Cost Calculating of Optoelectronics

An Analysis of Cost Items for a Camera Application used in the Automotive Industry at Volvo Cars Corporation

By

Nimisha Vekariya
Fredrik Hultenius Syversen

Diploma work No. 55/2011
At Department of Materials and Manufacturing Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden

Diploma work in the Master Programme Production Engineering (MPPEN)

Performed at:	Volvo Car Corporation SE-405 31 Gothenburg Sweden
Supervisors:	Thomas Lyrfors Cost Estimator (CE) Purchasing TVM Volvo Car Corporation
	Håkan Bråvi Senior manager TVM/Cost Estimating Plastic, Rubber, Glass, Electrical and Electronics Volvo Car Corporation
Examiner:	Peter Almström Assistant Professor Department of Materials and Manufacturing Technology Chalmers University of Technology SE-412 96 Gothenburg

Cost Calculating of Optoelectronics
An Analysis of Cost Items for a Camera Application used in the Automotive Industry at Volvo Cars Corporation
Nimisha Vekariya
Fredrik Hultenius Syversen

Diploma work no 55/2011
Department of Materials and Manufacturing Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover: Camera application of Collision Avoidance Detections System (CADS)

Chalmers Repro Service
Gothenburg, Sweden 2011

Cost Estimating of Optoelectronics
An Analysis of Cost Items for a Camera Application used in the Automotive Industry at Volvo Cars Corporation
Nimisha Vekariya
Fredrik Hultenius Syversen
Department of Materials and Manufacturing Technology
Chalmers University of Technology

Abstract

The purpose of the thesis was to define the manufacturing process of a camera application with included optics and its integration with electronics and verify the process information by Volvo Car Corporation's (VCC's) cost model and using it to calculate the total product cost.

The method used to fulfill the purpose was divided into three phases, understanding the product, creating process maps and performing a cost calculation. By the use of literature studies, observations and interviews, necessary data needed to perform a cost calculation was included in specific process maps. The data was then used as input for VCC's cost model to calculate the total product cost.

By analyzing gathered information using the methods described above, three specific process maps with necessary data were created. These were a process map of lens manufacturing, a process map of lens barrel assembly and a process map of final assembly. When calculating the cost of all the components, the cost of the lenses was estimated using the specific lens manufacturing process. After calculating the cost of all the ingoing components, the cost of the lens barrel assembly was calculated. This cost was then used to calculate the cost of the final assembly with all ingoing components.

The results showed that the total product cost was 72 €, the cost distribution showed that the lenses were the most expensive component constituting for approximately 72% of the total product cost. When presenting information about the cost distribution of each process within lens manufacturing, it could be seen that the polishing process was the most costly operation of all.

Due to lenses being the most expensive component in the product, it was recommended to do further research within optical manufacturing and to review the product requirements and specification regarding the optical system in order to reduce the total product cost.

Keywords: cost calculation, process maps, Value Stream Mapping, Activity Based Costing, lens manufacturing camera application.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

This report is the result of our master thesis, which is made as a part of our education in Production Engineering with specialization in Production Management at the Department of Materials and Manufacturing Technology at Chalmers University of Technology.

The scope of work is 30 credits in the ECTS-system at the D-level and is meant to demonstrate the knowledge acquired by us during our study period. In this work, we also convey our acquired skills in identifying and analysing problems and propose solutions to the problems.

This thesis was requested by Volvo Cars Corporation in Gothenburg.

1.1 Background

Volvo Car Corporation (VCC) was founded 1927 in Sweden and is a manufacturer within the car industry. The company is global and has two major production plants, one in Gothenburg, Sweden and the other one in Ghent, Belgium. For the year of 2009, the total number of employees was 13808 worldwide. The total turnover of 2009 was 78 022 MSEK with a sale of 334 808 units (Volvo Personvagnar AB, 2009).

The company manufactures a variety of cars within the premium segment and their core values are safety, environment, quality and design. VCC has approximately two percentage of the market shares in those markets were they operate, except in Sweden were they have around 20 percentage (Volvo Car Corporation, 2010)(Volvo Personvagnar AB, 2010).

The unit Team Value Management/Cost Estimating (TVM/CE) is subordinated to the division of Purchasing. The unit's main function is to carry out both work piece cost calculations as well as production tooling calculations. Another function assigned to the unit is to provide knowledge regarding production processes and material prices for the purchasing unit (Volvo Car Corporation, 2008).

Safety is a top priority for VCC and the trend for safety systems is going towards including more camera applications in the car to give the driver appropriate information needed for a safe drive. Currently, the safety systems are procured and developed in cooperation with suppliers. The importance of cost estimating rises when the amount of camera applications included in a car increases.

According to Håkan Bråvi[1], the first choice for the cost estimating unit is to perform a cost calculation where information about the manufacturing process is used with VCC's cost model. However, there are situations where information about the manufacturing of the product is insufficient, this leads to cost estimating with other methods.

In the present situation, the lack of knowledge and experience about the manufacturing process of the camera applications limits the ability to use the first choice of cost calculation. The method used instead is to estimate the cost by benchmarking similar technology and assessing similarities and differences. This method is less desirable but appropriate when input variables and information about the manufacturing process is insufficient in order to use the cost calculation method.

---

[1] Interview with Håkan Bråvi, Senior Manager at TVM/CE at Volvo Car Corporation

1.2 Purpose

The purpose of the thesis is to define the manufacturing process of a camera application with included optics and its integration with electronics and verify the process information by VCC's cost model and using it to calculate the total product cost.

1.3 Objective

The objectives for this thesis are listed below:

- To gain understanding of CADS3, its components and manufacturing methods.
- To create process maps with process information applicable to the VCC's cost model by using Value Steam Mapping (VSM), literature studies, observations and interviews as methods.
- To use VCC's cost model to perform a cost calculation of CADS3.
- To analyse all cost items included in CADS3.

1.4 Scope

The thesis only covers the camera application as a component included in the system for Collision Avoidance Detection System 3 (CADS3), as it has a high turnover and is representative for all camera applications in the car range. Costs concerning logistics between the supplier and the customer have not been included in the cost calculations.

1.5 Structure

In Chapter one the general information regarding the thesis is presented. This information is both information about Volvo Car Corporation, what extent the thesis should have and the purpose of the thesis.

Chapter two describes the working procedure and methods used in order to achieve the purpose of the thesis.

The necessary theoretical framework for the whole thesis gathered from various sources is presented in Chapter three.

In Chapter four, the analysis is presented where the gained information is analysed and applied in order to get the result.

The result of the thesis is presented in Chapter five, it contains the presentation of the cost calculation with a motivation of the cost items.

In Chapter six, a discussion of the thesis is presented.

The conclusion is presented in Chapter seven

The bibliography is presented in Chapter eight.

The appendix for the thesis is placed in Chapter nine.

2 Method

This chapter describes the methods used to reach the objectives.

2.1 Working procedure

The working procedure for this thesis was divided into three phases, understanding the product, creating process maps and cost calculation. The model for the working procedure is presented in Fig. 1 below.

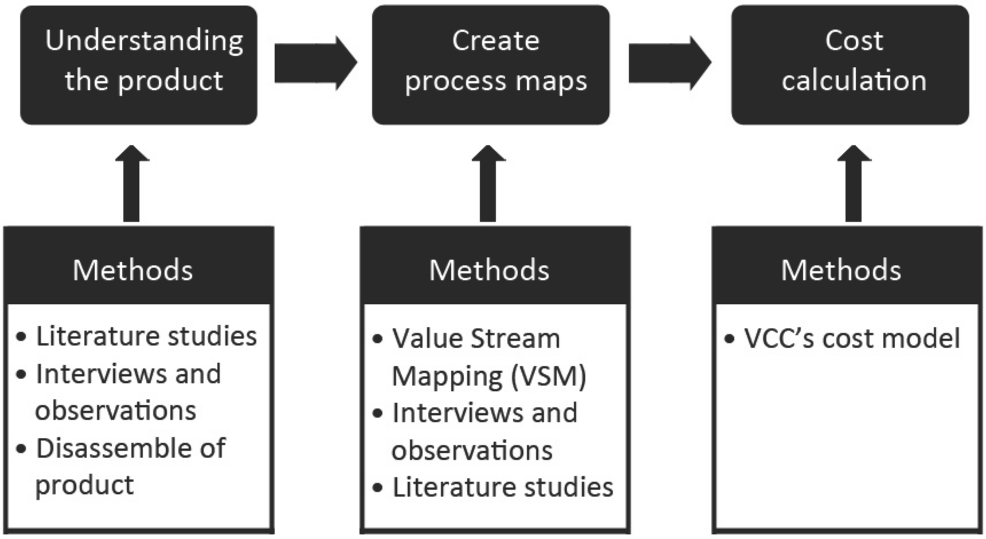


Figure 1 - Model for the working procedure of the thesis

2.1.1 Understanding the product

The first phase was to understand the product; this was done by literature studies, interviews, study visits and studying the product by disassembling it. Literature studies were performed to get a theoretical framework for all three phases, and used as a base when performing the other methods in the working procedure. Information regarding cameras in general was gathered from literature studies and by interviews and observations at VCC. Since there was no in-house knowledge regarding lenses and lens manufacturing, information has been gathered by literature studies in this phase. To get detailed information about the camera, the product has been disassembled and each component has been studied regarding function and specification.

