to various stakeholders' needs throughout its life cycle. The conditions in which a product is operating in service are often inadequately understood or specified, resulting in wrong material selection, which in turn leads to failure when the product is used. Many aspects interrelate with the initial part design and the essential rules of each should be taken into account to ensure a well-functioning plastic product. Regardless, a part design often passes sequentially from concept development to the manufacturing phase with features that unnecessarily complicate production, add costs and weaken the intended embodiment of the product. Therefore, a checklist was developed to ensure that oversights do not happen and verify that a design fulfills the requirements set for it.

The commissioning company in the project was the design office Sytyte Oy. The aim of this thesis work was to investigate the effects of design decisions on the product's feasibility and performance in service. The study focused on the underlying reasons for failures in plastic products, failure phenomena and ways of preventing them. The project started with literature research. To support the theoretical review, a small-scale survey was conducted among operators in plastic industry in Finland to strengthen the outcome of the project.

The findings from the research were compiled into a checklist. The approach into the list was adopted from the FMEA method aiming to create a stripped-down version of it. The result offers a tool for anticipating and spotting possible failures by bringing up the influences that most frequently affect the part performance. It contributes to preventing delays in processing and premature failures in service. The checklist was verified by specialist consultation to receive suggestions and requirements for improvements and to ensure its reliability.

Foreword

This Bachelor degree project has been held at the School of Technology and Society, University in Skövde, during the spring term 2014. The project was conducted for the purposes of a commissioning company, Sytyte Oy from Billnäs, Finland. The aim has been to compile a checklist for plastic design that improves the overall quality of a plastic product. Input for the research has been received from a number of professionals operating in a plastic industry. I want to thank people who have contributed to the progress of my project. I gratefully acknowledge the time, support and advices provided by my supervisors;

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Lastly, special thanks for my family and friends both in Finland and in Sweden who have reminded me the aspects of good quality, other than those discussed in my project.

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1 INTRODUCTION

This chapter presents the description of the project, the background information and the research problems. The commissioning company is introduced and the objectives as well as the limitations of the research are defined.

1.1 Background

Designing plastic parts and components involve implementing wide knowledge from different engineering areas. A successful design process requires a coherent teamwork between a designer and other specialists such as a tool designer and a manufacturing operator. Regardless, a part design often passes sequentially from concept development to the manufacturing phase with features that unnecessarily complicate production and add costs. It can result to a decreased product performance and a premature failure (Bayer Material Sience, 2000; Mitchell, 1996).

Before manufacturing can start, the design is frozen during a design freeze phase (Eger et al., 2005). Before tools are fabricated, the embodiment of a design should be determined. During the tool fabrication, it is difficult as well as expensive to implement further modifications into the design. According to Boothroyd et al. (2011) it is a broadly accepted fact that over 70 % of the final product costs are determined during the design phase. Simultaneously, the later in the design process changes occur, the more expensive they are to apply and alternatives for changes decrease (Pahl & Beitz, 1988).

Frequently a failure stems from a human error. Sometimes plastic products are designed without a consideration for load, time or ambient temperature (Shah, 2007). Smithers Rapra (2014a) estimates that most plastic products fail before reaching the anticipated life expectancy; even 70 % of all plastic products fail prematurely. The underlying reason for failures is not only designers' limited knowledge of plastic designing but also the fallible nature of human memory. Even a product designed to the best of the designer's ability, mistakes and oversights can occur, leading to unintentional mistakes. Thus, a design should be verified during the design freeze phase to ensure a robust embodiment that fulfills the quality expectations during all of its life cycle stages.

The aim of this thesis work is to do a research of possible errors in a design process of an injection molded plastic part and to compile a checklist, which contributes to preventing unanticipated failures. The principal reasoning behind the list is to increase the overall quality of a plastic product. A checklist is intended for designers to be used as a support in identifying and eliminating possible pitfalls and shortcomings in a part design. By making minor design changes, the processability of a plastic part can be increased and the intended embodiment of a product achieved. By using the checklist, it is aimed to achieve benefits such as improved product quality and increased rate in workflow thus reduced lead-time.

1.2 Commissioning company Sytyte Oy

This thesis work is done in collaboration with Sytyte Oy, a private enterprise design office in Billnäs, Finland. Their line of business is plastic industry in which they are serving design and consulting services for manufacturers throughout the whole design process. Sytyte is well known within the field and it is just about the only company in Finland focused specifically on designing plastic products and components. Sytyte has a long experience and a wide knowledge of injection molding, tooling techniques and polymer material understanding. Their special field of knowledge is creating solutions for different mechanisms by utilizing technical properties of plastic materials. (Sytyte, 2014).

1.3 About the Problem

As the checklist aims for overall quality improvements throughout the product lifecycle, diverse aspects of quality and the lessening influences on it are to be considered. According to Morup (1993), end users look at the product from a different perspective than assembly or manufacturing operators, which means that there are different types of quality observations depending on a standpoint. The performance of a product and the expectations of a customer create the perception of the quality level. Otto and Wood (2011) defines robust design as a combination of engineering quality and customer quality. Engineering quality, or in other words expected quality, aims to ensure that a product functions as intended without falling short of a customer's inherent expectations and confirms that a product has suitable strength, reliability and accident prevention measures. Customer quality is the perception of the performance of a product under all environmental and user conditions.

Plastic parts have had a bad reputation over the decades due to their characteristics that vary according to ambient conditions (Tres, 2000). Therefore, knowledge about the influences that cause a failure is a prerequisite to develop a robust design and to prevent failures (Shah, 2007). Several factors influence on the performance of both plastic products and others as well. These factors can be divided into three different categories called 'noise factors' based on Taguchi method presented by Lochner & Matar (1990):

1. External noise: Variation in environmental conditions, such as dust, temperature and humidity
2. Internal noise: Corrosion, such as product wear, material aging and other changes in component or materials with time and use
3. Unit-to-unit noise: Difference in products built to the same specifications caused by variability in materials, manufacturing equipment and assembly processes

1.4 Objectives

The purpose of this Bachelor's thesis work is, given a distinctive focus on a designer's point of view in a product development process, to

1. Study
   - influences which cause product failure
   - service conditions that affect plastic products performance
   - factors that facilitates activities during a product's life cycle
2. Compile a checklist that contributes to improve the workflow in processing and to prevent premature product failures

This project is divided into two parts. The work begins with research on concerns as stated above and based on the findings, a checklist for ensuring the design's functionality during different life cycle stages, will be compiled. The main focus is on part design, its effect on customer quality, tooling and manufacturing without understating the importance of other stages. Research will focus on principles of plastic part design, commonly overlooked issues in design and the shortcomings in initial part design that most frequently leads to a failure. The study will focus on the mechanical and visual properties that defines the function of a plastic product.

1.5 The Checklist

The objective of the checklist is to gather essential factors that contribute to that a product to meets the requirements set for it. The approach of the list is based on the Failure Mode and Effect Analysis (FMEA) method but aims for a stripped-down implementation. Like FMEA, it is aimed that the checklist stands for evaluating the robustness of a part design and identifies the issues related to the expected quality of a certain product. The focus is on concerns that a designer can influence and that are affected by the performance variations of a plastic material.

By using the checklist, it is aimed to achieve the following benefits

- Embodiment of a product that is in accordance with its design and fulfills the requirements in varying service conditions
- Adequate part geometry that facilitates tool fabrication
- Adequate part geometry that supports production stability
- Reduced lead time and savings through the complete workflow

The checklist is meant to be used latest at the design freeze stage by the members in a product development team such as industrial designers and design engineers. It also endorses communication between a designer, tool fabricator and manufacturer. A validation of the list will be performed by asking feedback from specialists working in the plastic industry. The checklist will be utilized in the own use of the commissioning company but also for commercial purposes. Since the implementation method of the list is yet undefined, the focus is on the content of the list and not on its layout.

1.6 Limitations

The limitations of the research and the checklist are as follows:

- The study is limited to design of injection molded parts according to the wish of the commissioning company
- The checklist does not provide information of design methodologies but focuses on issues to be verified during the design freeze stage
- The user of the checklist is assumed to have a basic knowledge of plastic design, materials and manufacturing methods as it is not a teaching manual
- The checklist provides a practical screening tool for inspecting possible shortcomings in the part design, hence it is not a substitute for strength analysis, calculations etc.
- Defects caused by poor processing parameters are not included in the checklist since that is beyond a designer’s influence. Nevertheless, it is significant to inspect the part’s performance with respect to varying processing parameters as they impact on a final product’s properties

2 THEORETICAL FRAMEWORK

This chapter offers the theoretical background information for this project. It informs about principles of underlying reasons for failures, service conditioning factors and the life cycle stages of a plastic part. The essentials of polymer materials and the noteworthy factors in checklist design are described shortly. At the end of the chapter, a brief conclusion of the key issues is presented.

2.1 Why Plastic Products Fail?

Failure is a practical problem with a product and it denotes that the component does not fulfil its function anymore (Lampman, 2003). Jansen and Rios (2013) define failure as an undesirable event or condition that results in the inability of a component to perform its intended purpose safely, reliably or economically. Some failures are rapid and catastrophic while in other cases a part might be operable to some extent but not fully functional (Jansen & Rios, 2013; Smithers Rapra, 2014a). Some failures are imperfections in the surface quality or other aesthetical alterations but do not affect the part performance (Goodship, 2004). According to Smithers Rapra (2014c), Kazmer (2011) and Shah (2007), the underlying causes for plastic failures can be categorized in four main factors:

1. Inadequate product specification and wrong material selection
2. Poor design
3. Processing faults
4. Misuse

Nevertheless, in many cases it is not possible to identify only one underlying cause for a failure because many factors may have contributed to the failure. Based on the estimation by Smithers Rapra (2014b), 45 % of all failures stem from poor specification or a poor material selection. Inadequate design and processing practices are both the reason of a failure in 20 % of all cases, whereas the smallest portion, 15 % is caused by misusing the product. These are presented in Figure 1 below.

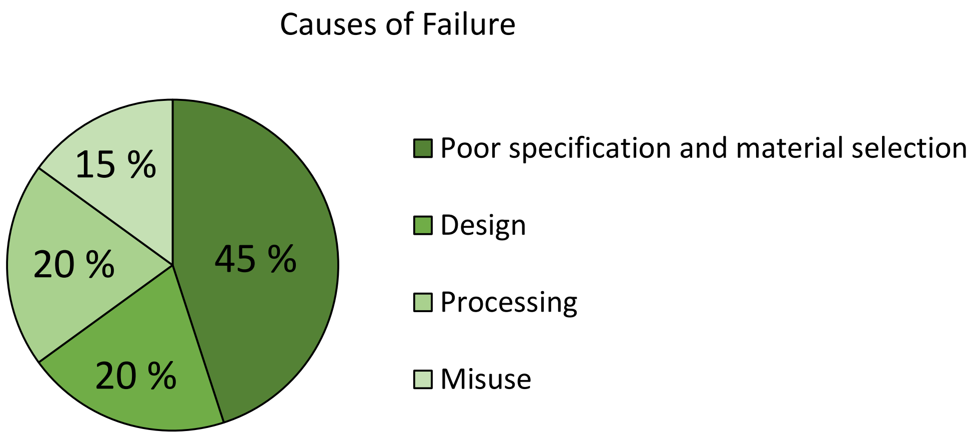

Figure 1. Distribution of causes of failures (Smithers Rapra, 2014b).

1. Poor specification and material selection – underestimation of the requirements

Material considerations are important as the selected material greatly effects on the performance of the product (Mitchell, 1996; Rosato & Rosato, 2003). The imposed loads on the part are frequently not fully understood and therefore underspecified. To ensure that the part performs as intended throughout its expected lifetime, the service conditions and their influence on a part's properties should be correctly specified and understood.

2. Design insufficiency

A proper material selection alone does not guarantee a robust design; part geometry influences the durability as well (Shah, 2007). According to Rosato and Rosato (2003) a noteworthy number of failures occur due to overlooking the basic plastic design guidelines. Anyhow, the design criteria vary from part to part and the basic guidelines do not apply to all cases. Therefore, each design should be handled separately.

3. Processing issues

Poor processing practices diminish the intended performance of the part. Manufacturing parameters such as pressure and temperature of a mold influence on the properties of the final part (Goodship, 2004).

4. Misuse of a product

Misuse refers to the cases when a product is being used beyond its intended purpose, lifetime or service conditions (Shah, 2007).

2.2 Designing a Quality Plastic Part for Life

In product design, all of the part's life phases from designing to disposal should be considered. Each life cycle stage delivers certain input to the design and sets certain requirements for it (Morup, 1993). The conditions and needs of each life phase should be considered and optimized with respect to the other phases' needs. Generally, the different life cycle stages of a product are design, manufacturing, distribution, service and end of life (Huang, 1996). Figure 2 below presents the life cycle stages adapted to a plastic product.

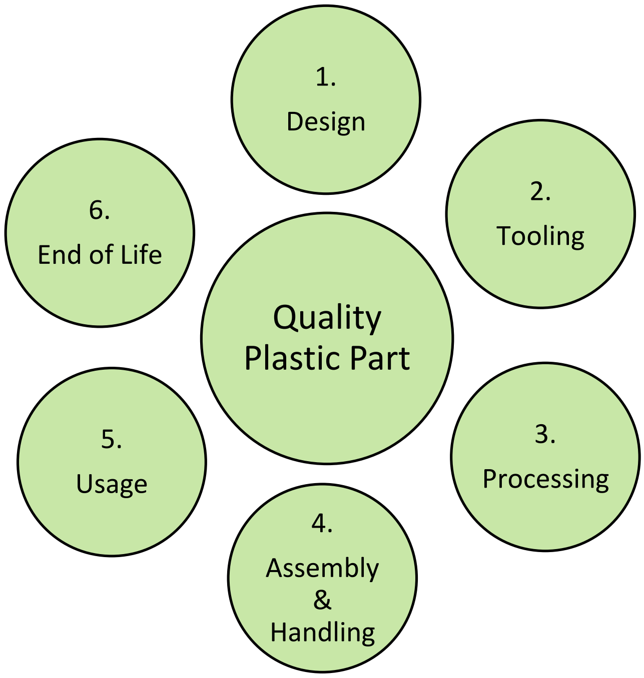

Figure 2. Life cycle of a plastic product.

1. Design

Plastic part design is a combination of a part geometry and material selection. These two factors are interrelating with each other and knowledge of each area is important in order to achieve a comprehensive design. Along with past experience, design guidelines and raw material suppliers can be used as sources for reference information (DuPont, 2000; Bayer Material Science, 2000; Mitchell, 1996). For plastic design there are certain rules of thumb regarding part geometry, which supports in achieving the intended embodiment. Elements such as walls, ribs and holes require detailed scrutiny, for which general design guidelines and checklists provide fundamental principles. Guidelines help to avoid defects caused in manufacturing, such as sink marks or warpage due to uneven cooling. An excerpt of a design guideline is shown in Figure 3 below.

