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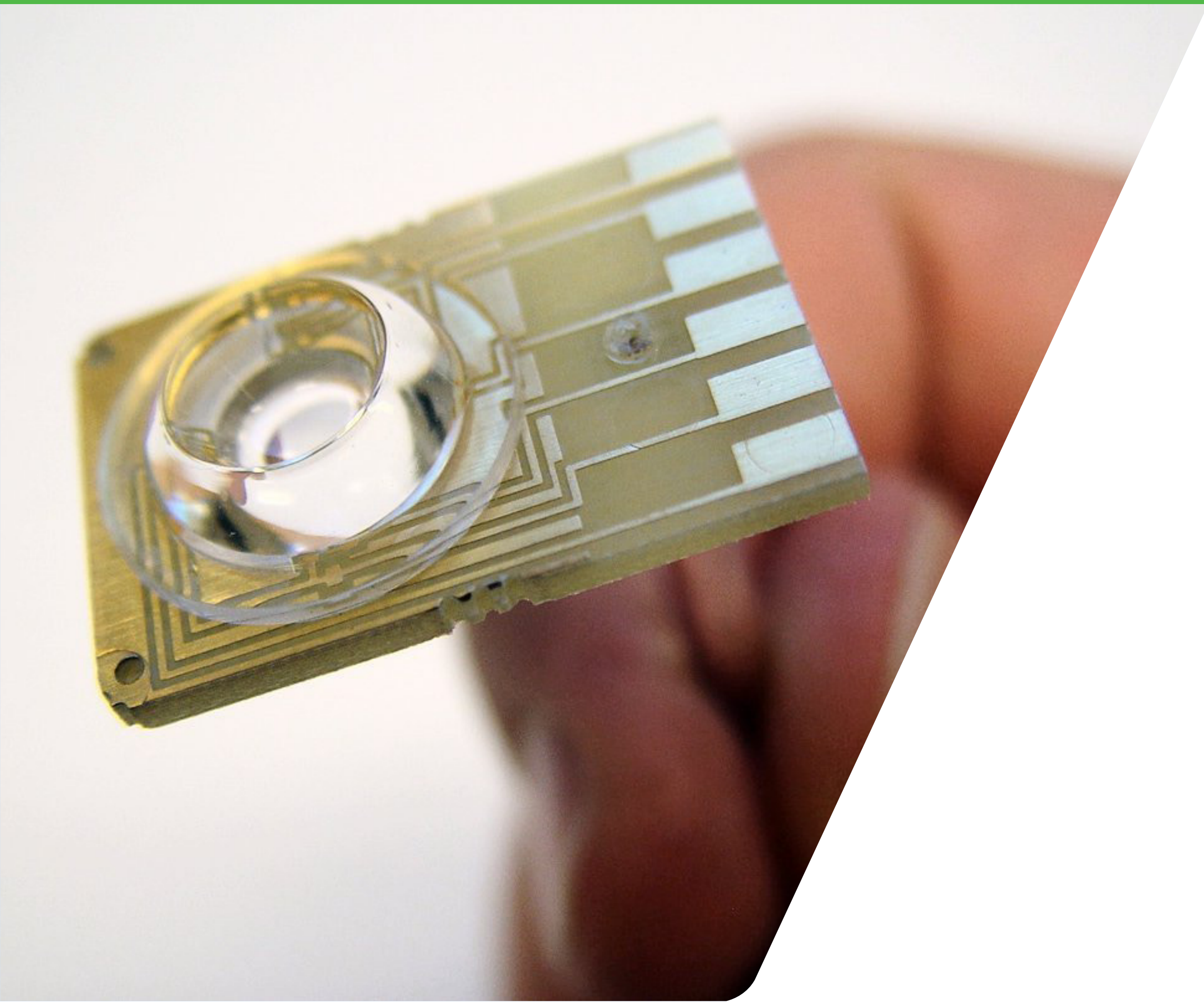

Jukka-Tapani Mäkinen

Concurrent engineering approach to plastic optics design

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Abstract

Engineering can be seen as a balancing act in which several partially of fully conflicting needs have to be satisfied with one single solution. Concurrent engineering (CE) is a philosophy that aims for better products by improving the different design processes inside the whole development process. This is achieved by emphasizing holistic thinking.

In this thesis the most relevant terms and definitions of CE and product design are compiled into one literary work. In the context of product design, optical design has to be considered as a broader entity that embodies the holistic nature of engineering. The first major contribution of this thesis is the sketching of the basic optical design and development process and its connection to the larger frameworks of product design and CE. The emphasis is on the implementation of the philosophical ideas in practice.

Two major aspects that need to be balanced in every product are performance and cost. Design for manufacturing (DFM) is an engineering concept that guides the design process towards better consideration of manufacturing issues. It lies at the core of CE and its purpose is to reduce the costs of manufacturing by fitting the product features and manufacturing processes together. The second major contribution of this thesis is to show how this connection can be made in the field of injection-moulded optics.

In order to make the treated topics more concrete, seven optical design case studies are presented and their specific CE features highlighted. The presented applications range from consumer electronics to telecommunications and solar energy, whereas the example component and module designs vary from low performance illumination optics to relatively high performance imaging lenses. All the case studies have been published in Papers I–VI included in this thesis.

Preface

The work covered by this thesis has been carried out at VTT Technical Research Centre of Finland during the years 2001–2010. The major part of the research was performed in the projects BARREL, SIMO, AKTIVA, MERI and Production4µ funded mainly by Nokia, the Finnish Funding Agency for Technology and Innovation (Tekes), the EU and VTT.

I wish to thank my supervisor, Prof. Risto Myllylä (University of Oulu), for his guidance and support during the course of this research. I also thank Prof. Pentti Karioja (VTT), Prof. Harri Kopola (VTT) and Dr. Mauri Aikio (VTT) for encouragement to complete post-graduate studies and their efforts to generate research projects. Dr. Jani Tervo (University of Eastern Finland) and Docent Ari Tervonen (Helsinki University of Technology) are greatly acknowledged for comprehensive peer-reviewing of the manuscript of the thesis. I especially wish to emphasise the contributions of Dr. Kimmo Keränen (VTT), Dr. Janne Aikio (VTT) and Rien de Schipper (Penta HT Optics). I also thank all colleagues whose expertise, contribution, example and fellowship have made the presented research work and results possible. Special thanks to Dr. Antti Keränen, Dr. Kari Kataja (Specim), Dr. Karri Niemelä, Dr. Veli Heikkinen, Dr. Mikko Karppinen, Aila Sitomaniemi and Kai Ojala. I would also like to acknowledge the financial support for the thesis from the National Graduate School of Electronics Production Technology and Reliability, Infotech Oulu and Wihuri foundation.

Finally, I wish to thank my intelligent and exquisite wife Katri and our three active sons Elias, Akseli and Iivari for their great patience and support.

Oulu, December 2010
Jukka-Tapani Mäkinen

Contents

Appendices of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://www.vtt.fi/publications/index.jsp).

List of publications

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:

I. Mäkinen, J.-T., Aikio, J., Putila, V.-P., Keränen, K., Karioja, P., Kolehmainen, T. & Haavisto J. 2004. *Prototyping of miniature plastic imaging lens*. Proceedings of SPIE, Vol. 5178. Pp. 89–100.

II. Heilala, J., Keränen, K., Mäkinen, J.-T., Väätäinen, O., Kautio, K., Voho, P. & Karioja, P. 2005. *LTCC technology for cost-effective packaging of photonic modules*. Assembly Automation, Vol. 25, No. 1, pp. 30–37.

III. Mäkinen, J.-T., Keränen, K., Hakkarainen, J., Silvennoinen, M., Salmi, T., Syrjälä, S., Ojapalo, A., Schorpp, M., Hoskio, P. & Karioja, P. 2007. *In-mould integration of a microscope add-on system to a 1.3 Mpix camera phone*. Proceedings of SPIE, Vol. 6585. Pp. 658507-1–10.

IV. Keränen, K., Mäkinen, J.-T., Korhonen, P., Juntunen, E., Heikkinen, V. & Mäkelä, J. 2010. *Infrared temperature sensor system for mobile devices*. Sensors and Actuators, A: Physical, Vol. 158, No. 1, pp. 161–167.

V. Mäkinen, J.-T. & Nollau, S. 2010. *Optics cost modelling and design optimization*. Proceedings of SPIE, Vol. 7717. Pp. 77170G-1–15.

VI. Mäkinen, J.-T. 2010. *Cost Modeling of Injection-Molded Plastic Optics*. Handbook of Plastic Optics. 2nd ed. Bäumer, S. (ed.). Wiley-VCH, Weinheim, Germany. Pp. 219–249.

Publication I presents the design and prototyping process of a miniature plastic imaging lens for a mobile phone camera application.

Publication II describes the development and manufacturing process of a fibre-pigtailed laser module prototype based on LTCC structures. The module can be used in telecommunication, sensor or tooling applications.

Publication III presents the design, implementation and characterization of a macrolens that can be used in a microscope add-on device of a mobile phone. The lens was injection moulded directly on top of a circuit board containing illumination LEDs, and it contains both imaging and illumination optics features.

Publication IV concentrates on the concept development phase of infrared temperature sensor modules. The paper describes the optical, thermal and electrical designs and simulations of a module aimed at mobile devices.

Publication V deals with cost modelling of plastic and glass hybrid imaging lenses. Two cost-modelling tools are presented. The first is a simplified tool intended for plastic optics. The second tool developed at Fraunhofer IPT was built for analysing the production costs of moulded and ground glass elements as well as injection-moulded plastic elements. Two case studies are shown that illuminate the use of the tools.

Publication VI is a book article that focuses on the cost modelling of injection-moulded optics. A calculation model that can be used in estimating production costs of plastic optics is presented as well as three case studies that illustrate the different uses of cost modelling.

Author's contribution

The results presented in this thesis have been achieved in co-operation with the research group and the co-authors.

For Publication I, the author was responsible for lens prototyping as a project manager. He participated in the design process by making image quality, stray light and optical tolerancing simulations. The author also participated in the characterization and analysis of the manufactured modules. The manuscript was prepared by the author.

For Publication II, the author made the optical designs and tolerance analysis. He also participated in the development of the process model presented in the article.

For Publication III, the author invented the concept of a microscope add-on lens and made the integrated illumination and imaging optics design. He assembled the prototypes, performed the characterization measurements and analysed the results. The manuscript was also prepared by the author.

For Publication IV, the author created the different optical structure concepts and designed and simulated the final optics. He also participated in the analysis of the characterization measurements.

For Publication V, the author performed the cost calculations for all the plastic components in the presented case studies. He also created all the optical designs and carried out the performance versus cost analysis. The manuscript was prepared and edited by the author.

For Publication VI, the author created the presented cost-modelling tool and all the optical and mechanical designs presented in the article. He also performed the cost calculations, tolerance analysis simulations and final analysis in each of the case studies. The manuscript was prepared by the author.

List of abbreviations and symbols

3D	three-dimensional
AR	anti-reflection
ASAP	advanced systems analysis program
CAD	computer aided design
CAM	computer aided manufacture
CE	concurrent engineering
CMOS	complementary metal oxide semiconductor
CODE V	optical design and simulation software
COO	cost of ownership
CPC	compound parabolic concentrator
CPV	concentrating photovoltaic
DFA	design for assembly
DFM	design for manufacturing
DFMA	design for manufacturing and assembly
FEM	finite element modelling
FloTHERM	fluid dynamics simulation software
FOV	field of view

FWHM	full width at half maximum
HD	high definition
IR	infrared
LCD	liquid crystal display
LED	light-emitting diode
LTCC	low-temperature cofired ceramic
MC	Monte Carlo
MTF	modulation transfer function
NA	numerical aperture
PC	polycarbonate
PMMA	polymethyl methacrylate
POE	primary optical element
QE	quality engineering
QVGA	quarter video graphics array
R&M	repair and maintenance
RVC	rear-view camera
SOE	secondary optical element
SQF	subjective quality factor
TIR	total internal reflection
VGA	video graphics array
VisVSA	dimensional tolerance analysis and simulation software
Zemax	optical design and simulation software
Zeonex	optical grade plastic material

1. Introduction

1.1 Background

The Engineers Council for Professional Development has defined the term engineering as follows: ‘The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behaviour under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property.’ [Encyclopædia Britannica] The Encyclopædia Britannica clarifies this definition by stating that: ‘Unlike the scientist, the engineer is not free to select the problem that interests him; he must solve problems as they arise; his solution must satisfy conflicting requirements. Usually efficiency costs money; safety adds to complexity; improved performance increases weight. The engineering solution is the optimum solution, the end result that, taking many factors into account, is most desirable. It may be the most reliable within a given weight limit, the simplest that will satisfy certain safety requirements, or the most efficient for a given cost.’ According to these descriptions, engineering can be seen as a balancing act in which several partially or fully conflicting needs will have to be satisfied with one single solution. The requirements cover many different aspects such as physical properties, performance, cost, ergonomics and safety. Even the ideal engineering solution does not have to satisfy fully all the needs however. The optimum design is simply the one that is most desirable considering the given set of requirements.

The success or failure of any given product depends largely on the conception of value for money attached to the particular item. By choosing only the best materials and most accurate manufacturing processes, it is possible to make high-performance products that fail to generate large sales volumes due to excessive pricing. If lower quality materials and processes are used, the production costs will decrease, but this is usually followed by deterioration in performance. In some application areas, such as scientific instruments, the importance of performance largely outweighs the importance of cost. These devices will need to be made extremely accurate and reliable in order to make them desirable. At the other extreme, with products like disposable cutlery, the cost is clearly the main driver, as the items will need to perform just one function with adequate reliability for a very short period of time. Most products fall between these two categories, and a big part of their development process is concerned with finding the right balance between performance and cost.

1.2 Motivation

It has been stated that as much as 50–80% of manufacturing productivity can be determined at the design stage [Suh 1990, Newnes et al. 2007]. Figure 111 depicts the general relation between costs engaged by design decisions and actual evolution of expenses during a generic product life cycle. The decisions made during the concept development and design phases largely establish the cost of the final product. For this reason, the different design processes play a key role in product development.

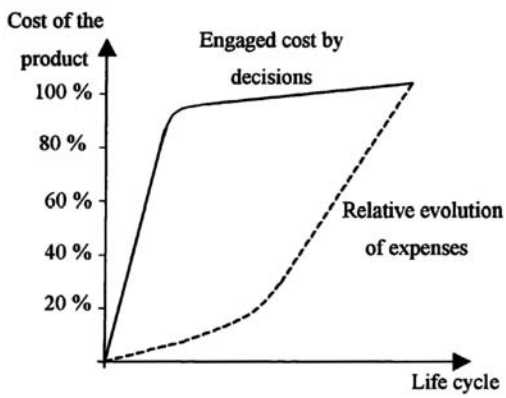


Figure 1. Evolution of the expenses and the engagement of costs during product life cycle [Farineau et al. 2001].

Concurrent Engineering (CE) is an engineering concept that aims for better products and lowered costs by improving the design processes themselves [Mistree et al. 1993]. This philosophy contains several methods that have been adopted in product development practices. The main idea of CE is to consider all aspects affecting the design simultaneously. By analysing the different parts of the design chain it is possible to see, e.g., what needs to be specified, which features of the product concept have a co-dependence and how the changes to one aspect affect the others. The concurrent design of a system enables designers to make sensible trade-offs at the earliest stages of product development in order to find solutions that have the most desirable combination of manufacturability, quality, robustness and cost.

For centuries, optics has been used to design and manufacture precision instruments in small volumes and by relatively small development groups. During the last few decades, optical components, modules and systems have been adopted in many new large-volume applications [Butler 2000, Beich 2002, Tolley 2003, Bäumer 2010a]. Today, optics can be found in, e.g., the built-in camera and display backlight modules of mobile phones, medical diagnostic systems, head-up displays [Hua & Rolland 2003], LED illumination modules and telecommunication devices [Heiney et al. 1995]. In these devices, optics may only have a small but significant role. As the main driver for development is no longer the optical functions, optical design practices need to evolve in a way that better addresses the multiple requirements. The methods that emphasize pure optical performance are no longer sufficient on their own in supporting the multidisciplinary approach required in the development of new products. In the context of product design, optical design has to be considered as a broader entity that embodies the holistic nature of engineering.

The fact that optical components are buried in more complex devices also creates a need for guidelines on how to make design integration possible. Teams developing future integrated systems are becoming larger; the engineers have very different technical backgrounds and they work at different geographical locations. In many cases, it is no longer possible for a single person to know and understand all the details of the whole product development process. This divergence of knowledge requires better communication between experts working towards a common goal. By giving the ‘good way of engineering’ the specific title of concurrent engineering, we are equipped with terminology and ideas that help us to analyse the complicated development processes of modern optical devices [Kusiak & Larson 2009]. In order to reap the full benefits of CE, the ideology needs to be internalized. The application of CE to practical product development work can be helped with enabling software and organizational arrangements, but the main issue lies in understanding the basic philosophy [Thamhain 2005].

1.3 Scope and objectives of the thesis

In associated literature, the term *concurrent engineering* has a variety of definitions, and the concept also has many different approaches. Brookes and Backhouse conclude that CE can be seen from three points of view: tactical, strategic and objective [Brookes & Backhouse 1997]. When CE is viewed at a tactical level it contains a series of tools, techniques and organisatorical structures. Typical elements include cross-functional teams, interdisciplinary workgroups, integrated computer-aided engineering environments and the use of quality engineering methods. At strategic level, the emphasis is on the parallel consideration of all aspects in contrast to a sequential product development process. The goal is to reduce the time to market and gain a competitive edge by minimizing the amount of rework and successive prototypes. From this perspective, the tactical issues are seen as support tools. The last point of view, the objectives level, aims to enhance the whole product introduction process and hence pursues to improve the overall business performance. In this case, CE becomes synonymous with business process re-engineering.

This thesis aims to analyse the optical design process from the CE-strategic point of view and to show how the current design practices and tools can be extended to support better the product development efforts. The emphasis is on the implementation of the philosophical ideas in practice. Injection-moulded optics are used as an example of the way manufacturing knowledge can be put to use in optical product development. Plastic optics is chosen because it is a field of industry in which CE practices are in particular need and are used in everyday work. The same general methods can also be used in other areas of optics. This requires a wide and deep understanding of the manufacturing processes involved however. For this reason, processes other than injection moulding are left outside the scope of this work.

1.4 Contribution of the thesis

The foundations of CE were built on the concepts of design for manufacturing (DFM) and design for assembly (DFA) [Kusiak & Larson 2009]. The terms are generally used for the art of engineering with the goal of finding an optimum design with respect to the manufacturing cost of the component, module or whole system [Bralla 1999]. These terms and the associated techniques have been used successfully in many fields of technology. DFM is a topic that is rarely discussed in the context of optical design [Barber 2003, Xu & Luger 2007]. There are many textbooks available that describe the design and manufacturing methods of optics, but they usually fail to make the connection between the two disciplines in terms of cost. The first major contribution of this thesis is to show how this connection can be made in the field of injection-moulded optics with the help of a cost model. The created model ties together the main features of the product and manufacturing process.

Only a few articles have been written about CE practices in optics. They are mostly concerned with either technical details like enabling software [Czajkowski & Tipps 1992, Ahmad et al. 1995, Moore et al. 2001] or administrative issues like team-work strategies [Oxnevad 1998]. Both are essential parts of tactical level CE, but there is a clear lack of a more comprehensive and philosophical approach to CE in optics and especially in optics design. In this thesis the most relevant terms and definitions of CE and product design are compiled into one literary work. The second major contribution of this thesis is the sketching of the basic optical design and development process and its connection to the larger frameworks of product design and CE.

In order to make the treated topics more concrete, seven optical design case studies are presented and their specific CE features highlighted. The case studies illuminate the fact that the same approaches can be applied to all kinds of optical product development tasks. The presented applications range from consumer electronics to telecommunications and solar energy, whereas the example component and module designs vary from low performance illumination optics to relatively high performance imaging lenses. All the case studies have been published in Papers I–VI included in this thesis.

2. Concurrent engineering and design

2.1 Product development process

A product development process can be defined as the sequence of steps or activities that an enterprise employs to conceive, design and commercialize a product. In practice, there are large differences in the way organizations define and carry out the detailed sequences. The same organization may also follow different procedures in different kinds of projects. In some cases the steps are not even clearly defined. There are distinct benefits of having a well-defined development process however. It enables better co-ordination of team members and organized communication between different disciplines. Proper planning of milestones helps the management in assessing the progression of a single project and in ensuring the high quality of the development efforts, which is reflected in the quality of the product. [Ulrich & Eppinger 1995]

A generic product development process consists of five main levels [Ulrich & Eppinger 1995]. In the first concept development phase, the ‘customer need’ is identified and formulated as a set of general functional requirements. Competitive products can also be studied in order to analyse the economic feasibility of the product idea. The outcome of concept development is a set of preliminary specifications. These specifications are used as a starting point in the second phase of the process in which the system-level design is made. It includes the definition of product architecture and its division into modules and components. Product assembly procedures and production processes are also defined at this stage. The output can be a geometric layout of the whole product and functional specifications for the different modules. The third level of the process is detailed design in which the specifications are completed and detailed layouts created for the geometry, materials and tolerances of all the components in the system. Tooling design and component sourcing plans are also made, with process plans for the actual fabrication and assembly of the parts and product. Mechanical drawings and computer files describing the geometric details of the components are the outcome of this phase. At the fourth testing and refinement level, a set of prototypes are built from parts that resemble, as closely as possible, the components that are designed for production. They are not necessarily manufactured with the same methods as the final products, because the mass manufacturing processes can be too expensive and slow for the product development tasks. There can be several prototyping rounds used in testing different areas such as product usability and reliability. The last stage of the whole product development process is production ramp-up. In this phase, the product is made with the intended production system. It provides training for the workforce and helps find any remaining problems in the process. The transition from ramp-up phase to actual production can be gradual and continuous.