2.1.2 Creating process maps

When calculating the cost of the whole product, the assembly process had to be understood and all the input data for the VCC's cost model had to be gathered. This was done in the second phase by creating necessary process maps to be able to calculate the total cost of the product. The three necessary process maps with included process information needed to calculate the cost of the product were the CADS3 assembly flow, the lens manufacturing flow and the lens barrel assembly flow.

A model for the cost calculation was created and is presented in Fig. 2 below. Since accurate process information about the CADS3 assembly was hard to obtain by literature studies, it was decided to gather as much data as possible by observation and interviews. This data was to be presented in a process map, a method for doing a process mapping is Value Stream Mapping (VSM), first all data will be gathered and analysed, finally the map will be visualized and all the necessary data will be presented.

Due to difficulties in obtaining a study visit at the CADS3 manufacturer to map their assembly process, another camera process was chosen as a substitute. The chosen camera was the Front Side View Camera (FSVC), which is a similar camera application in size and number of components, it was chosen as a substitute in discussion with a Cost Estimator[2] at VCC. This meant that the process mapping was performed at the assembly process of the FSVC instead. To complement the information gained from the process mapping, a document was received from the supplier including the process steps of the CADS3 assembly. By combining the information, a process map for the CADS3 assembly with needed process data could be created.

To create a process map of the lens manufacturing and necessary data, the general manufacturing from the theoretical framework was considered in combination with a process mapping at a metal lens manufacturer and a document from the supplier regarding general lens manufacturing. By combining the information and estimating needed data, a process map of the lens manufacturing could be created.

Furthermore, a process map of the lens barrel assembly with complementary process data was needed to complete the cost calculation, this was created by using literature studies.

The process mapping was performed on the assembly process of this camera. However, the documented assembly process for CADS3 was obtained and studied. Combining the information from the process mapping with the documented flow gave a complete process map for CADS3.

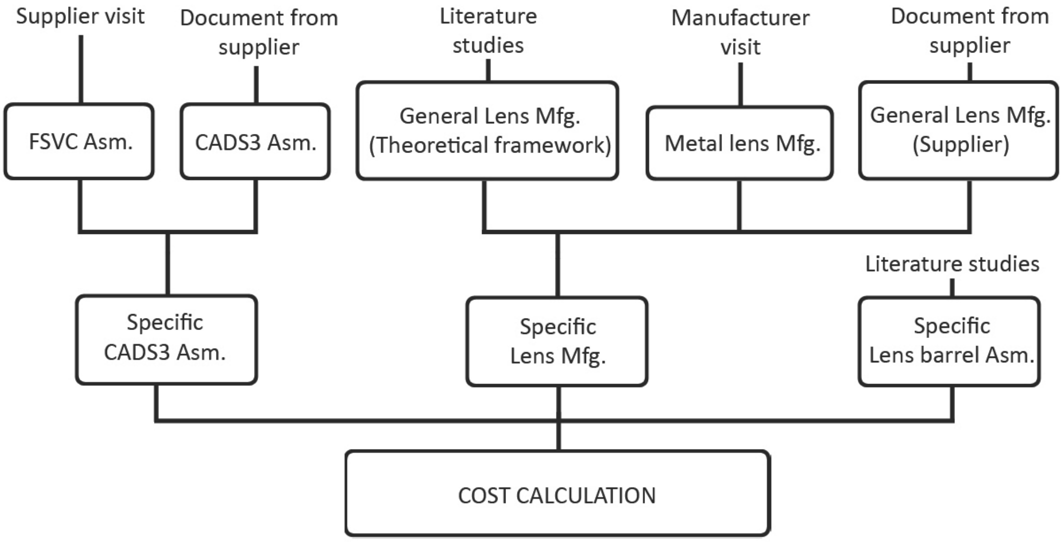


Figure 2 - Model for creation of process maps

2.1.3 Cost calculation

In the last phase, the cost for the whole camera was calculated. This has first been done by calculating the cost of each component included in the camera, and then calculating the cost of the assembly process. The model for how the cost of the camera was estimated can be seen in Fig. 3 below. The cost of two assembly processes, the lens barrel assembly and the camera assembly where calculated with all the ingoing components in order to obtain a total cost of the product.

---

[2] Discussion with Thomas Lyrfors, Cost Estimator at Purchasing TVM at Volvo Car Corporation.

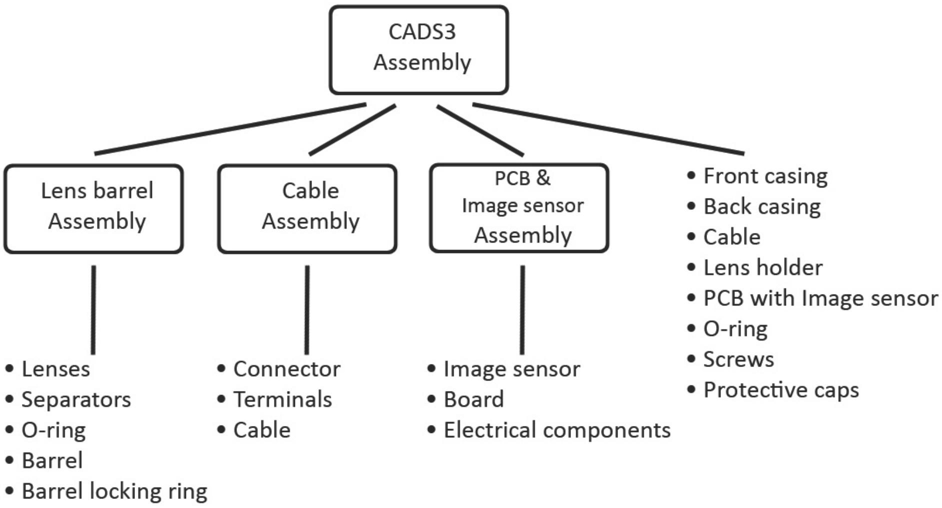


Figure 3 - Model for cost calculation

2.2 Data collection

Data collection methods can be divided into two categories, qualitative and quantitative. The qualitative methods yield data with more intangible, personal and subjective measures as in attitudes and assumptions. The quantitative methods result in objective and measurable data e.g. frequency and time (Phillips & Stawarski, 2008). The Table 1 below categorizes the methods.

Table 1 - Data collection methods

Method	Type
Interviews	Qualitative & Quantitative
Observations	Qualitative & Quantitative
Product documents	Quantitative
Disassembly	Qualitative & Quantitative

2.3 Interviews

Interviews are useful for collecting and securing data that are not available in performance records or data that are difficult to obtain through written responses or observation. There are mainly two types of interviews: structured and unstructured. The structured interview resembles a questionnaire where the questions asked are specific and prepared, the advantage is that it can be assured that the participant’s responses are understood. An unstructured is based on a few general questions that can lead to more detailed information gathered if the interviewer is skilled in asking relevant follow-up question (Phillips & Stawarski, 2008).

2.4 Observations

For observation to be a valid data collection method, it has to be applied thoughtfully. The observers must be prepared by completely understanding the information that is needed from the observation and should be provided a chance to practice their observation skills. To get more objective data, bringing in a third-party observer could be an alternative.

If data is to be collected regarding a participant’s routine application, it is crucial not to influence the behaviour of the participant. The presence of the observer must therefore be minimized; options are to blend into the work environment to the extent possible or to allow participants to become accustomed to the observer’s presence by extending the observation period (Phillips & Stawarski, 2008).

2.5 Product documents

By examining product documents about specifications of the product and its manufacturing process, information useful for calculating the product cost was gained. Documents were received both from VCC and the supplier of the camera. The documents were not open to the public, all the information gathered could therefore not be published directly in the report, it has instead been rewritten in order to provide necessary facts without breaking the confidentiality agreement.

2.6 Disassembly

When information gathered by other methods was insufficient, the product was disassembled in order to get necessary data. After disassembling the product, all components were examined and photographed to be able to document the analysis made. The documents received from the supplier were also secured by disassembling the product down to the detail level required and comparing the information sources.

3 Theory

The theory chapter describes the theoretical framework from which the practical function is used in the report and information that helps the reader to get a greater understanding of the underlying technology of the camera application.

3.1 Camera technology

The word camera comes from the Latin word *ca´mera* that means room. Simplified, a camera is a case containing an objective on one side and a light-sensitive material on the other. By passing light through the objective, a picture is captured on the light-sensitive material (Nationalencyklopedin, 2011). In a digital camera, an image sensor is used instead of a light-sensitive material to capture an image. The image sensor or imager consists of light-sensitive points or pixels, which transforms the light to electrical signals (Christiansson & Rondell, 2006).

3.1.1 Lenses

The function of a lens is to both provide enough light (Chapter 3.1.2) to enable a camera to operate and to refract the light in order to create a clear image. The point where light converges is called focal point, and the distance between the lens and the focal point is called focal length (Chapter 3.1.4).

An optical system can be constituted of either one single lens or a compound of lenses. A compound of lenses is a series of lenses with a common axis. The reason to use a series of lenses is to correct as much chromatic aberration as possible. Chromatic aberration occurs when different colours of light have different focal points, see Chapter 3.1.5 (Ikumo, 2003).