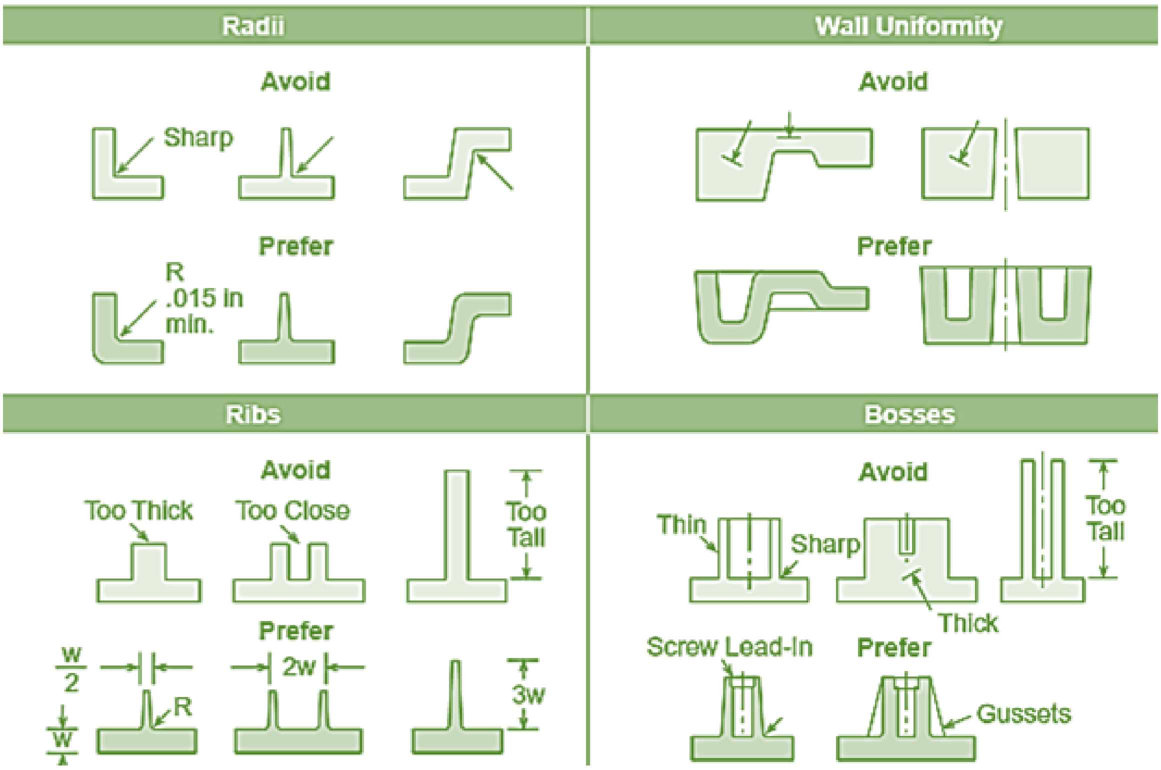

Figure 3. Design guidelines for plastics. (Bayer Material Science, 2000).

Nowadays there are over 35,000 polymer compounds available and each of them has a specific performance and processing capabilities (Rosato & Rosato, 2003). Raw material suppliers provide a material data sheet, which includes test data of materials' properties. The information listed is based on typical values obtained in tests, which are conducted generally in ideal conditions under short-term loading. The given values disregard the diminishing effect of temperature, chemicals and time. Additionally, the plastic part to be designed is likely different to the tested sample by its shape and thickness, fiber orientation and weld lines which all affect the performance of a plastic part. Therefore, data sheets should be used as screening tools and for comparison purposes only, not a basis for the final material selection for a part of an engineering application (Rosato & Rosato, 2003).

Material selection and part geometry are based on the part requirements that are stated in a product specification. The specification is a set of requirements in forms of metric values addressed to the final product (Ulrich & Eppinger, 2000). It is intended to satisfy functional, aesthetic and economic requirements by controlling variations in the final product. In case of plastic materials, the specification should include target values or definitions for the following aspects (Rosato & Rosato, 2003; Bayer Material Sience, 2000; DuPont, 2000):

- Required strength (including impact and flexural strength)
- Specified range of service temperatures
- Exposure to chemicals and harsh environments
- Appearance requirements
- Dimensional tolerances
- Required agency approvals
- Processing method
- Assembly method
- Recycling considerations

Since the part's performance is a combination of its geometry and the selected plastic material, which is affected by service conditions, Lampman (2003) suggests to test a part function under a worst-case scenario situation within the limits of a specification. To predict the part performance in the anticipated operational conditions, experiments should done under the maximum applied stresses in the maximum service temperature. Time and temperature accelerate certain failures and worst-case scenario testing helps to anticipate and avoid them.

Once the intended part performance is assessed and confirmed together with a part geometry and material, the design is frozen before the production ramp-up and ongoing production. Design freeze is the end point of the design phase at which a technical product description is handed over to production (Eger, Eckert & Clarkson, 2005). The aim of the freeze is to reduce the likelihood of further engineering changes. Changes that need to be implemented after freeze are costly and time-consuming if tooling is already in place. Crosby (1979) lists the costs of scrap, rework, product callbacks and manufacturing concerns to be 'the cost of quality', and claims that 20 to 30 percent of sales profits are misspent on these expenses. Therefore, spending more money and time upfront on preventing actions, such as specification review, prototype inspection and testing as well as tool control is worthwhile (Mitchell, 1996).

2. Tooling

Each part to be manufactured by injection molding requires a dedicated mold. It is generally called 'tool' and is designed by a tool designer and fabricated by an internal or external tooling supplier. The tooling principles have to be considered early in the design process since the tooling costs are greatly dependent on the design features and appearance requirements (Mitchell, 1996). A tool consists of two mold halves, which form a cavity that defines the shape of a final part. Tooling principles that have to be considered in part design include a gate, through which the molten plastic is delivered into the cavity, a parting line which is an interface separating the mold halves and ejector pins which assists in part removal from the mold (Strong, 2006). The number of cavities in a tool can vary from one up to dozens. Figure 4 illustrates a two-cavity mold.

As mentioned before, needs for changes in a part design should be observed before the tool is fabricated. The volume of a plastic material is greater in a molten stage than in solid, hence plastic shrinks while cooling. Therefore, the selected material's shrinkage behavior has to be known since the tool is prepared accordingly (Mitchell, 1996).

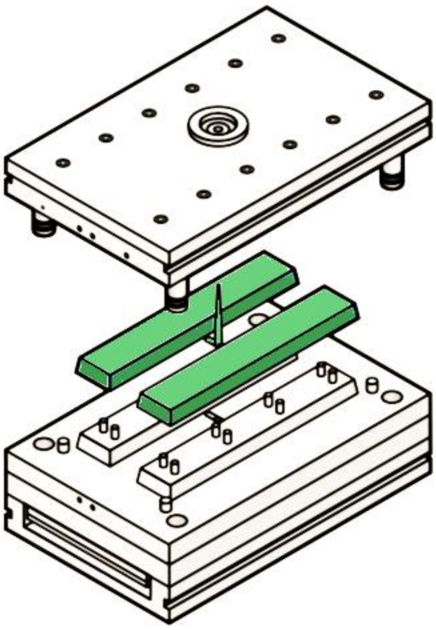

Figure 4. A mold with two cavities (Bayer Material Science, 2000).

3. Processing: Injection Molding

Injection molding is the most common and versatile manufacturing method of all the plastic processes (Strong, 2006). A wide range of part shapes with varying sizes and complex details can be manufactured by injection molding. It is a cyclic process that consists of sequential steps, which are simply stated the following (Muccio, 1997):

- **Melting** of the plastic granules and conveying the melt towards the injection unit. A shot, predefined amount of melt is injected into the mold to produce the part.
- **Injection** of the plastic melt into the mold under a high pressure through the gate. Gate location has a great impact on mold filling and to the embodiment of a part. Design features such as wall thickness and ribs influence on the mold filling.
- **Cooling** and solidifying of the plastic in the mold, while a part is also shrinking. Differential shrinking causes visual defects.
- **Ejection** of the molded part from the mold by ejector pins or rings. A draft angle in the wall of a part facilitates ejection.

Once the part is removed, the mold closes and a new shot is injected. The duration required to complete one round is called cycle time. Normally the longest phase in each cycle is cooling and therefore thin nominal wall thickness is preferable no speed up the process. The quality problems and processing variability in manufacturing can be reduced by good part design and by following the relevant principles included in the design guidelines (Mitchell, 1996). Apart from the defects related to part design, certain issues as moisture in the plastic resins and inappropriate processing practises can cause faults in a final product.

4. Assembly and Handling

In plastic design, the opportunity to create varying shapes can be utilized to reduce the amount of additional components or fasteners (Tres, 2000). Assembly methods specific to plastic parts are press fittings, living hinges and snap fits. Press fitting is an assembly method in which one part is force-fitted into a mating part. A living hinge is a thin connecting portion of plastic between two thicker walls allowing the part to flex relative to each other without a failure, and a snap fit joins two parts without additional fasteners. When considering assembly, certain aspects should be considered such as the components' relative movement to each other, request for different materials and possibility for disassembly in terms of maintenance and recycling or disposal (Tres, 2000). Distribution and storability are frequently overlooked in a design and therefore complicate handling. Rosato and Rosato (2003) mention that in some cases shipping conditions may be more severe than the conditions in the service. A lack of storability can cause difficulties and increase costs of distribution, therefore these issues should be addressed in a part design (Huang, 1996).

5. Service

As an initial step in the design process, the conditions of use and the part performance requirements must be understood and specified (Rosato & Rosato, 2003). The environment in which the part will operate may decrease the durability, resulting in a failure prior to the life expectancy. Therefore, the longer the list of end-use environmental conditions that are assessed and respected, the more successful the plastic product will be. The part properties alter when it is exposed to chemicals, temperature changes and applied stresses, hence the requirements should be carefully specified (Lampman, 2003). When determining the effect of the above-mentioned influences, both short-term and long-term effects should be considered. Additionally, the joint effect of the applied loads and environmental influences should be studied as well.

6. End of Life

Design decisions determine the overall environmental impact of a product throughout its life cycle (Otto & Wood, 2001). Good environmental practices can be carried out not only by considering the end of life phase, but considering the earlier phases as well. Impact on environment can be decreased in many ways, such as reducing waste by minimizing the produced reject during manufacturing and the required packaging for the product.

The strategy of disposal after the intended lifetime should be discussed. Maier (2009) lists the common recycling and disposal methods for injection molded plastic parts as mechanical recycling, feedstock recycling and energy recovery. In mechanical recycling, plastic products are sorted, cleaned and grinded into resins to be used as a material for new products. Feedstock recycling means breaking down the plastic into chemical constituents, which are used to synthesize new chemical products. Plastics have a higher energy value than coal. Hence, the stored energy can be reclaimed by burning, that means energy recovery. Based on research results presented by Association of Plastic Manufacturers in Europe (APME), O'Neill (2003) states that large pieces of plastic items in waste are environmentally profitable to recycle, while small plastic items are of more benefit when recovered as energy.

2.3 The Nature of Plastic Materials

Molecular behavior of the polymer determines the performance of the plastic product. Depending on chemical bonds between molecular chains, plastics are divided into two groups: Thermoplastics and thermosets. Further grouping of thermoplastic polymers is based on orientation of the molecular structure. These two sub-groups are amorphous and semi-crystalline polymers (Strong, 2006). Failure within a plastic material principally occurs through disentanglement, whereby polymer chains slide past each another. The cause for failure is the same regardless if the polymer is amorphous or semi-crystalline (Lampman, 2003).

- **Thermoplastics** are described by the Association of Polymer Manufacturers in Europe (APME) (2014) as polymers, which can be repeatedly softened when heated and solidified when cooled. This characteristic is due to the intermolecular forces that allow molecules to rebond many times. According to APME (2014) this polymer type is considered the most important class of all commercially available plastics. In this thesis, the focus is on thermoplastics.
- **Thermosets**, contrary to thermoplastics, retain their strength and shape when heated. During molding process, covalent bonds form between molecules. After solidifying, these cross-linked molecular chains cannot be separated by applying heat and pressure. Hence, thermoset plastics can be formed once (Strong, 2006).
- **Amorphous polymers** refer to a molecular structure, in which molecules are structured randomly (Strong, 2006). Generally, amorphous polymers exhibit low chemical resistance.
- **Semi-crystalline polymers** refer to a molecular structure, in which molecules are arranged in an ordered fashion (Strong, 2006). Semi-crystalline polymers exhibit larger shrinkage variation than amorphous polymers.

Characteristics of plastic materials

Plastic is a viscoelastic material and it responds to stresses as a combination of elastic solids and viscous fluids (Strong, 2006). As such, all properties of plastics vary under the influence of load, temperature and environment. Each polymer has its own mechanical and physical properties to consider when designing with plastics. These properties are, for example, the following described by Rosato and Rosato (2003):

- **Strength** represents the stress required to break or cause a failure of a material under external forces
- **Impact strength** is a material's ability to absorb impact energy and deflect without rupture
- **Modulus** is a material's ability to resist deformation under stress, hence the constant denoting the ratio between a physical effect and the force producing it
- **Toughness** indicates material's ability to absorb energy by plastic deformation rather than crack or fracture. That is to say, the energy required to break a material is equal to the area under the tensile stress-strain curve
- **Ductility** is a material's ability to sustain large permanent deformation in tension
- **Brittleness** is a material's tendency to break without significant deformation due to poor ability to absorb energy prior to fracture
- **Glass transition temperature (Tg)** is the temperature under which a plastic behaves like glass and is rigid. Glass transition is a reversible change in phase from a viscous state to a brittle glassy state. Simply stated, it means plastics exhibit brittle properties as temperature decreases and it is also called as ductile-to-brittle transition

2.4 About Checklists

The use of checklists is a common part of several industries from aviation to building construction to medicine and space travel (Gawande, 2009). They provide an effective strategy for ensuring accuracy in complex tasks since the important steps of a procedure are not relying on human memory. Despite their essential role in many industries, very little serious research of them has been carried out (Hawkins, 1993).

According to Bridger (2003) the storage capacity of short-term memory is seven items, plus or minus two. Also, based on this fact Gawande (2009) recommends that a checklist should provide a pause after five to nine items in order to reduce mental workload. The language in a checklist should be simple and exact. A good checklist is efficient and practical and it provides a reminder of important issues and decreases the amount of potential mistakes. On the other hand, checklists cannot make anyone follow them and the attitude of a user influences its effectiveness (Hawkins, 1993).

When creating a new checklist and in order to benefit the most of it, the right type of a checklist must be selected. According to Hawkins (1993) and Gawande (2009), two methods of creating a checklist exist. In a 'do list', tasks are carried out simultaneously when checking them off. Therefore, the checklist can be considered as a recipe for the action. The other method is a 'verification list' where the tasks are performed by memory and experience, and afterwards verified as completed. In this project, the selected type for a checklist is a 'verification list'. This was selected since the list will not be a guideline for designing a plastic part, but a tool for spotting possible failures before tooling.