2.2 Design process

Design can be defined as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between functional requirements and design parameters through the proper selection of parameters that satisfy the requirements. Functional requirements define the objective of the process in the functional domain, whereas design parameters describe the solution in the physical domain. These two domains are independent of each other, and they are related to each other through the design. The mapping process is not unique and there are an infinite number of plausible design solutions. In addition to the requirements, however, there is always a set of constraints that directs the design process. The difference between requirements and constraints is that the former state the desired result, whereas the latter represent the bounds of an acceptable solution. The precise value of the constraint parameter is not important as long as it does not exceed the given limits. Constraints can be expressed as bounds on design parameters such as size, weight, materials and cost, or as system constraints such as the capacity of the production process or even laws of nature. [Suh 1990]

As the number of functional requirements grows, the solutions become more complex. A good designer has the ability to identify the most important requirements and find solutions to them first, at the expense of secondary requirements. This ability demands both broad and in-depth knowledge of the issues involved. In addition, a good designer has to operate in the conceptual world of the functional domain as well as in the physical world. The designer must also analyse which functional requirements are independent of each other and which can be combined into one. Without this analysis, the designs easily become unnecessarily complex. Another attribute of bad design is features that can only be manufactured with much difficulty and at great expense. It is also possible that the result of a design task cannot be manufactured at all due to, e.g., the limitations of available production technologies. In order to avoid this situation, the designer must be familiar with the manufacturing processes and the laws of nature. This situation is emphasized in the development of multifunctional products, which have a large number of modules that perform different tasks. As the number of modules increases, the number of interfaces at system level also increases, and this is followed by more functional requirements for individual modules.

Design processes are usually iteration loops that follow the same basic steps over and over. They begin with the recognition of needs, which are formalized to a set of functional requirements. Different product schemes are created and their design parameters are analysed and compared with the original set of requirements. When the product does not fully satisfy the specified functional requirements, a new product idea is created or the requirements changed in such a way that they reflect the original need more accurately. This iterative process continues until the designer produces an acceptable result. The loop is not just a continuous ring, as the additional insight obtained in one iteration loop may change the set of requirements. An even better description of the design process is probably a continuous helix that produces new generations of improved designs or products as time progresses, and new information is gathered based on the experience from the previous generations [Suh 1990].

The same idea of iteration can also be applied to the design process in product development as it progresses from system level to component level. The functional requirements of one level are transformed into constraints at the next level of the design parameter hierarchy. When a good solution is found at system level, it locks the possible concepts at module level inside certain bounds, and as the number of functional requirements decreases with the increase in constraints, the number of possible solutions also decreases and forces design convergence. It is easier to select the set of functional requirements at module or component level when the problem is highly constrained and the design task simpler.

2.3 Concurrent engineering

The concept of CE is not new. In his article on the historical roots of CE, Smith concludes that CE can be seen rather as a summary of best practices developed since the beginning of industrialization to solve the various problems encountered during product development [Smith 1997]. According to Ziemke and Spann, 'concurrent' or 'simultaneous' engineering was commonly used in the development of the US weapon and transportation arsenal in the World War II era [Ziemke & Spann 1993]. After this period, many US and Western producers forgot this 'good way of engineering' as corporations grew, products became more complex and greater specialization of the work force took place. Large companies developed departmentalized cultures with high walls between specialized units. The common goal of good products was blurred when the different groups developed their own objectives. In Japan, however, the approach based on co-operation was conserved and also combined with a new movement focusing on quality [Prasad 1996]. At the beginning of the 1980's, the threat from Japanese manufacturers forced many US firms to look more closely at their own product development practices. As a result, the philosophy of CE was compiled. The actual term *concurrent engineering* began appearing in the 1980's and since then has been adopted in many textbooks on engineering and management. It has been one of the essential elements of product development in several large electronics and telecommunication companies such as, e.g., Hewlett-Packard, Cisco Systems [Wheeler et al. 1991] and Nokia [Ketola 2002]. During the last decade, CE has also expanded from its original design-based foundations to include the holistic view of product life cycle management [Kusiak & Larson 2009].

One original definition of CE is as follows: Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements [Winner et al. 1988]. This definition does not give any guidance on how to implement the philosophy in practice. In order to overcome this shortcoming, it has been followed by a range of lists that try to collect the 'fundamentals' or 'first principles' of CE into a form that can perhaps more easily be adapted to product development practices in industry. The most elaborate lists contain as many as eleven items [Linton et al. 1992] and the shortest ones only three [Yoshimura 1993]. The main ideas are usually the same but the viewpoints or levels of abstraction vary. According to Smith, the four fundamentals of CE typically listed are: 1) the big role of manufacturing process design in product design decisions, 2) the formation of cross-functional teams, 3) a focus on the customer and 4) the use of lead time as a source of competitive advantage [Smith 1997].

All the lists emphasize the idea of straightforward communication between different individuals. Complete transparency of the development process and decision-making is at the core of CE. It can be aided by structuring the organization in such a way that the cross-functional teams are formed. Common databases, performance visualization with simulations, and virtual and rapid prototyping are all the kinds of tools that help communication. It is sometimes forgotten that these tools do not actually generate the information exchange; they only facilitate it. The second core idea is the concurrency of decision-making. Designs should be analysed collectively from all the different angles so that sensible trade-offs can be made. As this requires good communication between different specialists, the visualization of designs and their performance characteristics becomes very important. From a designer's viewpoint, the concurrent decisions help to reduce the amount of rework that has to be done in a typical iterative design process. The overall quality of the design is also better because no last-minute fixes are needed. From the management's point of view, this means that the projects can be finished faster and at a lower cost. The penalty of the CE approach is naturally the difficulty of having to balance multiple variables in decision-making and the need to analyse the design processes thoroughly in order to be able to define when the specific decisions are needed. In some situations, especially when there is a big risk of failure, the CE methods can actually increase the initial development costs due to the higher complexity [Pennell & Winner 1989, AitSahlia et al. 1995].

2.4 Relation of concurrent engineering to design and product development

With respect to the design process, the main idea in CE is to make sensible trade-offs between different design parameters. The purpose is to find the optimum global design with respect to cost, quality and performance of the whole system. The philosophy includes [Clausing 1993] the concepts of Design For Manufacture and Assembly (DFMA) and Quality Engineering (QE). DFMA is a technique in which a designed product is systematically analysed with respect to the cost of manufacturing and assembly. The lowest cost is usually achieved by selecting the right manufacturing method, designing the components in such a way that they comply with the particular features of the method and reducing the number of parts. The best way to reduce the number of parts is to integrate the features into somewhat more complex pieces that are still fairly easy to manufacture. Savings come from fewer machines, tools and people being needed for production, simpler and faster assembly procedures and lower costs of logistics and documentation. In QE, the principal idea is to evaluate the quality (or customer satisfaction) of the product with respect to cost [e.g., Ross 1988]. Good quality products can cost less because there are fewer customer returns, the yield in production is higher and the need for product inspection after manufacturing is reduced. The best way to achieve this is to make robust products with little variation in performance even when they are subjected to varying external conditions. In many cases, although this cannot be generalized, a design will become more robust when the number of parts is reduced. From a technical point of view, the concepts of DFMA and QE are therefore inherently related.

CE can be seen as the underlying principle behind all the design processes involved in product development. Communication and consideration of all aspects are both tools for finding good solutions to specific problems at every level of the bigger process. During concept development, much information on the different phases will need to be gathered and trade-offs balanced. A product concept can be defined as an approximate description of the form, working principle and technology of the product [Ulrich & Eppinger 1995]. This definition includes the multidimensional aspect of a concept. It is not just a quickly drawn sketch on a piece of paper, but rather a collection of many different issues affecting the design. At this phase of the development process, all functional principles, production methods and possible layouts should be considered. Cost modelling can be used in estimating the effects of design decisions [Newnes et al. 2008]. The ranking of the concepts requires teamwork in which the different specialists will have to work together to find the best solution. The same applies to system-level design. At this level, all the various requirements and constraints will have to be balanced and compiled into a set of specifications that maintain the optimal solution found at the concept phase. By definition, there is always some room for the design parameters to change in any design process. This means that all the details cannot be fixed with specification, because that requires the very act of design. The different individuals who make the detailed designs for modules or components can benefit from a deeper understanding of the requirements and constraints that limit their work. This can only be achieved by creating a common goal for all the people involved in product development, and it requires continuous, concurrent effort.

2.5 Concurrent engineering and optical design

Many of the main features of CE can be found from traditional optical system development practices. Optical designs have always been restricted by manufacturing possibilities. This means that out of necessity, a rough form of DFM has become a natural part of the design process. For example, glass lens systems are usually designed by avoiding aspherics, because they are expensive to manufacture and their quality is more difficult to control [Kingslake 1978]. The assembly process for complex or high-quality optics is often also considered during tolerancing, when the variables and compensators are set for the analysis. It is quite difficult to perform any meaningful tolerance analysis if there is no plan of how the mechanical features will be designed. In his book, *Opto-mechanical Systems Design*, Yoder calls for close co-operation between optical and optomechanical disciplines in order to ensure good quality and robust optical designs. There is also a notion that review sessions in which different specialists take part to make collective decisions are important aspects of the design process [Yoder 1986]. Although the term *concurrent engineering* is not mentioned, the main idea of interdisciplinary co-operation is clearly the same.

Quality issues are usually also considered during optical design. The effects of part manufacturing and assembly-related variations are routinely taken into consideration in the tolerance analysis. Most optical design software (e.g., Zemax and CODE V) supports the statistical approach to performance variation predictions by providing Monte Carlo analysis routines. In the optical interconnects application field there have been articles [Zaleta et al. 1996, Ozkan et al. 2002] that describe how to use these methods for estimating the yield of such systems in production in order to evaluate the relative cost of designs. A similar approach has also been taken by a Japanese group that has built a simulation system for evaluating a general optical product's productivity in mass-production [Sasaki et al. 1998]. Performance degradation caused by thermal or other environmental variations is a great cause of concern for some optical systems, especially in the aerospace industry. Some custom-made simulation tools and data transfer systems [Ahmad et al. 1995, Moore et al. 2001] have been developed to aid the concurrent design process in these fields. Due to the physical nature of light and matter interaction, optical systems are extremely sensitive even to minute changes in their environment and, as a result, quality issues have become mandatory in optical designs.

What seems to be missing from the current optics textbooks and scientific papers is a more in-depth and methodological approach to the concepts inside CE. For example, there are collections of ‘rules of thumb’ [e.g., Fischer & Tadic-Galeb 2000] that state what to avoid while designing a lens system, but these guidelines are easily too crude to be used in the finely detailed work of product design. Even the basic task of choosing the right manufacturing methods at the system design level can be quite hard, because it is difficult to find any knowledge to support the cost evaluation of different options. There are tables available that show the feasible tolerances in optical component manufacturing and in some cases they are also connected to relative cost figures [Plummer 1979, Fischer & Tadic-Galeb 2000] or trendlines [Willey 1985]. It is common knowledge that tighter tolerances mean higher manufacturing costs, but absolute values are generally hard to obtain. Optical designers can easily create several different design concepts, but their analysis is frequently only restricted to performance. Instead, the analysis should be used to find the right balance between performance and cost or the lowest cost design concept that satisfies the performance requirements. At the detailed module or component design level, the designers should be able to compare optical layouts that are very similar. A small change in the thickness of a lens element may only cause a minor drop in the modulation transfer function (MTF) value, but it can mean large savings in the production of a high-volume lens. This value for money analysis is not possible without tools and understanding that relate the features of the particular design to the cost structure of the manufacturing process.

The importance of concurrent design practices increases as the optical parts and modules are adopted into complex systems and multifunctional devices. One example of a more complicated optical device is a digital camera module that uses wavefront coding technique [Dowski & Cathey 1995]. In these systems, the image resolution is dependent not only on the optical performance of the lens, but also on the camera sensor and signal processing. The wavefront technology can be used in enhancing the image quality or in relaxing the manufacturing tolerances [Lee et al. 2010]. In such a system, the trade-off situation is even more complex than in the case of a standard camera lens. When the signal processing software can play a major role in the performance of the whole camera device or module, some optical performance can be sacrificed in order to obtain a more robust design with looser tolerances and a lower manufacturing cost. The major engineering effort in such a case goes on balancing the cost and performance of optical as well as electrical components. This situation can become even more complex when the human visual system is taken into account [Olivés et al. 2004].

The holistic approach to optical design requires deep and wide levels of understanding of all the issues involved as well as good communication. The typical methods, such as MTF, used in describing the performance of optics are not very easy to understand without a proper technical background. This information needs to be conveyed to the system designer and the designers of the parallel modules or components. The image simulation features available in the commercial optical design software are good tools for assisting better communication. New custom-made tools can also be developed for specific needs and for cases in which the final performance of the system is also dependent on factors other than optics [Kolehmainen et al. 2004].

3. Design and development process of plastic optics

3.1 Optics design and development process cycle

Figure 222 shows a simplified process scheme that describes the iterative optics design and development cycle. The sequence is divided into five main phases: concept creation and specification, optical design, mechanical design, manufacturing and testing. Although, in principle, the process can be seen as sequential, the multitude of issues involved in each part of the loop make it practically impossible to divide the process into separate and self-sufficient parts. A large number of trade-offs are needed in order to be able to satisfy the different requirements from the various sub-disciplines. The main purpose of drafting out the process description is to make clear which development phases will need to be considered in finding a good quality optical product design. In the CE approach, the entire process cycle needs to be passed through at every product development level in order to find the optimal solution. If the concept creation phase is realized by only making optical designs, it is very easy to end up with a layout that has the potential to fulfil all the optical performance requirements but is impossible to manufacture at a feasible cost. Even the testing phase will need to be considered during concept creation, because it is possible to design optics that are very hard to measure, and without proper metrology the output of the production line cannot be controlled and used in adjusting the production process. CE can lower the development costs of optical devices by improving the design process itself. As all the aspects are considered during the design, unnecessary redesigns and prototypes can be avoided.

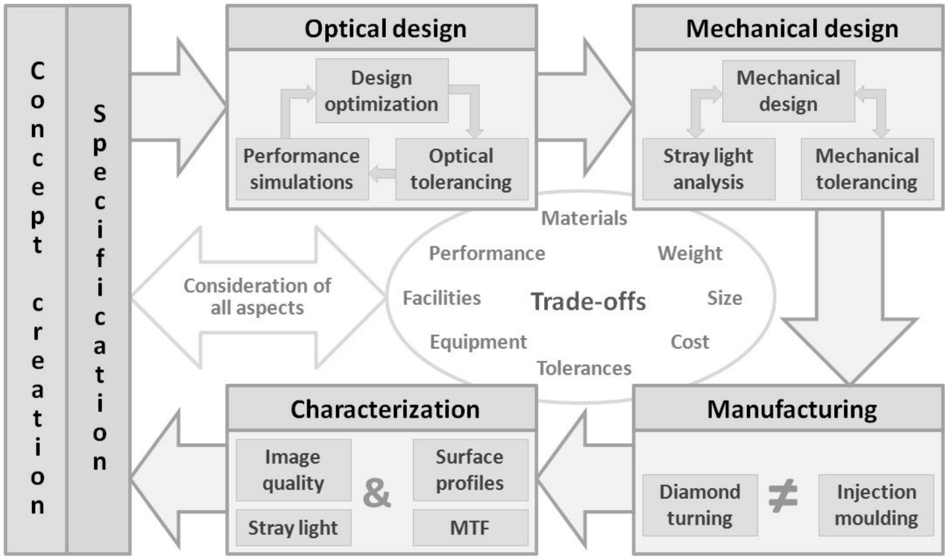


Figure 2. Optics design and development process with five main phases.

At the first level of product design, the emphasis of the optics development process is on concept creation and specification. Functional requirements for the optical module are formulated by, e.g., stating that the imaging lens should provide a 3x zoom or that the illumination pattern produced with the optical structure should look even to the human eye. It may also be stated that, e.g., the size of the system should be small enough to be carried around in a pocket and that it should be affordable to the average consumer. One of the main issues at the first level is to identify the most important trade-offs between different modules of the whole product as well as between different phases of the optics development process. Available commercial products, patents and optical design libraries can be analysed for a better understanding of customer requirements, achievable performance and economic feasibility.

At the second level of the product design process, the system design phase, the emphasis is on optical and mechanical design tasks. These are used in creating a set of concept designs for the optics. For example, different optical methods for collecting and directing the light emitted from an LED can be explored by making rough designs that are based on lenses, mirrors, TIR structures or hybrid solutions. Manufacturing and testing phases are used in evaluating the production and metrology costs associated with each design concept. Available facilities and equipment can also be considered. After the first iteration loop through the whole optics development process, the design parameters of the developed concepts are compared with the preliminary specifications. If a good match is found, the process can continue to the next phase of detailed design, and some of the original functional requirements can be transformed into limitations that constrain the design process to the optimal concept. For example, it can be specified that the imaging lens should be made with plastic components because the weight and cost of the module will need to be minimized. If there is a big gap between the concept parameters and requirements after the first iteration round, or if the gained insight is used to alter the requirements, a new system-level design cycle will be needed.

At the third, detailed design level, the emphasis in optics development is on manufacturing. The optical and mechanical designs are fitted to the selected manufacturing processes by analysing all the design features. Design alterations are made in order to eliminate expensive details and make the component structures and module assembly easier to manufacture. For example, the flange area around a plastic lens can be increased in order to allow more room for sprue cutting. A suitable optical part maker will need to be involved in the design process in order to obtain some technology guidance and realistic tolerance values. A tolerance analysis is carried out with possible design and assembly scheme alterations in order to make the design more robust for production process variations. Plans are also created for testing the prototypes and ramp-up series. Special features can be designed for the mechanics, ensuring that the optical pieces can be placed on the measurement equipment reliably and with the correct orientation.

In the fourth, testing and refinement, stage as well as the fifth, ramp-up, stage of the product development process, the main emphasis in optics development is on testing. Several different prototypes can be manufactured in order to verify the feasibility of the design. Much testing is also needed in the ramp-up phase in order to ensure that the process is able to produce pieces with predicted accuracy and performance. Many different characterization methods, from MTF to surface profile measurements, can be used. Optical simulations can be used in assisting the measurement result verification task and in locating the sources of possible problems. Feedback from the measurements can be used in altering tolerance analysis parameters for new simulations in order to obtain better predictions of yield or for analysing the possibilities for production process improvements.

3.2 Concept development and specification

In optical design it is sometimes quite difficult to know what the outcome will be, due to the inherently complicated nature of optics optimization. The connections between optical design features and their consequences are not always intuitively clear, and sometimes many time-consuming simulations are needed to test the ideas. Even a simple lens can have a near infinite number of possible solutions in a multidimensional space [Fischer & Tadic-Galeb 2000]. Not all of the options can be considered, and for this reason concept development can become a hit-or-miss activity that requires much trial and error. Due to the fact that optics is a highly specialized field of engineering that requires a large amount of knowledge about the physical processes involved, it is extremely important to have an experienced optical designer involved in the concept development, even if optics only plays a small role in the whole product.

The goal of concept development is first to explore the ‘design space’ of possible solutions as thoroughly as possible and then to select the concept that has the best potential for fulfilling all the requirements. This part of the process requires a combination of external searches, creative problem solving and systematic exploration of partial solutions. It is very useful to have people with multidisciplinary backgrounds involved in this work, as one method for creating new concepts is through analogy. Creativeness can also play a major role in concept development. Plastic optics is especially suitable for creative solutions, as the manufacturing method allows incorporation of various features and functions for untraditional monolithic designs. In general, imaging systems can be considered a field of optics in which the design space is more limited than the field of non-imaging optics. As the technical requirements for imaging component manufacturing are very high, the number of possible production methods is also limited, and they restrict the number of feasible solutions. With non-imaging optics, the same optical function can be realized with a wider selection of structures, and as the manufacturing tolerances are not as high as with imaging optics, there are also more possibilities for making them. This difference is reflected in the fact that much software code is available with built-in features and functions for optimizing imaging systems, but no universal routines are available for optimizing non-imaging structures.