Optical lenses can be made of either glass or plastic. The most important criteria is that the lens has to be transparent over the visible spectrum of lights. The drawback for optical plastics compared to optical glass is that that the refractive index in relation to temperature is about 50 times greater for optical plastics. The refractive index of a material describes the ratio between the speed of light in vacuum relative to the speed of light in any given material (Encyclopedia Britannica, 2011). For that reason, optical plastics are less stable for thermal variations and better suited for high-volume, low-cost optics for non-critical applications (Karow, 2004).

An issue regarding lenses is surface roughness, which through tests confirms a surfaces' suitability for its function. Surface roughness is a measurement used to determine the surface finish after the lens has been processed. Surface roughness in a lens should be at a minimum since roughness can distribute the incoming light in an unwanted way (Zemetrics, Inc., 2011).

3.1.2 Light and colour

Light consists of electromagnetic waves and the human eye is sensitive to electromagnetic waves within the wavelength of 380 to 760 nm. Each wavelength within this range is to the human eye presented as a different colour (Ikumo, 2003). If the wavelength is lower than 380 nm, it is called ultra violet light and above 760 nm infrared light. Camera image sensors (Chapter 3.1.3) does not have the same limitations as the human eye and can therefore capture lights outside that interval.

3.1.3 Image sensor

The image sensor or imagers, have the same functions as photographic films in analogue cameras. It is a light-sensitive component, which converts optical images to electrical signals. The imager is normally of a semiconductor chip. There are two types of imagers; Charge Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS).

Both sensor types have advantages over each other. For instance, CCD sensors create high quality and low noise images while CMOS typically consumes less power and less expensive to manufacture.

Since CMOS sensor have several transistors located close to it, photons many times hits the transistors instead of the photodiode.

So based on this CCD cameras most often have higher quality and more pixels while cameras with a CMOS sensor have a lower price, lower quality but a longer battery life (HowStuffWorks Inc., 2011).

3.1.4 Focal length

Focal length is the distance from a single lens, which the light passes through to the focal point. This can be seen in Fig. 4.

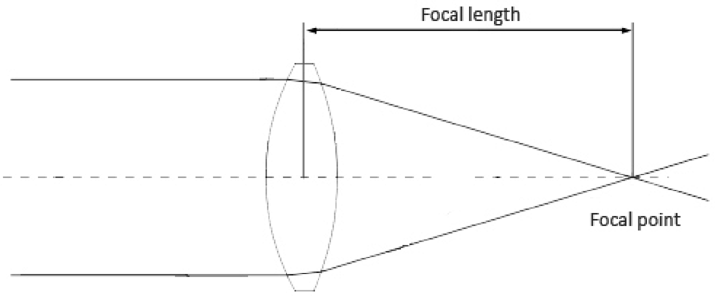


Figure 4 - Focal point in a single lens adapted from Ren (2003)

A compound of lenses, which is a series of lenses have a virtual focal point called principal point to prevent chromatic aberration (see Chapter 3.1.5) (Nationalencyklopedin, 2011). This can be seen in Fig. 5.

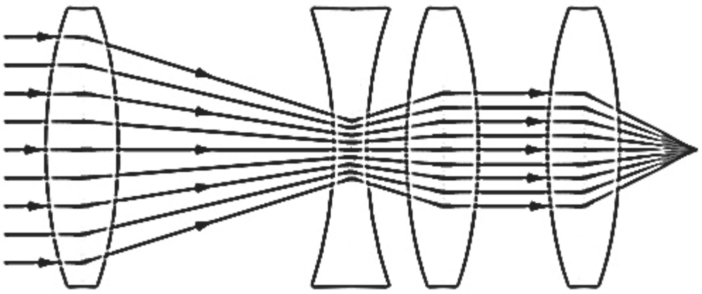


Figure 5 - Principal point for a compound of lenses adapted from Ren (2003)

Focal length is an optical characteristic built into the lens. Nevertheless, adding or removing lenses can change the characteristics. The characteristics of a lens are the same regardless if it is mounted on a camera, video camera or a projector (Wildi, 1996).

3.1.5 Chromatic aberration

Different colours or wavelength that passes through a lens has different focal points. This occurs to the fact that different wavelength has different refractive index for different lights (Ikumo, 2003). A single lens therefore converge lights with a lower wavelength more intensive than a higher (Nationalencyklopedin, 2011). An objective is therefore composed with convex and concave lenses to overcome this and enable the incoming lights to have the same focal point (Nationalencyklopedin, 2011).

3.1.6 Flare, Ghost images and Vertical smear

Flare is a type of reflection that might occur when strong light passes through the lens. The flares is when an object has a type of glow around it, or when there is a main image and a secondary one next to it. Nowadays this phenomenon can be prevented by using coatings. However, it can still occur on ultra-fast lenses or low-cost ones. There is also another type of flare caused when light shines straight into the lens and generates an image of the lens diaphragm. A proper designed lens hood can prevent this (Ikumo, 2003) (Hicks & Schultz, 1994).

A ghost image is a phenomenon that can occur when light is reflected between different lenses in an optical system, this causes an extra image of an object being portrayed. Thereof the name ghost image (Svenska Optiksällskapet, 2008).

Vertical smear can happen on cameras with a CCD images and occurs when insufficient light passes straight into the vertical/horizontal shift register or an excess of electrical charges accumulated in the photo site. This creates a glow around a light source and most of all, vertical or horizontal lines sticking out from the object. The amount of the smear is proportional to the intensity of the light (Ikumo, 2003).

3.1.7 Coating and multi-coating

Coating is a type of surface treatment, a thin layer of fluoride, which has the characteristics that it reduces the light. The basic idea with coating is to decrease the reflections and increase the transmission. Therefore, in a coated lens, about one per cent of the light is reflected and about 99 per cent is transmitted. Coatings are less likely to have an effect on lenses of lower optical quality (Wildi, 1996) (Hicks & Schultz, 1994).

Multi-coating is more layers of coating on the glass surface and this can reduce the reflection even more, to about 0,3 per cent reflection. As mentioned above a good coating reduces reflection that is a root cause for flare, which is mentioned more in Chapter 3.1.6 (Hicks & Schultz, 1994) (Wildi, 1996).

3.2 Lens manufacturing

There are several ways of producing glass lenses for cameras, the different process maps can be seen in Appendix I, II, III and IV. Fig. 6 below summarizes all the flows and presents a general process map, which will be described in the following subchapters.

For manufacturing of large number of lenses of the same kind there are generally two ways of shaping glass into lenses, either moulding or trepanning (Twyman, 1988).

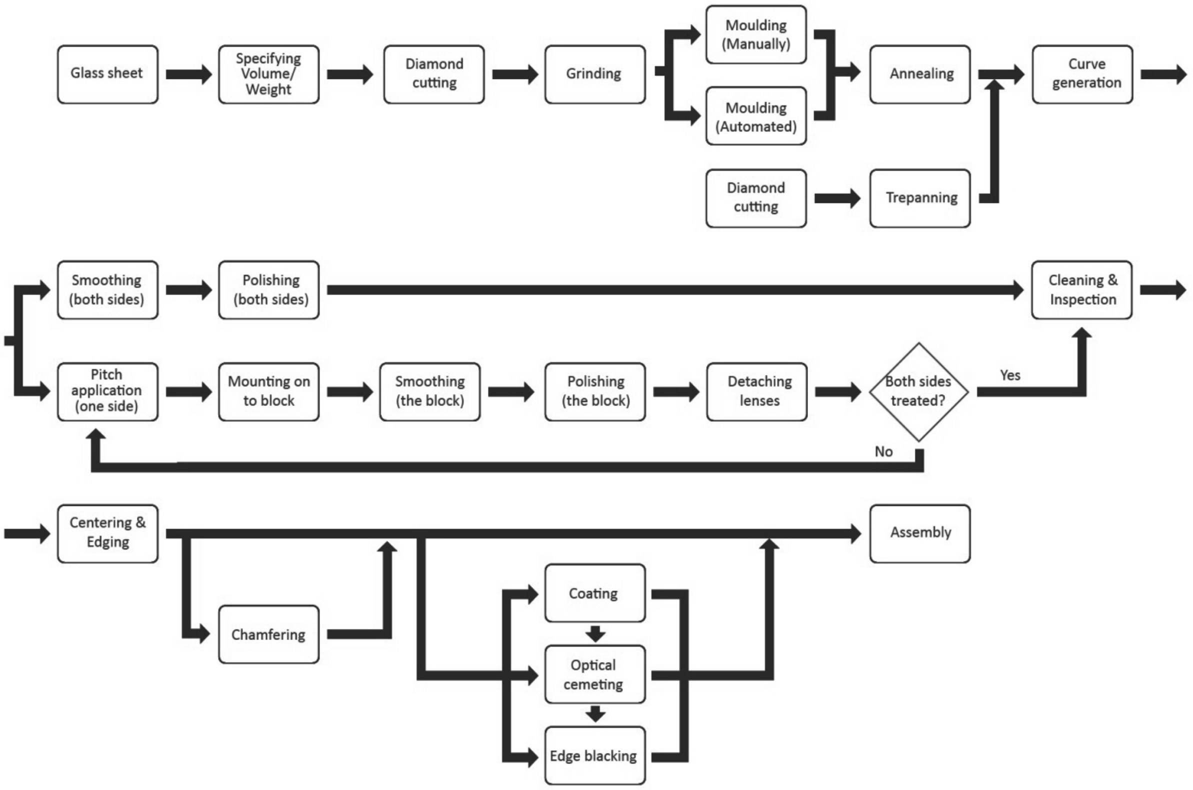


Figure 6 - Schematic process map of lens manufacturing

3.2.1 Moulding

Historically, this method has been uncertain due to the heterogeneity resulted from chilling of the piece. Since the effect has been studied and is better understood, the problem of heterogeneity can is avoided by effective annealing (Twyman, 1988).