2.5 Summary of the Main Points

A designer of a plastic part has to evaluate a part's function and requirements from different standpoints. By integrating and optimizing the part relative to the needs of its life cycle stages, benefits can be gained through saved costs, time, environment and improved product quality. The life cycle stages to focus on in this project are:

1. Design
2. Tooling
3. Manufacturing
4. Assembly and handling
5. Service
6. End of life

The reasons leading to a product failure can be seen as a chain reaction. If the designer does not understand the service conditions of the part, the required properties to withstand those conditions will not be identified. This leads to a poor product specification. In turn, this results in poor material selection that reduces the product performance, which falls short of a customer's expectations. The external stresses affecting plastic part's performance can be grouped under four main headings: Short-term mechanical, long-term mechanical, thermal and chemical stresses. The part performance is a combination of its geometry and material properties influenced by processing issues. The plastic part design and manufacturing process are highly interdependent. Tooling and manufacturing set certain constraints to the part design, which influence on the mechanical and visual properties of the product. To facilitate tooling and manufacturing as well as avoid unnecessarily high costs, a designer should integrate the production considerations to the part design early in the design process. The strategy of disposal after the intended lifetime should be considered. For instance, when determining the assembly method the possibility for disassembly can be implemented.

3 METHOD

This chapter describes the approach used in this project. The reasoning behind the selected methods and the analysis of data for the development of the checklist will be explained. At the end of the chapter, the validation method for the study will be described.

3.1 Research Strategy

The aspects to be studied during the research were stated in chapter 1 *Introduction* as follows:

- influences which cause a product failure
- service conditions that affect plastic products performance
- factors that facilitates activities during a product's life cycle

The aim is to study the relationship between design decisions and processing, intended embodiment and part functionality. A challenge in this research is to set apart the essentials that matters only for a designer. Based on these research interests, two research methods were selected. The strategy in this study has been to first achieve a basic understanding of the pitfalls in a design process by a literature review. As the topic rests greatly upon engineering sciences, relevant literature and previously conducted researches were studied. After that, the relevance of the literature findings were assessed by comparing them to the survey results. The purpose of conducting the survey was to filter out the irrelevant details and highlight the key factors and the real life problems. In addition, survey results offered varying aspects into the problem and drawing from different sources increased versatility of the content in the checklist.

3.2 Survey in Companies within Plastic Industry

A survey was conducted to gain subjective experiences of people working in plastic industry and to sum up the occurring shortcomings in the real life. Glenn (2010) states that by conducting a survey, tacit knowledge can be achieved which leads to a deeper understanding of the observed questions. The checklist can be constructed more precisely with the help of practice-based information; hence it fulfills its intended purpose more truthfully.

Sampling strategy

The sampling strategy utilized was theoretical sampling in which the emphasis is put on the potential of each respondent, not on the size of the sample (Taylor & Bogdan, 1984). Glenn (2010) defends this principle by stating that it is better to select purposely fewer samples than randomly many, as it will often give a better insight and it is more appropriate for the validity of the survey. Due to a fixed schedule, the sample was limited to five respondents working in plastic industry in Finland. To cover the full range of perspectives that were of interest, the sample was drawn from different special areas. The final respondents represented professions such as raw material supplier, quality manager and chief designer.

Conducting method

Mail survey was selected as the most appropriate method for conducting the survey. Mangione (1995) names rationales for using mail survey, such as wide geographical distribution of the research sample, modest budget, admit of privacy and relatively free time for answering. The questionnaires were sent during March 2014 and responses were received within 1-2 weeks. All the selected companies answered the questionnaire. Despite the option to answer by phone, all companies chose to answer by mail.

Questionnaire

The approach was intended to collect each respondent's personal interpretation and perception regarding matters diminishing the overall quality. The questionnaire used open-ended questions about how to ensure the feasibility and intended function of a product, and what are the most common pitfalls in the specific areas. The areas of interest were:

- Tool design and fabrication
- Part manufacturing
- Required mechanical and visual properties
- Additional thoughts on designing and manufacturing plastic product

The given themes aimed to provide discussion topics, rather than setting predefined constraints for the answers. Respondents were free to specify what to answer in given topics. The questions or the answers were no further detailed due to the disparity of the companies. However, it was emphasized that the focus is on problems that could be avoided by improved part design. The questions can be seen in Appendix 2: Survey questions.

3.3 Categorization and Data Analysis

The data from the literature review and the survey were analyzed simultaneously. Results from the survey helped to reflect on the literature review and highlighted important issues. The purpose of the survey was not to collect data for statistical investigation. Since the survey was small-sized, the answers were not concerned as a comprehensive truth but a good source to reflect common concerns in plastic part design and processing.

Categorization is a systematic way to develop and refine interpretation of the collected data. The process begins by developing coding categories according to relevant themes, ideas or concepts (Taylor & Bogdan, 1984). The data was categorized into the following sections:

- Requirements in each life cycle stage
- Influencing factors that prevent the product from fulfilling these requirements
- Resulting failure modes due to these influences

The process was carried out simultaneously with compiling the checklist and this procedure will be discussed further in chapter 5 *The Development and Verification of the Checklist*.

3.4 Working Method to Compile the Checklist

The approach for developing the checklist was adapted from Failure Modes and Effect Analysis Method (FMEA). FMEA is an advanced and complementary technique to identify, define and eliminate potential failure modes of a product system (Otto & Wood, 2001). Different types of FMEA methods exist with focus on different aspects. In this work, a Design FMEA (DFMEA) was used. DFMEA is used to uncover design risks and life cycle analysis.

The FMEA method consists of steps by which a Risk Priority Number (RPN) for each failure mode and effect can be produced (Otto & Wood, 2001). RPN is calculated by multiplying the numbers for the likelihood of occurrence, potential severity of the failure and expected control method for detecting the failure. The process also includes development of recommended actions, implementing the corrective actions and recalculating the RPN for the updated design. While FMEA is a suitable method to detect the issues related to the expected quality of a product, it is generally time-consuming and tedious to be carried out by the whole design team. As stated in the objectives, it was desired to create easier and stripped-down version of FMEA that still brings up and prevents possible failures. The comprehensive rating system of FMEA increases the effort and time required to carry out the entire FMEA process and for this reason a rating system was left out. Moreover, as the checklist was developed to be generic enough to apply to diverse plastic part designs, it was impossible to prioritize the severity of any failure mode. The checking method in the list aimed to be based only on yes or no alternatives. The implemented steps in this project were:

1. List requirements of the part
2. List possible causes or mechanisms of the failure
3. Identify and list potential failure modes that could occur

Method to translate the failure modes into questions

The failure modes established were results of overlooked features in a part design or underrated customer service conditions. They were considered as negative needs, which were to be avoided and translated into need statements. Due to the generality, the modes were expressed as written statements without any metric values. The guidelines presented by Ulrich and Eppinger (2000) for writing customer need statements were used in the process:

- "What" not "how" – Express clearly what is expected from the product, but not how to do it.
- Specificity – Express the statement as clearly as the raw data to avoid loss of information
- Positive not negative – Prefer positive phrasing instead of negative, unless it sounds awkward
- An attribute of the product – Express the need as an attribute of the product
- Avoid "must" and "should" – These words imply a level of importance for a statement

These guidelines were considered as general recommendations. Since the statements were expressed in a questioning form, some exceptions were made to avoid weird sentences. In this context, a failure mode is a general term referring to all unwanted occurrences.

3.5 Reliability and Verification of the Checklist

The reliability of the content of the checklist is connected to theoretical research and to the survey results. However, verification is important to ensure that the information included in the list is correct and precise. According to Huang (1996), the aims of verification are to identify the strengths and weaknesses as well as recognize opportunities and requirements for improvements. To identify the opportunities for improvement in the list, Huang (1996) suggests to ask:

- Does it provide focus of attention?
- Is it general enough to cover the specified process range?
- Is the output adequately accurate and useful?
- Can the specialists understand it?

Consulted specialist from plastic industry tested the checklist. As the survey was conducted among experts presenting various professions, also the verification was performed by people from different line of business areas. The consultation of the list was done by persons who did not participate in the survey.

4 DESIGN CONSIDERATIONS

This chapter presents the findings from the literature review and the conducted survey. Aspects related to design concerns, such as choice of material, specifying part requirements, processing effects among others will be discussed.

4.1 Factors in Plastic Part Performance

There is a wide variety of aspects to consider when establishing and evaluating performance requirements for a plastic part. Rosato and Rosato (2003) among others list such concerns as mechanical loading, weather resistance, chemical compatibility, agency approvals, appearance and dimensional tolerances. Expected properties for certain products may be such as coefficient of friction, transparency, flammability, high impact resistance, ultraviolet stability and chemical compatibility. Some of them are specified as absolute values or plain choices while others are a result of concurrent factors (Lampman, 2003).

Part performance and life expectancy

In general, all parts need to meet certain lifetime expectations. During the defined life expectancy, a product is expected to perform its intended function without failure (Jansen & Rios, 2013). It may require a part to withstand repetitions of applied loads and conditions or certain time duration at a specific environment, such as snap-fit arm deflections, repeating steam sterilizations in an autoclave or years in outdoor exposure. Lifetime prediction of plastics requires specifying all types of mechanical loading applied from short-term static loads to vibrational loads. According to Jansen and Rios (2013), predicting the absolute lifetime for a plastic part is nearly an impossible task. However, understanding the mechanisms behind a failure helps to predict how a specific plastic type behaves under certain influences in the user conditions (Shah, 2007). Plastic parts can fail through diverse mechanisms as shown in Table 1, in which failures are categorized by the affecting influence on them.

Table 1. Examples of failures occurring in plastic parts.

Influence	Failure Mode	Cause
Short-term mechanical loading	Brittle fracture Rapid crack propagation	Impact Scratches
Long-term mechanical loading	Creep Cracking Dynamic fatigue Ductile deformation Wear	Constant applied load Cyclic load Vibration
Temperature	Dimensional instability Embrittlement Thermal fatigue Melting	Glass transition Elevated and sub ambient temperatures
Environmental factors	Dimensional instability Environmental Stress Cracking (ESC) Molecular degradation, shattering	Moisture Chemicals, essential oils UV-radiation Extreme weather

Structural part design

Certain performances such as stiffness, strength and impact resistance cannot be specified as absolute values (Lampman, 2003). That is to say, the part's mechanical performance is a combination of part geometry and material's property. For example, a part may require certain stiffness, which means the maximum deflection under a given loading. Part stiffness is the combination of a material's modulus (E) and the moment of the inertia (I) of part geometry. These factors together produce the required ability for a part to resist deformation under stress. In other words, material cannot be selected without some knowledge of basic design principles and vice versa. Figure 5 illustrates stress-elongation curves of stiffness, strength and impact strength performances.

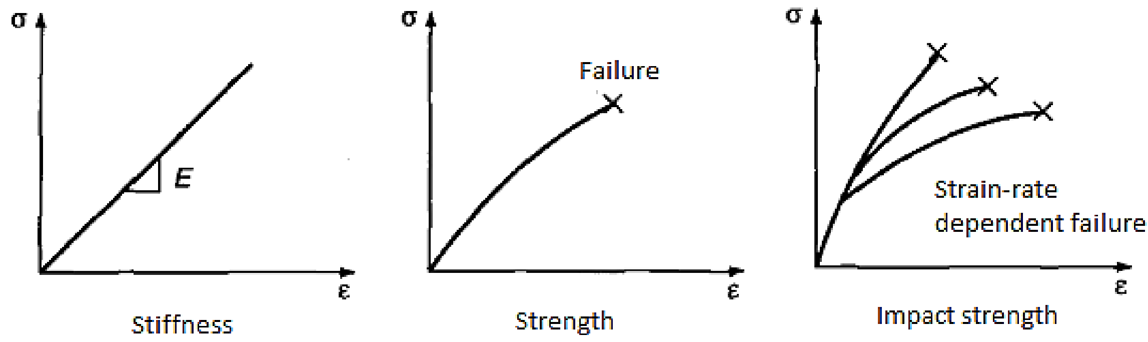

Figure 5. Plastic part performances (Lampman, 2003).

Stiffness can be improved by selecting a material with higher modulus, adding corrugation features and curvature in sidewalls, increasing wall thickness or by reinforcing the plastic resin with glass-fiber. Ribs are also used to increase the strength and stiffness of a part without increasing the nominal wall thickness. User conditions such as elevated temperatures and moisture decrease stiffness (Rosato & Rosato, 2003). If high stiffness is not needed, unnecessary stiffness should be avoided. In general, flexibility improves toughness to a certain extent and provides better durability in use.

The strength of a part refers to the load it can withstand without breaking. Maximum load occurs when the maximum strength of a material is exceeded, resulting in a part failure. The part performance is always influenced by many factors, such as the type of plastic, stress level, temperature and environmental conditions. In some cases, moisture can diminish the performance, especially of polyamide (Rosato & Rosato, 2003). Most plastics lose their strength and stiffness properties as the temperature increases. In addition, the presence of weld lines, gate location and stress concentrations occurred through manufacturing influence on both strength and stiffness. In a cross-flow direction the strength is lower than in a parallel direction (Lampman, 2003). This applies especially to the design of glass-reinforced plastics, but is good to be noted in any case.

Impact resistance can be considered as certain type of stiffness with distinction that the applied loads are impacts or drops. When a high impact resistance is a concern, a part's ability to absorb and distribute impact energy is important. Several design features may decrease a part performance under impacts. Sharp corners and ribs can act as stress concentrators that initiate cracking that leads to a failure. To increase impact strength, a part should be designed to be able to flex. Reducing wall thickness or relocating ribs contributes to energy absorption and distribution.

However, some plastics have a certain wall thickness above which their ability to absorb impact energy reduces (Bayer Material Science, 2000). Additionally, temperature conditions influence impact resistance. The reduction in impact strength is especially severe if the material undergoes a glass transition, which is the ductile-to-brittle transition. It should be noted that even if a product is not to be imposed to high impacts, lower energy impacts should still be considered. According to Tuschak (1985), a sufficient amount of low energy impacts will lower the energy required to break the structure. This phenomenon is known as impact fatigue. When designing machine components and other engineering applications this should be considered to ensure a long fatigue life.

Effect of time

Apart from environmental effects, a plastic part's stiffness or strength does not decrease over time. However, the occurring deformation over time is a response to a constant loading, by which long-term mechanical properties of a part are affected. Based on the type of the applied load, plastics exhibit time-dependent behaviors such as creep, stress relaxation or fatigue. In Figure 6 below, each phenomenon is clarified by presenting them as a function of time.

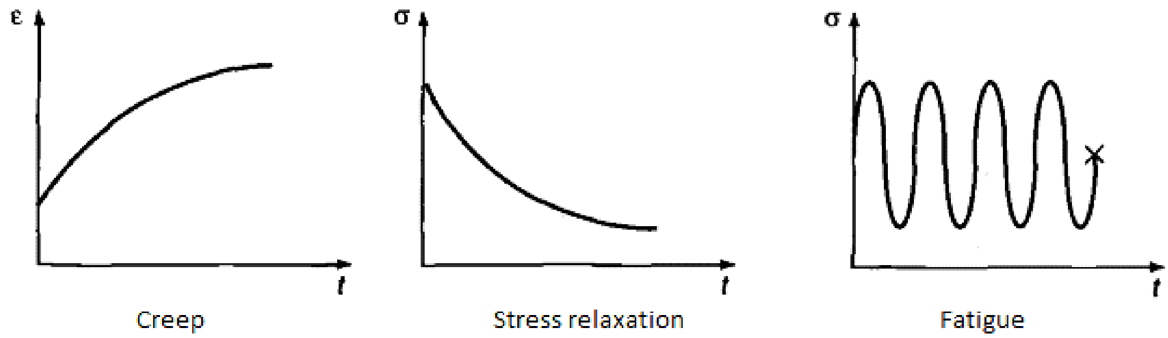

Figure 6. Creep, stress relaxation and fatigue behavior of plastics (Lampman, 2003).