During specification, the optical and mechanical requirements of the optics module are defined. A manufacturing method will also have to be selected as this has an effect on the available materials, achievable tolerances, feasible surface shapes and cost. Specifications are used as a gate to the rest of the device development process and are therefore also the channels through which the trade-offs between different modules of the whole device are routed. The task of specifying optics can be quite difficult, especially if the system to be designed is the first of its kind and there is only a small amount of prior knowledge available that is relevant to the application at hand. In many cases, optics are also made with the highest possible precision the manufacturing method can support, and sometimes the specifications will need to be relaxed in order to meet the cost target. More than one functional prototype is usually built before the actual product is manufactured, and by verifying successive builds it is possible to improve the specifications for the next round of the design iteration. For this reason, it is also important to specify those things that can be measured in the characterization phase. In order to be able to improve some feature its progress will have to be monitored in each prototyping cycle.

3.3 Design of optics and mechanics

In the optical design phase, the system is optimized and a tolerance analysis carried out. The best possible merit function value design is not necessarily the best one to choose, as one major trade-off is between the tolerances required by the optical performance and tolerances achieved in manufacturing. If the nominal performance of the designed system is close to the optical specification, a set of very tight tolerances is required in order to keep the performance inside the specification after manufacturing errors. Unfortunately, tight tolerances tend to cost more than loose ones. For this reason, the manufacturing method and its restrictions will need to be carefully considered in the optical design phase. In other words, DFM is needed.

Mechanical design is performed by considering the geometrical specifications and optical tolerances of the system. In addition, for example, stray light and thermal analysis can be carried out to verify the performance of the whole system in different environmental conditions. Although, for an optical designer, it is not a difficult task to scale down the design on a computer screen, the reduction in size can be seen in the optical design phase through the trade-offs that will have to be made with manufacturing tolerances and mechanical design. With strict size requirements, the mechanical designers have to rely on simple and robust structures. Very small parts can be hard to manufacture and handle during the assembly. In plastic optics, one great advantage is the possibility of integrating mounting structures into the optical elements and this way reduce the complexity of the system. Adding a mechanical feature to the plastic component may induce some degradation in the optical performance, however, if the feature is not designed carefully. Sudden changes in mould cavity thickness cause uneven flow of material during the injection moulding and may cause shrinkage and birefringence problems. If, for example, a hole or rib is placed too close to the edge of a lens surface, the shape may become locally distorted when the component shrinks during the cooling period. The integrated mountings also provide additional paths for unwanted light through the module, and plastic optics can therefore be particularly vulnerable to stray light [Hasenauer 1995].

In optomechanical design, the optical and mechanical sections are practically inseparable. Despite this close relationship, the two tasks are usually performed by different individuals with different technical backgrounds, namely optical and mechanical designers. This means that information exchange in the form of, e.g., CAD files is a crucial factor in the process. In a typical plastic optics development process, the created optical designs first have to be transferred from the optics software to the mechanical design software, where the geometry of the actual component model is created. The component model then has to be transferred to the mould designer, who in turn has to translate the mould shapes into a format that is understood by the software, which calculates how the machine tool should move the tip of the milling cutter. Great care should be taken that the whole chain of software and people can maintain the appropriate level of geometric accuracy required from many optical components. The standard mould design, mould manufacturing and injection moulding companies are used to dealing with much larger tolerances for surface shapes than might be required from, e.g., an imaging lens. CAD/CAM software stores the geometry of parts in files that contain lists of 3D points as well as instructions on how to connect them to each other. Each file format has its own way of listing the data, and each mechanical design software program has its own way of translating and using that data. If the accuracy requirements and the functioning of the software are not clear to the part and mould designers, unacceptable geometry errors can be generated even before anything physical is manufactured.

3.4 Manufacturing and characterization

Injection moulding imposes some clear limitations but also great benefits for optical and mechanical designs. Flat surfaces are very hard to achieve due to the shrinkage of the part inside the mould during the curing phase of the injection moulding cycle. If the mould has a flat facet, the resulting component will have a slightly concave surface. Curved surfaces are easier to control, though they will also experience some changes in shape. The diamond-turning machines can produce aspheric shapes as easily as spheric shapes, and this method will therefore also give additional freedom to the optical design. One major limitation is the short list of plastic materials [Gross 2005] that can be used for refractive optics. Good colour correction is difficult to achieve with only a few lens materials. By using diffractive structures, this problem can be somewhat relieved. Diffractive components that also perform other optical functions can be integrated into the designs, but they will require specialized design and manufacturing expertise.

In prototyping, the injection moulding technique is somewhat problematic due to the high costs. Mould inserts for very small series are relatively expensive to produce even if a standard mould base is used. For this reason, separate machined and polished or diamond-turned components are a compelling alternative for at least the first prototypes. With diamond turning, it is possible to produce relatively low-cost lenses with the same complex surface shapes as those that can be expected from injection-moulded components. Due to the fact that direct diamond turning or machining can be a more accurate method than injection moulding, some consideration is needed in the evaluation of the results.

After the system is manufactured, it is characterized and the experimental results compared with the original specifications and estimations obtained from the previous design verification simulations. Several different measurements are necessary for thorough characterization. When an imaging system is considered, the most important characterization method is probably the MTF measurement. This is especially true if the specification of the lens states a value for the MTF. Other characterization possibilities include interferometric shape measurements of individual optical surfaces, roughness measurements with a profilometer and, for example, a stray light measurement of the whole system.

Shape measurements are very important to injection-moulded optics, as the shape of the optical surface is not identical to the shape of the mould. Injection moulding process parameters and plastic material selection have their own effects on the resulting surface shapes and the replication accuracy of surface microstructure. Diamond turning of the lenses or moulds can give a surface rms roughness under 10 nm [Cheung & Lee 2003], which is a good optical quality for most applications, but some roughness-induced light scattering will appear.

If there are several optical components in the system, the accumulation of scattered light may cause a stray light problem.

If the performance of the prototype is not sufficient, a new prototyping iteration cycle will be needed. New error analysis simulations can also be performed in order to pinpoint faults in manufactured modules. Simulation software provides an ideal environment in which perfect systems can function without disturbance from the outside world. By introducing controlled perturbations to the virtual design, it is possible to isolate the effect of one particular error source from the system performance. In real life, all of the error sources act simultaneously and it can be difficult to see which of them have the biggest impact. By systematically going through these possible sources and comparing the simulation results with the measurements, it is possible to extract some information that would not be possible to obtain with empirical methods alone.

3.5 Tolerancing optics

An optical design is not complete until it has been toleranced. Tolerance analysis is part of the design process in which perturbations to an ideal layout are systematically introduced in order to analyse the robustness of the design. The purpose of tolerancing is to determine the number and type of errors that can be introduced and still have a system that performs to requirements [Koch 1978]. Without taking into account the various perturbations caused by manufacturing and the environment, an optimized optical layout can turn out to be totally useless for any practical purposes.

There are many different sources of error that may act on the same design simultaneously [Peschka 2007]. Fabrication errors include things like an incorrect radius of curvature and component thickness. Decentration and tilt of components are examples of assembly errors. Materials are not perfect either, and there are always some fluctuations in the refractive index between different batches of material. Environmental factors such as temperature variations and vibration may also cause the optics and mechanics to change their shape or position slightly. The designs created should have large enough performance margins that can tolerate all possible combinations of these error sources in a realistic environment during the lifetime of the product. It is also common practice in engineering to leave some room for unexpected errors by incorporating a safety margin into the design.

There are four types of initial data that need to be defined before analysis: 1) A figure of merit (or merit function) determines the metrics that are used to evaluate system performance. For example, in an imaging system this can be the lowest MTF value at a certain frequency [Rimmer 1978], or in an illumination system the uniformity of light distribution on the target surface. 2) Performance criteria specify the lowest acceptable value of the chosen merit function. As an example, an MTF value of 0.3 at 100 cycles per millimetre can be defined as the lowest acceptable value for a lens. 3) An initial set of tolerances is a set of easily achievable tolerance values that can be used as a starting point in the analysis. These should be based on realistic information on the chosen manufacturing method accuracy. 4) Possible compensators can also be defined that can be used actively to lower the effect of errors on system performance. As an example, a common compensator in camera modules is the back focal length, which can be designed as an adjustable parameter by adding the possibility to move the whole lens module closer or further away from the image sensor.

Two types of analysis are needed in a thorough tolerance evaluation. A sensitivity analysis is used in determining the most critical tolerances [Ginsberg 1981]. In this analysis, each tolerance variable representing a specific error source is considered separately. This is done by changing the value of, e.g., lens thickness to the extreme lower and higher limits and by simulating the resulting changes in a merit function. When all of the different variables are simulated, a list of the most sensitive tolerance variables can be compiled. There are usually large differences between the type and magnitude of performance deterioration caused by the diverse variables. By analysing these differences, the designer can concentrate on those factors that have the greatest effect on system performance. The second type, the Monte Carlo (MC) analysis, is used for obtaining statistical information. In this analysis, all of the tolerance variables are simulated simultaneously. A statistical distribution will need to be assigned to each variable [Peschka 2007] as the discrete limits of positive and negative tolerance values are not sufficient to describe the random nature of error generation. In the MC analysis, a large number of systems will need to be simulated in order to obtain results that are statistically relevant. Factors such as yield and width of performance variation can be predicted with this method [Koch 1978, Forse 1996].

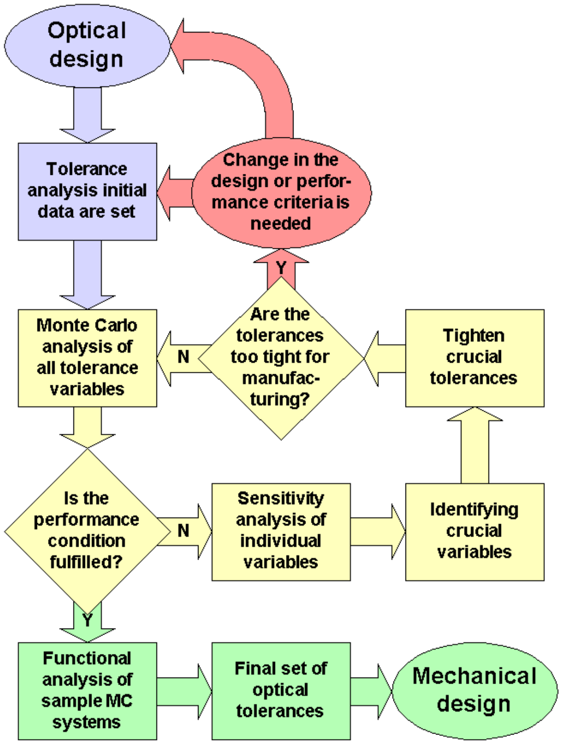


Figure 3. Optical tolerance analysis process flow.

Figure 3 shows the process flow of optical tolerance analysis. The process starts by setting initial data for the created optical design. Monte Carlo and sensitivity analysis are used in an iteration loop. The MC analysis is used in checking the robustness of the whole design. If the performance distribution of simulated systems is too wide and/or there are many systems below the specified limit, some of the tolerances will need to be tightened. Sensitivity analysis is used in the loop for identifying the variables that should be changed in order to improve the statistical performance. It is no use tightening the tolerances that do not have an effect on the functioning of the whole system. Over-tolerancing will only increase manufacturing costs unnecessarily. The main idea is to find the easiest set of tolerance values that can be used while still ensuring adequate performance. It is also possible that the tolerance values turn out to be too tight for manufacturing and that a change in the design or performance criteria is needed.

Tolerancing can be used during design optimization by including tolerance variables in the merit function. This way it is possible to find robust solutions directly with the design optimization routine. Unfortunately, the addition of tolerance parameters to the already time-consuming optimization process increases the simulation times, and for this reason tolerancing is usually performed as a separate task after optimization.

4. DFM aspects of injection-moulded optics

4.1 Manufacturing optics by the injection moulding process

Most plastic optics components are manufactured by injection moulding [Karow 2004]. This is a cyclic process in which 3D geometries are formed from the raw material in a single process step. The whole production process of moulded plastic optics has only two mandatory phases: mould manufacturing and injection moulding. Both of these can be further divided into sub-processes such as diamond turning of the optical inserts or spruce cutting of the pieces. There can also be several post-processes such as coating and inspection. The simplicity of the injection moulding process itself along with the physical properties of plastic materials allow very fast production of complex and accurate pieces cost efficiently however. As the size of the production series can be as high as tens of millions, the time spent making a single piece will have a drastic effect on the time spent for the production of the whole batch. If just a few prototype pieces are needed, moulding will always be an expensive method of making them due to the high cost of tooling and the initial costs of moulding. Many of the other plastic manufacturing processes such as fused deposition modelling that are suitable for low production volumes [Karania & Kazmer 2007] are not possible for optical parts due to the poor surface finish quality and material inhomogeneity. Prototypes diamond turned directly from plastics can offer a cheaper solution if just a few (tens of) of pieces are needed [Bauer & Marschall 2010].

As a manufacturing technology, injection moulding competes with other technologies capable of making components with a similar function. There are some inherent benefits such as the integration of mechanical features that can make plastic optics more attractive by lowering the cost of assembly [Bralla 1999], but there are also other factors such as mould cost that may restrict the use of moulding to high-volume applications. The injection moulding process makes a near perfect copy of the tool. The main benefit of this technology comes from the fact that the high accuracy of shape and finish of the part will only need to be tooled once into the mould and it can then be replicated to a very large number of nearly identical pieces. With standard injection-moulded parts, an annual production volume under about 25 000 pieces is considered ‘low volume’ [Bryce 1997], and it can be questionable if it is sensible to use moulding technology at all to make parts in lower quantities than this. In optics, the competing traditional glass-based manufacturing processes have fairly high costs associated with them due to the fact that each high-precision piece is manufactured separately. For this reason, the threshold of acceptable production series size can easily be lower in plastic optics [Karow 2004] than in plastic parts without any optical function.

Optical parts can be produced with standard injection moulding machines using high-precision moulds [Walther 2010]. The machines have two basic elements: a plasticizing unit that is used for processing the material and a clamping unit with two mounting platens for attaching the mould. The moulds have two halves that are brought together with the clamping unit in order to close the cavity machined to one or both sides of the tool. When the mould is closed, melted plastic is injected into the cavity from the plasticizing unit through sprue channels. The mould is cooled by pumping coolant through a network of cooling channels inside the mould halves. Plastic material cools down inside the cavity and becomes solid. As the newly created plastic piece goes through this transformation it shrinks. Some of this shrinkage can be compensated for by pumping more material into the mould and by keeping it at a high holding pressure. When a sufficient level of dimensional stability is reached, the part is ejected from the cavity by separating the mould halves and pushing the piece out with the help of ejector pins. Some shrinkage can also occur after the ejection as the part cools down to room temperature. The difficult task in optics injection moulding is to ensure that the shape and surface quality of the piece are on the desired level of precision even though the manufactured component has a slightly different geometry than the cavity tooled into the mould.

4.2 DFM and injection-moulded optics

The design for manufacturing approach is especially important in plastic optics due to the fact that the components are typically made by injection moulding.

Unlike the traditional grind and polish techniques used in making glass optics, injection moulding was not originally developed for making optical parts. The technology evolved for exploiting the good properties of polymer materials, and initially it was not tuned to the high-precision requirements of lenses and mirrors. As the methods used in mould manufacturing have developed towards higher accuracy, however, moulding has also become a viable option for optics. For some products, like the optical mouse, it is now the only feasible manufacturing method that can produce clear high-precision parts in sufficiently large volumes and at low costs. Due to the striving for high efficiency, injection moulding is a production technology that imposes strict constraints on part designs. For this reason, plastic optics pieces are process-intensive products and many ‘rules of thumb’ [e.g. Beich 2002] have been created. These kinds of products will need to be developed, even at the concept phase, by considering the restrictions of the manufacturing process [Ulrich & Eppinger 1995].

In order to fit designs to the production process, one of the most important tasks is to ensure that the tolerances required from the design are compatible with the tolerances achievable with the manufacturing method. What makes this task difficult is the fact that each manufacturer has its own specific manufacturing equipment and personnel who determine the achievable accuracy of the production. Detailed and realistic information in the form of tolerance tables may be hard to obtain as they form a part of a company’s competitive edge. Some general tolerance tables are available that can be used as a basis for tolerance analysis of plastic optics systems however. Table 1 shows one example [Pfeffer 2010]. Tolerance distributions in injection-moulded optics parts can be skewed but repeatability is good [Lytle 1979]. There will only be minor variations between the components produced with the same mould cavity. The offset from the designed nominal values in the distributions is problematic because it is the result of injection moulding parameters and mould geometry, which cannot be predicted accurately. Software is available that can be used to simulate the whole process of moulding from the filling of the cavity to the end of the cooling period, but its accuracy is not good enough for high-quality optics, for which shape accuracy in the sub-micrometer range may be required. The skewed distributions can only be considered properly in the simulations after enough feedback becomes available from production.

Table 1. Typical tolerances and specifications for injection-moulded plastic optics [Pfeffer 2010].

	low cost	**commercial**	**state of the art**
focal length [%]	± 3–5	± 2–3	± 0.5–1
radius of curvature [%]	± 3–5	± 2–3	± 0.8–1.5
irregularity [fringes/10mm]	2.4–4	0.8–2.4	0.8–1.2
scratch/dig	80/50	60/40	40/20
centration	± 3’	± 2’	± 1’
centre thickness [mm]	± 0.1	± 0.05	± 0.01
flange diameter [mm]	± 0.1	± 0.05	± 0.005 / ∅10
radial displacement [mm]	0.1	0.05	0.02
diameter/thickness ratio	2:1	3:1	5:1
surface roughness [nm_{RMS}]	10	5	2

Injection moulding technology has been studied thoroughly from the DFM perspective for decades. There are several books that describe the design rules for plastic parts with some indicative information on the costs of particular features [Bralla 1999]. In order to reap the full benefits of the manufacturing technology, plastic optics designs also have to follow these guidelines as closely as possible. One of the biggest advantages, compared with glass and metal optics, is the possibility of integrating several different features into the mass-produced parts. By merging several functions into one component, fewer pieces need to be handled and stored in the factory, and the assembly process becomes simpler. There will also be fewer machines and tools to maintain. When all these factors are combined, the injection moulding method turns out to be very cost-efficient. The combination of low cost and high functionality makes plastic components desirable. The DFM approach responsible for this state of affairs is one of the main reasons for the popularity of plastic parts in current consumer products. The use of injection moulding in optical part production has also enabled new optics products that would not have been developed at all without the low-cost components.

4.3 Estimating the costs of injection moulding

Plastic injection moulding is a manufacturing technology that is several decades old, and many tools are available for calculating the moulding costs of parts. Some of these tools can be used freely on the websites of, e.g., companies involved in injection moulding [IDES CostMate] or plastic material manufacturers [BASF Quick Cost Estimator]. Some of the tools are quite simple and easy to use, but there are also cost models that are very sophisticated and complex [Chen & Liu 1999]. Unfortunately, there is no standardized way of calculating moulding costs, and for this reason all of the tools are somewhat different from each other. In each case there is a set of input parameters that determines the cost via a series of simple arithmetic operations. The different operations tie together the main cost factors of the product and the process. What makes the tools complicated is the fact that many of the input parameters are connected to the output parameters through more than one route. For example, moulding yield is used in the formulas for material, machine and labour costs. This complexity makes it difficult to use the readily available models, as the relations between the input and output parameters are not clear to the user who has not made the calculation tool himself or herself.

Most optical design features have a direct or indirect influence on the cost of manufacturing. These connections will need to be analysed in order to adjust the designs to the specific features of the production process. Yield is among the most important factors that determine the cost of moulding. It defines the proportion of manufactured components that function as specified or that pass the different inspection stages. If all the manufactured parts fulfil the specifications, there is no need, e.g., to sort out the defective ones, the material loss is at minimum and no machine time is wasted. There is one optical design feature that is related to this cost factor. The size of the optics has an effect on the yield if there is a specification for the allowed number of defects on the surface of the piece or inside it. As the size of the piece is increased, the risk of having these defects also increases. Another major cost factor connected to the size of the moulded piece is the machine cost. The main trend in machine cost follows the size of the machine [Dewhurst & Kuppurajan 1989]. The machine size (and therefore rate) is also connected to the size of the moulded piece. A suitable machine for a particular product is chosen by considering the volume and total projected surface area of the product with all the mould cavities and the runner system [Bryce

1996]. The size of the optical piece is one example of a design feature that is connected to the main cost factors in the injection moulding process.

One of the most important cost factors in the injection moulding process that can be influenced by design is cycle time. The cycle time is the time it takes for the injection moulding machine to make a single part or, in the case of a multi-cavity mould, a set of parts. Closing the mould, forward movement of the injection unit, mould filling, mould opening and part ejection build up a time factor that is practically constant for each type of injection moulding machine [Bryce 1996]. The varying time factor and cooling time are dependent on the material used, part geometry, mould design and accuracy requirements. It is possible to eject the piece from the mould before it has finished cooling, but it then undergoes some small uncontrolled shape changes. Due to the demands for high precision, the cooling time can easily be the dominating factor in the cycle time of plastic optics moulding as well as the main driver of cost. The cooling time can be affected by two design-dependent variables, material selection and part thickness.