For products where a large number of identical lenses are required e.g. spectacle lenses, camera lenses and binocular lenses, the mouldings are available direct from the glass-making machine on line (Horne, 1972). The use of pressings or mouldings offer many advantages compared to traditional methods; less glass needs to be removed in the following shaping operations and that leads to less time required to shape a lens.

Furthermore, the labour of sawing, rough edging and sometimes roughing to curve in order to shape the lens is saved as the pressing forms the lens into shape directly. The process of shaping the lens starts with a ribbon of molten raw glass being poured into the orifice of the moulding machine; the lenses are then stamped out like cakes from a ribbon of dough (Twyman, 1988). The pieces from the same mould are consistent for diameter and thickness within close limits; this allows preparations of collets and fixtures for long production runs without alteration (Horne, 1972).

Mouldings are also available as remoulds in a separate moulding furnace. This alternative contains more process steps and requires more labour (Horne, 1972). Depending on the lens diameter, shape and specific gravity, volume and weight of the piece is decided and by using a diamond cutter, the piece is then cut. To obtain the precise weight demanded by the particular moulding, the cut glass piece undergoes various grinding processes (Canon Inc., 2011). The glass piece is then heated in a furnace to correct plastic temperature and then formed into shape by pressing in the mould (Horne, 1972). For small lenses the pressing is automated, the other alternative is pressing by hand (Canon Inc., 2011).

Pressed glass either produced automatically on line or in a separate moulding furnace has intense internal thermal stress, which is removed by annealing, this process is needed to restore homogeneity (Horne, 1972). The glass is first heated to 500°C in an electric furnace, it is then gradually allowed to cool whereas the internal stresses are relieved (Canon Inc., 2011).

3.2.2 Trepanning

Diamond cutting is the first part of the trepanning operation in which a plate of glass is cut out from a greater block of glass with a diamond cutter.

Trepanning is the operation in which one or more disks are drilled out from the glass sheet. A trepanning machine is a drilling machine with similar manual adjustments but a more powerful motor and cooling lubricates (Horne, 1972).

Trepanning is done either with a fixed abrasive or with a free abrasive. The basic difference between a free abrasive and a fixed abrasive is that the free abrasive is slurry and the fixed abrasive is incorporated on the drilling metal. The slurry for free abrasive is mostly either silicon carbide or boron carbide. Moreover, the trepanning tool is usually made from brass. The size of the abrasive particles is dependent on the material to be drilled and rotations per minute (rpm) of the machine. Softer materials are in general drilled with free abrasives, while harder material drilled with fixed abrasive. The abrasive material used in the fixed abrasive method is most often diamond. During this operation, water is also fed into the drilling area for cooling purpose. It also works to monitor pressure; if the drilling core gets broken the water-fed pressure will suddenly increase (Fynn & Powell, 1988).

Preferred lubricants is either Castrol Honilo cutting oil for quartz which is a chlorine-free, low viscosity, sulphur- and heavy metal free cutting oil, or Castrol Cleeredge for glass which is semi-synthetic ditto (Horne, 1972).

3.2.3 Curve generation

Curve generating is needed both after the moulding process and after the trepanning process. Nowadays the primary tool for curve generating is a sintered diamond tool used for the drilling operation. Before it was invented, at least three grinding operations where needed with increasingly fine grinding grain for the rough machining. Thereafter one or two grinding operations with finer grind would follow. Using sintered diamond tools makes the operation both faster and gives a more adequate result. For optimizing service life and best finish result the choice of bonding material in the sintering process is of importance. Copper bond gives the best optical finish on soft glasses but bronze is more commonly used (Horne, 1972). In Fig. 7, different ways of processing lenses are presented.

To guarantee optimal performance of the tool, a smooth wear is desired. This is done with a diamond concentration of 50 to 90 percentages. Higher concentration will reduce the grinding capacity but might increase service life (Horne, 1972).

There are two ways for curve generating. The first is to generate a spherical surface on a blank or individual moulding and the second is to generate a block filled with blanks or mouldings (Horne, 1972).

Generation of spherical surface on moulding is optimal for small lots since it is a very flexible method. In this process, two spindles are used: one with fine diamond grain and the other with rougher ones. For lenses smaller than 30 mm, the disks are held in place onto the chuck by vacuum. For greater lenses, a “drop in” chuck is more common (Horne, 1972).

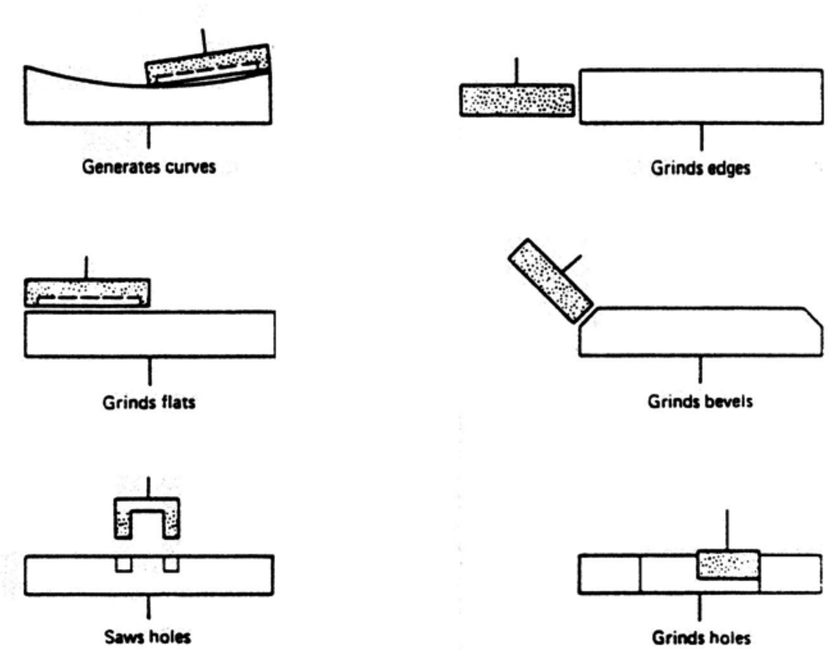


Figure 7 - Illustration of different lens machining operations by permission of Satisloh GmbH[3]

For larger quantities of lenses, generation of spherical surface on a block of lenses is more suitable from an economical point of view. The drawback is that a large number of blocking tools are needed since once the lens is stuck on the moulding it has to stay there until the polishing operation is finished. The blocking tool is mostly made of aluminium but blocking tools of steel, brass and epoxy resins also exist (Horne, 1972).

3.2.4 Mounting lenses on the blocking body

After the lenses have been given their shape, the following smoothing and polishing, processes are either performed on the lenses individually or on a block where several lenses have been mounted

During the following smoothing and polishing processes, the lens must be supported to avoid movement during the operation. This is usually solved by sticking hard pitch on the backside of each lens, there are several methods described to achieve this below (Horne, 1972). Fig. 8 below shows a schematic sketch of the blocking body.

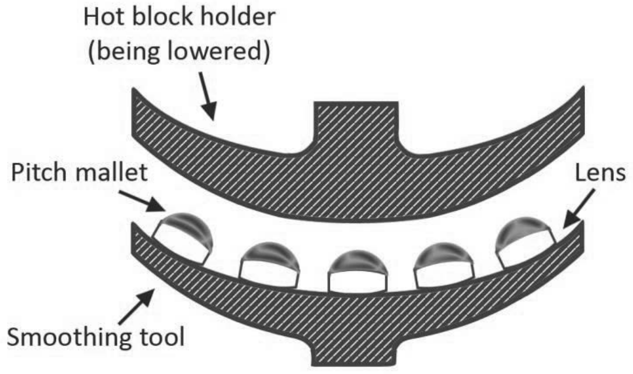


Figure 8 - A schematic sketch of a blocking body with lenses adapted from Horne (1972)

---

[3] Correspondence with a sales manager at a lens machine supplier

As mentioned above, lenses are smoothed and polished either individually or several at once on a block. Regarding small lenses which are processed on a stick rather than a block, the best way to provide support is to drip pitch right on the surface of the lens's backside.

Methods for small lenses to be processed on a block consist of placing the lenses in a blocking tool and pouring pitch on to the lenses. This step is followed by dissolving the pitch away in the area immediately surrounding the glass (Horne, 1972).

For larger quantities, machine pelleting is more common than performing pelleting by hand. It contains of a lens being placed in a water-cooled brass mould with hemispherical shape, the mould is located over a nozzle through which the hot pitch passes and makes contact with the lens. As the mould is cooled, it rapidly cools the pitch and the lens with hemispherical pellet can be removed (Horne, 1972).

Another method is to pre-cast the mallets by pouring pitch into moulds of hemispherical shape followed by heating the cooled mallet with flame on the bottom and press it on to the pre-warmed lens (Horne, 1972).