Creep is increased deformation of a part under constant static loading, which can be either tensile or compressive. Stress relaxation refers to reduction of stress when a part is placed under constant strain over time. As an example, in press fit design stress relaxation is a concern. Fatigue is a part failure due to dynamic loading, such as repeated deflections or heavy vibration. For instance, living hinges and one-piece salad tongs require plastics with good fatigue characteristics. Many factors affect creep and fatigue, including notch effects, temperature, stress mode and frequency and part geometry (Bayer Material Science, 2000).

Whenever long-term loading is a concern, it should be noted that over time the strength of a material decreases if placed under stress. In order to avoid a failure, the applied stress level of long-term loading must be significantly below the maximum strength. As mentioned earlier, the diminishing effect of stresses is accelerated in elevated temperatures, such a way that strength properties are gradually lessening above room temperatures (23°C). Additionally, cyclic temperature changes effecting on part should be noted in terms of thermal fatigue (Rosato & Rosato, 2003).

Effect of environment

Environmental influences such as chemicals, UV-light or moisture causes chemical degradation in polymeric materials, which is a reduction in molecular weight causing a failure (Rosato & Rosato, 2003). The concurrent presence of stresses, either internal or external, and chemical agents accelerates crazing of a part resulting in a brittle fracture. This phenomenon is known as environmental stress cracking (ESC) and it is one of the most common reasons for a product failure (Lampman, 2003; Shah, 2007). If a part will be exposed to chemicals in service, the compatibility of the substances must be verified. When specifying the possible chemical exposure on plastics used for consumer applications, the effect of household chemicals such as cleaning agents, makeup or makeup remover and essential oils should be noted (Muccio, 1997). Respondents of the survey stated that it is a common mistake to not consider chemicals and that this leads to last-minute material changes. Certain plastic resins lose their dimensional stability or properties due to water absorption when they are exposed to humidity.

Aesthetical requirements

Aesthetic requirements can set certain constraints for the material selection. For example, a need for transparency reduces the number of possible plastics, especially if the part needs high clarity, since generally semi-crystalline polymers are opaque. When part is being exposed to UV-radiation for long periods, it may cause yellowing of the surface. Visual appearance can be modified by treating the mold-surface, for example creating varying surface finishes or textures. A part's surface finish can vary from matte to highly glossy depending on the requirement. It was brought out among the responses that a rough surface exposes the part to dirt. Therefore, parts used in food-contact and medical applications require usually glossy finish to be easy to clean. On the other hand, by adding texture to a part, molding defects such as minor sink marks and weld lines can be faded and scratch resistance on the surface improved (Bayer Material Science, 2000). Mold-surface textures can be implemented by etching or sparking, in which the material choice has to be considered to ensure the desired result.

Selection between polymer types

As with all materials, also with plastics a designer should be aware of their advantages and limitations. The survey results emphasized the differences between amorphous and semi-crystalline polymers, and the selection between them should be considered early in the design process. A part design as well as tooling and manufacturing are also affected by the choice of material. Amorphous polymers generally have better dimensional accuracy and surface quality but are more prone to fail under continuous loading due to stress cracking. They are usually glassy and transparent. Semi-crystalline polymers exhibit better chemical resistance but their shrinkage properties are harder to control. Therefore, semi-crystalline plastic may be challenging if tight tolerances and dimensional stability are required.

Apart from deciding between the two polymer types, respondents stated that it is important to notice the need for using some special polymer compounding, fillers or additives early in a design process. By modifying the plastic resin used, a wide variety of properties can be improved, such as wear and creep resistance, mechanical properties, thermal properties and dimensional stability (Rosato & Rosato, 2003).

Agency approvals

Plastic parts are often specified for controlling quality and meeting safety requirements (Rosato & Rosato, 2003). In order to use plastic materials in these applications, national or association regulatory requirements may have to be met. Requirements vary from organization to organization and from continent to continent, hence standards must be checked for each material and application separately. As an example for common organizations involved in regulations and standards for plastics that were noted by the respondents and the research were:

- FDA (Food and Drug Administration) for articles with food and bodily-fluid contact
- IEC (International Electrotechnical Commission) for electrical devices
- REACH (Registration, Evaluation and Authorization of Chemicals) for toys or childcare articles
- RoHS (The Restriction of the use of certain Hazardous Substances in Electrical and Electronic Equipment) for electronic and electrical equipment
- UL 94 (Underwriters Laboratories, standard for flammability of plastic materials) for flame resistance requirement

In addition to the organizations listed above, compliance and approval from appropriate agencies must be checked.

4.2 Principles for Tooling

It is essential to consider the effects of the design and material selection of a part on its processability. The importance of understanding the tooling constraints arose clearly among the responses in the survey. Respondents stated that one of the common reasons that causes delays in processing was the unawareness of molding and processing principles among designers. This emphasizes the importance of taking the molding constructions in consideration in the early phases of the design process. Listed shortcomings were related to issues such as gating, parting line and feasible shapes for tooling. For instance, the visual effect of a parting line can be easily overlooked since it is not seen in the appearance of a 3D-model or a NC-machined or 3D-printed prototype.

Tooling basics

Tool fabrication is a complex work, which however can be eased by minor design changes and making compromise between the part aesthetics and the tooling principles. Important design elements which affect both the mechanical as visual performance of a part and which should be incorporated in the design for tooling are gating, parting line and ejector pins.

The gate location has a direct effect on a part's mechanical and visual properties and moldability. As stated earlier, gate area exhibits decreased strength properties, hence gating should not be placed on critical areas. It also determines the mold flow in the cavity, which in turn has an impact on a part's properties. Ideally, the gate is located near the center of a part, but frequently it is not acceptable for other reasons (Maier, 2009). Part removal requires a consideration for ejection surfaces of the part, which allows ejector pins to push the part out of the mold. Part geometry, material and mold finish determines the amount of ejectors needed. A part design that has a small area for ejector pins should be compensated with an extra draft to ensure proper ejection. Generally, ejection leaves pin marks on a part surface, which should be considered in terms of visual requirements.

According to Mitchell (1996), one of the first considerations in a part design is to determine the parting line location. The parting line can be placed on the bottom, top or along the centerline of a part. It can be either flat, stepped or angled. However, any sharp and abrupt lines should be avoided. The parting line is usually transferred onto the part surface as a witness line and flashes may occur in the interface of the mating halves. The need for undercuts should be minimized when selecting the parting line location. Undercuts are sections of the part that cannot be pulled out in the line of draw. If an undercut was to be machined into a mold without a mechanism to release it, the part would be destroyed while the mold opens. Undercuts that cannot be avoided, are realized by different mechanisms built into a mold, such as side-actions or collapsible cores. Often small design changes can eliminate undercuts, as shown in an example for a snap fit design in Figure 7.

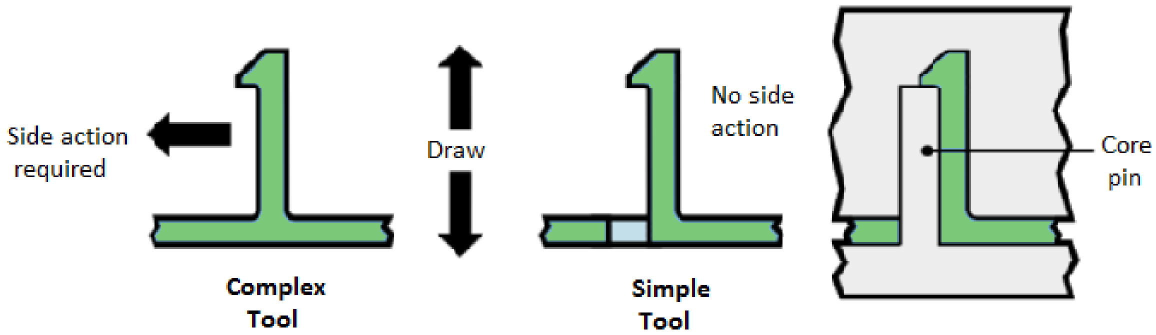

Figure 7. Simplified snap fit design for tooling (Bayer Material Science, 2000).

As mentioned, tool fabrication can increase unnecessarily costs if the principles of tooling are not considered and implemented to the design. For example, unnecessarily small inner radius in internal corners in a mold, which are the outer corners of a part, increases tooling costs due to their tedious feasibility (Kazmer, 2011). Likewise, the survey responses raised that in some cases the selected marking method can needlessly increase costs if the implementing method is not considered in terms of feasibility. Therefore when details such as raised or recessed logos and letters are included, it is good to discuss them with a tool designer. As such, costly, time-consuming and complicated work can be avoided if the certain detail is not a priority. Along with certain marking methods, long and thin cores as well as deep ribs were mentioned to cause issues in tooling. Therefore, such features should be avoided if not particularly needed. They also require special consideration for mold venting, which is a built-in system that allows air to escape from the cavity. The easiest method is to implement venting along the parting line. If venting is insufficient, the trapped air causes visual burn marks on the part's surface and a part may not be completely filled. Along with venting, a possibility for proper cooling system should be kept in mind. Cooling channels maintain the required mold temperature, ensures uniform part cooling and accelerates cycle time.

While a draft angle in a part exists to ease part ejection, a shutoff exists to prevent the two halves of the mold from crashing into one another if there is any slight misalignment on the mold closing (Figure 8). It also provides appropriate clamping force between the halves, that is to say the force required to maintain the mold closed during injection (Muccio, 1997). In general, it requires a draft angle of at least 5 degrees to fabricate a sufficient shutoff.

To achieve a part that is in accordance with its design, it is necessary to inform a tool designer about the required part properties. Based on the survey results, requirements which should be documented are for example the surface areas which are critical in terms of applied loads or aesthetical reasons, placement for the needed markings and the expected quality in each surface of a part. As such, a tool designer can prepare a mold that is in line with the intended part embodiment. Another important factor to discuss is the expected production quantities. It influences the tooling construction decisions, for example the number of cavities and the used steel type, which in turn influences costs.

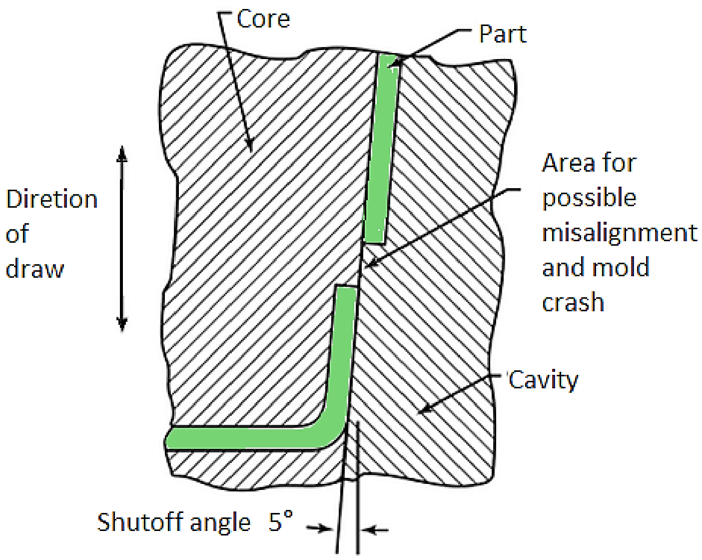

Figure 8. Shutoff angle for ensuring proper mold interface (Mitchell, 1996).

Tolerances and dimensions

According to Mitchell (1996), tolerances are defined as plus or minus a numerical allowance per unit of a linear measure. Tolerances should not be tighter than needed. Tight tolerances add tooling costs and the amount of rejected parts. Several factors effect on achievable tolerances, such as material, part geometry and processing variables. Tight tolerances should be avoided in areas close to the interface of mold halves and on part sections prone to shrink. The dimensions of the part design have to be converted into the dimensions of the mold cavity considering the respective shrinkage. Likewise, the survey results emphasized that it is substantial to make the final selection of polymer type beforehand. Part dimensions are categorized into three areas. Tooling constructive dimensions are the overall part dimensions for fabricating the mold. Critical dimensions impact on part functionality and a tool is revised if these dimensions are out of tolerance. Lastly, inspection dimensions are checked throughout manufacturing to control the processing variability.

Tool revision and ramp-up

During the production ramp-up, the intended embodiment of a part is achieved by testing and adjusting the mold together with the processing parameters. Generally product launch occurs after one or more rounds of pilot production and testing, in which the product design and tooling undergo revisions and the needed adjustments are implemented (Kazmer, 2011). Since the final embodiment of a plastic part is hard to predict in advance, some adjustments are always needed in order to optimize the required performance. Based on the survey results, it is preferable to implement adjustments on the tool by removing the steel than adding it as it is more effective in terms of time and costs. Therefore, a part's features should first be done slightly 'smaller' than intended to leave space for adjustments. This should be noted in a part design.

4.3 Manufacturing Aspects of Design

Along with knowing how to design a tooling-friendly part, it is important to be aware of the processing impact on the part's embodiment. Injection molding process can lower the required performance and visual properties of a plastic part. Mitchell (1996) emphasizes that inappropriate processing parameters cannot compensate for part geometry. While some parameters may decrease the overall embodiment of the part, any adjustments during injection molding cannot improve a poor design. Considerations such as mold flow and cycle time should be included in the design and material selection process. For smooth production, the availability of the selected material is convenient to check in advance.

Part design considerations for molding

Uniform nominal wall thickness in a part design is important. Wall thickness influences several part characteristics, including mechanical performance, appearance, moldability and costs. Uneven wall thickness and thick sections in the nominal wall thickness cause warpage and dimensional instability and visual defects, as sink marks and voids. Sinks refer to local depressions on the part surface and voids are enclosed holes inside a part, as shown in Figure 9 below. While a part's function is not affected by sink marks, they are still to be avoided. Contrary to sink marks, voids can critically diminish the structural performance of the part. Sharp corners in a part create thick sections to the nominal wall thickness, therefore the external radii is ideally equal to the internal radii plus the wall thickness.

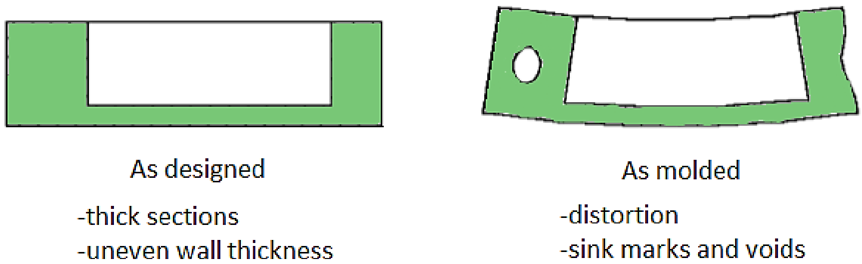

Figure 9. Problems caused by thick sections and uneven wall thickness (Maier, 2009).