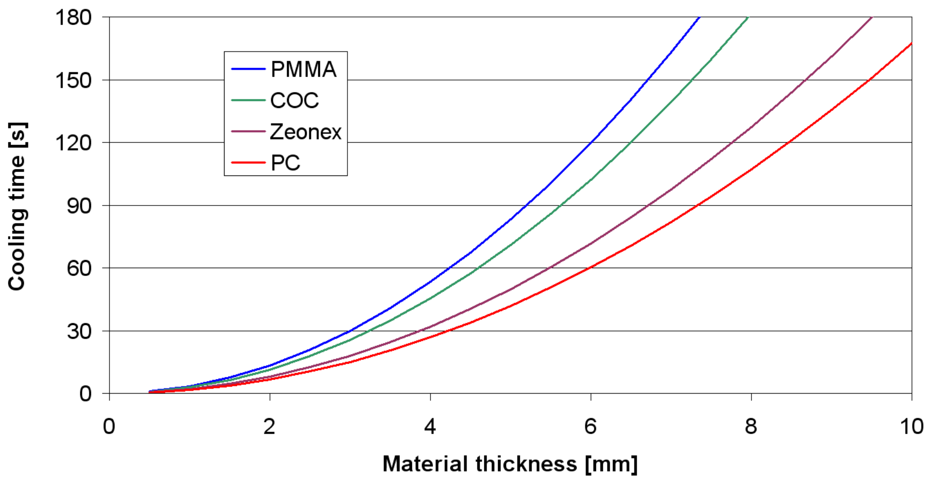


Figure 4. Relations between cooling time and material thickness calculated for four optical plastic materials with common material characteristics and moulding process parameters.

Figure 4 shows the relation between material thickness and cooling time calculated for the geometry of a flat plate [Beiter et al. 1995]. The process-specific characteristics of four common optical plastic materials were used in the calculations in order to show the large differences between materials. For example, a 4-mm-thick piece of PMMA will have a cooling time of ~53s, which is almost twice as long as the ~27s of PC. This means that the same plate manufactured from PMMA will take almost twice as long to mould as it would take if it were made from PC. In general, with all materials, the cooling time will increase exponentially when the thickness is increased. For this reason, the most important geometric factor in plastic part design is wall thickness [Bryce 1997].

Calculating the cost of material per single manufactured piece is a straightforward task when the material price, product geometry and mould design are known. In some cases the runner system may form a big part of the total material volume used. The yield is also included in the calculation, as some of the produced parts will always fail to meet the high quality criteria. In optics injection moulding, the material cannot usually be recycled into the process due to the fact that it needs to be homogeneous and clean. The moulding and material regrinding introduce, e.g., dust particles into the plastic, which affect the optical properties. For this reason, a large portion of material is wasted in plastic optics production. There can be big differences in the cost per kilogram between two optical plastics such as PMMA and Zeonex. At first glance this may tempt a designer to choose a cheaper material if the optical functioning of the piece allows it. The material price may have a much smaller impact on the cost than the cycle time, however, which is also directly linked to the choice of material. In many optical cases, the direct cost of material is only a small part of the total moulding cost and the selected material mostly affects the moulding cost through the physical properties of the plastic. It can be much more effective to reduce the part costs by shortening the cycle time than by selecting a lower cost material.

4.4 Estimating the costs of additional processes

Estimating the cost of the mould is especially important for low- or medium-volume injection-moulded products in which the main concern is the amortization of the mould. There are several different methods for estimating the cost of a mould [Nagahanumaiah & Mukherjee 2005]. Some of these methods are based on tooling time and some are based on geometric features. The estimation itself can also be made by intuition based on the mould maker's experience, or it can be calculated with a dedicated computer software or calculation tool [Chan et al. 2003]. In general, moulds can cost anything from a few thousand euros to a few hundred thousand euros depending on, e.g., the size and complexity of the part, number of cavities and accuracy requirements [Dewhurst & Kuppurajan 1989, Bryce 1998, Fagade & Kazmer 2000]. The cost risk associated with the sensitive optical surfaces is usually managed using separate insert pins or pieces as part of the mould cavity [Bauer & Marschall 2010]. The cost of renewing an exchangeable pin is much lower than the costs of reworking a whole mould half. A pin can also be replaced quite quickly whereas the tooling of a mould half will stop production for a considerably longer period of time. Spare inserts can be manufactured along with the set required for filling all of the mould cavities. A single insert is typically more expensive than the individual inserts in a series of identical pieces. In a multi-cavity mould, the fact that the cavities are identical will give a definite cost advantage [Dewhurst & Kuppurajan 1989]. The best way to estimate costs is to discuss them with a mould maker and ask for ballpark figures.

Coatings usually make up a significant part of the manufacturing cost of an optical piece, and notable savings can be made if they are not needed in the system. In many cases, they are simply mandatory in order to meet the optical specifications set for the design. Coating costs can be estimated by taking into account the batch cost and piece holder size of the coating chamber [Fischer & Tadic-Galeb 2000]. The distinct difference between moulding and coating is that the former is a continuous process whereas the latter one is a batch process. This means that a group of components is coated as a single batch in the coating chamber under identical processing conditions. If the conditions are not ideal and something goes wrong with the coating, the whole batch has to be discarded. It also means that coating can be a very expensive process for just a few pieces. The batch cost remains the same even if the chamber only has a few components in it and the high batch cost has to be divided between a small number of parts. In addition to the actual processing costs, coating increases the total manufacturing costs of plastic optics by introducing a new irreversible process into the production chain. As in any real-life manufacturing process, there is an associated yield factor. The parts that are coated with defective layers have to be wasted and the costs of both coating and moulding factored into the sales price. For this reason, the importance of a high yield at the coating stage becomes even more pronounced. Organic polymers are much more complex materials with respect to coating than inorganic glasses and, for this reason, the same processes as those used for glass optics cannot be used for coating plastics [Schultz 2010].

In addition to the three key processes mentioned in the previous chapters, there are several other processes that belong to the whole production chain of plastic optics products [Bryce 1996, Bryce 1997]. Some processes, such as sprue cutting, can be very similar, with optical components rather than normal mechanical moulded parts. As the requirements for functionality are different, however, there are also many differences in some of the subsequent processes needed to build whole plastic optics modules and systems. One example of an additional process that is very specialized for optics is inspection. There are numerous ways to measure the components or modules that come out of the production lines of plastic optics factories [Bäumer 2010b]. A large number of devices along with skilled personnel who can use them are needed to make these measurements. The cost of all this equipment, the floor space it occupies, the electricity it uses, etc. need to be factored into the costs. Another process that has the potential to increase the cost of plastic optics products is packaging. Optical surfaces of plastic pieces are very sensitive to scratches and contamination, which means that great care must be taken to protect the parts during shipment to the module or device integrator. Special trays are usually needed for this purpose. As these trays are custom-made for each product type, they add directly to the costs. This type of expense can also be influenced by design. If the part is designed with mechanical features that protect the optical surfaces, the pieces can be packaged faster and more efficiently without extra packaging material. It may also be possible to fit more pieces into a container, reducing the cost of shipping.

4.5 Cost modelling of injection-moulded plastic optics

Cost modelling can be used to play 'what if' games in order to determine if the part is worth the trouble and cost of producing it or to find an optimum design concept for it at system level [Dewhurst 1988]. Optical design software is routinely used in simulating the performance of optical systems with high accuracy. Completely different designs or just small variations of one solution can be compared by simulating them in ray-tracing software without the need to build expensive prototypes. Tolerance analysis routines can be used to determine the probable production yield based on performance distributions, and the design can be optimized for maximum yield instead of maximum nominal performance, which can never be reached in real life. Cost models can be used for simulating the effects of design variations in manufacturing costs in a similar manner. A cost model closes the feedback loop between design decisions and the resulting manufacturing cost in very much the same way as optical design software closes the loop for performance optimization. By using these two tools concurrently, a designer can make the jump from part optimization to true module or system-level optimization.

Table 2. View of a simplified cost-calculation tool created in Excel for estimating manufacturing costs of injection-moulded optics.

Basic information

Product:	Viewfinder optics
Material:	Zeonex E48R

Moulding input parameters

Material price	25	€/kg
Product weight	1.8	g
Machine rate	18	€/h
Machine uptime	85	%
Yield	90	%
Number of cavities	4	
Cycle time	240	s
Work cost1 (operator)	10	€/h
Work cost2 (skilled)	20	€/h
Indirect costs	70	%
Workers per machine	0.5	
Batch size	50 000	
Batch setup time	8	h
Repair & Maintenance	8	h/batch

Capacity calculations

Day (24h)	1 047	pieces
Week (7 days)	7 326	pieces
Month (year/12)	29 303	pieces
Year (48 weeks)	351 631	pieces

Tooling cost calculations

Mould design cost	2 000	€
Mould cost	30 000	€
Optical insert cost	1 000	€
Mould life	500 000	cycles
Insert life	100 000	cycles
Inserts per cavity	3	
Tooling costs	**0.0460**	**€/piece**

Moulding cost calculations

Material	0.0500	€/piece
Machine	0.3950	€/piece
Labour	0.1121	€/piece
Tool R&M	0.0032	€/piece
Indirect	0.3573	€/piece
Molding costs	**0.9176**	**€/piece**

Coating cost calculations

Coating batch cost	250	€/batch
Pieces per batch	1 600	
Coating yield	95	%
Coatings per piece	1	
Coating costs	**0.2104**	**€/piece**

Total cost	**1.17**	**€/piece**

A parameterized cost-modelling tool is needed for use in a typical iterative design loop [Farineau et al. 2001]. Table 2 shows one example of a simplified tool created for estimating the production costs of injection-moulded optics [Paper VI]. In the example calculation sheet, separate cost estimations are made for three plastic optics key processes: mould tooling, injection moulding and coating. The results are calculated per single manufactured piece in large-scale production in which the mould cost can easily be amortized. The total cost is calculated by simply adding the three separate process expenses together. The moulding cost input parameters deal with both process- and product-related issues. Examples of process-related parameters are the hourly wages of workers, machine rate, machine up-time, yield, price of electricity, etc. Many of these parameter values are based on knowledge that has been built up inside the moulding company during its operational years or that can be obtained from the company's accounting department. Examples of product-related parameters are thickness and weight of the part.

Many of the parameters in a cost model can be very difficult to estimate outside the company manufacturing optics. Some educated guesses can be made, however, and parameters ‘calibrated’ with the help of official part quotations. Even ballpark figures can be very useful when similar designs are compared with each other. One major benefit of such a model is that the designer can gain a much better insight into the cost structure of an optical product just by playing around with the input parameters. This insight is hard to obtain without a dedicated tool, as the connections between optical design features and manufacturing process cost factors are so complex. At best, the model is not just a sophisticated calculator, but also a true expert system that includes cross-linked databases for things like manufacturing equipment, process tolerances and labour costs [Paper V]. With such a system, even a person who is not directly involved in optics manufacturing can make sensible cost calculations and find the best balance between performance and cost in true CE fashion.

5. Optical design cases using a concurrent engineering approach

The design cases presented in this chapter serve as examples of how CE principles can be put into practice inside the optical design and development process. Five cases out of the total seven deal with plastic optics designs. In addition, the case presented in Section 5.5 deals with hybrid lenses and expands the range of examples to also compare different manufacturing methods. In the case presented in Section 5.2, the analysed design is not based on plastic optics but serves as a good example of how CE can be used effectively in the concept development phase of a new optical product. All the case studies have been published in Papers I–VI included in this thesis.

The demonstrated CE features applied in the case studies are:

- analysing optical product design concepts based on device usability
- choosing the right optical concept based on cost analysis
- using cost modelling in the feasibility analysis of different manufacturing methods for hybrid imaging lenses
- visualizing the quality of an imaging system in order to facilitate communication between the optical designer and project management
- fitting together optical and mechanical requirements
- integrating imaging and illumination optics features into a one-piece design for cost-effective manufacturing
- analysing stray light properties of an optomechanical design
- making optical tolerancing for DFM analysis
- balancing performance and cost in order to find optimum component design at module level.

5.1 Miniature imaging lens

This case study (Paper I) presents the development process of a miniature plastic imaging lens prototype for a mobile phone camera module. All the project phases are described in order to show an example of the dynamics involved in such a development task. The development process flow follows the graphical presentation shown in Figure 222.

5.1.1 Specification

The specification for the resolution of the lens was set to an MTF value above 0.3 at 40 lp/mm. The number of lens elements was set to two or three. The module's mechanical diameter with the outer screw thread was limited to 8 mm, and the maximum length to 4 mm. Another mechanical requirement was that the module should be built in such a way that it could be taken apart and reassembled. The main reason for this was that it would make it possible to characterize the different components separately in order to find out where the possible problems were in the prototype. This also enabled the testing of different f-numbers by changing the aperture plate inside the lens. The nominal f-number value was set to 2.8. Due to the fact that the final goal was to produce a prototype for a very low-cost camera module, the tolerances and designs should also be compatible with the injection moulding manufacturing method. This also restricted the choice of lens materials to optical plastics. Direct single-point diamond turning was chosen as the manufacturing method for the prototypes due to the lower costs compared with injection moulding.

5.1.2 Optical design

The final lens design was found using iteration cycles between lens optimization, tolerancing and mechanical design. Doublet and triplet designs were considered. After the optical and mechanical designs of the doublet lens were finished, an observation concerning the acceptance angle of the image sensor was made, resulting in the rejection of the whole doublet design. A few new doublets were optimized, but no other two-component design with good enough performance could be found. Moving to a triplet was an obvious choice because it allowed more freedom in controlling the ray angles in the image plane. Two other triplet designs were created before the final layout was found. The first design had adequate performance, but due to the strict size restrictions and tolerance, it induced large back focal length fluctuations. There was not enough room for mechanical structures when the required focus adjustment range was considered. In the second design, this was improved and the aperture plate was also positioned on top of the first lens planar back surface in order to simplify the construction of the housing. Unfortunately, the performance of the lens became worse and it did not have an adequate resolution after the tolerance analysis. The third and final design was found by modifying the first triplet design in such a way that the aperture plate could be attached to the back of the first lens in a similar manner to that in the second design. This eliminated one important tolerance variable and shortened the required distance for focus adjustment.

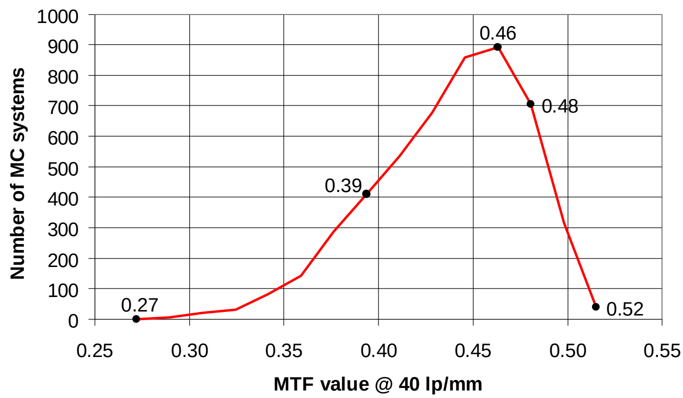


Figure 5. Final triplet design Monte Carlo tolerance analysis result showing the average MTF values of 5 000 simulated systems.

Figure 5 shows the results of a tolerance analysis run with 5 000 Monte Carlo systems. Approximately 98% of the simulated systems had an average MTF value over 0.34 at 40 lp/mm. This was considered to meet the specifications set for the lens. The histogram is too wide if mass production is considered, but as the purpose of the project was to produce only a few prototype lenses, the graph was just seen as an indicator that there would be a good chance of obtaining a decent lens.

Image simulations performed with a custom-made simulation tool [Kolehmainen et al. 2004] were used to verify and visualize the performance of the lens. The simulations made it possible to compare different lens designs with metrics that are easily understandable without an optical design background and the ability to read, e.g., MTF graphs. The optical design was made with Zemax using the optimization routines of the program and a merit function based on MTF. A Subjective Quality Factor (SQF) calculation routine was used after the lens designs were finished to numerically evaluate the quality of the lens with a system that connected the optical performance to the image quality perceived by humans [Cranger & Cupery 1972]. Figure 6 shows example simulation results of the final triplet design. The SQF graph shows values ranging from 0.87 to 0.63, which means that the quality of the lens changes from very good to acceptable when the field changes from 0 to 35 degrees respectively.

a) b)

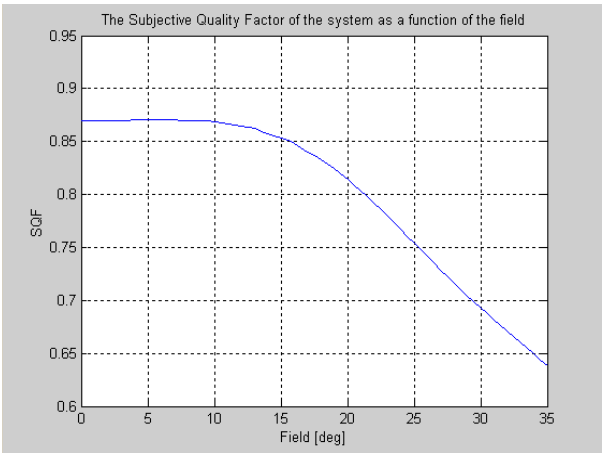


Figure 6. a) An image simulated with the nominal triplet lens design with the custom-made image analysis tool and b) the results of SQF calculations of the same design.

5.1.3 Mechanical design

The basic mechanical layout was a drop-in structure in which the lenses were mounted inside a barrel-shaped housing part. A fixing element was screwed to the housing and it compressed the lenses, aperture and spacer parts together. Different size apertures were also made for testing different f-numbers.

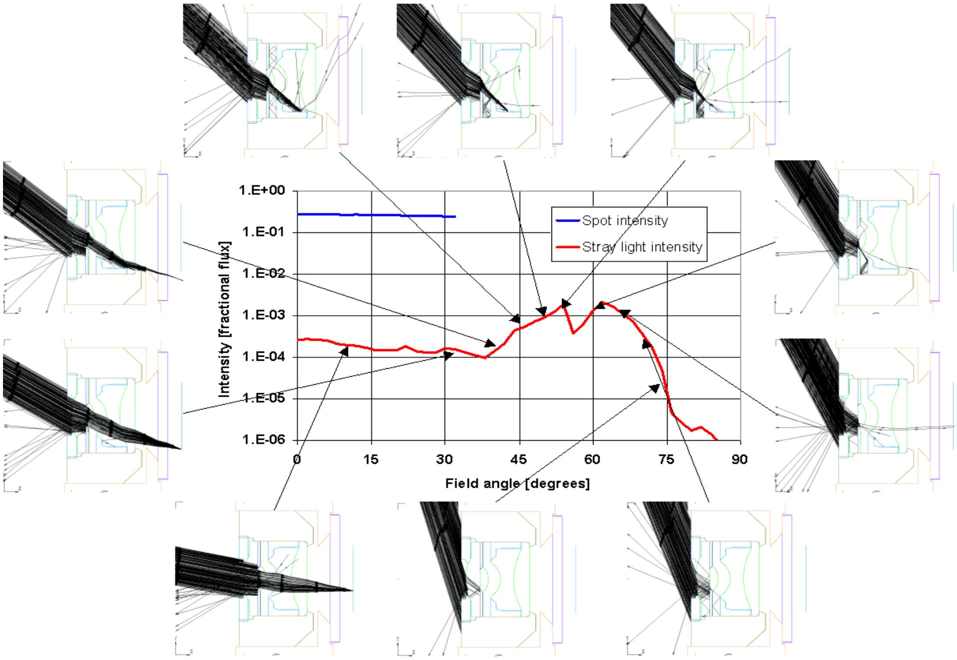


Figure 7. Example stray light analysis result. The graphs show the intensities of the imaged spot and stray light on the image sensor. The small pictures around the graph show the ray-trace paths at ten illumination angles.

Several stray light simulations were made with the non-sequential ray-tracing software ASAP and the results were used to alter the optomechanical design in an iterative manner. With the help of these simulations it was also possible to determine which components needed the relatively expensive AR coatings most. The stray light analysis of the triplet showed that if most of the lens surfaces are coated with good AR coatings the ghost reflections are reduced and will not cause a specific problem. The mechanical design had some problems with stray light suppression however. The unwanted light that could enter the lens was not sufficiently attenuated by the mechanical structures, mainly because the module was so small that additional baffles could not be used for this purpose. Figure 7 shows how the intensities of the imaged spot and stray light changed with respect to the illumination angle. The stray light level is higher between angles of 45 to 70 degrees, mostly due to the scattering from the spacer part of the inner wall. The analysis showed that a separate lens hood would probably be necessary if the lens were used under conditions in which a very bright source (Sun) illuminated the lens at these critical angles.

5.1.4 Manufacturing

Finding a suitable manufacturer from Europe to manufacture the very small lens surfaces was not an easy task at the time the project was carried out. The chosen manufacturer also had expertise in injection-moulded optics, which was a very important factor in the selection process. With the manufacturer's prior knowledge of injection moulding, it was possible to drive the overall construction of the lens module towards a more mass-producible design and gain knowledge about the achievable tolerances in the manufacturing process. The manufacturer was able to provide the basic guidelines for optomechanical design features and tolerances for the optical design.