For the lenses to be processed on a block, the step of mounting the lenses onto a block follows, after having a mallet of pitch on each lens. The tools used for smoothing the lenses in the next process step is prepared by screwing the tool to one of the noses and cleaning it thoroughly as the lens surface will face the tool. The lenses are also made sure to be free of any dirt particles as they are placed in the tool with the lens surface facing down (Twyman, 1988). Meanwhile the block holder is heated uniformly and then placed centrally over the lenses, the heat of the block holder will cause the mallets to deform and settle down equally around the block. The block holder is then cooled off by water and the lenses have been mounted on to the block (Horne, 1972).

The following smoothing process can also be performed on lenses attached on recessed tools. The tool is made from aluminium, brass, epoxy resin or steel where the recesses are machined by a special cutter ground to the designed shape. Before sticking the lenses in the recesses with wax, the block has to be heated. When the block has achieved consisted heating, the lenses are put in the recesses by the use of heated wax (Horne, 1972).

3.2.5 Smoothing

If the lenses are to be smoothed on a block, they should start the smoothing process soon after the blocking is completed to avoid movement of the pitch as the mallets are inclined to sink unequally (Horne, 1972).

The smoothing machines contain a tool that is rotated around a vertical axis while the other oscillates in a straight line, however the detail in construction and capacity between the machines vary. As the process is on-going, adjustments for variation of crank speed, variation of spindle speed and variation of the ratio between crank and spindle speeds are usually possible (Twyman, 1988). For grinding with loose abrasives, the lenses should be smoothed twice in each of the grades of abrasives selected. When changing grades by an operator, precautions to avoid contamination and scratching of the lenses are essential (Horne, 1972). For machines where less operator attention is needed, abrasive slurry is continuously fed on to the tools. This type of feeding is faster and gives consistently good results (Horne, 1972).

If the lens quantities are large enough and recessed blocks have been used in the previous process, diamond smoothing can be used to reduce smoothing and subsequent polishing times. The result of this smoothing method is very good where a semi-polished surface is being produced. The smoothing tools have sintered coating on the tool shell, the therefore gives a time save of more than 50 per cent compared to fine grinding with loose abrasives (Horne, 1972).

3.2.6 Polishing

There are four common polishers: pitch, felt, cloth and wax mixtures (Horne, 1972). Regarding polishing machines, the most important property is a steady flow polishing material. The flow must be slow or else the force from the polisher will not be suitable for the surface that is to be polished. If the polisher is too soft it will lose its shape and reforming it consumes a lot of time. To minimize scratches on the surface of the lens, the viscosity cannot be too high. Furthermore isolating the polishing machine eliminates dusts on the surface which is to be polished, and minimizes the possibilities for scratches to occur (Twyman, 1988).

The polishing operation is an important operation in the lens manufacturing process since it has the function of minimizing the surface roughness. The roughness is sub-micron variations in height and shape so precise machines have to be used (Zemetrics, Inc., 2011).

3.2.6.1 Polishing materials

The main materials used for polishing optics are rouge, cerium oxide and putty powder. Rouge is a ferric oxide, it needs to have good red colour and a minimum of sulphate for a good polishing result. If the rouge has a light-red colour, the conversion of metal into their oxide has not been complete or that the heating temperature was too low. If contrary, the colour is too dark, the temperature has most likely been too high. For best polishing results, one quarter of rouge free from sulphate mixed with three quarters of water should be used (Twyman, 1988).

Cerium oxide is another polishing powder which makes the polishing process both faster and gives rise to fewer sleeks and stains on the material which is about to be polished. It has smaller grain size than rouge and smaller doses are needed, between 20 – 50 per cent. However, cerium oxide is more expensive than rouge but is better for the environment and for the operators. Cerium oxide is more common in precision polishing since labour cost is high and process times decrease with the use of this material (Twyman, 1988). There are also polishing materials for other materials than glass.

3.2.6.2 Polishing machines

Most smoothing- and polishing machines have one thing in common, they have one tool rotating around a vertical axis while the other tool is moved to and from in an even pattern (Horne, 1972).

To achieve this even pattern; one or both tools must rotate while one or both tools sweep. The tools must also be able to do reverse motions. The polishers also have to be accurately shaped either flat or spherical (Fynn & Powell, 1988).

Spindle speed in common commercial polishing machines varies from 65 rpm. up to 800 rpm., and can process lenses up to a diameter of 381 mm. Furthermore, the machines have automatic fed of polishing materials (Horne, 1972).

3.2.7 Detaching lenses from the blocking body

After the polishing is complete, it is time to remove the lenses from the block. Since the surface of polished glass is delicate and easily scratched it is immediately rinsed in water to remove polishing compound and dried. To protect the surface it could either be brushed with shellac or sprayed with protective cellulose paint (Horne, 1972). Before detaching the lenses from the block, the block is checked for radius, spherecity and surface marks (Twyman, 1988). The lenses are then removed from the block usually by cooling the block in a refrigerator for 20 min in -20^{o}C until the pitch has contracted (Horne, 1972). The lenses are easily pulled from the block and the pitch and left until the frost film has melted and then soaked for an hour in turpentine (Twyman, 1988). Polished lenses should never be left to dry or they will stain, they are instead wiped with a soft cloth (Horne, 1972). Depending on if the second side is still to be treated or not, the lenses are either sent back to be covered with pitch or bathed in methylated spirit and cleaned for final inspection (Twyman, 1988).

3.2.8 Centring, edging and chamfering

After polishing both sides, it is time to reduce the diameter of lens to required specification as well as centring the lenses co-axial with the optical axis.

For normal commercial accuracy, there are two types of methods for centring; conventional which is visually by inspection of the reflected images of the lens and automatically by bell-chuck clamps. In conventional centring, the lens will be centred when being glued on a mandrel. In bell-chuck centring, the floating lens is being aligned between two mandrels (Optic, 2010).

After the alignments have been centred, the lens gets fixed on a chuck so that the outer edges of the lens are grinded in order to get the right diameter. This process is called chamfering or bevelling.

There are some different techniques for this process. The first one, the Taylor-Hobson method by the Taylor-Hobson factory requires very precise and accurate machines. Hand chamfering is a method for chamfering where a negative chamfering tool is used and the operator counts the number of strokes. This is a manual way of centring and chamfering. A third method is the photoelectric centring with exchange spindle. In photoelectric centring is the lens mounted with pitch or wax on a bell chuck that is mounted on a spindle. The lens is centred by tilting it around the curvature until it reaches the centre. This method can be either done manually or automatic (Horne, 1972).

3.2.9 Coating

The coating process consists of a chemical cleaning before the actual coating. The cleaning and the coating processes are described in the subsections below.

3.2.9.1 Cleaning

To begin with, the lens surface to be coated must be free from molecular layers of gas, water or grease to produce god adhesion between the film and the surface (Twyman, 1988). This is usually achieved by a chemical cleaning of the lenses before they enter the vacuum chamber, additionally the lens surface is exposed to ionic bombardment of high-tension glow discharge after the air is pumped out of the chamber (Horne, 1972).

The first stage in the chemical cleaning is to clean off the lens from e.g. shellac, waxes, pitch and resin used in the smoothing and polishing process. These materials are removed by use of detergents such as methylated spirit, alcohol and turpentine. For good adhesion of the coating material, the detergent cleaning should be followed by an isopropyl alcohol treatment. The lenses are first wiped and then placed in a jig where the lenses are held in the ultrasonic and vapour tanks during the treatment. After the iso-propyl alcohol treatment, the lenses usually have a static charge that attracts dust particles. Therefore, the next stage of the cleaning process is to use a static eliminator where ionized air is provided to remove static electricity (Twyman, 1988).

3.2.9.2 Coating

Before the lenses are assembled, some of them require coating to e.g. improve the image contrast. The most common thin films that are manufactured are anti-reflecting coatings, they reduce light absorption which makes optical systems composed of many lenses improve image contrast and avoid ghost images (Horne, 1972). Ghost image is a problem that occurs when light is reflected between the lenses in the optical system, by using coatings these reflections can be reduced thus producing an image with better quality (Ikumo, 2003).

Anti-reflection coatings can be of multiple layers, however about 95 per cent of the lenses have a single-layer coating. The advantage of single-layer coatings over multiple-layer coatings is that glasses of different refractive indexes can be coated simultaneously (Twyman, 1988). The refractive index of a material describes the ratio between the speed of light in vacuum relative to the speed of light in the material (Encyclopedia Britannica, 2011). Other advantages are that the lenses could be coated with the same charge and that the reflectance would never be greater than uncoated glass, even with wrongly chosen thickness of film. The thickness of the film can be controlled to suit the lenses for best optical result (Horne, 1972).