The optimal wall thickness is often a compromise between different aspects, such as part durability versus costs. According to Mangione (1995) thickness should be such that it is thick enough for a part to fulfill its function in use, but thin enough to be profitable in terms of cycle time and costs. Thick walls are uneconomical as they unnecessarily waste material, increase the risk of reject parts and lengthen the cycle time by requiring longer cooling time. In rib design, the right location, height and thickness is essential for avoiding visual defects and mold filling problems in processing (Maier, 2009). Sinks are prone to occur to the opposite surface of a rib that is usually the outer surface, hence more critical surface of a part. Rib thickness also determines the cooling rate and degree of shrinkage in ribs, which in turn affects overall part warpage.

Certain part properties are dependent on a wall thickness and therefore determine the minimum required thickness. These properties are for example flammability and electrical resistance. In such a case, the needed mechanical performance of a part should be tested to be functional with the thickness chosen (Bayer Material Science, 2000).

Mold filling

Part geometry and the gate location defines the flow of the molten plastic in a cavity (Mitchell, 1996). When locating the gate, the selected material's flow properties should be noted. The distance from the gate to the farthest spot to fill must be in line with the flow capabilities of the selected plastic resin. The material's flow properties must also be checked relative to wall thickness variations and thin wall sections.

Flow orientation impacts the shrinkage of a part. It has especially a large influence on fiber-filled plastic, which generally exhibit two or three times as much shrinkage in the cross-flow direction than in the parallel direction. On the other hand, unfilled plastics that have even shrinkage properties are only slightly affected by flow orientation (Muccio, 1997). Along with shrinkage, the flow orientation should be considered in terms of the required mechanical properties of a part.

Weld lines affect both mechanical and visual properties of a part. They occur when two plastic melt fronts merges. Consequently, whenever there are holes in a part, there will be a weld line as shown in Figure 10. They should be placed on areas that are not critical for part's function by relocating the gate, if possible. The location of weld lines can be anticipated by mold flow simulation.

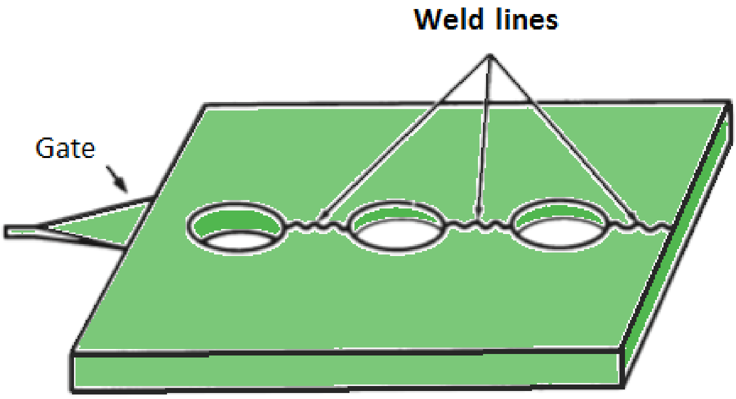

Figure 10. Weldlines (DuPont, 2000).

If there are varying thicknesses in a part, the filling should be initiated from the thickest section of a part. Thin-to-thick finning scenario causes sinks and filling problems, such as pressure drop in a cavity. Another concern is the so called hesitation effect. That is to say, the melt flow first fills the thick sections of a part and hesitates in the thin wall sections, leading to improperly filled part and surface defects. The fact that any fluid, including plastic melt, takes that flow path which transfers the least amount of resistance to it causes this phenomenon (Mitchell, 1996). Likewise, the survey responses mentioned that the gate location must be paid extra attention if there are living hinges in the part design. Due to the nature of flow, if the gate is located near to the hinge, the melt fills the cavity only partly and do not flow across the hinge area to fill the entire mold evenly. It may cause material reaching solidification around the thin hinge area and a pressure drop in the cavity resulting in a product with bad quality and a hinge failure. To overcome the filling issue with hinges, gating should be placed far away perpendicularly to the hinge so that once the melt reaches the hinge, it will continue flowing across it without interruption. The proper filling can be aided by generous radii in the inlet to and exit from the hinge area (Tres, 2000).

While molten plastic is injected into the cavity under a high pressure, it can cause internal stresses between molecules in the plastic. As the molded-in stress level increases, mechanical properties and dimensional stability decreases, chemical properties lower and optical properties diminish (Rosato & Rosato, 2003). Especially the gate produces stresses around it, so also for that reason it should be placed in a non-critical area in terms of a part's function. Molded-in stress can be reduced by ensuring that part geometry with proper gating allows balanced melt flow in a cavity along with avoiding sharp corners and radii. If a part is completely filled with uniform pressure and cooled evenly, internal stresses between molecules come to equilibrium and the part is less likely to warp (Rosato & Rosato, 2003). As such, with less distorting of molecules, the less stress concentrations are built into the part.

Cooling

Cooling is generally the longest phase of a molding cycle. Based on the design guideline of Bayer Material Science (2000), the cooling time of a part increases as a function of part thickness squared. That is, by doubling wall thickness the cooling time quadruples. This should be noted in defining the nominal wall thickness. In addition, sharp corners and small pockets in a part also require longer cooling time leading to a longer cycle time.

As mentioned earlier, plastics tend to shrink while cooling. Amorphous plastics exhibit more uniform and predictable shrinkage behavior than semi-crystalline. If tight tolerances are required, asymmetrically shrinking polymers should be avoided (Mitchell, 1996). Besides the choice of material and part geometry, shrinkage behavior is influenced by factors such as possible additives, injection pressure and mold heat (Rosato & Rosato, 2003). Changes in nominal wall thickness should be minimal and gradual for ensuring equal cooling of all surfaces and minimizing residual stresses. Wall thickness variation causes differential cooling, when thin sections of a part are cooled faster than the thicker ones. It leads to sink marks and warpage, which means the part twists and bends out of shape.

Ejection

Draft angles facilitate ejection of the part during manufacturing. Based on the survey results, examples of shortcomings regarding improper draft are damaged or distorted parts or a part that stays on the wrong side of a tool when the mold opens. Therefore, all surfaces parallel to the direction of draw should be drafted, including ribs and other design features. If texture is used in the part decoration, an extra draft should be added. In the case when draft is not acceptable, ejection may require collapsible cores or such mechanism that increase the cost of tool fabrication. Furthermore, the mold steel can be polished in the direction of ejection to ease part removal.

4.4 Assembly and Storage

Any assembly or secondary operation on processed part must be evaluated for compatibility to avoid failures. According to Shah (2007), failures arising from stress cracking around metal inserts or other joins are quite common. As in part design any feature critical for function should not be placed near sharp corners, sink marks, gating or weld lines, similarly should not be assembly features either (Mitchell, 1996). The underlined issues regarding assembly concerns among the respondents were the joined materials movement relative to each other, tolerances and the effect of the applied stresses in parallel with environmental stresses among others.

Designing plastic parts for assembly

When product assemblies are designed, there is a possibility for minimizing the number of parts and a need for non-plastic parts. Replacing mechanical fasteners in assembly, such as screws and bolts, reduces assembly costs and facilitates dismantling for repair, maintenance and recycling (Bayer Material Science, 2000). As listed in chapter 2.2 *Designing a Quality Plastic Part for Life*, the assembly methods utilized in plastic design are snap fits, press fittings and living hinges.

In product assemblies, foremost is the understanding of the instance of use relative to the intended life expectancy and the long-term part performance. For instance, a snap fit may be permanent (joined only once) or reusable (allows repetitive cycles) (Tres, 2000). Hence, in reusable assemblies, the selected material's capability to withstand the deflections relative to the anticipated instance of use has to be noted. The flexure during assembly should be below the allowable strain limit of the material. The force required to assemble and disassemble parts is depending on the part geometry and coefficient of friction. Besides the material's property, the friction coefficient varies also according to the surface roughness of the mating parts. As material wear due to usage, the gradual smoothening of the surface should be noted when high friction is required. When dissimilar materials are being joined, differences in thermal expansion must be considered. It may result in decreased interference due to shrinkage or expansion of one material away from another, or occurrence of thermal stresses as temperature increases. Similarly swelling due to moisture absorption is to be considered. Another concern is plastic material's stress relaxation under continual loading as discussed earlier. Therefore, for instance, reduced holding power of press fit assemblies can be expected in the long run (DuPont, 2000).

Supported assembly

Molded parts can be designed with various features that simplify assembly and secondary operations, reduce scrap and costs and prevent assembly errors (Bayer Material Science, 2000). Often a part only needs minor modifications in order to apply the facilitating details into it. For instance, chamfers added to the leading edges align the mating parts, which reduces the positioning accuracy needed in the assembly. Orienting features prevent assembly unless the components to be joined are positioned right. Responses mentioned that accommodating the processing variability to the part design reduces the need for tight tolerances and enables assembly even if a part is slightly distorted. Furthermore, it was stated that frequently in a factory parts are being handled by robots, for which a proper place for suctions cups is requested.

Finishing operations

According to the information given in responses, the possible required finishing method is frequently missed in the design. Once the part has been molded, plastic part may need finishing operations due to aesthetical reasons. Decorating can be implemented in several ways depending on the desired result; choices are for instance laser marking, tampo printing, hot stamping and vacuum metallization among others. The finishing of a part should be discussed and considered in the design process since they may limit the choice of material and part design. One comment among survey results raised that the use of silicone as a mold-release agent to ease removal reduces the adhesion of the paint. This can cause issues in finishing, hence it is good to be noted in draft design.

If the cold-runner type is used, that is to say, the gate stays to the molded part after removal form the cavity, the remaining gate has to be removed from the part. This process is called degating. Degating can be done in several ways, such as by simply "snapping off" the gate system, using hand tools such as side cutters or employing dedicated trimming fixtures. If aesthetical requirements are high, the gate mark can be faded away, for instance by using hot-air remelting (Bayer Material Science, 2000).

Storability

Practical storability refers to organized and efficient approach towards storing the product (Huang, 1996). Plastic parts are frequently being stacked either in a warehouse or a store. Storage may be inefficient if the parts cannot be stacked, thus using unnecessarily much space. Sometimes parts are damaged while stacked. For instance, visual defects may occur. To support stacking, features such as ribs can act as stoppers to prevent defects and parts from sticking to each other while being stacked. Another concern is transportation conditions. Muccio (1997) presents a case, in which the presence of vibrating cyclic loading during shipping was not considered in material selection, leading to products being cracked or broken. Similarly, the temperature range during transportation and in a warehouse can greatly differ from the specified end-user environment (Lampman, 2003).

4.5 After Use and Recycling

In plastic design, there are several ways to implement good environmental practices. Optimizing the wall thickness, reducing the scrap material and considering the packaging of the part, natural resources can be saved, as well as it generally reduces costs, too. In choice of material, thermoplastics are better for recycling than cross-linked thermosets (Maier, 2009).

Plastic recovery

The common recycling methods for plastic were found to be mechanical recycling, feedstock recycling and energy recovery (Maier, 2009). For mechanical recycling, suitable feed material is plastic containers, post-industrial waste, post-consumer waste and such. In mechanical recycling, the concern is the separation of different plastics. If different polymer types are mixed, the value of the regrind material reduces since its properties distinguish. The streams for feedstock recycling are laminated and composite plastics, low quality mixed plastics and contaminated plastics. All plastic feed cannot be sustainably recycled due to lacking technology for sorting or the amount of non-plastic waste among the plastic fraction. For this type of stream, energy recovery is the most efficient recycling method from economic and environmental perspectives (APME, 2014).

Disassembly

In cases where a product is to be assembled, assembly techniques that allow easy disassembly should be used. Implementing a possibility for disassembly facilitates recycling and removal of hazardous materials (Huang, 1996). As disassembly is a converse action of assembly, therefore recycling aspect should be implemented in parallel while considering assembly methods (DuPont, 2000).

Snap-fits are the easiest to dismantle and recycle. Similarly, screws and press-fits are suitable for recycling but more time-consuming and difficult to dismantle. Living hinges are not applicable for disassembly as it unifies two parts. Therefore, in cases of 2K-living hinge applications, that is two separate materials combined, the application is not suitable for recycling but to be recovered feedstock or energy (DuPont, 2000; Maier, 2009). These are presented in Table 2 below.

Table 2. Comparison of assembly methods for recycling and disassembly.

Assembly technique	Recyclability	Disassembly
Screw	Good	Good/ time consuming
Snap-fit	Very good	Very good
Press-fit	Good	Poor/ reasonable
Living hinge	Not applicable if it contains mixed materials	Not applicable

When product assemblies are to be dismantled for recycling, foremost is the need for identification of the plastic material (Maier, 2009). Ideally, products would consist of only one polymer type, but as applications often need to perform various duties, it requires the use of different materials. The part material should be recognizable by coding, for example PA66-35GF, which is for polyamide 66 with 35 % fiberglass reinforcement. Inserts, labels, chromium plating and other additional non-plastic materials should be easily removable (DuPont, 2000). As the part design is a compromise, recycling is only one consideration at the product development stage. Therefore, design for recycling is essential but should not be done at the expense of function or service life of a product. From the environmental standpoint, the most essential is to design an unbroken part with the required properties and a long-lasting lifetime.

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5 The Development and Verification of the Checklist

This chapter presents the development process of the checklist. It clarified the method for implementing the collected data and the tool used in the process. Lastly, the results of the reliability testing are presented.

5.1 Requirement and Influence Analysis

The procedure for arranging the data was carried out concurrently with the research. The preliminary framework for categorizing requirements and influences was based on the findings drawn from the pre-study. As mentioned in chapter 3.3 *Categorization and Data Analysis*, the findings from the survey and the literature review were analyzed and divided into three sections. These sections were the requirements in each life cycle stage, influences that prevent the product from fulfilling these requirements and the resulted failure modes due to these influences.

The process started by listing requirements of a robust design relative to the different life cycle stages. The aspects which should be defined in a product specification in terms of a plastic material according to Rosato & Rosato (2003) among others were used as a base for scrutiny of the requirements. These aspects were listed in chapter 2.2 *Designing a Quality Plastic Part for Life.* The requirements were listed on the assumption that the goal is to produce a part that functions as intended under all environmental and user conditions, facilitates processing and takes environmental issues into consideration. While the study proceeded, some factors were added and others removed according to the results from the survey and the later literature review. The possible sub classification under sections was done afterwards based on the similarity of the items. It is worth noting that certain requirements regarding part performance are not relevant in all cases and specifications vary from application to application and from material to material. The final requirements in each life cycle stage are discussed below and altogether they can be seen in table 3.

Design

In the design stage, the product specification must be appropriately defined. Therefore, the first step is to specify the user requirements. The requirements of a part performance must be understood and specified since that is a prerequisite for material selection. The service conditions in which a part will be operating must be specified and the functionality of a part in the given environments must be verified. A request for agency approvals must be considered as well as the effect of the manufacturing process on the part embodiment. Obviously, during the design stage the whole life cycle is to be considered. Hence, design decisions are also influenced by all the proceeding life cycle stages.

Tooling

In the tooling stage the requirements were divided into three categories: Proper documentation for a tool designer regarding a part design, integration of tooling constraints into a part design and facilitators for production ramp-up.