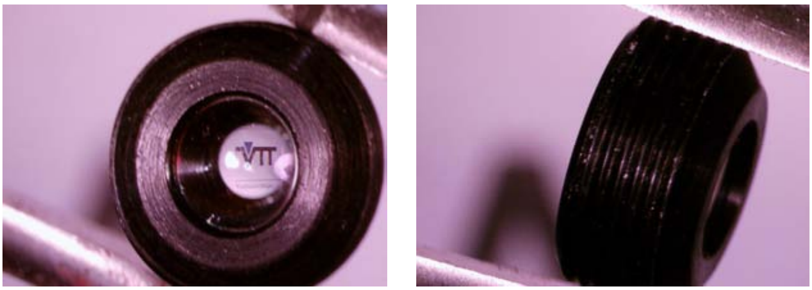


Figure 8. Two pictures of one manufactured prototype lens.

Figure 8 shows two pictures of a manufactured lens prototype. The lens elements were made by mounting them on a precision vacuum chuck, and each surface was turned by single chucking to the final surface quality. Two of the lenses were plano-convex and there were therefore no decentring problems with the opposite optical surfaces. In one of the lenses, both surfaces were curved and there was a risk of a decentring error between the two surfaces due to the fact that the part had to be detached from the chuck and turned around in order to be able to machine the second surface. The outer mechanical structures of the lenses were accurately machined at the same time as the lens surfaces. This way, the difference between the optical and mechanical axes of the lens element was minimized, which was a very important factor when the lenses were assembled to the housing. The housing, diaphragm and fixing elements were made by standard precision turning and milling. The length accuracy of the spacer was important because it determined the distance between the second and third lens and thus had a straight effect on the optical performance. The thickness of the diaphragm similarly determined the distance between the first and second lens.

5.1.5 Characterization

A set of MTF measurements were made with three prototype triplet modules. Two changes were needed to the optical design files in order to be able to compare the results obtained from the measurements with the simulated data. The first change was to remove the IR filter from the design and the second was to adjust the back focus length of the lens to the best value in the on-axis geometry.

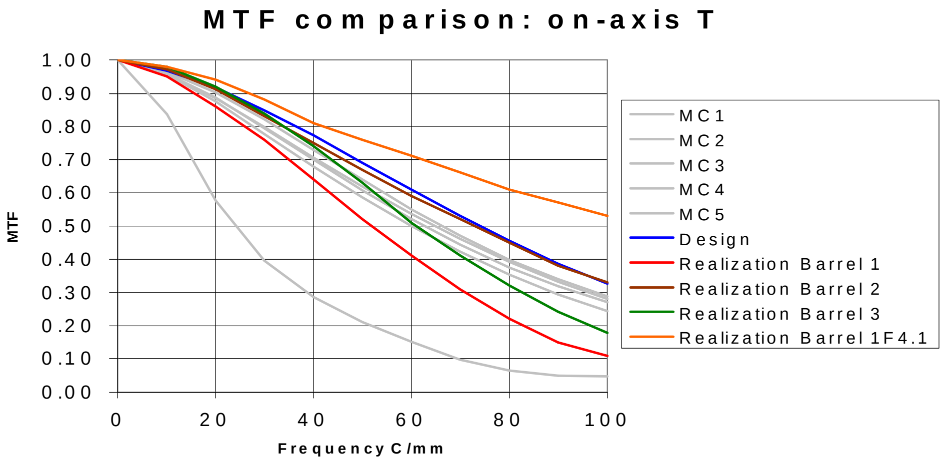


Figure 9. Comparison of measured and simulated MTF values of the triplet lens prototype.

As an example, Figure 999 shows the measured MTF data from the three manufactured prototypes at on-axis illumination and with tangential orientation. In the figure, there is also one line that shows the improved performance of the module after the aperture was changed to one with a smaller hole, thus making the f-number of the lens larger. The graph has five gray lines that describe the simulated MTF values of the five tolerance Monte Carlo systems that were used in the image analysis to evaluate the performance of the design in the optical design phase. The MTF values of these systems can also be seen in Figure 5 as the black dots in the histogram. These imperfect designs cover the whole range of simulated lens performance and provide a kind of reference area inside which the measured data should be located if the lenses are manufactured to the specified tolerances. The MTF calculated from the original design without the filter and with an incorrect back-focus length is also drawn. The figure shows that at on-axis the measured tangential MTF fits quite well with the simulated data. At the other measured field points, the correlation was not as good as in the example picture, but the overall tendency proved that the resolution of the lens was quite close to what was expected from the basis of the simulations.

5.1.6 Case-specific concurrent engineering features

Several features of the described development process show the holistic approach required by CE. The quality of the lens design was visualized and evaluated with software, which facilitated better communication between the optical designer and project management. It was possible to see the performance differences between two similar optical designs without an extensive background in optics. The optical and mechanical parts were designed in an iterative loop in which the mechanics were affected by the optics and vice versa. This required very close collaboration between the optical and mechanical designers, as the specified small length of the lens module had to be shared by optical and mechanical components. Stray light analysis is also an example of a work task that lies between these two disciplines. Ghost analysis can be performed with just the optical design, but light scattered from the mechanics can only be simulated when the layout of the mounting structures exists. In order to improve the manufacturability of the design, tolerances in manufacturing had to be taken into account. Values used in the optical tolerance analysis were discussed with the lens manufacturer who knew the exact process of making the components. Again, communication was a crucial part of making the optical draft into a realistic design. The characterization phase of the prototype lens was considered during the specification and mechanical design phases by designing the structures in such a way that the module could also be disassembled for better analysis. This made it possible to physically test f-number variations and obtain some feedback information for refining the lens specifications at the module level. Optical design and characterization phases were also connected, as some alterations to the design were necessary in order to make it possible to compare the measurement results with simulation predictions.

5.2 Fibre-pigtailed laser module

This case study (Paper II) presents the tolerance analysis of a fibre-pigtailed photonics module that can be used in telecommunication, sensor or tooling applications. Optical simulations were used concurrently with software that calculated the effects of tolerance stacking in the assembly process on the placement of the optical components. In miniaturized optical systems, automated assembly methods are needed in volume production. The combination of mechanical and optical simulation software can be used when the assembly process is analysed during the module design. A process model that can be used in concurrent optimization of optical module performance and cost was also created during this case study.

5.2.1 Module design

Designs of the considered photonics modules were based on low-temperature cofired ceramic (LTCC) structures. LTCC is a manufacturing technology in which several layers of ceramic substrates are laminated together. It can be used as a multilayer substrate for electronic circuits, and many useful features such as via holes and hermetically sealed cavities can be produced with the technology. It can also be used in creating accurate, miniature-scale, alignment structures that can be exploited in the assembly of, e.g., optoelectronic components. Miniaturized photonic modules are generally very sensitive to alignment tolerances between the optical and optoelectronic components. Decentration errors on the micrometer-scale between a laser diode and a fibre can cause optical losses of several decibels. A typically defined performance limit attenuation value for optical coupling is 1dB. The shape accuracy of the alignment structures combined with the realized positional tolerance errors and component optical property fluctuations should provide coupling efficiencies that only vary within this limit.

The basic idea of the developed module was to couple light from an edge emitting laser to a multimode optical fibre. Two different optical design concepts were investigated. The first approach was based on a ball lens that was positioned between the laser diode chip and the fibre as shown in Figure 10. Two different sized ball lenses (diameters 250 µm and 500 µm) were simulated. The second concept studied was a butt-coupling layout in which the laser diode was simply put very close to the fibre end in order to couple light into the fibre core directly from the source. Optical design simulations showed that with the chosen laser diode and the physical dimensions and optical properties of the fibre, there was no significant benefit in using the ball lenses when compared with butt-coupling. As butt-coupling is the simplest and most straightforward method of connecting the laser to the fibre, it was chosen as the coupling method for the prototype modules.

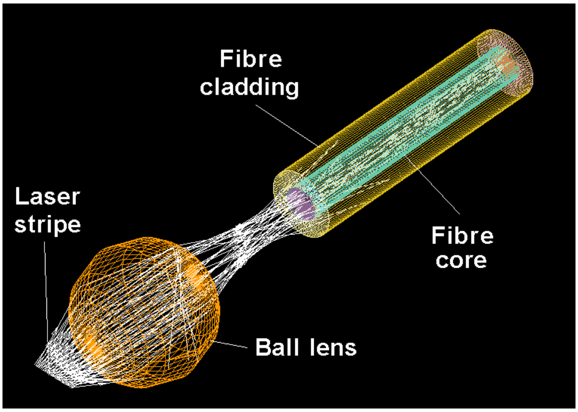


Figure 10. Coupling a diode laser light to a multimode fibre with a ball lens.

5.2.2 Module tolerance analysis simulations

In order to analyse the manufacturability of the fibre-pigtailed laser module, a set of tolerance analysis simulations was needed. As the two main components, the laser diode and the fibre, were aligned to each other with the help of structures created on an LTCC substrate, it was first necessary to analyse the tolerance stacking effects of substrate manufacturing and component assembly. This task was accomplished with the help of specialized software (VisVSA). The assembly simulation in VisVSA produced tolerance distributions depending on the precision substrate manufacturing tolerances, geometrical feature shapes, dimensions and component attachment tolerances achievable with the selected automated pick-and-placement machine. The output from the first stage of the simulations was the combined positional and rotational tolerances of the laser and fibre.

Optical design software such as Zemax has its built-in features for optical tolerance analysis. The routines are generally used for tolerancing imaging optics, however, which are evaluated with a set of metrics that is not easily compatible with non-imaging optics analysis. Furthermore, there are limitations on the way the tolerance probability distributions can be programmed into the software code. In this case the standard software could not be used for the asymmetric distributions simulated in VisVSA. In order to overcome these limitations, an automatic tolerancing routine was programmed into the optical simulation software ASAP. This made it possible to use the coupling efficiency as metrics during tolerancing as well as the partially asymmetric distributions.

Table 3. Tolerance sensitivity analysis results of a 1 x 100 µm laser and a 62.5/125 µm multimode fibre butt-coupling.

Tolerance variable	Value	Power	Impact (per cent)
Source power min	– 0.150	0.405	– 15.0
Source power max	0.150	0.548	15.0
Source div. *x* min	– 2.000	0.493	3.4
Source div. *x* max	2.000	0.459	– 3.6
Source div. *y* min	– 2.000	0.501	5.1
Source div. *y* max	2.000	0.454	– 4.7
Source position min	0.000	0.476	– 0.1
Source position max	0.000	0.477	0.0
Source decent. *x* min	– 0.005	0.469	– 1.5
Source decent. *x* max	0.005	0.473	– 0.7
Source decent. *y* min	– 0.007	0.463	– 2.7
Source decent. *y* max	0.007	0.463	– 2.8
Source tilt *x* min	– 0.600	0.476	0.0
Source tilt *x* max	0.600	0.477	0.1
Source tilt *y* min	– 0.410	0.477	0.0
Source tilt *y* max	0.410	0.476	0.0
Fibre NA min	– 0.015	0.459	– 3.7
Fibre NA max	0.015	0.492	3.3
Core index min	– 0.001	0.476	– 0.1
Core index max	0.001	0.476	0.0
Core diameter min	– 0.003	0.460	– 3.5
Core diameter max	0.003	0.490	2.9
Fibre position min	– 0.001	0.478	0.3
Fibre position max	0.001	0.474	– 0.6
Fib. decentre *x* min	– 0.004	0.474	– 0.6
Fib. decentre *x* max	0.004	0.474	– 0.6
Fib. decentre *y* min	– 0.003	0.474	– 0.6
Fib. decentre *y* max	0.003	0.474	– 0.5
Fibre tilt *x* min	– 0.019	0.477	0.1
Fibre tilt *x* max	0.019	0.476	0.0

Table 3 shows the tolerance sensitivity analysis results of a system in which a 1 x 100 µm laser was butt-coupled to a 62.5/125 µm graded-index multimode fibre. A Gaussian single-mode beam model was used in the source simulation. The dimensional values are shown in mm or degrees and the power is expressed as the light coupling efficiency value. The nominal coupling efficiency was about 0.48, which means that about 48% of the light emitted by the laser diode was coupled to the fibre core. The impact column shows the relative change in coupling efficiency caused by each tolerance variable, as the values of the variables were set to correspond to the values obtained from the VisVSA simulations and component data sheets. We can see from the table that the most critical tolerance after the source output power fluctuations was source y divergence. A two-degree increase in source divergence caused a 4.7% drop in the coupling efficiency, as a smaller portion of the Gaussian beam was coupled to the fibre core. A similar decrease in the source divergence allowed more light to be coupled to the fibre and, in this case, the coupling efficiency increased by 5.1%. From the optical system point of view, the output power of different modules should remain as stable as possible, and the increase in coupling efficiency can therefore also be seen as a negative effect. The table shows that all of the most critical tolerances are connected directly to component-level variations such as laser power fluctuations, beam divergence, fibre NA and core diameter. The most sensitive tolerance connected to module design is the source decentration in the direction of the LTCC substrate. It indicates that this particular feature should be controlled and inspected more thoroughly during module manufacturing. If the output power variations between different modules need to be reduced, the best solution is to find better quality laser or fibre components, as the module geometry tolerances have lower impact on the performance.

Figure 11 shows the results of a Monte Carlo tolerance analysis made for the same butt-coupling system. The figure has two graphs that show the cumulative distribution of modules with and without the laser power and divergence tolerances. As we can see, about 90% of the modules have attenuation under 3.6dB and practically all are above 2.6dB. This means that most of the modules are inside the generally allowed 1dB power fluctuation tolerance limit. If the laser power and divergence fluctuations could be eliminated, the differences between the modules would be inside 0.6dB. If the specified maximum attenuation for the module is set to, e.g., 3.4dB, the simulation predicts a manufacturing yield of only about 70%. If, however, the laser diode could be changed to a very stable component, the yield could be increased to over 90%.

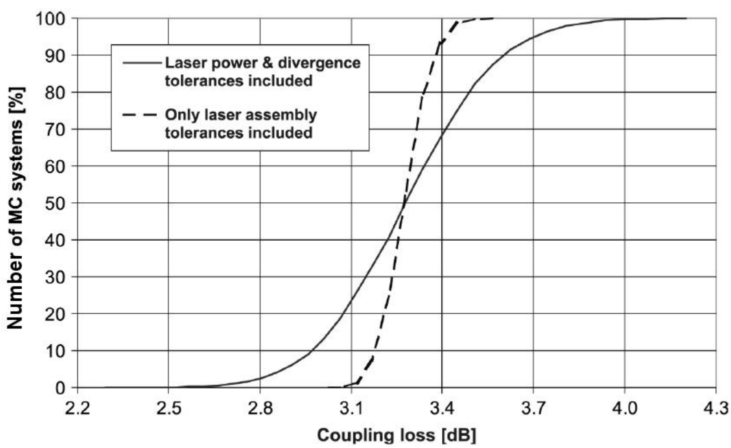


Figure 11. Tolerance Monte Carlo analysis results of a 1 x 100 µm laser and 62.5/125 µm multimode fibre butt-coupling.

5.2.3 Photonic module optimization process model

A process model that can be used in the optimization of photonic module production cost and performance was also created and is presented in Figure 12. The module manufacturing cost efficiency can be estimated using Cost Of Ownership (COO) [Ragona 2002] models in which one critical factor is the production yield. In order to determine the COO, the full cost of the equipment and its operation must be divided by the total number of good parts produced over the commissioned lifetime of the equipment. The COO value that is calculated represents the cost of the process step per good part produced and indicates the cost added to that part by the process. Normally, the yield should be maximized in order to obtain the best COO value, but this typically considers the allocation to defective and correct modules. In this case study, however, the simulated yield depends on the optical performance limit setting in the specification. All modules are not necessarily functional due to bonding failures and other production errors in the manufacturing process, though these are taken into account in the definition of the final yield in the manufacturing. This methodology can be used for the optimization of cost and performance in simulated production. The simulated performance distribution of the modules can suggest the most cost-effective performance limit location, and the module specifications can be altered accordingly.

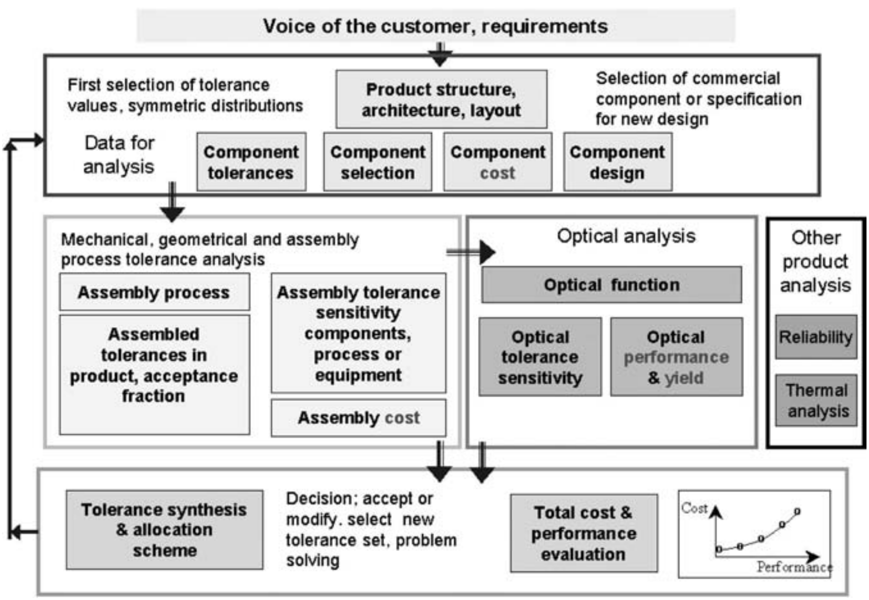


Figure 12. Process model for optimizing photonic module performance and cost.

5.2.4 Case-specific concurrent engineering features

Several CE features were presented in this case study. Close co-operation between the mechanical and optical designer was necessary in determining the tolerances of the whole module. The LTCC manufacturing and component assembly processes were considered in the optical design phase using realistic tolerances achievable with the specific manufacturing technology and equipment. Tolerancing revealed the most sensitive parameters in the module design. The results showed that the module performance was dominated by component-level tolerances. This means that in module production some manufacturing features such as assembly times or substrate accuracy could be reduced in order to cut down the costs, with no excessive penalty on performance. The developed process model can be used in concurrent optimization of cost and performance characteristics of new photonic modules in an iterative design loop. The optical simulation system can also be used as an assisting tool for setting new optical performance specification limits for the actual product.

5.3 Microscope add-on device for a mobile phone

This case study (Paper III and Paper VI) presents the design process for a macrolens that can be used in an add-on device with a mobile phone camera. The main emphasis is on the way the advantages of injection moulding technology are taken into account in the optical design process. By using plastic moulding, it was possible to integrate several functions into a single optical piece. Cost modelling was also used to show that the optics can be produced cost-effectively in large volumes, extending the usability of the design to low-cost applications.

5.3.1 Device concept

Figure 13a shows the add-on microscope device optical concept. It is not an actual microscope in the sense that high magnification is not needed. A 1:1 object-to-image ratio is sufficient due to the fact that the CMOS image sensor has very small pixels (< 5 µm) and the actual magnification is done electrically when the recorded image is displayed. A high level of integration is achieved in the design by combining the two optical functions (imaging and illumination) into one piece and embedding the active LED components with the circuit board into the same structure. Figure 13b shows the whole device concept. The selfcontained add-on optical module completed with the macrolens, light sources and a battery is attached on top of the miniature camera on a cellular phone without altering the base device itself.

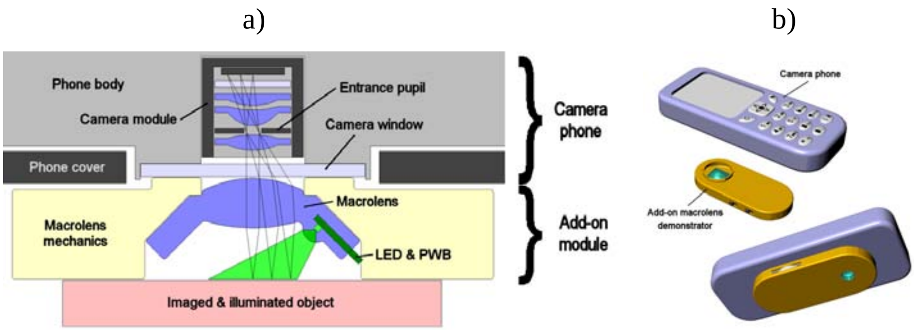


Figure 13. Concepts of a) the integrated illumination and imaging optics and b) the whole add-on device.

5.3.2 Optics specification

A field of view of approximately ±32 degrees was needed for the camera optics to fill the whole image sensor. The minimum distance of the macrolens back surface from the camera optics entrance pupil was set to 3.6 mm, which positioned the lens just above the camera window. There was no actual specification for the size of the optics other than that it should not be too large for a prototype mobile system. One goal of the design was also to integrate the illumination optics into the imaging optics as a single piece. The illumination optics should be able to provide even and bright illumination adequately to the same area that is imaged with the macrolens.

5.3.3 Optical design

The optical design of the imaging path was made with Zemax. A simple system with a double aspheric plastic (PMMA) lens was created. The camera optics was modelled as one ideal lens with a 4.5 mm focal length. The aperture stop was set to the ideal lens, and its diameter was fixed to the estimated camera entrance pupil size. The merit function was based on MTF calculations. The demands of a single element, small size and large field of view made it a somewhat difficult task to find a good quality design.