The most usual way to coat glass lenses is to deposit the film by evaporation in vacuum (Twyman, 1988) i.e. heating the metal in a high vacuum to a temperature sufficient to make it evaporate freely (Horne, 1972). In the chamber, the lenses are placed on round racks called planets with the surface to be coated facing down towards the filament (MAJ MEDIA SEC, 2011). The coating material to be deposited is put on or attached to a filament mounted on the base of the chamber. The filament is of tungsten or molybdenum mounted in a suitable shape (Twyman, 1988). When the lenses have been arranged at a certain distance around the coating material, the vacuum chamber is lowered and pumped out. According to the process requirements, the chamber is pumped until a vacuum between 10^{-5} and 10^{-6}Torr (10^{-3}Torr equals 1 Pa) is reached (Horne, 1972). When vacuum has been reached, the filament is heated by an electric current until the coating material, which is in contact with the filament, evaporates. The operator is enabled to warm up the source slowly to prevent blasting the coating material by examining an ammeter. The controlled heating of the coating material makes the vapour molecules spread from the source in all directions. As the chamber contains practically no gas molecules in the way of the vapour, the coating material is spread in straight lines and eventually condensed on any cold surface that collides the path (Twyman, 1988). The condensed vapour forms a film where the thickness is dependent on the duration and rate of evaporation, the geometry of the source and the distance between the filament and the lens surface (Horne, 1972).

Regarding single-layer coating, which is the most common type of coating, the coating material is chosen to match the lens material by use of refractive index. To achieve zero reflectance at the centre wavelength, the coating materials refractive index should be the square root of the lens materials refractive index. Magnesium fluoride is the only material of low refractive index that is mechanically robust and chemically stable, from which films can be made (Horne, 1972). Magnesium fluoride has a refractive index of 1.38 (Corning Incorporated, 2003), since the most common type of optical glass, crown glass, has a refractive index of 1.52 (Encyclopedia Britannica, 2011) magnesium fluoride is a good material to use as a coating material considering reflection reduction (Twyman, 1988).

3.2.10 Optical cementing

In order to minimize chromatic aberration within an optical system where several single lenses have been mounted optical cementing is used. The system of lenses held together with optical cement forms an achromatic lens in order to minimize the chromatic aberration. For best quality, cement is applied before edging, but it is more common to cement after the final lens edging. Clean conditions when assemble cemented lenses are of utter importance (Horne, 1972). There are several types of optical cement, two common characteristics are brittleness and tenacity (Twyman, 1988).

3.2.11 Edge blacking

Edge blacking has two functions, to minimize unwanted inner reflections (flare) and to avoid loss of contrasts in lenses. The edge blacking machine is schematically described as a machine in which the lens is mounted on a spindle with a clamp rotating vertically while paint is being sprayed on the lens (Horne, 1972).

3.2.12 Assembly of lens system

The lenses are assembled in the optical system by a specification made from careful optical design. The spacing between the lenses is very important to prevent aberrations in the image (MAJ MEDIA SEC, 2011). Each lens is carefully checked for dust and wiped with a cloth before they are put in the barrel with the help of tweezers. As the lenses are assembled in the barrel, spacers are put between the lenses to separate them (Horne, 1972). The lens barrel is covered with a lint free material between the installations to avoid dust being trapped in the optical system (MAJ MEDIA SEC, 2011).

3.3 Process mapping

Using process mapping is an effective way to visualize any kind of process. It is often used as a tool for improvement work. There are different types of process maps (Damelio, 1996). For example;

- Relationship map that shows the relationship between customers and suppliers. This type of map gives a good overview but is less detailed. In other words, it does not show the processes between different functions.
- Cross-functional map shows functions, steps or sequence of steps within an organization. This type of mapping shows a medium level detail.
- Flow chart is a detailed mapping on task level. The drawback is that it does not show the customer/supplier relationship.

There are mainly three basic methods to gain the information needed to perform a process map: self-generate, one-on-one interviews and group interviews. Self-generate is a method used when one already knows the process and can draw the map on its own. This method is not very time consuming but on the other hand lays the limitation in how much information one possess. One-on-one interviews is a series of interviews with the participants and together with them draw up the map. Group interview is used when one interviews all the participants as a group to create the map. This method gives a direct interaction (Damelio, 1996).

3.3.1 Value Stream Mapping

Value Stream Mapping (VSM) is a process mapping technique to visualize and understand a process. It has gained rapid acceptance for its ability to gather, analyse and present information that enables all stakeholder in an organization to understand the map. When mapping a process on the manufacturing floor, the focus is on the point of raw material delivery to finished goods shipping. The map contains of three sections; *Production or Process map, Communication or Information flow, Timelines and travel distances* (Poling & Nash, 2008). The symbols used when creating the map can be found in Appendix V.

The purpose of mapping the value stream is amongst others to discover root causes of waste and eliminate these by creating a more lean value stream in the future. The work towards creating a more effective future state starts by analysing the current state in the production (Rother & Shook, 2001).

3.3.1.1 Current state

The first step when performing a mapping of this type is to choose a product family that is to be studied. The narrower the product range is the closer to the actual flow of a product the map will show. The decision of what product family to choose depends on the purpose of the study and what the map will be used for in further studies.

When drawing the map, one should start with focusing on the customer demands. The customer's plant is marked by drawing an outside sources symbol in the top right corner of the map. Below this symbol, a data box is drawn where the customer demands are specified (Jones & Womack, 2002). An example of a current state map is shown in Fig. 9 below.

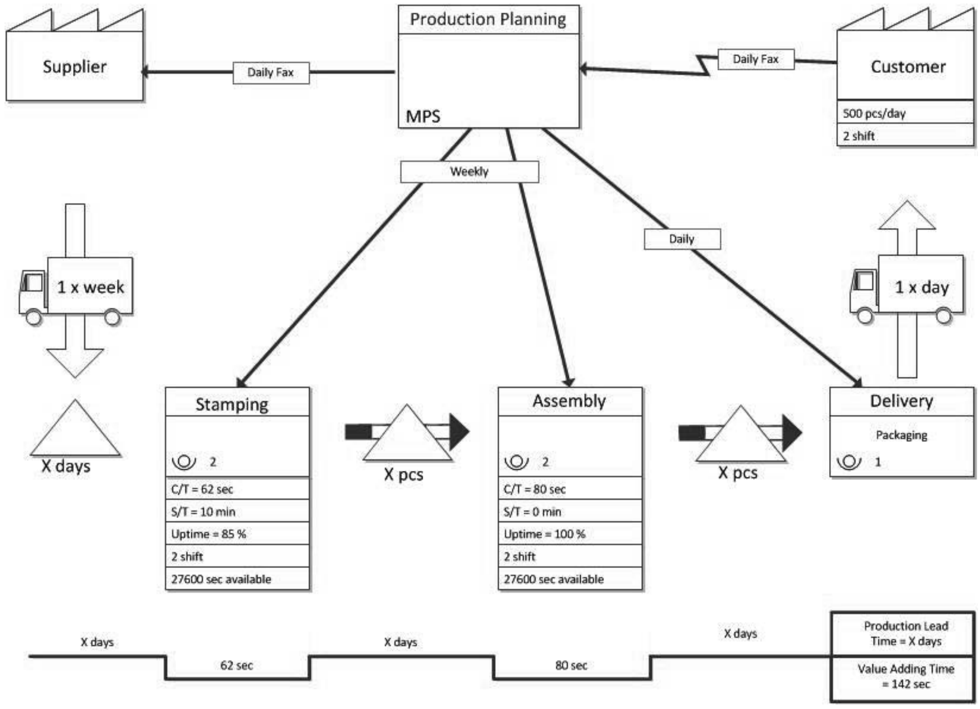


Figure 9 - A schematic current state map adapted from Rother & Shook (2001)

3.3.1.2 Production or Process flow

The production flow contain all process steps from raw material delivery to finished goods shipping. Each step is shown on the map by a process box, the rule of thumb is that the process box represents a process where the material is being treated and value is added. When doing the process walk i.e. walking beside the production flow and mapping each process step, necessary facts should be gathered in a data box below each process box (Rother & Shook, 2001). What information to gather depends on the purpose of the study, some common facts mentioned by Lars Ohlsson[4] in a discussion are summarized below

- Cycle time (C/T) – The time between two outputs from a process
- Value adding time (V/A) – The total time spent in an operation from start to finish
- Setup time (S/T) – The time spent on performing a changeover
- Batch size – The number of parts being processed at once
- Uptime – The percentage of time when the machine/labour is available
- Scrap rate – The percentage of rejected parts

Whilst doing the process walk, places where the material flow stops and is gathered in intermediate buffers should be noted. These buffers are marked in the map as a triangle between two process boxes; the size of the buffer is also noted under the triangle. If there are several buffers between two process steps, each should be noted with size.

---

[4] Interview with Lars Ohlsson, Lean deployment at Volvo Car Corporation

After the last process step, a shipment symbol is drawn with an arrow pointing to the customer. The shipment symbol represents delivery to the customer. The frequency of delivery is also noted on the symbol. In similar way, the supplier of raw material is marked by an outside sources symbol in the top left corner. The delivery frequency is marked in the same way as with the customer, with an additional inventory symbol before the first process step, representing the raw material storage and its size (Rother & Shook, 2001).

3.3.1.3 Communication or Information flow

The communication ways with the customer and the supplier are also marked on the map. The company's production planning is drawn in the centre as a process box, the information flow between each plant is then marked by arrows with labels indicating what type of information is exchanged and whether or not is done electronically. There is also information exchanged between the process steps in the production flow, depending on how orders are trigged at each step, a withdrawal symbol or push arrow is used to indicate the type of material flow (Jones & Womack, 2002).

3.3.1.4 Timelines and Travel distances

When the production flow is mapped, the total lead-time and the value adding time is calculated and visualized by drawing a timeline under the process boxes. The timeline shows the total lead-time from raw material received to final product being delivered to customer (Rother & Shook, 2001).