By proper documentation is meant the information regarding the part design that a tool designer should be aware of in order to be able to prepare the mold, which is in accordance with the intended product embodiment. Items included are critical dimensions, areas requiring defect-free surface, material's shrinkage behavior and suchlike. Secondly, integration of tooling constraints into a part design stands for understanding the molding principles and considering the part design in terms of tool feasibility. For example parting line, gating strategy, surface finish and unnecessary small radii are mentioned in this section. The third point, facilitating production ramp-up provides considerations for adjustment allowance. Altogether, the tooling requirements aim for easing the job but also considering the tooling related costs. The influencing factors on tooling were part design, material selection and the expected production volume.

Table 3. Requirements and influences relative to a corresponding life cycle stage.

Life cycle stage	Requirements	Influences
Design	Specified and understood part behavior under anticipated service conditions Consideration for the whole life cycle Agency approvals	Part geometry Material selection Manufacturing Short-term mechanical stresses Long-term mechanical stresses Thermal stresses Environmental stresses
Tooling	Proper documentation Integrated tooling principles Adjustment allowance	Part geometry Material selection Production volume
Manufacturing	Effective cycle-time Proper mold filling Material availability	Part geometry Material selection
Assembly and handling	Error-free assembly, Practical handling	Part geometry Material selection
Service	A product that functions as intended; Sufficient strength Impact resistance Stiffness Friction Dimensional accuracy Surface quality	Part geometry Material selection Manufacturing Short-term mechanical stresses Long-term mechanical stresses Thermal stresses Environmental stresses
End of Life	Minimal environmental impact	Part geometry Material selection

Manufacturing

In the manufacturing stage the requirements were divided into three categories. The requirements aim to support process stability and efficient cycle time and ensure the availability of a selected material. The process stability can be supported by part design by enabling balanced and proper mold filling. It should be noted that the various manufacturing parameters has an effect too, not only the factors listed here. Effective cycle time is dependent on the part geometry. Therefore, wall thickness, unnecessary thick sections in a part as well as small pockets among others are brought out in this section. The relationship between the design features and production costs is also included. Affecting factors relative to manufacturing process are part geometry and material selection.

Assembly and handling

Requirements of the assembly stage were based on practicality and possibility for error-free assembly. These needs can be facilitated by certain small design features such as alignments and drafts. Handling requirements consisted of practicality. By practical handling is meant that a part can be easily stacked if needed, parts do not stick to one another and parts do not get damaged under transportation. Part geometry as well as material selection has impact on facilitated assembly and handling practices.

Service

From an end user's standpoint, the categories of requirements consisted of the expectations of the part performance under varying environmental conditions. Based on the research results, the important properties in terms of a part's durability and robustness were strength, impact resistance and stiffness. In terms of functionality of a part, dimensional accuracy as well as friction properties are important. The aesthetical properties of a part are of interest to a customer as well. The part's performance is influenced by the design decisions, which were material selection and part geometry, and also by the external stresses and time.

End of Life

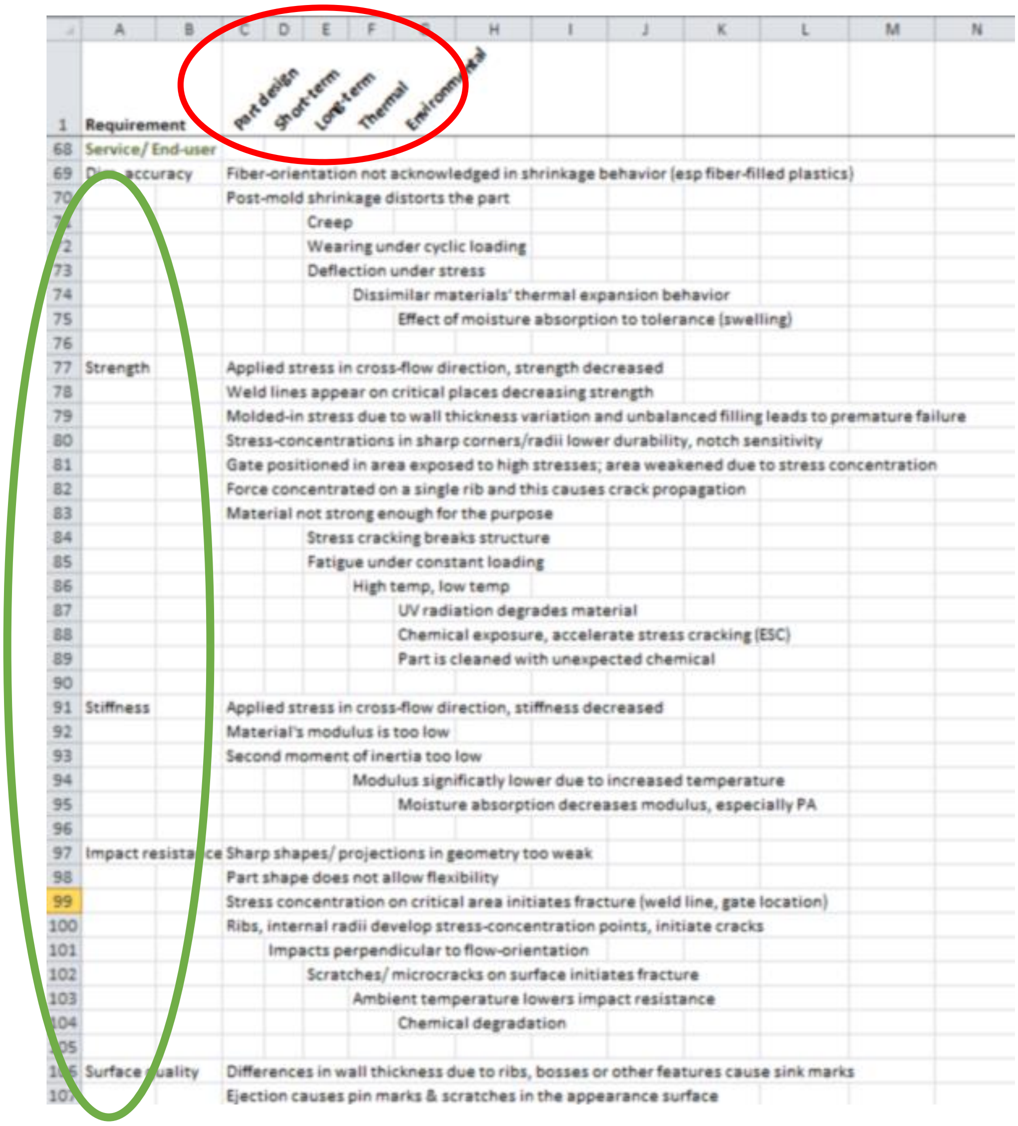
Requirements in end of life stage aims for a minimal impact on environment. Aspects such as identifying mark of the polymer type, material consumption and possibility for disassembly are included. The end of life and possibility for recycling a part after its intended lifetime are affected by part geometry and material selection.

5.2 Formulating the Content of the List

To organize the wide array of data, the tool called failure mode matrix was developed. The requirements and influences listed above were used as factors, that when summed up produced a possible failure mode. As mentioned earlier, in this context a failure mode is a general term referring to all unwanted occurrences.

Screening failure modes

To find the potential failure modes relative to each requirement, a systematic screening method was used in the process. A screenshot of this tool is shown in Figure 11 below (for a detailed picture, see Appendix 3: A screenshot of the failure mode matrix). Requirements were placed as row labels (pointed by a green circle), and diminishing influences were used as column labels (circled with red). By cross-checking each influence with each requirement, it was studied if the desired property or facility is affected by the influence. The possible failure modes were thoroughly scrutinized and listed into the corresponding cells. By this method, all requirements and influences were systematically cross-checked.



	Requirement	Part design	Short-term	Long-term	Thermal	Environmental
68	Service/ End-user					
69	Dim. accuracy	Fiber-orientation not acknowledged in shrinkage behavior (esp fiber-filled plastics)				
70		Post-mold shrinkage distorts the part				
71				Creep		
72				Wearing under cyclic loading		
73				Deflection under stress		
74					Dissimilar materials' thermal expansion behavior	
75						Effect of moisture absorption to tolerance (swelling)
76						
77	Strength	Applied stress in cross-flow direction, strength decreased				
78		Weld lines appear on critical places decreasing strength				
79		Molded-in stress due to wall thickness variation and unbalanced filling leads to premature failure				
80		Stress-concentrations in sharp corners/radii lower durability, notch sensitivity				
81		Gate positioned in area exposed to high stresses; area weakened due to stress concentration				
82		Force concentrated on a single rib and this causes crack propagation				
83		Material not strong enough for the purpose				
84				Stress cracking breaks structure		
85				Fatigue under constant loading		
86					High temp, low temp	
87						UV radiation degrades material
88						Chemical exposure, accelerate stress cracking (ESC)
89						Part is cleaned with unexpected chemical
90						
91	Stiffness	Applied stress in cross-flow direction, stiffness decreased				
92		Material's modulus is too low				
93		Second moment of inertia too low				
94					Modulus significatly lower due to increased temperature	
95						Moisture absorption decreases modulus, especially PA
96						
97	Impact resistance	Sharp shapes/ projections in geometry too weak				
98		Part shape does not allow flexibility				
99		Stress concentration on critical area initiates fracture (weld line, gate location)				
100		Ribs, internal radii develop stress-concentration points, initiate cracks				
101			Impacts perpendicular to flow-orientation			
102				Scratches/ microcracks on surface initiates fracture		
103					Ambient temperature lowers impact resistance	
104						Chemical degradation
105						
106	Surface quality	Differences in wall thickness due to ribs, bosses or other features cause sink marks				
107		Ejection causes pin marks & scratches in the appearance surface				

Figure 11. A screenshot of the failure mode matrix.

As an example, in the manufacturing stage one requirement was “efficient cycle time”, which is influenced by part design. The troubles occurring in the manufacturing process were then studied from the literature as well as the survey results, and listed in a corresponding cell in the matrix. The possible failure modes caused by part design were established as follows:

- Too thick nominal wall thickness for required cycle time
- Sharp corners extend cooling
- Small pockets in geometry cool slowly which extend cooling time
- Inadequate draft in part complicates ejection and increases cycle time
- Lack of extra draft in parts with textured surface complicates ejection
- Part sticks to the wrong side when mold opens
- Part is being distorted by unbalanced ejection
- Part surface is being scratched by ejection

The modes were searched for in a broad-minded manner. Diminishing issues related to each requirement were listed quite freely and afterwards the non-essential things were shifted out. Items were reduced by analyzing and comparing the data together with Sytyte Oy.

Translation of Failure Modes

The established failure modes needed to be altered in question format for the checklist. The guidelines for translating written statements presented by Ulrich and Eppinger (2000) listed in section 3.5. *Working Method to Compile the Checklist* were used in the process. Since there were hardly any metric values established among the failure modes, it was important to express the questions clearly. Correspondingly, Gawande (2009) states that a checklist must be simple and exact, as mentioned in chapter 2.4 *About Checklists*. The translation was done in collaboration with the commissioning company.

As mentioned, the checking method in the list was to be based on yes or no alternatives without prioritizing the severity of failure modes. The questions were formed in such a manner that by checking "yes" the certain issue has been discussed and under control, whereas "no"-cross signifies a concern which is not thought about and is a relevant risk for causing a failure. The sentences were formulated to be informative in order to indicate a possible consequence of each concern. For instance, the above-mentioned sentences were translated as follows:

- Is the nominal wall thickness observed and unnecessary thickness removed to decrease cycle time and material consumption?
- Is a single thick area that dominates the cycle time observed?
- Are unnecessary small pockets eliminated which cannot be cooled efficiently?
- Is there adequate draft to ease ejection and to ensure that the part stays on the right side of the mold as the tool opens?

5.3 Establishing the Checklist

The objective of the checklist was to enable the user to perform scrutiny in a logical order, understand the relation between a part requirement and a diminishing influence without missing important aspects. Unnecessary overlapping of subjects and repetition of concerns were to be avoided. When organizing the content, many items were left out and many were combined.

The approach in building the structure for the list was based on the sequence of life cycle stages in a way that each stage forms a separate section. Each failure was concerned from that standpoint to whom it appears and positioned into a respective life cycle section where it can be discovered. For instance, a tool designer fabricates a mold without sufficient draft but it is the manufacturing operator that confronts the lack of adequate draft. Therefore, a question regarding drafts is placed in the manufacturing section. Similarly, weld lines occur during manufacturing but their possible diminishing consequences are shown to the end user hence that is counted as a concern of the service section.

As stated earlier in chapter 1.3 *About the Problem*, a robust design is a combination of engineering quality and customer quality (Otto & Wood, 2001). At first, engineering quality and customer quality were to be discussed separately in the design section and in the service section respectively. However, it turned out that the concerns regarding these qualities were overlapping and the dividing line between them was somewhat vague. For simplicity, the working assumption was that the target for engineering quality is defined in a way that a customer's quality perception will be satisfied. A case apart is customer needs that are unrealistic to fulfil due to the nature of plastic materials, such as a wish for using a plastic container as an oven dish. As such, these both quality ideas are included and handled as a whole in the service stage. In the service section, the questions were subcategorized under three segments according to the initiation of the influence. These are design, manufacturing and long-term effects. The design segment includes questions concerning part geometry and material selection. The manufacturing segment consists of issues occurring through processing and lastly, long-term effects are occurrences that are effected by time and user conditions.

The results from the pre-study showed that an improper product specification together with a poor material selection cause a majority of premature product failures. Additionally, the survey results pointed that the selected material frequently has to be changed relatively late in the process due to discovering important properties that were previously overlooked. For this reason, a preliminary checkup-list was formed that questions the product specification. It aims to ensure that the product specification is adequate and important aspects have been discussed and understood early in a design process. Hence, the checklist is of more benefit if this section is noted at first and upfront.

Since the implementation method of the complete list was undefined, there were no objectives regarding its layout. As such, the visual appearance was not the focus during the process. Minor changes were made to reduce the heavy impression of the list. Alternating the background color of each row eased the perception. For the same reason, the line style between the items was made lighter.

The recommendation discussed in chapter 2.4 *About Checklists* according to which the number of items between a pause should be seven, plus or minus two (Gawande, 2009) was followed to a certain extent. The list of proper documentation for a tool designer exceeded this rule, otherwise the number of items in each section was kept below nine.

5.4 Verification

Testing and verification are important steps in all kinds of development processes. As stated in section 3.5. *Reliability and Verification,* the aim of verification was to identify the strengths and weaknesses as well as recognize opportunities and requirements for improvements. The attendants in testing were asked to give thoughts concerning possible irrelevant, unclear or missing issues as well as good and important points. They represented different lines of businesses within a plastic industry and if applicable, they were asked if such a list was useful in their own work. The respondents were gathered by inviting them to participate in assessment through social media. Feedback was received from four persons, to whom the checklist was sent per mail and also the responds were received per mail.

Suggestions for improvements

A wide array of feedback and new aspects were given through the testing. The content was said to be fully relevant, yet it was pointed out that a user of the list is required to be familiar with the terminology of plastic design and manufacturing in order to understand it completely. One reviewer was of the opinion that going through the entire list might be too heavy for some designers, even though these factors should be of interest to all product designers dealing with plastics. Some parts of the list was said to be overlapping, which was not considered wrong, but only emphasizing the interrelationships between varying factors in plastic design.