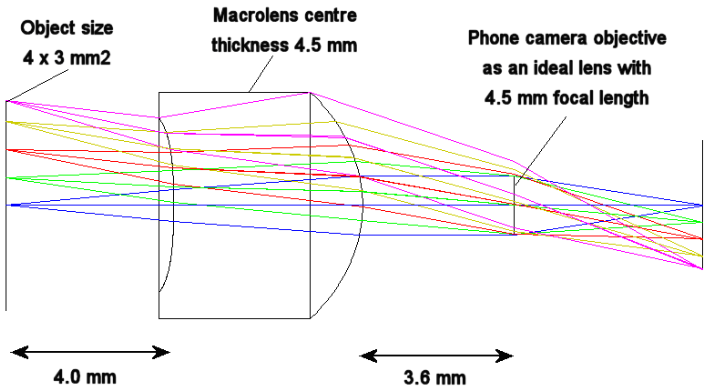


Figure 14. A ray-trace picture of the final lens design with an ideal lens that models the phone camera optics.

Figure 14 shows a ray-trace picture of the final design. The two highest object points in the picture are located at heights of 2.5 mm and 2.0 mm. The highest object point rays have incident angles of 24 degrees at the ideal lens, which also models the camera lens entrance pupil. The lens thickness (4.5 mm) became slightly too high for an object that could be injection moulded easily and fast. The final design had an optical loupe-type behaviour in which the central part of the image was clearly sharper than the edges. Although the image quality was compromised at the edges, the benefits of keeping the layout as a single lens design were considered to have higher importance.

The design of the whole add-on lens piece was quite challenging due to the fact that an illumination system needed to be integrated with a double aspheric singlet lens structure. The idea of the illumination system was that the light from LED chips placed around the imaging path was collected and guided to the surface under inspection. The optical surfaces needed for illumination were designed with a combination of a CAD program (Rhinoceros) and optical design program (Zemax). Imaging lens surface profiles were first exported from Zemax and combined with the illumination surface profiles inside the CAD software. The whole add-on lens piece created inside the CAD program was then imported back to Zemax, and optical simulations were performed with a non-sequential ray-tracing mode. Figure 15a shows a ray-tracing picture of the macrolens with two embedded LED sources. Figure 15b shows the simulated distribution of light under the whole lens piece.

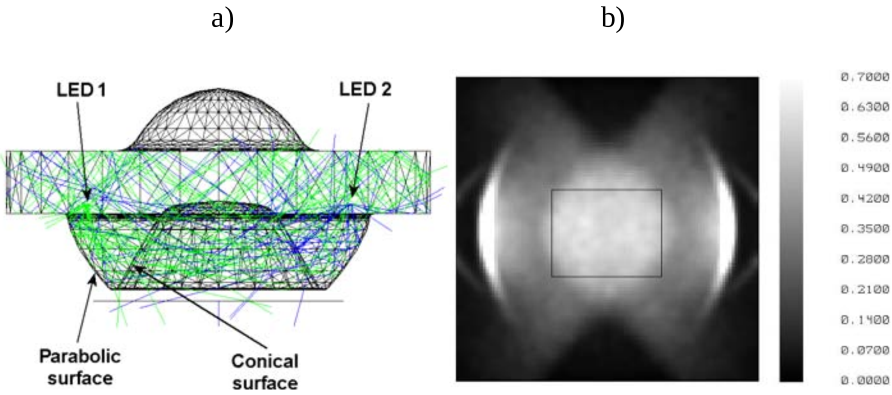


Figure 15. a) A ray-trace picture of the macrolens illumination with two opposite LEDs. b) A simulated illumination distribution under the whole lens piece with an outlined rectangle that shows the area to be imaged.

In an integrated piece with embedded light sources, the risk of stray light entering the camera pupil and ruining the image is very high. Figure 15a shows that no rays exit the lens piece from the top dome. Practically all of the rays exit the piece from the object side and not from the camera side. In the actual manufactured prototype pieces, the embedded circuit board also acts as a baffle inside the lens as it blocks some of the direct paths of light from the illumination optics to the camera aperture. This was also checked with a separate stray light simulation, which showed that only a small fraction of the light reaching the image sensor came outside the imaged area.

5.3.4 Moulding of the macrolens prototypes

Several series of macrolenses were injection moulded. Figure 16 shows two photographs of the manufactured integrated parts. Integration of LED chips and the circuit board was also achieved, as most of the sources were still functional after the moulding. Several test series were needed, however, in order to find the optimal injection moulding parameters that produced good quality optical structures without any air bubbles or other typical defects associated with injection-moulded parts.

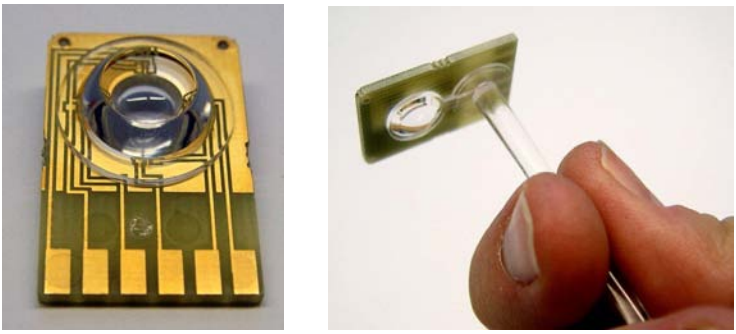


Figure 16. Some images of injection-moulded macrolenses with the integrated circuit board and LEDs.

5.3.5 Cost calculations

The production costs of the macrolens were estimated with the example calculation tool presented in Paper VI. Figure 17a shows a cross-sectional drawing of the macrolens design that was used in the analysis. In this case, the lens was considered a separate piece without the integrated circuit board. Figure 17b shows a 3D view of the piece with the sprue and runner features necessary for injection-moulded parts. The piece was estimated to weigh ~0.6 grams including the sprue.

a) b)

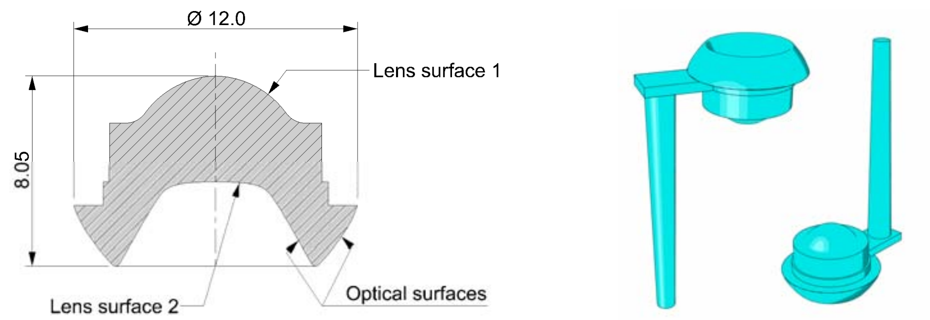


Figure 17. a) A cross-section drawing of the example macrolens and b) a 3D model of the injection-moulded piece.

Four different mould constructions were used in order to find the optimal number of cavities associated with different production volumes. The initial costs of the moulds were set at: 1-cavity 15 000 €, 2-cavity 23 000 €, 4-cavity 31 000 € and 8-cavity 39 000 €. The mould and optical insert lifetimes were set to each production volume value in order to take into account the relatively high cost of the moulds at low volumes. Geometry and material information were used as input parameters, as the cycle time of the piece was estimated at 60 seconds. The basic set of process input values (e.g., labour costs) was fitted to a 'generic' European production environment. Yields, machine uptimes, etc. were estimated for each case by taking into account the number of mould cavities used. No coatings were included in the calculations, as the performance was considered adequate without any AR coatings.

Figure 18 shows the calculation results at production volumes between one thousand and one million. The costs range from 41 000 €/piece to 0.38 €/piece. Naturally, the highest costs were found at production volumes of one single piece, for which the initial mould costs dominated the calculation. The lowest costs were found at the high-volume end, for which the total came mostly from the moulding costs. Figure 19 illustrates this division between mould tooling and moulding costs at different production volumes in the case of the 4-cavity mould. The graph shows that up to a volume of about 1 000 pieces, the mould cost clearly dominates the total manufacturing cost. This result just presents the well-known fact that injection moulding is not a very suitable manufacturing method for very low volume parts. The graphs in Figure 18 show how fast the production costs drop from the initial mould cost peaks and level off at certain cost levels determined by the moulding process. The 1-cavity mould offers the lowest cost option up to volumes of about 20 000 pieces, at which point the total costs are about 1.63 €/piece. The 8-cavity mould becomes the lowest cost alternative after a volume of about 100 000 parts when the pieces cost 0.73 € each. If the production volume is one million parts, the 1-cavity mould can be used to reach a value of 0.89 €/piece, which is over twice as expensive as the 0.39 €/piece that can be reached with the 8-cavity mould. This example shows that the cost is highly volume dependent and that the choices made at the beginning of production have a big impact on the total cost.

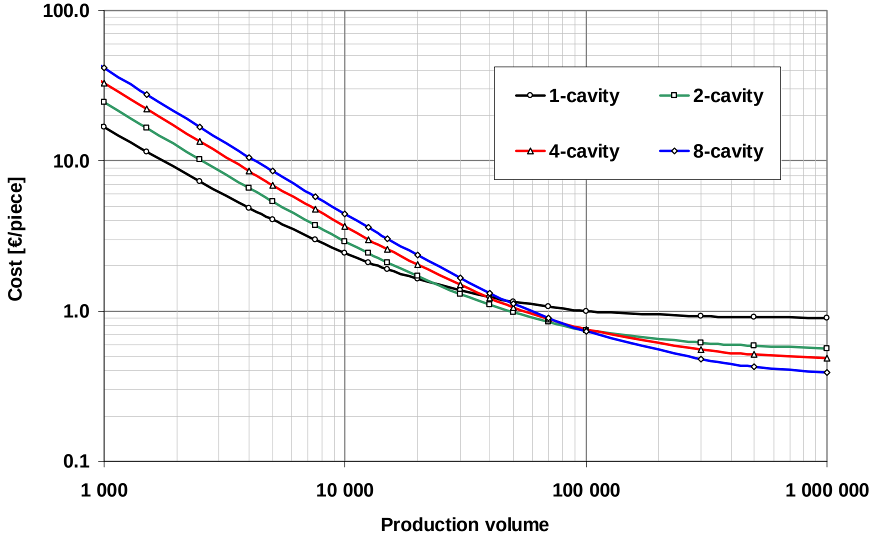


Figure 18. Calculated production costs of the macrolens with four different mould constructions (1, 2, 4 and 8 cavities) and different production volumes.

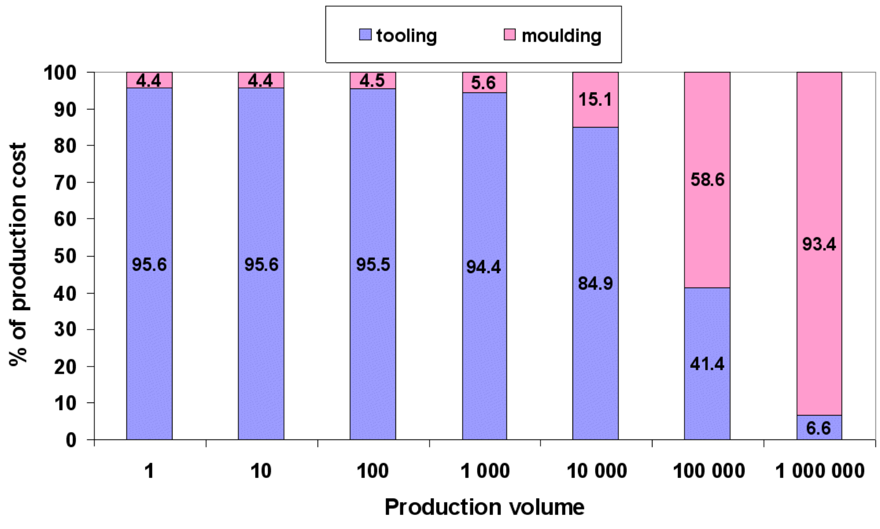


Figure 19. Division of production costs between tooling and moulding with the 4-cavity mould at different volumes.

5.3.6 Case-specific concurrent engineering features

This optical design case illuminated two aspects related to CE, especially DFMA. The first aspect is integration, which was taken to an extreme level by combining the two optical functions and electronics into one single monolithic piece. Integration brings clear benefits to the optical system. The number of parts is reduced to a minimum, which means that there is no need for an expensive assembly process in manufacturing, and the demand for logistics is also reduced. Integrated structures are also more robust against many environmental factors and, e.g., assembly errors. Injection moulding is ideally suited to producing complex pieces. This can only be fully exploited by having a deep understanding of the manufacturing technology and by using a holistic approach to optical design. The second illuminated aspect was the use of cost-calculation tools. In this example case, the graphs calculated for the volume-dependent cost reduction could be used, e.g., to convince an investor that a low-cost product idea based on the macrolens design is feasible. Another interesting way to use cost-calculation tools would be in comparing different design options. If the lens is made thinner, the moulding cycle time is shortened and the production costs reduced. Concurrent analysis of the performance and cost of optical design makes it possible to find the best design for a given application not only from the technical performance but also from an economic point of view.

5.4 Infrared temperature sensor

This case study (Paper IV) presents the design process of an infrared temperature sensor system for a mobile device application. It shows how optical simulations can be used in the selection of the best measurement system design concept concurrently with thermal simulations. Product usability and contamination effects were also considered during the concept design phase.

5.4.1 Challenges of the IR temperature measurement principle

The infrared (IR) temperature measurement is based on the fact that the intensity of IR radiation emitted by a surface depends on its temperature. In a practical application, an optical system is used to collect the radiation emitted by the object from a distance to a thermopile detector. The field of view (FOV) of the IR sensor has to be restricted in order to select the right object from the other surrounding emitters. Unfortunately, all the components and surfaces in the measurement system itself have their own specific radiation characteristics depending on their temperature, and the material and surface properties. In idealized conditions, it is possible to calibrate the detector to compensate for some of this Narcissus effect [Howard & Abel 1982] using an internal compensation circuit that measures the temperature of the sensor element itself. The other visible parts of the system may not be at the same temperature as the sensor, however, due to their different location in the mechanical structure. This situation is emphasized when the sensor module is embedded into a device such as a mobile phone in which there are active electrical components that generate heat. The mechanical outer parts are in contact with the environment and can be several degrees cooler or warmer than the IR detector inside the device. Even when there are no temperature differences between the different parts of the system, the close proximity of the components causes an IR noise signal that may overrun the measurement signal.

5.4.2 Analysis of one commercially available IR sensor

Figure 20 shows the optomechanical design of an example IR sensing system. The design was based on a commercially available device in which the FOV of the sensor was restricted using a Fresnell lens as a focusing element. A simulation model of the device optics was created in the design software ASAP in order to analyse the magnitude of the Narcissus effect in such a structure. Emissivity values of different elements were estimated by considering the probable materials used in the components and making some IR measurements of components found from the existing device. The FOV of the simulated detector surface was limited to a value corresponding to that found in the actual component data sheet. The emission characteristics of all the surfaces visible to the detector were set to correspond to the situation in which all of the parts were at a temperature of 25^{o}C. A target surface (disc diameter 10 mm) was placed in the model at a distance of 50 mm from the device. Although the simulation model was quite crude with many approximations, it helped to analyse the magnitude of noise signal from the different parts of the system.

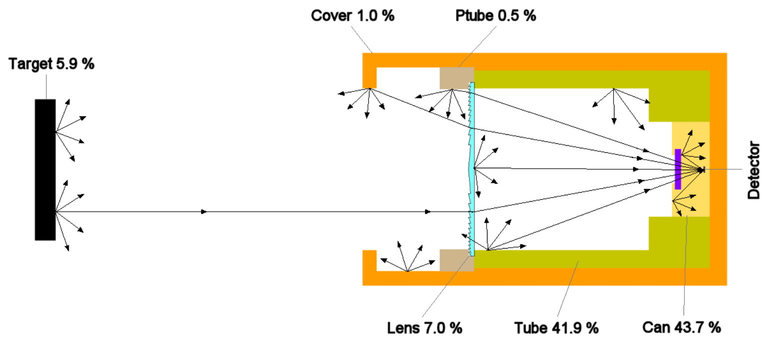


Figure 20. Simulated amounts of IR radiation falling on the sensor from the different parts of a commercially available temperature-sensor system.

The results of the simulation are shown in Figure 20. In the picture, each part of the system has a name tag with a number attached to it. The numbers show the relative amounts of IR radiation emitted from the object in question that fall on the detector. We can see that the second biggest source of noise in the system after the detector can (Can) is the mounting tube (Tube). These two components dominate the optical signal value seen by the detector. The amount of IR radiation coming from the target (Target) is only about 6% of the total radiation falling on the detector. It is also important to note that the lens (Lens) used in the measurement system produces an optical signal of the same order as the measurement target itself. This is due to the fact that the low-cost lens material is not totally transparent. The lens has absorption at the measurement wavelength band (8–14 µm), which corresponds to emittance at the equal band.

5.4.3 Improving measurement accuracy with system design

There are several possibilities for increasing the accuracy of IR temperature measurement devices with good system level design. It is possible to calibrate the system by measuring the noise levels at different temperatures and then using these values in the calculation of the target temperature with the help of the sensor element's secondary temperature sensor. In order to be accurate, this calibration method requires all of the structures to be at the same temperature. Another possibility would be to use several sensors that monitor the temperature differences inside the system and use this data for the creation of a more complex look-up table for the calibration. Unfortunately, it is not feasible to add new sensors to the structure of a low-cost module.

One option to improve the thermal properties of the system is to design the mechanics in such a way that temperature differences between components seen by the sensor are minimized. This can be achieved by using materials and connection structures that conduct heat through the system. The major drawback of this approach is the need for metallic components, which can be too heavy for a mobile device and are also relatively expensive to manufacture. A better solution is to limit the amount and radiation from the objects inside the sensor component FOV. This can be achieved using metal-coated reflectors that have high reflectivity, which corresponds to low emissivity. Reflectors can also cover the whole detector FOV without the need for separate mounting structures.

The ideal design with the best signal-to-noise ratio would have a single metallic reflector attached directly to the detector component for good heat conductivity. The reflectance coefficient of the mirror should be as high as possible and there should not be any other objects in the FOV of the sensor. The use of an open-air optical system in mobile applications is not practical because the sensitive surfaces can be scratched and contaminated, impairing system performance. During the case study, an optical simulation was carried out to analyse this issue further. The results showed that if a parabolic aluminium reflector is used and its reflectivity drops from 95% to 75% it would induce an error of about 8% in the detected signal. This was the result of just one single simulation case, but it showed that an uncontrolled surface property change could cause unacceptably large errors in the measurement result.

5.4.4 Optical design concepts

Several alternative optomechanical design concepts were created for further analysis. Five concepts with different optical layouts are shown in Figure 21. Concept 1 represents the refractive lens approach realized in the previously mentioned commercial device. The major drawbacks of this design have already been discussed in Section 5.4.2. Concepts 2–4 are all based on metallic reflectors but they have different concepts for protecting the optical surface. In concept 2, a removable lid is used. From the optical point of view, this is the best design, as it corresponds to the ideal open-air, single-component approach. Unfortunately, separate sliding or rotating covers are relatively expensive to make and are prone to damage. Concept 3 has a protective window that is transparent at the measurement wavelengths, and concept 4 has a metallic grid that can protect the surface from scratching. The window in concept 3 acts as a noise source in a similar manner to the Fresnel lens in the commercial example device case. The reflective metallic grid produces less noise, but it also blocks some of the measurement signal and cannot protect the mirror surface from contamination as effectively as a solid window. The last concept (5) is different from the previous approaches as it uses a filled reflector structure. In this concept, the reflecting surface is well protected, but the solid material produces a big noise signal that is difficult to cancel out if a material with very good transparency cannot be found.

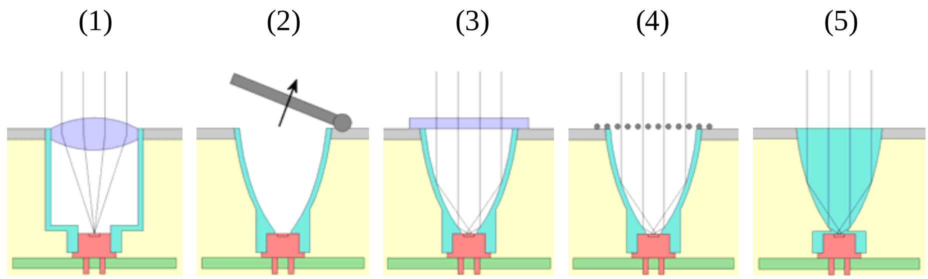


Figure 21. Five different concepts for IR temperature sensor optics.

The thermal performance of different concepts was evaluated by making thermal simulation models and simulations with the fluid dynamics software FloTHERM, which is capable of predicting airflow and heat transfer in and around electronic equipment including the coupled effects of conduction, convection and radiation. The results showed that the open-air system is the fastest at adapting to a temperature change in the environment and also has the lowest temperature differences. The system with the protective aluminium net had the second-best performance.