3.3.1.5 Future state

The goal in the future value stream is to create a flow in the production where all processes are linked, either by a continuous flow or by a pull system. Every process step should to the greatest extent, only produce what is needed in the following process step and exactly when it is needed. When the future state is created, an action plan on how to reach the future state should also be formed, this plan should contain actions on both short and long term (Rother & Shook, 2001).

3.4 Cost calculation

There are several costing models to define the total cost of a product; Activity Based Costing (ABC) is the one used by Volvo Car Corporation. The ABC model will described in the subchapter below.

3.4.1 Activity Based Costing

In modern manufacturing companies, the overhead costs are increasing related to the direct costs. When the share of overhead costs compared to the total costs increases, so does the difficulty of allocating the costs (Skärvad & Olsson, 2011). The advantage of ABC compared to other models is that ABC addresses this problem by allocating the overhead costs more accurate and fits modern manufacturing companies better than traditional costing models (Kullvén et al., 2005).

The basic steps when calculating the cost of a product with ABC are described below as well as in Fig. 10 below:

1) Determine direct costs
2) Determine overhead costs and activities
3) Determine cost drivers for each activity
4) Calculate the activity cost per cost driver
5) Calculate costs for the object

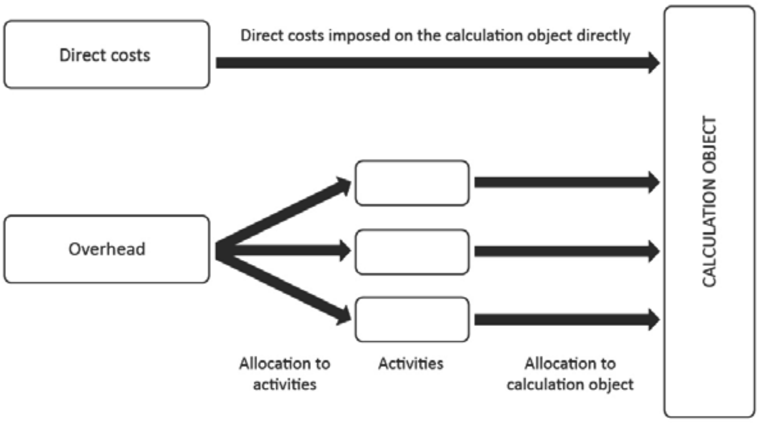


Figure 10 - Model for activity based costing adapted from Kullvén et al. (2005)

3.4.1.1 Activity

The term activity is central in ABC; the whole company is seen to consist of a set of activities where each activity is an assignment or a task. The process of producing a product would e.g. consist of activities such as production planning, purchasing of material, machining, quality control and transport (Kullvén et al., 2005). The goal is to break down the process into as many well defined activities as needed, the more activities there are, the more detailed the cost analysis will be but it would also require more resources to identify the cost of each activity (Lin et al., 2001).

In ABC there are different levels of activities forming a hierarchy of activities (Kullvén et al., 2005):

- Unit-level activities are proportional to the produced volume and can be referred to as volume related activities. Examples of costs related to unit-level activities are material and machining.
- Series-level activities are activities that do not consider the batch size e.g. setup times, quality inspections and production planning.
- Product-level activities are activities that support a specific product and are not related to production volume e.g. product development and product specifications.
- Customer-level activities are activities carried out to support a customer and do not consider number of series and production volume.
- Corporate-level activities are activities that concern the whole company e.g. administration, personnel, security and economy.

3.4.1.2 Cost drivers

The second step is to uncover the costs of the relevant activities that have been identified for the process. This is done by finding a link between the activities and the product, the link is called cost drivers. The resources used for each activity must be identified in order to calculate the cost of each activity related to the product (Lin et al., 2001). The cost drivers can be e.g. transaction related or time related. For the activity of production, planning the number of production orders could be the cost driver whilst for machining the cost driver could be the number of machining hours (Kullvén et al., 2005).

After identifying the activities and cost drivers, the cost per cost driver must be determined. This can be done by dividing the activity cost for a certain cost driver volume by the cost driver volume. When that cost has been determined, the cost driver volume for each activity should be determined and the cost of each activity can be calculated. Summing up the direct costs and the overhead costs, i.e. each activity cost would give the total cost of an object (Kullvén et al., 2005).

4 Analysis and Data collection

The information gathered and analysed in order to present the results is described in this chapter. The chapter is divided into five main subchapters starting with information about VCC's cost model, a product description, description of the assembly process, description of the lens barrel manufacturing process and information about the how cost calculation was executed.

4.1 VCC's cost model

VCC's cost model works according to Fig. 11 below. The total product cost is a sum of three costs. For ingoing components that are procured, a handling charge is added to the procured part cost. The handling charge is a handling charge mark-up percentage of the procured part cost.

For ingoing components that are processed, material overhead (OH), end item scrap, selling, general and administrative expenses (SG&A) and profit are added to the raw and semi-raw material cost. The material OH is a material OH mark-up percentage of the material cost. Further information about calculation of end item scrap, SG&A and profit can be found in Fig. 11 below.

The last part that is added to the total cost of the product is related to the production cost. The labour cost for production is calculated by adding fringe benefit OH and labour related production OH to the direct wage cost. Examples of cost items included in the fringe benefit category are sick leave and health insurance. More information about how fringe benefit OH and production OH are calculated can be read in Fig. 11 below. The machinery cost for production is a sum of the machine cost and the machinery related production OH.

By summing up labour cost of production and machinery cost of production, the production cost is obtained. Finally, end item scrap, SG&A and profit are added to the production cost. The sum of the cost of ingoing components and the cost of production with mark-up gives the total product cost at last. The different items included in the cost categories and the mark-up percentages have been censured according to a confidentiality agreement. The information about VCC's cost model has been retrieved from Christer Larsson.[5]

VCC's cost model uses activities at the unit-level, series-level and corporate-level in the hierarchy of activities in the ABC-model. Furthermore, more than one cost driver is used in VCC's cost model, more information about ABC can read in Chapter 3.4.1.

---

[5] Interview with Christer Larsson, Cost Estimator at TVM/CE at Volvo Car Corporation

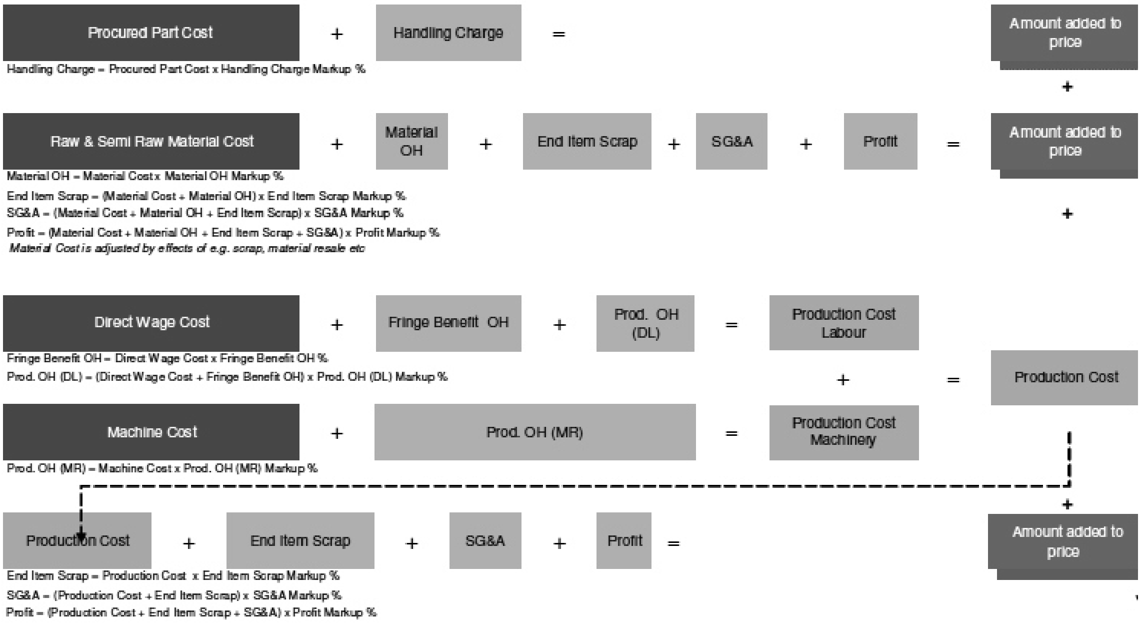


Figure 11 - Visualisation of VCC's cost model with permission from Håkan Bråvi[6]

4.2 Product description

This subchapter is divided into three sections where the FSVC, the CADS3 and the lens barrel assembly are presented. Each section contains of pictures of components and a short description of each component. The subchapter is initiated by a description of the FSVC to understand the process map presented in the following subchapter. The structure of the product descriptions in this subchapter resembles the structure of the process maps in the next subchapter in order to be consequent.

4.2.1 Front Side View Camera

As described in the Chapter 2.1 the FSVC was disassembled for identification of the ingoing components. The components are presented in Fig. 12 and Table 2 below. The casing contains of 2 parts, rear casing (1) and front casing (3), the rear casing has tracks inside used when assembling the product and is made from polyoxymethylene (POM). The PCB (2) also includes an image sensor mounted on top of it and a connector. The lens barrel (4) is put into the front casing, which is also used as a lens holder.