It was recommended to outline the constraints related to material selection and the difference between amorphous and semi-crystalline polymers. Additionally, outlining a need to use special compounding, additives or resin fillers were requested. The importance of proper documentation for a tool designer was emphasized and some new aspects were pointed out to be added in there. Furthermore, the total life cycle management in terms of quality related costs was noted. Decisions made with a view to save money or time in production during the early phases of a design process frequently turn out to be costly over long-range production due to condition of tools, maintenance and poor product quality. To bring out more of this aspect, it was suggested to emphasize the influence of decisions regarding part and tool design on costs of production and tool maintenance.

Strengths of the list

The general estimation of reviewers was good. All respondents stated that the content of the checklist is comprehensive and understandable. The different standpoints and the life cycle approach in the checklist were found practical. The list was said to bring out the whole picture and remind of aspects throughout the process. A separate list of the needed documentation for a tool designer was considered good, also certain issues such as consideration for the effects of user conditions, tolerances and compatibility of assembled materials were said to be well noteworthy. The reviewers were of the opinion that some kind of a checklist would be useful in their own business since from time to time there are certain issues causing problems. Frequently a feature in a part design has to be redesigned due to inappropriateness for tooling. Similarly, often the selected material has to be changed due to overlooked, insufficient properties when a tool has already been fabricated.

Implementation of the feedback

The feedback was covering issues that affect functionality and processability of a part. The implemented points into the list were concerning for example a part’s suitability for secondary operations, material selection, aesthetical defects and external loads. The difference between amorphous and semi-crystalline polymers was emphasized as it is recommended to be aware of the diverse limitations and challenges they set for a design. Also several items were amplified according to the given proposals. These were regarding tolerances, agency approvals and production quantities among others.

When applying new points into the list, the existing balance between generality and particularity in the list was maintained. Naturally, experts from different areas tend to consider diverse issues to be important according to their own line of business and offer recommendations according to their view. Some of the suggestions were highly relevant but quite detailed and to keep the content somewhat simple, certain issues were left out. Since the pitfalls and shortcoming were to be considered from a designer’s standpoint only, some comments were ignored as they were beyond a designer’s influence. To overcome the problems that were brought out but ignored, a coherent communication and cooperation between the product designer, tool designer and manufacturing operators alike is required.

6 THE RESULTS OF THE PROJECT

In this chapter, the outcome of the project is presented and summarized. The embodiment of the checklist is compared to the objectives set for it.

6.1 The Completed Checklist

The project resulted in a checklist for plastic design which covers the life cycle stages of a product from design to the end of life. The list provides various aspects to consider in terms of external disturbances which may affect the intended embodiment of a product. In addition, the standpoints of facilitated production as well as environmental issues are included. By considering the aspects brought out in the list, the occurrence of regular undesired shortcomings can be minimized. An excerpt of the list is shown in Figure 12 below and the full checklist in Appendix 1: The checklist.

The list consists of questions regarding design issues cause unanticipated troubles or premature product failures. The questions are divided into sections based on the life cycle stage to which they are related to and in which they occur. Additionally, a list of important things that should be noted and discussed early in a design process was compiled. The total amount of questions in the list became 112, out of which the majority are addressed for concerns related to part performance in service. The order of the sections is as follows:

- Preliminary specification checkup
- Design for service
- Design for tooling
- Design for manufacturing
- Design for assembly and handling
- Design for after use and recycling

Please, consider the effects stemming from each section to ensure the required part performance.		✓	CHECK THIS
DESIGN FOR SERVICE			
	Strength		
Design	Is it tested that part geometry together with the selected material is able to withstand specified loads, e.g. by calculations, prototype?		
	Is the part's ability to withstand the expected loads tested at the highest specified service temperature?		
	Is the part's ductility tested to be sufficient in lower service temperatures despite a decreased toughness?		
	Are stress concentrators which may initiate crack propagation eliminated, e.g. single rib, small inner radii?		
Processing	Is the decreased strength in a cross-flow direction considered?		
	Is gating located on area that is not critical in terms of strength?		
	Are the areas subjected to external forces free of weldlines? (NB. decreased strength and durability)		
	Is the occurrence of molded-in stresses minimized by even wall thickness (especially critical on amorphous polymers)?		
Long-term	In case of continuous loading, is the stress level significantly below the maximum strength to avoid stress cracking? Is the effect of elevated temperature noted in this?		
	In case of cyclic loading, is the stress level significantly below the maximum strength to avoid breakage due to fatigue?		
	If the cyclic loading is varying between pulling and compression, is this noted on fatigue calculations as highly aggressive exposure?		
	Are cyclic temperature changes considered in terms of thermal fatigue?		
	Is the selected material compatible with all identified chemicals?		

Figure 12. An excerpt of the checklist.

The difference between the newly developed checklist and the existing guidelines and checklists is the divergent concept. During the benchmarking in the pre-study, nothing alike was found. The new checklists provides pre-considered failure modes and additional information of the consequences. Apart from covering for the whole product life cycle, it also brings attention to the combination of the part geometry and the selected material.

6.2 Analysis of the Outcome

The objective of the checklist was stated improve the overall quality of a plastic part. The main benefits to be achieved by using the checklist were listed in chapter 1.5 *The Checklist* as follows:

- Embodiment of a product that is in accordance with its design and fulfills the requirements in varying service conditions
- Adequate part geometry that facilitates tool fabrication
- Adequate part geometry that supports production stability
- Reduced lead time and savings through the complete workflow

The product requirements vary from application to application and are dependent on the material of choice. In the list, the customer requirements listed were the factors that most commonly are of a concern when predicting the part performance. In specific applications, additional requirements may be defined. Therefore, a generic checklist as developed in this case may be lacking of certain factors regarding distinctive concerns.

Tooling costs are directly related to the part geometry, and these issues were brought out in the list. As stated, part geometry influences production variability along with several injection molding parameters. Therefore, not only the part design but also the manufacturing operators are responsible for the stability of production. If the part design is inspected before tool fabrication, the compatibility with the material and user environment is verified and the required part performance is tested properly. This minimizes the need for major changes which leads to a smooth production ramp-up.

The research problems regarding quality perceptions and affecting influences were to be covered in the process. Two quality perceptions were stated; customer quality and engineering quality. In the list, both these perceptions were covered. In addition to these, product quality is perceived during the life cycle stages by operators dealing with the product. For example, the moldability of a part design affects a tool designer's quality perception and a distributor perceives storability related quality. It led to the conclusion that the total quality of a part consists of the optimized solutions in terms of the needs occurring during throughout its all life cycle stages. As such, the checklist covers the stages from design to disposal.

Several factors influence the performance of a part. These were specified as external, internal and unit-to-unit factors. In the case of plastics, external factors such as temperature and loads, greatly affect internal factors, like material wear and other changes. These were covered and used as a base for specifying service conditioning factors. Unit-to-unit is related to production variability due to alternation in raw material. This aspect was beyond the area of this research, hence not discussed. However, variability in processing due to part design was covered and included as mentioned above. As such, the main objectives set for the checklist can be stated to be very nearly fulfilled.

7 CONCLUSION

This chapter concludes the project. The outcome of the research is reflected to the objectives set for it and the main points are summarized.

7.1 Summary of Results

As stated in chapter 1.4 *Objectives*, the objectives of this project were, given a distinctive focus on a designer's point of view in a product development process, to:

- Study the influences which cause a product failure
- Study the service conditions affecting plastic product's performance
- Study the factors which facilitates activities during a product life cycle
- Compile a checklist which contributes to improving workflow in processing and preventing premature failures of a plastic product

The results were the following:

- The underlying reasons for a product failure were studied and four main categories, to which they are falling, were found. Based on the literature review, these categories are defined as inadequate product specification and material selection, design flaws, processing influences and misuse.
- Affecting influences were studied through the literature review and the conducted survey. In conclusion, the performance of a plastic product is a combination of its geometry and the properties of the material used. The external stresses effecting on a plastic part's performance can be divided into the following sections: short-term mechanical, long-term mechanical, thermal and chemical.
- Data regarding the facilitators during a product life cycle was gathered through the literature review and the survey. Tool fabrication, production time, assembly as well as storage and end of life are all effected by the part design. By considering the requirements occurring in each stage and optimizing the part design according to the requests, benefits can be gained by saved money, time and environment.
- A checklist which covers the life cycle stages of a plastic product from part design to end of life was compiled and its reliability was tested by a specialist consultation.

Defining the underlying reasons for failures

The causes for a product failure are stemming from a human error and overlooking the interrelating influences in plastic part design. With respect to plastic as a material, the viscoelastic behavior is poorly known or unconfirmed in altering conditions. The inadequate specification leads to poor material selection, which together with the part geometry is not capable to withstand the imposed loads in service. Additionally, the expected performance may be diminished due to weld lines or flow orientation or other processing factors, therefore manufacturing effect has to be considered to avoid loss of product properties.

Defining service conditioning factors

When evaluating the functionality of a product in use, the influence of applied stresses and the ambient environment has to be considered. A failure is rarely a reason of a single influence but a joint effect of many factors. Hence, failure often takes place when two or more distracting factors appear concurrently. Time and temperature act as catalyzers, strengthening the effect of imposed loads. This diminishes the durability of a part and lowers the maximum load that a part is able to withstand. When specifying the life expectancy, these influences should be regarded. Thus, understanding the true effects of time, temperature and rate of loading on a plastic material makes the difference between a profitable product and a disastrous failure.

Defining facilitations for life cycle stages

It was shown that a designer can ease the processing in several ways during a part's life cycles. Implementation of the tooling principles and manufacturing constraints into the part design as well as considering for assembly, storability and recycling have an effect to the product quality which is perceived by the operators handling the product. Apart from facilitating the stages, also the expenses are dependent on the design decisions. Impractical detailed features in part design increase the processing costs unnecessarily due to the increased workload, if the principles of part and tool fabrication are not considered. Changes required after the design freeze phase cause rework and manufacturing concerns leading to increased costs, which were defined to be the costs of quality. Consequently, the product quality can be built into a part design by optimizing the design features to conform to the needs of different parties at reasonable costs.

The Checklist

The checklist was developed based on the findings from the literature review and the small-scale survey. The approach into the list was derived from the FMEA method insomuch as that it aims to represent various possible failure modes that could occur. The outcome of the list covered the objectives set for it and discussed the defined research problems. The reliability of the completed list is founded on specialist consultation given by professionals in the plastic industry. The results of the verification were satisfying and based on the given feedback, the checklist would be useful and of help in confirming the adequacy of a part design in the design process of a plastic product. Nevertheless, for a final conclusion, the list shall be tested in a real life development process.

8 Discussion

The last chapter contains an evaluation of the process and discusses possible alternative methods that could have been implemented in the research. Finally some recommendations for future development of the checklist are given.

8.1 Evaluation on the Process and the Final Results

It seems to be easier to accept that the properties of plastic parts are affected by the environment and that they diminish through manufacturing, than to explore the potential and use the opportunities of the material. The research showed that designing plastic products is highly demanding and requires knowledge from various engineering areas. As the literature review and the survey results showed, the best resource for knowing the tricks and overcoming the challenges is direct experience.

Reflection on the development and outcome of the checklist

Assembly and storage issues are not playing a great part in the final checklist. It does not mean that these considerations have lower priority than the other aspects. This was decided in the beginning of the project. Hence, those life cycle stages were purposely studied less detailed. A designer with less experience of plastic design can use the list in the early phases of the design process to gain knowledge of different aspects to consider before the design freeze phase, which was the original intention.

The approach derived from the FMEA method for the development of the checklist was applicable. It helped in considering the issues that could cause a failure. When cross-checking the failures in the matrix, many issues were overlapping and the same failure modes turned up in more than one cell. As overlapping wanted to be avoided, the solution for finding a functioning and reasonable order for the list was occasionally quite challenging and the large amount of data was tedious to modify. However, the matrix was a big help in organizing and arranging the items into a rational order.

The checklist turned out to be relatively large and containing lot of data but on the other hand, it can be seen as a large but informative databank. As mentioned, the effectiveness of a checklist is always dependent on its user since a checklist will not make anyone follow them. Based on the given feedback from the survey, there is an interest for a checklist for plastic design. Even if a designer has a long experience of polymer materials and processing practices, still some aspects can be accidently left unconsidered. These comments were in line with the survey results, which showed a similar opinion. Verification of the checklist shows that the content of the list conforms to the theoretical basis and it is reliable. So far, testing has been carried out only by specialist consultation. Therefore, the final conclusion of the effectiveness and competence of the list can be made only after the real life use.

Reflection on the methods

The research method was a combination of a theoretical research and a small-scale survey among operators in a plastic industry. Many responses in the survey were pointing out the same issues regarding part design and processing, while the aspects of the end user conditions were somewhat varying. The amount of participants in the survey and testing could have been greater to receive more opinions and input for the project. Nevertheless, despite the small size, the results gave a lot of valuable input to this project.

8.2 Suggestions for Future Work

Over the course of the project the two main areas in need of further development have occurred. These shall be the development of the checklist concept according to its final implementation method and based on that, the possible further research and expanding the content respectively. Obviously, if maintained as a physical checklist, scrutiny becomes heavier while the amount of data increases. Given suggestions for further improvements are the following:

- Analyzing the necessity of each point according to specific fields of business and altering the content to come up to the expectations of applications with distinctive requirements
- Considering more of human factors in terms of human information processing ability and decreasing mental workload, such as implementing Gestalt laws of grouping
- Implementing the checklist as an Internet-based application in the webpage of the commissioning company
- If implemented as an internet-based application, the content could be completed and be modified by the user according to one's level of experience and interest, for instance by linking related clarifying pictures and articles
- If implemented as an internet-based application, an interactive analyzing system could be made for summing up all insecure points for denoting the greatest areas of concerns

References

APME. (2014). *The Plastics Portal*. Retrieved March 30, 2014, from http://http://www.plastics-europe.org

Bayer Material Sience. (2000). *Part and Mold Design: A Design Guide.* Pittsburgh, PA: Bayer Corporation.

Boothroyd, G., Dewhurst, P. & Knight, W. (2011). *Product Design for Manufacturing and Assembly* (3rd ed.). Boca Raton, FL: CRC Press.

Bridger, R. (2003). *Introduction to Ergonomics* (2nd ed.). London: Taylor & Francis Group.

Crosby, P. (1979). *Quality is Free.* New York: McGraw-Hill.

DuPont. (2000). *General Design Principles for DuPont Engineering Polymers.* E.I. du Pont de Nemours and Company.

Eger, T., Eckert, C. & Clarkson, J. (2005). The Role of Design Freeze in Product Development. *International Conference On Engineering Design.* Melbourne.

Gawande, A. (2009). *The Checklist Manifesto: How to Get Things Right.* New York: Metropolitan Books.

Glenn, J. (2010). *Handbook of Research Methods.* Jaipur: Oxford Book Company.

Goodship, V. (2004). *Troubleshooting Injection Moulding.* Shrewsbury: Smithers Rapra.

Hawkins, F. (1993). *Human Factors in Flight* (2nd ed.). Brookfield: Ashgate.

Huang, G. (1996). *Design for X - Concurrent Engineering Imperatives.* London: Chapman & Hall.