5.4.5 Optical design of the prototype module

The preliminary optics specifications stated that the system should be compatible with similar IR detectors to those used in commercially available sensors. Light should be collected with an object diameter at a distance ratio of approximately 1:6. A maximum height of 10 mm was also specified for the whole optical structure.

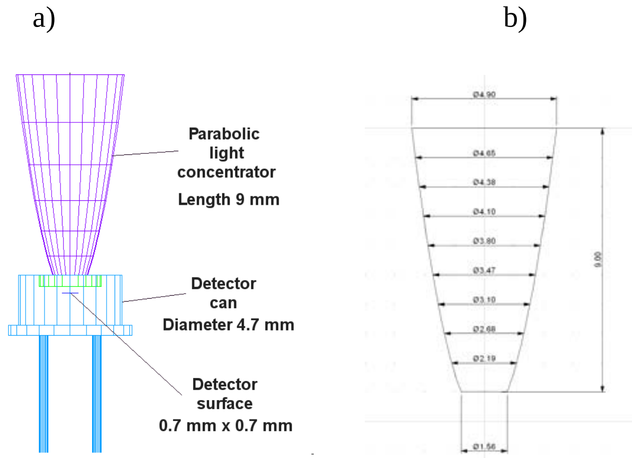


Figure 22. a) Design of the detector-concentrator combination and b) the dimensions of the parabolic concentrator.

A parabolic reflector was designed on top of the thermopile detector to fulfil the FOV requirement. Aluminium was chosen as the reflector material because it has high average reflectivity (> 97%) in the 8–14 µm measurement wavelength band. Gold would have been the second possibility, but aluminium was chosen for lower costs. The parabolic shape was chosen because it limits the sensor's field of view and ensures a sufficiently narrow acceptance cone. The compound parabolic concentrator (CPC) and conical surfaces were also considered, but they were not able to limit the FOV sufficiently. The designed reflector shape and its dimensions are shown in Figure 22. The parabolic reflector surface was 9 mm long with an input aperture diameter of 4.9 mm and an output aperture diameter of 1.56 mm. The output aperture was designed in such a way as not to obscure any rays inside the FOV. ASAP simulations showed that the parabolic reflector amplifies the detector signal approximately 34 times at the 0 degree viewing angle when compared with a bare detector without the parabolic reflector (Figure 23). The sensor module FOV with the parabolic reflector was approximately 10 degrees (FWHM).

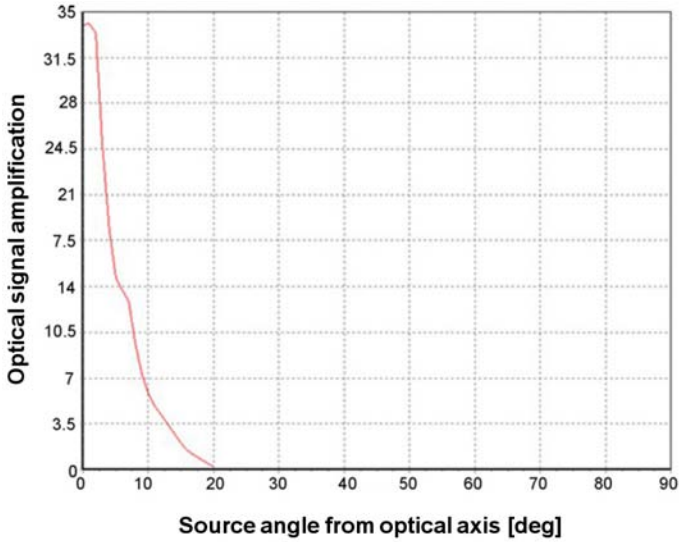


Figure 23. Simulated amplification of the optical signal at different FOVs.

5.4.6 Case-specific concurrent engineering features

In this case study, the optical simulations were used concurrently with thermal simulations in order to find the best design concept for an IR sensing system. The simulations showed that covering reflectors with a protective component improves the robustness of the light collector, but, at the same time, it adds a new source of thermal noise to the measurement system. In addition, the protection of the system against contamination increases the manufacturing cost. Several types of simulations will need to be used to find the best design starting point for a multi-technological system that needs to function in a realistic environment. In the case study, a large number of optical concepts that can be manufactured by the injection moulding method were used to find the right balance between various requirements.

5.5 Hybrid imaging lenses

This case study (Paper V) demonstrates how cost modelling can be used to find the best optical design when different manufacturing methods are used in optical element production. The presented hybrid plastic-glass, wide-angle lenses can be used in many different applications ranging from low-cost car rear-view cameras

(RVC) to somewhat higher cost security applications. Cost modelling can be used in exploring the ‘design space’ of possible optical layouts. Simple optical performance is not a sufficient indicator of design compliance with the module or system-level requirements in competitive application fields in which cost can be the main driver rather than technical quality.

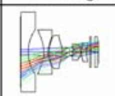
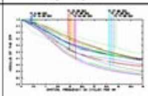
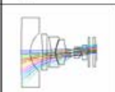
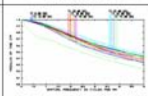
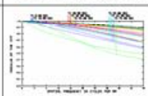
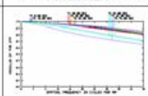
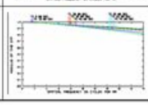
5.5.1 Specification and optical design

A set of five hybrid imaging lens designs was created. They all basically had the same specifications for size, distortion characteristics, field of view (FOV) and image circle diameter. The lenses were specified to work with ¼” colour image sensors and their FOV was set to ± 75º. The different designs were created by changing the material and surface properties in such a way that sampling of different manufacturing methods would be needed in making them. The three manufacturing methods considered were glass grinding, glass moulding and plastic injection moulding. All of the ground glass elements were restricted to spherical shapes and standard materials that were easily available from the Schott glass catalogue. As the main benefit of glass moulding comes from the fact that aspheric surfaces are as easy to create as spherical surfaces, all of the moulded glass lenses were allowed to be shaped to even aspherics. Again, the Schott mouldable glass catalogue was used in restricting the selection of materials. Aspherics were also allowed in the case of plastic lenses. The choice of optical plastic materials is very limited and this was reflected in the fact that only two materials, PC and Zeonex, were used in the final designs. The main idea of this exercise was to create a set of designs with different manufacturing requirements and performances.

5.5.2 Performance comparison of designs

Table 4 shows a performance comparison between the five lenses. One of the designs (named 0gg1mg4p) had five elements: one moulded glass and four plastic. The other four designs had six elements with various combinations of ground and moulded glass elements as well as plastic elements. In each of the five design cases, the MTF graphs were used in determining the achievable resolution of the specific lens. The adequate resolution limit was set to an MTF value of 0.3. This limit was used in determining the Nyquist frequency of the image, which in turn defined the feasible pixel size of the image sensor. From the pixel size and image sensor area it was possible to calculate the camera resolution and also choose a suitable display that could be used in the whole camera system.

Table 4. Performance comparison of five different designs.

Design name	Raytrace drawing	MTF graph	Nyquist freq. @ MTF 0.3	Pixel size [µm]	Camera res. [Mpix]	Display resolution
0gg1mg4p			25	10.0	0.10	QVGA (320 x 240)
1gg0mg5p			45	5.5	0.32	VGA (640 x 480)
3gg0mg3p			72	3.5	0.80	XGA (1024 x 768)
3gg3mg0p			100	2.5	1.56	HD 720 (1280 x 720)
5gg0mg1p			125	2.0	2.43	HD 1080 (1920 x 1080)

The general trend that can be seen from Table 4 is that by changing the plastic elements to glass elements it is possible to improve the performance of a hybrid lens considerably. The much better selection of glass materials makes a big difference that cannot be completely compensated for with aspherical surfaces easily available by injection moulding. A comparison of the five designs also shows that glass moulding is a viable method for improving the performance of the lens. The aspherics improve the quality of the design by eliminating some optical aberrations with a lower number of elements. With respect to glass grinding, there is a small penalty on the cost at low volumes, but for higher volume products the moulded glass elements do not have such a big impact.

5.5.3 Cost calculations

Cost calculations were performed for each of the five designs at production volumes of 100, 1 000, 10 000, 100 000 and 1 000 000 pieces. A calculation tool developed at Fraunhofer IPT [Nollau 2009] was used for this purpose. Each element of each design was analysed in order to determine the parameters needed for the cost-modelling tool. The analysed group had a total of 29 elements. There were 13 injection-moulded plastic components, 12 ground glass elements and 4 moulded glass elements. The costs were only calculated for the elements and no calculations were made for the assembly costs, as this would also have required mechanical designs. As the designs are very similar to each other, however, we can assume that the assembly would not be that different inside the group. The only big difference is that the plastic optical elements (and to some extent also the moulded glass elements) can have additional mechanical features that simplify the assembly process and lower the costs. Figure 24 shows the results of the cost analysis.

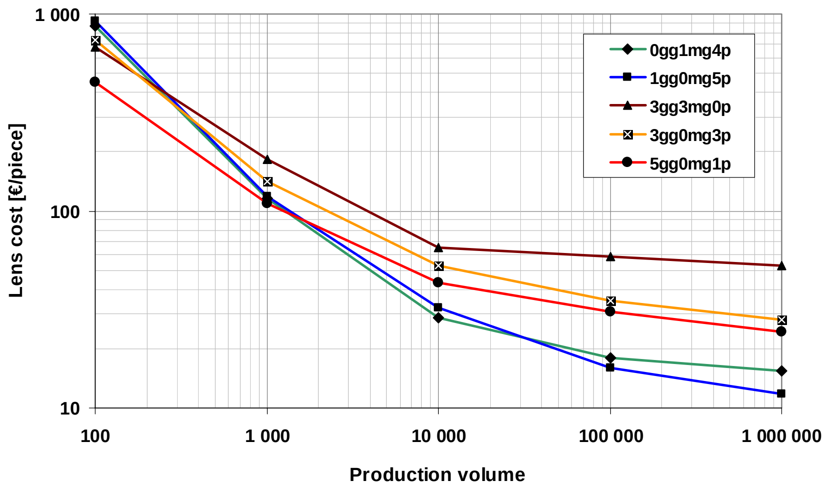


Figure 24. Comparison of lens costs at different production volumes.

Designs 0gg1mg4p and 1gg0mg5p follow very similar cost-reduction paths when the production volume is increased from 100 to 1 000 000 pieces. They both have total component costs of ~900 €/lens at 100-piece volumes, and the costs drop to about 10 € – 15 € per lens at very large volumes. Similar behaviour can be expected from these two designs as they both have mostly plastic elements and only one glass element. Another general trend that can be seen from the graphs of Figure 24 is that lenses containing several ground glass elements (e.g., 5gg0mg1p) are cheaper to produce at lower volumes as the initial investment for the start of production is not that high. At a volume of 100, the lenses for injection-moulded components are more expensive than the lenses that are mostly glass. At volumes of one million, the lenses with a majority of plastic elements easily make up 25–50% of the cost of the lenses that have many glass components. The only full glass design (3gg3mg0p) is clearly the most expensive lens, even below a volume of 1 000, and the cost is still at 53 €/piece at a volume of 1 000 000. As the average cost of an injection-moulded lens is only a small fraction of its glass counterpart at very high volumes, even one element in the group of six can make a notable difference. In the full glass case, the individual differences between elements also have a big effect on the total costs.

5.5.4 Combining cost and performance information

When we combine the results of the performance and cost analysis, we can draw several conclusions that help us to find suitable applications for all of the analysed designs. The results show the well-known fact that injection moulding is not a very feasible manufacturing method for products that have low projected sales volumes. The point at which injection-moulded elements start to be more cost effective is surprisingly low however. Plastic elements make a clear difference to the cost at volumes above 10 000 pieces, and at high volumes the cost savings can be substantial. The lowest performance and lowest cost lenses (0gg1mg4p and 1gg0mg5p) could fit nicely into an RVC system with only a small, low-resolution (QVGA or VGA) display on the car dashboard. In addition to suitable resolution requirements, the RVC system also needs to be quite low cost at high volumes. If a High Definition RVC system is desired, improved performance can be achieved by changing more plastic elements to glass components (designs 3gg0mg3p and 5gg0mg1p) with the penalty of increasing the cost. If robustness is a major factor in the decision-making, the most expensive design (3gg3mg0p) may be the best choice, as the all-glass design is more stable against temperature variations than the designs containing plastic components. The robustness factor is not that important in applications for which the camera is used indoors. The best performance design (5gg0mg1p) has such good resolution that it could be used in tandem with a large 50” full HD LCD display. This setup would fit nicely into a surveillance system in which high-resolution images covering large areas are essential. The lower resolution lens options would simply be too low quality for this particular application.

5.5.5 Case-specific concurrent engineering features

In this case study, the optical designs were used in exploring the 'optical design space' in which there are usually several alternative options to realize the same optical function. The different manufacturing methods available for optical component manufacturing drive lens production costs in different directions. All manufacturing methods have their inherent restrictions that need to be taken into account when designing an optical system, but they also have benefits that can be exploited. As the selection of optical surface shapes and available materials vary from method to method, the range of achievable performance characteristics also change. Traditional optical designs based on ground spherical lenses may be so far away from the cost target of an imaging system that they cannot even be used as the starting point for finding a custom design for a particular low-cost application. By using cost modelling, it is possible to explore the 'design-cost space'. Here, the interesting issue is the relation of manufacturing cost to volume. When the two 'design spaces' are combined into one entity, the designer has a much better picture of the whole field of opportunities, and it is possible to improve the optimization of the intended module or system.

Cost modelling can be used most effectively in the beginning of a new product development project. By making some performance and cost calculations already at the concept creation phase, it is possible to avoid extra design iterations as the different options can be discussed not only with the engineers but also with people in sourcing and marketing.

5.6 Viewfinder optics

The purpose of this case study (Paper VI) is to illuminate the use of cost modelling at the concept creation phase of a new optical product. Concept creation is the starting point of all product designs and has great influence on the production costs, as the selected concept steers the design towards specific structures, materials and manufacturing methods.

5.6.1 Optical design concepts

Figure 25 shows two alternative design concepts for a viewfinder. Both of the designs are able to perform the same required optical functions: the optical path is tilted by 90 degrees and the image is magnified by a factor of 1.5. Additional specifications stated that the sharp image Field Of View (FOV) is 4.8 degrees, the aperture diameter is 8 mm and the transmission of the optics is higher than 88%. The first design in Figure 25a is more traditional in the sense that it is made up of separate components using two lenses and a surface mirror. This design could also be made with glass lenses, but in order to have adequate performance the surfaces will need to be aspheric, and plastic offers a lower cost solution for the intended volumes of this application. The second design uses the potential of plastic optics more extensively by integrating three optical surfaces into a single monolithic piece.

a) b)

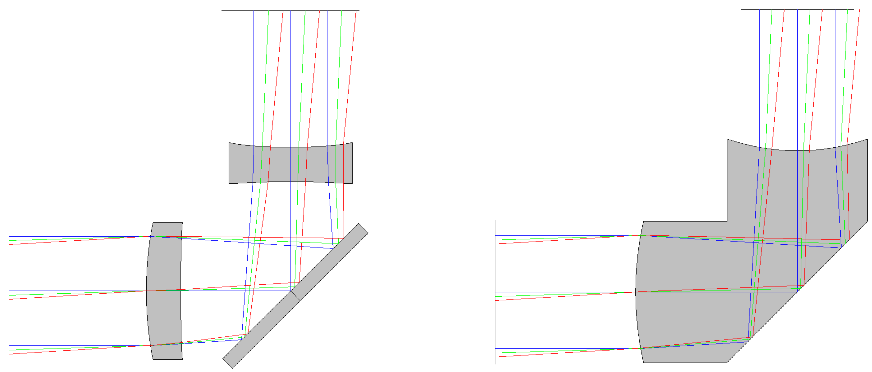


Figure 25. Two alternative optical design concepts for a telescopic viewfinder: a) made with separate optical components and b) made with a single integrated optical component.

5.6.2 Comparing the concepts

As both of the design concepts have the potential of producing basically the same optical performance, the designer is left with the difficult task of choosing the one that can be made at the lower cost. The first design is more complex and requires more parts, as the separate components need to be assembled into a module, as shown in the concept module design in Figure 26a. The higher part count and assembly process will definitely add to the cost. In the second monolithic approach, the optical component is a very thick piece, as shown in Figure 26b. This means that the cycle time will be very long and the manufacturing costs of this single piece relatively high.

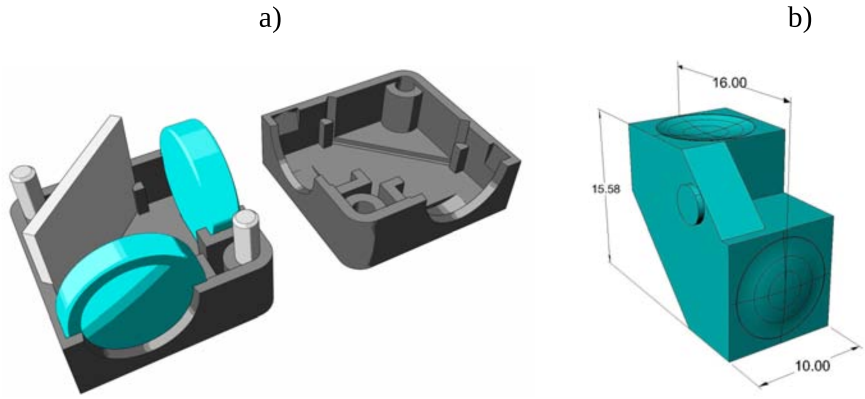


Figure 26. Two module design concepts: a) made with separate optical and mechanical parts and b) made with a single integrated optical component.

The first design will require at least three moulds: one for the two symmetric casing halves that hold the optical elements together and two for the different lenses. The two optical moulds can be very simple, however, whereas in the second case, the mould for the imaging prism is much more complex with three optical surfaces that need to be aligned in a single cavity.

If the required transmission of the system is > 88%, the first design will need AR coatings on all the lens surfaces due to the fact that the surface mirror will lose some light (~8%) on the optical path. In the monolithic approach, there are actually two alternative ways to make and protect the mirror surface. The first option is to use a cap to protect the surface. It works by the principle of total internal reflection (TIR). In this case, no coatings are needed and the reflectance is nearly 100%. The second option is to put a simple aluminium mirror coating on the tilted surface, but this would make the reflectance worse and some coatings on the two lens surfaces would be needed to meet the specified transmission. If the mirror coating were used, there would be no need for the moulding and assembly of the protective cap. Overall, it is very difficult to come to any kind of conclusion on which design to choose for further development without first doing some cost-estimation calculations.

5.6.3 Cost calculations

Table 5 shows the calculated manufacturing costs for the three presented module options. In the separate components case, the time it takes to assemble the module was estimated at 30 seconds, and this was used in the calculation of the assembly cost. The cost of the additional components was also estimated in order to calculate the total cost of the module. The protective cap was considered as a part manufactured in the same factory, but it could also be a component that is purchased outside the company that makes the optical modules. In this case, the cap assembly time was estimated to be 10 seconds.

Table 5. Calculated manufacturing costs of the three design concept cases.

Assembled from separate components

	Tooling	Moulding	Coating	Total
Lens 1	0.028	0.130	0.270	0.428
Lens 2	0.028	0.167	0.272	0.467
Case h1	0.011	0.127	0.000	0.138
Case h2	0.011	0.127	0.000	0.138
Pins	-	-	-	0.020
Mirror	-	-	-	0.100
Assembly	-	-	-	0.083
Total	0.078	0.552	0.541	**1.374**

Monolithic imaging prism with protective cap

	Tooling	Moulding	Coating	Total
Imaging prism	0.043	0.918	-	0.961
Protective cap	0.005	0.070	-	0.076
Assembly	-	-	-	0.028
Total	0.049	0.988	0.000	**1.064**

Monolithic imaging prism with coatings

	Tooling	Moulding	Coating	**Total**
Imaging prism	0.043	0.918	0.539	**1.500**

The lowest cost (1.06 €/piece) is achieved with the monolithic prism that has a protective cap. A module made from separate components would cost ~30%, more, and the fully coated imaging prism would be over 40% more expensive to make. Figure 27 shows, with graphics, how the costs are divided in each case between the different factors. The biggest difference between the two main design concepts is the cost of moulding. The separate parts can be moulded at approximately 60% of the cost of the imaging prism. Coating is a major cost factor in the separate parts case. If the specification for transmission were relaxed to, e.g., a value of 82%, then the separate parts concept would be competitive, with the cap-protected imaging prism, as only two AR coatings would be needed for the system and the manufacturing cost would drop to a value of 1.11 €/piece. A similar cost/performance trade-off would not be possible with the imaging prism as the cost of moulding dominates the overall cost of the system. In the monolithic case, the size of the optical piece would have to be reduced in order to obtain a lower cost module.