Jansen, J. & Rios, A. (2013). *The Role Of Multiple Factor Concurrency And Statistical Distribution In Plastic Part Failure.* The Madison Group. Retrieved April 13, 2014, from http://www.madisongroup.com

Kazmer, D. (2011). Design of Plastic Parts. In M. Kutz, *Applied Plastics Engineering Handbook: Processing and Materials* (pp. 535 - 552). Waltham: Elsevier.

Lampman, S. (2003). *Characterization and Failure Analysis of Plastics.* Materials Park, OH: ASM International.

Lochner, R. & Matar, J. (1990). *Designing for Quality.* London: Chapman and Hall.

Maier, C. (2009). *Design Guides for Plastics.* Orpington: Econology.

Mangione, T. (1995). *Mail Surveys: Improving the Quality.* California: Sage Publications.

Mitchell, P. (1996). *Tool and Manufacturing Engineers' Handbook: Plastic Part Manufacturing* (4th ed.). Dearborn: Society of Manufacturing Engineers.

Morup, M. (1993). *Design for Quality.* Ph.D. dissertation, Technical University of Denmark, Institute for Engineering Design.

Muccio, E. (1997). Design for Plastics Processing. In *ASM Handbook* (Vol. 20: Materials Selection and Design). ASM International.

O' Neill, T. (2003). *Life Cycle Assessment and Environmental Impact of Plastic Products.* Shrewsbury: Smithers Rapra.

Otto, K. & Wood, K. (2001). *Product Design: Techniques in Reverse Engineering and New Product Development.* Upper Saddle River, NJ: Prentice Hall.

Pahl, G. & Beitz, W. (1988). *Engineering Design: A Systematic Approach.* London: The Design Council.

Rosato, D. & Rosato, D. (2003). *Plastics Engineered Product Design.* Oxford: Elsevier.

Shah, V. (2007). *Why Plastics Fail and What Can Be Done About It?* (The Prospector Materials Database) Retrieved March 28 2014, from http://articles.ides.com

Smithers Rapra. (2014a). *Why Plastic Products Fail*. Retrieved March 27, 2014, from http://www.rapra.net

Smithers Rapra. (2014b). *Failure Relating To Material Selection*. Retrieved March 27, 2014, from http://www.rapra.net

Smithers Rapra. (2014c). *Plastic Design & Material Selection*. Retrieved March 28, 2014, from http://www.rapra.net

Strong, B. (2006). *Plastics: Materials and Prosessing.* Upper Saddle River, NJ: Prentice Hall.

Taylor, S. & Bogdan, R. (1984). *Introduction To Qualitative Research Methods.* New York: John Wiley & Sons.

Tres, P. (2000). *Designing Plastic Parts for Assembly.* Munich: Hanser.

Tuschak, P. (1985). Impact Fatigue - A New Way of Looking at the Durability of Engineering Plastics. *Engineering Design*. Retrieved May 9, 2014, from http://plastics.dupont.com

Ulrich, K. & Eppinger, S. (2000). *Product Design and Development* (2nd ed.). New York: McGraw-Hill.

Appendix 1: The checklist

The final checklist is not published per the request of the commissioning company.

Please, note the following in the early phase of a design process.		✓	[illegible]
PRELIMINARY PRODUCT SPECIFICATION CHECK-UP			
Structural requirements and part performance	Is the level and type of cyclic and continuous load understood and specified?		
	Is the requirement for stiffness in terms of allowable displacement understood and specified?		
	Is the rate and energy of impacts understood and specified?		
	Is the required strength for the intended use understood and specified?		
	Are the areas with desired low/high friction properties specified?		
	Are the requirements for visual quality appearance specified, e.g. visible surfaces, straightness?		
Environment of use	Is the range of ambient temperatures for service (short and long term exposure) specified, including storage and transportation?		
	Is the alteration of the part properties as a function of temperature understood?		
	Are possible chemicals and moisture identified in the service conditions?		
	Is exposure to UV-radiation identified, e.g. indoor vs. outdoor use?		
	Is life expectancy of the part determined relative to time and instance of use?		
Design and material selection	Is the general choice between amorphous and semi-crystalline polymers done?		
	Is there some feature, function or requirement on the product that requires special compounding, additives or use of uncommon grades?		
	Are any secondary operations that need special consideration, e.g. laser marking, coating and painting?		
	Is the requirement for agency approvals checked?		
	Are the environmental issues considered in the product specification?		

Please, consider the effects stemming from each section to ensure the required part performance.		✓	CHECK THIS
DESIGN FOR SERVICE			
	Strength		
Design	Is it tested that part geometry together with the selected material is able to withstand specified loads, e.g. by calculations, prototype?		
	Is the part's ability to withstand the expected loads tested at the highest specified service temperature?		
	Is the part's ductility tested to be sufficient in lower service temperatures despite a decreased toughness?		
	Are stress concentrators which may initiate crack propagation eliminated, e.g. single rib, small inner radii?		
Processing	Is the decreased strength in a cross-flow direction considered?		
	Is gating located on area that is not critical in terms of strength?		
	Are the areas subjected to external forces free of weld lines? (NB. decreased strength and durability)		
	Is the occurrence of molded-in stresses minimized by even wall thickness (especially critical on amorphous polymers)?		
Long-term	In case of continuous loading, is the stress level significantly below the maximum strength to avoid stress cracking? Is the effect of elevated temperature noted in this?		
	In case of cyclic loading, is the stress level significantly below the maximum strength to avoid breakage due to fatigue?		
	If the cyclic loading is varying between pulling and compression, is this noted on fatigue calculations as highly aggressive exposure?		
	Are cyclic temperature changes considered in terms of thermal fatigue?		
	Is the selected material compatible with all identified chemicals?		
	Is prolonged exposure to chemical agents and elevated temperatures under stresses considered to prevent environmental stress cracking?		
	Is the effect of UV-radiation considered to avoid degradation?		
	Is the weakening effect of moisture considered (especially on PA)?		
	Impact Strength		
Design	Is it tested that part geometry together with the selected material is able to withstand specified impacts, e.g. by calculations, prototype?		
	Is the material's impact strength/ notch sensitivity considered?		
	Is the impact strength checked in low temperatures to prevent ductile-to-brittle behavior?		
	Does the part structure and wall thickness allow absorption of impact energy?		
	Are unnecessary sharp corners that may crack under impacts eliminated?		
Long-term	Are low but repeated impacts recognized in order to prevent impact fatigue?		

Stiffness			
Design	Is it tested that part geometry together the with selected material meet stiffness requirements in terms of allowed bending/ displacement, e.g. by calculations, prototype?		
	Is it tested that stiffness requirements are fulfilled in the top of the specified service temperature range?		
Processing	Is the decreased stiffness in a cross-flow direction considered?		
Long-term	Is decreasing effect of moisture considered (especially on PA)?		
Friction			
Design	Are friction properties of the related surfaces appropriate for the intended use?		
	Is the surface finish appropriate for required friction?		
Long-term	Are friction changes due to polishing considered?		
Dimensional accuracy and stability in terms of function			
Design	Are thermal expansion and contraction considered?		
Processing	Is shrinkage considered?		
	Is fiber orientation noticed in shrinkage behavior (especially in fiber-reinforced plastics)?		
Long-term	Is effect of possible stress relaxation and creep considered under constant loading?		
	Is loosening of press fittings etc. considered?		
	Is swelling due to moisture absorption considered?		
	Is wear leading to dimensional inaccuracy considered?		
Visual Appearance			
Design	Are thick sections that may cause warpage and sink marks due to slow cooling observed?		
Processing	Are the wall thickness transitions smooth and small to prevent hesitation effect?		
	Is the showing of weld lines considered? (NB. especial attention if metallic colors in use)		
	Is the showing of gating, parting line or witness lines from slides and inserts accepted in terms of visual requirements?		
	Are the visible marks of ejection, e.g. pin marks and scratches considered and accepted?		
	Is the desired surface finish consistent with the draft angles used on the part?		
Long-term	Is the surface hardness appropriate to prevent scratches?		
	Is surface roughness and finishing method, e.g. sparking, etching and polishing considered in terms of scratch sensitivity?		
	Is the surface finish smooth enough to prevent part from getting dirty?		
	Is yellowing considered if exposed to UV radiation?		

Agency Approvals			
Are necessary regulations considered, such as	FDA (Food and Drug Administration) for articles with food and bodily-fluid contact		
	REACH (Registration, Evaluation and Authorization of Chemicals) for toys or childcare articles		
	IEC (International Electrotechnical Commission) for electrical devices		
	UL 94 (Standard for Flammability of Plastic Materials) for flame resistance requirement (note wall thickness)		
	RoHS (The Restriction of the use of certain Hazardous Substances in Electrical and Electronic Equipment) for electronic and electrical equipment among others		
	Are there additional business specified approvals required?		

For facilitating the life cycle stages, please check the following.		✓	CHECK THIS
DESIGN FOR TOOLING			
Proper documentation for a tool designer			
2D-drawings and additional information including	Tooling construction dimensions		
	Critical dimensions which impact part functionality		
	Material, its shrinkage behavior and required special considerations for tooling e.g. high tool temperature (also substitute polymer grades)		
	Required surface quality/finish on all surfaces, note for proceedings with unspecified surfaces		
	Gating strategy if need for special requests		
	Volume of the part		
	Areas exposed to critical mechanical loading i.e. undesirable areas for weld lines, gating etc.		
	Areas requiring defect-free surface finish		
	Placement and information of the needed markings, e.g. recycling codes, country of origin, part number, part revision clock, production month & year clocks, cavity number etc.		
	Expected production quantities per year and per lifetime		
	Number of cavities		

Tooling constraints			
Mold principles	Is the gate location and type in terms of visual appearance and mold filling considered? (NB. special attention to living hinges)		
	Is there proper area for ejection pins/ring to prevent part distortion when ejected and to speed up cycle time?		
	Are all surfaces parallel to the direction of mold opening drafted?		
	Is there an angle of minimum 5 degrees in the shutoff area between the contacting mold surfaces?		
	Is the parting line path as simple as possible, e.g. can possible sharp peaks be eliminated with small design changes?		
Easy tool fabrication	Is unnecessary small outer radius eliminated from part to avoid sharp inner radius in tool to avoid increased machining time and costs?		
	Is the principle of implementing markings discussed to avoid costly and complicated methods?		
	Does the part provide space for proper cooling system?		
	Are there unnecessary thin and long cores or deep ribs that are difficult to fabricate or require special consideration for venting?		
Allowance for adjustments			
Fluent ramp-up	Is there enough trimming allowance?		
	Can trimming be implemented by removing material from the tool rather than adding it?		
	Is trimming going to show on the appearance surface? If so, may it be avoided?		

DESIGN FOR MANUFACTURING			
Cycle-time			
Effective cycle-time	Is the nominal wall thickness observed and unnecessary thickness removed to decrease cycle time and material consumption?		
	Is possible single thick area that dominates the cycle time observed?		
	Are unnecessary small pockets eliminated which cannot be cooled efficiently?		
	Is there adequate draft to ease ejection and to ensure that the part stays on the right side of the mold as the tool opens?		
Mold filling			
Proper mold filling	Are the selected material and the wall thickness of the part coherent to ensure proper mold flow?		
	Is thin-to-thick filling scenario avoided to prevent pressure drop in the cavity?		
Material availability			
Smooth delivery	Is the selected material easily available?		
	Is it checked if the selected material grade is available in stock?		

DESIGN FOR ASSEMBLY AND HANDLING			
Practical assembly and storability	Is there sufficient area for suction cups if handled by robots?		
	Are there alignment features and angled lead-ins to ease assembly?		
	Is the part accommodated to process variability to enable assembly even if slightly distorted?		
	Are obvious errors in assembly avoided by design features, e.g. poka-yoke?		
	Does the part support required secondary operations, e.g. degating, positioning in a fixture for tampo printing, laser marking, if needed?		
	Are parts possible to stack parts to save space?		
	Can parts be stacked without causing any visual defects?		
	Are the parts being prevented from getting stuck onto one another when being stacked?		

AFTER USE AND RECYCLING			
Minimum impact on environs	Is plastic type identifiable for recycling?		
	Can materials which are hazardous and difficult to recycle be avoided, e.g. PVC?		
	Is disassembly possible and practical?		
	Is part geometry optimal in terms of material consumption?		
	Can part design support minimizing the material required for package?		

Appendix 2: Survey questions

Questions in the survey translated from Finnish to English.

What are the common issues causing problems in feasibility and robustness of a part design in terms of the given specification and how do you avoid these faults, for instance

- issues diminishing the required physical properties
- issues diminishing the required aesthetical properties
- factors complicating tooling and manufacturing
- additional frequently occurring pitfalls in a design process causing rework and postponements

Appendix 3: A screenshot of the failure mode matrix

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Requirement		Part design	Short-term	Long-term	Thermal	Environmental							
68	Service/ End-user													
69	Dim. accuracy		Fiber-orientation not acknowledged in shrinkage behavior (esp fiber-filled plastics)											
70			Post-mold shrinkage distorts the part											
71					Creep									
72					Wearing under cyclic loading									
73					Deflection under stress									
74						Dissimilar materials' thermal expansion behavior								
75							Effect of moisture absorption to tolerance (swelling)							
76														
77	Strength		Applied stress in cross-flow direction, strength decreased											
78			Weld lines appear on critical places decreasing strength											
79			Molded-in stress due to wall thickness variation and unbalanced filling leads to premature failure											
80			Stress-concentrations in sharp corners/radii lower durability, notch sensitivity											
81			Gate positioned in area exposed to high stresses; area weakened due to stress concentration											
82			Force concentrated on a single rib and this causes crack propagation											
83			Material not strong enough for the purpose											
84					Stress cracking breaks structure									
85					Fatigue under constant loading									
86						High temp, low temp								
87							UV radiation degrades material							
88							Chemical exposure, accelerate stress cracking (ESC)							
89							Part is cleaned with unexpected chemical							
90														
91	Stiffness		Applied stress in cross-flow direction, stiffness decreased											
92			Material's modulus is too low											
93			Second moment of inertia too low											
94						Modulus significatly lower due to increased temperature								
95							Moisture absorption decreases modulus, especially PA							
96														
97	Impact resistance		Sharp shapes/ projections in geometry too weak											
98			Part shape does not allow flexibility											
99			Stress concentration on critical area initiates fracture (weld line, gate location)											
100			Ribs, internal radii develop stress-concentration points, initiate cracks											
101				Impacts perpendicular to flow-orientation										
102					Scratches/ microcracks on surface initiates fracture									
103						Ambient temperature lowers impact resistance								
104							Chemical degradation							
105														
106	Surface quality		Differences in wall thickness due to ribs, bosses or other features cause sink marks											
107			Ejection causes pin marks & scratches in the appearance surface											
108			Gate marks on the surface & gate removal leaves notches or scratches on the surface											
109			Flashes from parting line or vents											
110			Burn marks due to incomplete venting appear onsurface											
111			Slides and inserts leave undesired witness lines on surface											
112			Visible weld lines on surface											
113			Differences in colour due to wall thickness variation											
114				Scratches due to low surface hardness										
115							Rough surface exposes for catching dirt							
116							Yellowing by UV exposure							
117							Hazing by chemical exposure							
118														