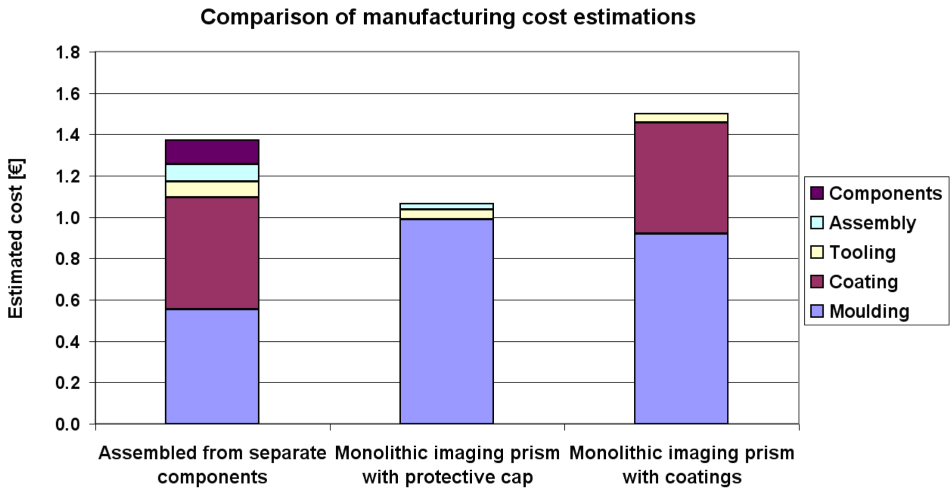


Figure 27. Ratios of different cost factors for the three design concept cases.

5.6.4 Case-specific concurrent engineering features

This case study shows how different optical concepts can be compared in order to find the lowest cost solution. The viewfinder case also shows that all of the manufacturing stages involved in production will need to be taken into account when making the estimations. It is an easy task for the optical designer to add AR coatings to lens surfaces in the design software, but the consequences of that action can be drastic for the production costs of the system. Furthermore, the example showed that the order of competing systems can be influenced by using different specifications. Therefore, it is also important to have good information exchange between the optical designer creating the optical concepts and a module or system-level designer who makes the component-level specifications. Again, a good optical design can only be made by incorporating many different points of view. This is facilitated by communication between different experts.

5.7 Solar concentrator optics

In this case study (Paper VI), a Concentrating Photo Voltaic (CPV) module is used as an example showing how an optical component can be designed for the module-level optimum. If the optical design process is only driven by technical performance, the end result can be a component that has very good optical properties but is too expensive to manufacture in relation to the module cost. If cost is used as the main driver, however, there is great risk of ending up with a component that is not of adequate quality and lowers the performance of the module or system excessively. Concurrent simulations with optical design software and cost calculation tools can be used to find the right balance between performance and cost.

5.7.1 CPV module optical system

The main idea of a CPV module is to concentrate light with low-cost optics to a small multi-layer solar cell that can operate at much higher conversion efficiency than a standard silicon panel. In such a module, only a small area of expensive semiconductor surface is needed to convert the Sun's radiation into electricity. A large amount of mechanics is needed to make the module and tracking system that keep the optics in line with the solar cell and pointed in the direction of the moving Sun. One type of such systems uses Fresnel lenses as the Primary Optical Element (POE). A Secondary Optical Element (SOE) such as a CPC (Compound Parabolic Concentrator) is used to relax the aiming tolerances of the tracking system, but the POE is responsible for the concentration of light (see Figure 28).

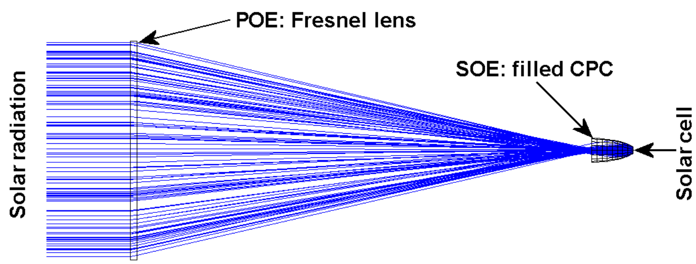


Figure 28. A ray-trace picture from a CPV optical design.

5.7.2 Relation between optical design choice and component cost

An aspheric Fresnel lens with a certain aperture size, focal length and spot size can be designed in several different ways. If the lens is injection moulded, the thickness of the piece becomes very important. Figure 29 shows three example POE designs that are 50 mm x 50 mm in size and have basically the same optical function. As the number of rings is increased, the thickness of the piece is reduced. Figure 30 shows this relation between the number of rings and the thickness calculated for eight designs. All of the lenses were designed with a 2-mm-thick base layer, and the ring structure was formed on top of this layer as shown in Figure 31. As the total thickness dropped from the 8.1 mm of the one-ring case to the 2.5 mm of the 26-ring case, the moulding cost also went down as the cycle time was reduced. Figure 32 shows the relation between the number of rings and the moulding cost. The graph shows that the design with only one ring costs more than four times as much to mould as the design with 26 rings.

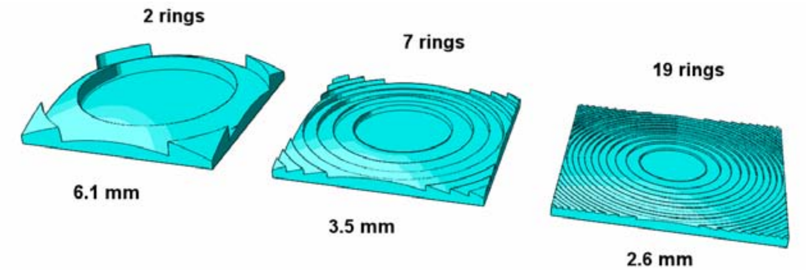


Figure 29. Three example 50 mm x 50 mm Fresnel lens designs for the POE.

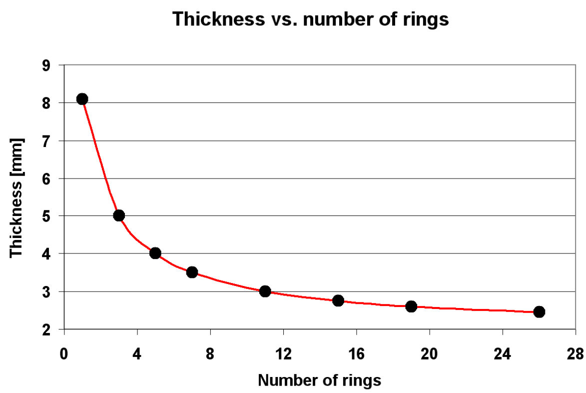


Figure 30. Relation between the number of rings and the component thickness.

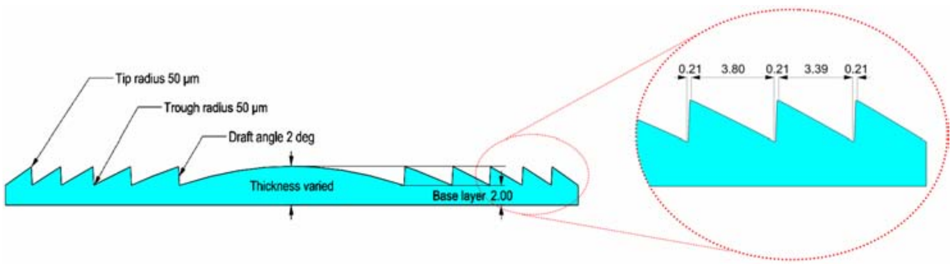


Figure 31. Design parameters of the example POEs: base layer thickness 2 mm, tip and trough radius 50 µm and draft angles 2 degrees.

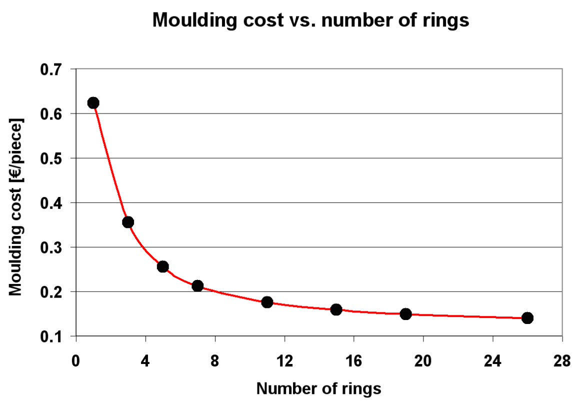


Figure 32. Relation between number of rings and moulding cost.

5.7.3 Relation between component cost and performance

From the component cost point of view, the thinnest design would be an obvious choice. As the number of rings is increased, the area covered by the rounded ring tips, troughs and drafted walls between the rings is also increased. This area is wasted because the light falling on it is not focused on the solar cell but is instead scattered around as stray light. The relation between the number of rings and the component transmission, as shown in Figure 33, was simulated with optical design software Zemax. When the design values shown in Figure 31 were used, the 1-ring case had transmission of 90% while the 26-ring design transmitted only 81% of the light. Therefore, from the performance point of view, the 1-ring case would definitely be the best choice. Figure 34 shows the relation between the POE transmission and the moulding cost. This 'value-for-money' graph shows that the relation between performance and cost is not linear. The costs start to rise fast after a transmission value of about 88%.

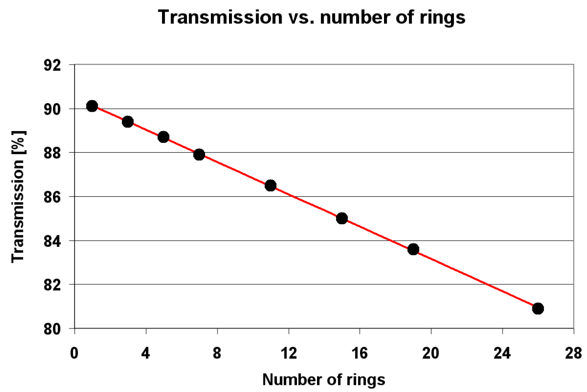


Figure 33. Relation between the number or rings and transmission.

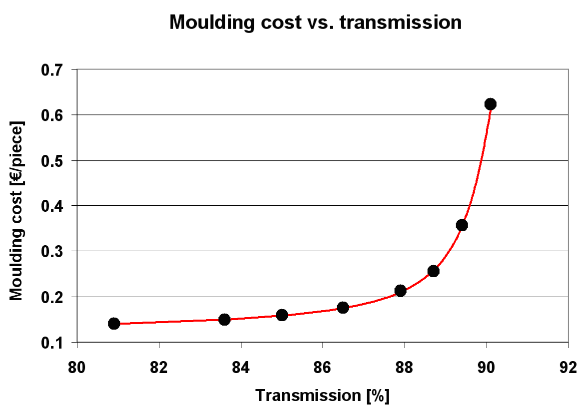


Figure 34. Relation between transmission and moulding cost.

5.7.4 Finding the optimum at module level

As all of the light falling on the solar cell comes through the POE, the performance of the whole module is affected by the transmission of the Fresnel. This means that the component performance and cost will need to be balanced with the performance and cost of the whole module. If we assume that the maximum amount of light falling on the CPV module is 1 000 W/m^2, the module conversion efficiency is 25% (without the Fresnel) and the module cost is 600 €/m^2, the graph shown in Figure 35 can be calculated for the eight example designs. The graph shows that the minimum module manufacturing cost in euros per Watt is achieved with a POE design that has 10 rings. If the design with the best performance had been chosen, the module cost would have been as much as 22% higher. If the component-level cost-optimum design had been chosen, the module cost would have been 5% higher than with the intermediate design that is now the optimal solution for module-level performance and cost.

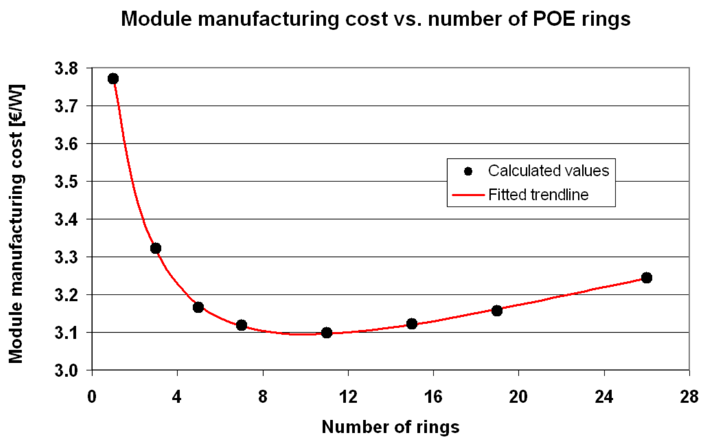


Figure 35. Relation between the number of POE rings and the module manufacturing cost calculated for the example designs.

5.7.5 Case-specific concurrent engineering features

This case study shows that a holistic, concurrent approach is simply necessary to find the best possible component optical design for a module. As both the Fresnel lens transmission and manufacturing cost depend directly on the component layout, the best possible structure can only be found with concurrent analysis during the design phase. It would not have been possible to make a component specification that could have covered both the performance and economical sides with enough detail to direct the design process towards the right conclusion. A similar situation can occur in any module or system in which the performance of the whole entity depends on the optical component and there are several choices for the component design and/or manufacturing method.

6. Discussion

CE can be considered a kind of opposite force to specialization in product development. As science and technology develop, greater specialization is needed due to the huge amount of knowledge associated with any given discipline and the limited amount of time and effort an individual person can spend internalizing it. This is a trend that is clearly visible in the growing number of scientific and technical papers coming out each year. Specialization can easily lead to a situation in which one technology, function or feature of a product gains more attention than others, and the end result is not optimal considering all the requirements. By emphasising the idea of a common goal, the design processes can be developed to support concurrency in decision-making. CE and the different techniques associated with it can assist engineers in their efforts to find good solutions in an environment that is becoming more complex. One of the key questions of product development in the future may be how to deal with the situation in which the information of the whole product structure and functioning is distributed to a large network of people. When no single person can handle the vast number of trade-offs that need to be balanced in good product design, the importance of communication increases. Along with this trend, the design practices and tool used in optics will also have to be developed. Better communication could be achieved by, e.g., making fast simulation tools that can present the quality of a lens in the form of images rendered from natural environments. These pictures would not bring anything new to the optical design itself, but they could be used in figuring out, without any background in optical design, what the best-value-for-money lens module is for the whole system. The requirements that determine optical specifications could also be better connected to the usability of the device. When the optical function is not the main driver of product development, the question of adequate performance becomes urgent.

Good optical design is optimized to meet the tolerances of the intended manufacturing process. This means that some of the peak performance of the ideal design can be sacrificed in order to make performance distribution inside a production series narrower and/or the yield higher. In a similar way, the cost models could be used for tolerancing costs. Parameters such as cycle time are sometimes very difficult to predict accurately for optics, as the high requirements may drive the values to extremes. With false predictions, the estimated costs can either be too high for, e.g., a competitive quote or too low for, e.g., a feasible profit margin. Both qualitative and quantitative analyses can be made with a parameterized cost model. The sensitivity analysis of the injection moulding process shown in Paper VI is an example of the former case. The latter case could be covered by a Monte Carlo analysis in which the input parameters of the model varied according to an estimated distribution, and the outcome would be the probability distribution of cost. These kinds of simulations could make cost-risk management a little easier. Furthermore, the cost factors related to tolerances could be built into the optical design software. This would enable the designers to optimize robustness, cost and performance inside one iteration loop.

There are several ways of estimating the cooling time of a plastic piece and this determines the cost of injection-moulded optics to a large extent. Unfortunately, the currently available methods are all quite inaccurate, which makes it difficult for an optical designer to estimate the costs of designs even with the help of a working cost model. Currently, the exact cycle time can only be determined by making the actual mould and performing some test runs with optimized process parameters. By creating a large database of actual pieces manufactured by injection moulding, however, it would be possible to create a pool of knowledge that could be used in connecting the specific features of designs to actual cycle times achieved with real production tools and machines. The products that are similar in size, shape, precision and material could be categorized and their features correlated to realistic cycle times. This kind of information and these kinds of databases can only be found from injection-moulding companies specializing in plastic optics. An expert system that includes the relations in the form of look-up tables or formulas could be an extremely useful tool for a designer. If similar systems were also built for other optical manufacturing processes, the task of comparing design options would be much easier. The cost-modelling tool presented in Paper V is one step towards this goal but more research work is needed to make these kinds of expert systems possible in the future.

7. Summary

Engineering can be seen as a balancing act in which several partially of fully conflicting needs have to be satisfied with one single solution. The requirements cover many different aspects, but even the ideal engineering solution does not have to satisfy all of them fully. The optimum design is simply the one that is most desirable from the set of imperfect choices. Concurrent engineering (CE) is a philosophy that aims for better products by improving the different design processes inside the whole development process. This is achieved by emphasizing holistic thinking, which makes it possible to balance all the different facets of product development. Two major aspects that need to be balanced in every product are performance and cost. Design for manufacturing (DFM) is an engineering concept that guides the design process towards better consideration of manufacturing issues. It lies at the core of CE and its purpose is to reduce the costs of manufacturing by fitting the product features and manufacturing processes together.

CE and DFM are rarely discussed in connection with optics, although many of their main features can be found in traditional optical product design practices. For a long time, optics has been designed for precision instruments and small volumes, but during the last few decades, optical components, modules and systems have been adopted in many new large-volume applications and multifunctional devices. The design methods that emphasize pure optical performance are no longer sufficient to support the multidisciplinary approach required in the development of these new products. In the context of product design, optical design has to be considered as a broader entity that embodies the holistic nature of engineering.

A major part of the thesis is the analysis of the basic optical product design and development process. By analysing the different phases and their co-dependence, it is possible to see where the trade-offs between various disciplines are needed in true CE fashion. The cyclic development process has five main phases, from optical concept development and specification to testing. This whole cycle needs to be considered at all levels of the product design process. The different phases also have sub-processes. One example is the design optimization, tolerancing and performance evaluation cycle in the optical design phase, which can be used to find the best solution with regard to manufacturing tolerances and optical performance. Stray light analysis of optomechanics is an example of a design task that needs to be performed concurrently in two design phases and requires close co-operation by two specialists. Case studies of the miniature imaging lens, fibre pigtailed laser module, add-on macrolens and IR temperature sensor published in Papers I, II, III and IV, respectively, served as examples of the way concurrent thinking can be used in practical optical design work. In order to complete the optical design tasks presented in the case studies, much co-operation and many trade-offs were needed to balance the different requirements of size, manufacturability, performance, usability and cost.

Another major part of the thesis concentrates on connecting the injection moulding manufacturing method to optical design in order to deal with the DFM aspects of plastic optics. This was done by analysing the different characteristics of the production process and the connection of optical design features to manufacturing costs. The strongest connection between a single design feature and cost was found in part thickness. When the thickness of the piece increased, the cooling time and related cycle time in the moulding also increased. This relation is not linear and it is distinct for different materials, which makes it difficult to predict the impact of, e.g., the choice of plastic material to cost. As the cycle time is one of the dominating factors that determine the cost of moulding, thickness is also the main feature of plastic optics parts that should be optimized for cost-effective manufacturing.

In order to help optical designers to make a practical DFM analysis, a cost model for injection-moulded optics was developed in Paper VI. With this tool, separate estimations can be made for three plastic optics key processes: mould tooling, injection moulding and coating. Cost modelling in the first phases of design cannot be made accurately due to a lack of information on the crucial process parameters. There is value in making the estimations, however, as the designer can gain a much better insight into the variables affecting the cost of the design. Even though absolute cost calculations cannot be made, the knowledge of the relative expense of optional designs can be used for balancing with other requirements set for the product. Case studies of the viewfinder and solar concentrator optics published in Paper VI showed how cost modelling can be used effectively during practical, optical concept development tasks. The solar concentrator case also showed how cost optimization can be extended from component level to module level. It also proved that they do not necessarily share the same design optimum. The case study of hybrid imaging lenses published in Paper V extended the use of cost models by showing how the design space of imaging lenses can be explored by comparing the performance and cost attributes connected to hybrid designs with ground and moulded glass elements, in addition to injection-moulded pieces. A balanced layout can only be found by comparing the costs of different manufacturing methods, as the performance of an optical design is heavily dependent on the materials used in its components.

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Abstract
Engineering can be seen as a balancing act in which several partially of fully conflicting needs have to be satisfied with one single solution. Concurrent engineering (CE) is a philosophy that aims for better products by improving the different design processes inside the whole development process. This is achieved by emphasizing holistic thinking.

In this thesis the most relevant terms and definitions of CE and product design are compiled into one literary work. In the context of product design, optical design has to be considered as a broader entity that embodies the holistic nature of engineering. The first major contribution of this thesis is the sketching of the basic optical design and development process and its connection to the larger frameworks of product design and CE. The emphasis is on the implementation of the philosophical ideas in practice.

Two major aspects that need to be balanced in every product are performance and cost. Design for manufacturing (DFM) is an engineering concept that guides the design process towards better consideration of manufacturing issues. It lies at the core of CE and its purpose is to reduce the costs of manufacturing by fitting the product features and manufacturing processes together. The second major contribution of this thesis is to show how this connection can be made in the field of injection-moulded optics.

In order to make the treated topics more concrete, seven optical design case studies are presented and their specific CE features highlighted. The presented applications range from consumer electronics to telecommunications and solar energy, whereas the example component and module designs vary from low performance illumination optics to relatively high performance imaging lenses. All the case studies have been published in Papers I–VI included in this thesis.

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