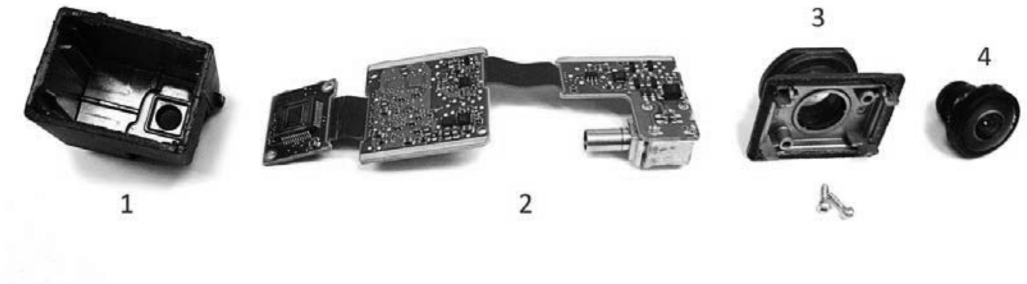


Figure 12 - Disassembly of the FSVC

---

[6] Correspondence with Håkan Bråvi, Senior Manager TVM/CE at Volvo Car Corporation

Table 2 - Components in the FSVC

No.	Part
(1)	Rear case
(2)	PCB with image sensor and connector
(3)	Front case (lens holder)
(4)	Lens barrel

4.2.2 CADS3

The components are presented in Fig. 13 and Table 3 below. The casing of the CADS3 camera contains of two parts, front casing (1) and rear casing (8). The front casing contains of a cable (3) inserted through a hole, a ventilation pad of Gore-Tex (2) and a metal block (4) assembled on top of it. The PCB (6) already has a lens barrel with a lens holder (5) mounted on top of it. Under the optical unit, there is an image sensor mounted on top of the PCB that cannot be seen in Fig. 13.The casing is made out of aluminium cover with a coating treatment. Finally, there is an O-ring (7) assembled between the two casings to seal the product better.

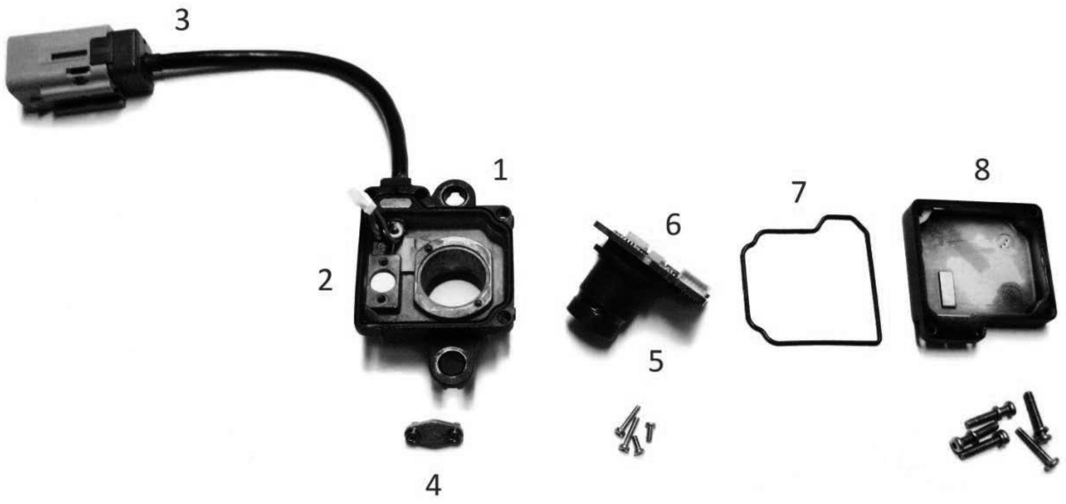


Figure 13 - Disassembly of the CADS3

Table 3 - Components of the CADS3

No.	Part	No.	Part
(1)	Front case	(5)	Lens hold with lens barrel
(2)	Ventilation pad	(6)	PCB
(3)	Cable with connector	(7)	O-ring
(4)	Metal block	(8)	Rear case

Table 4 below presents some measures for specific parts in the CADS3 camera application.

Table 4 - Measures for the CADS3

Part	Measure
Front casing	31,7 x 37,45 mm (w x d)
Back casing	31,7 x 37,45 mm (w x d)
Lens holder	20,0 mm (ø)
Casing	30,42 mm (h)
Cable	105 mm (l)
Total camera weight	90 g

When the camera is received, it contains protective caps made from polyvinyl chloride (PVC) to avoid damage of the product. These components are presented in Fig. 14 and Table 5 below. Protective cap 1 (1) is used to protect the connector and protective cap 2 (2) is used to protect the optical unit from the environment.

Figure 14 - Protective caps

Table 5 - Protective caps

No.	Part
(1)	Protective cap 1
(2)	Protective cap 2

4.2.3 Lens barrel assembly (CADS3)

The components in the lens barrel assembly are presented in Fig. 15 and Table 6 below. The lens barrel (1) is made out of aluminium and surface treated with either black painting or black anodisation. It contains four lenses, lens 1 (2), lens 2 (4), lens 3 (5) and lens 4 (7), an outer lens (9). It also contains three separators; separator 1 (3), separator 2 (6) and separator 3 (8), an O-ring (10) and a barrel-locking ring (11).

The raw material that the lenses are made from is melted silicon dioxide (SiO_2) mixed with minerals e.g. barium oxide (BaO), the actual ingredient list is unique for every manufacturer and an industrial secret. Three of the lenses, lens 1, lens 2 and lens 4 are manufactured in the same way. Lens 3 (5) is also made in a similar way, but has another shape and has also undergone an edge blackening operation. The outer lens has been manufactured following the same process steps as previous but has been chamfered to hold an O-ring, which is made from silicon. The measurement of lens 1 is 6 mm in diameter and the outer lens is 9 mm in diameter, the diameters of other lenses are within these dimensions.

The separators between the lenses are made from aluminium and have been surface treated in the same way as the lens barrel. The same material and surface treatment has also been used for the barrel-locking ring.

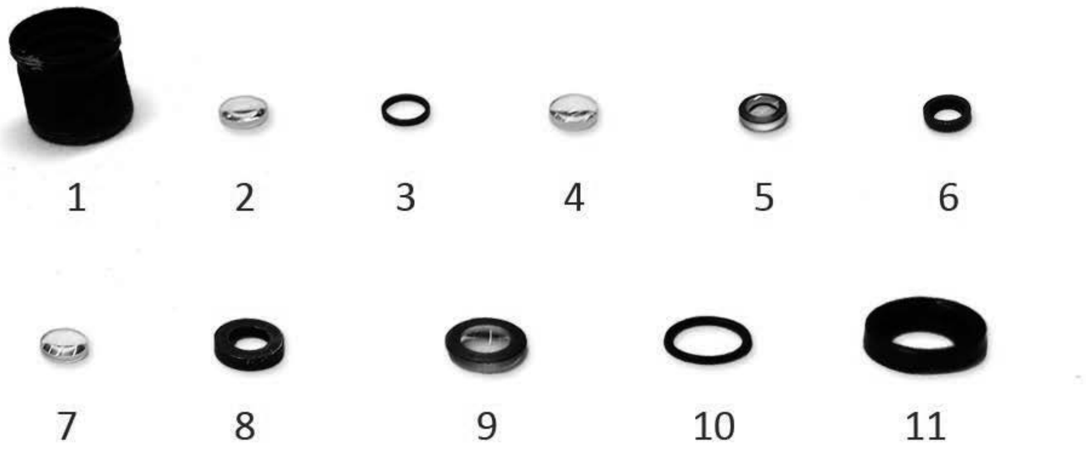


Figure 15 - Lens barrel disassembly

Table 6 - Components of the CADS3 lens barrel assembly

No.	Part	No.	Part
(1)	Lens barrel	(7)	Lens 4
(2)	Lens 1	(8)	Separator 3
(3)	Separator 1	(9)	Outer lens
(4)	Lens 2	(10)	O-ring
(5)	Lens 3	(11)	Barrel-locking ring
(6)	Separator 2		

4.3 Final assembly process of product

As described in Chapter 2.1.2, the process of the final assembly for FSVC was mapped as a substitute for the CADS3 assembly. This is presented in the first section including a brief description of the process map. The section is then followed by process maps of the CADS3 final assembly.

4.3.1 Process mapping of Front Side View Camera (FSVC)

The process map of FSVC is presented in Fig. 16 below. The flow starts with an In Circuit Testing (ICT) of the PCB with an image sensor mounted on top of it; the operator loads the piece in a device where points on the PCB are physically contacted. In parallel with the testing, the operator assembles the lens barrel in to a lens holder and puts it in a device for automatic pre-focusing. In the next step, the PCB is assembled together with the optical unit by screwing the two components together.

When the lens barrel is mounted on top of the image sensor, the piece is ready for adjustment to achieve the best image quality. This is done automatically in a machine with different stations where the piece goes through. The first station it passes is focusing where the optical unit is focused relative the image sensor. The piece is then continued to the adjustment station where the optical unit is adjusted to get the best sharpness. When the image quality is satisfying, the conditions are fixed by gluing the optical unit. In the next station, the piece is exposed to UV- light to harden the glue. The piece is then unloaded and loaded into another machine to fix the screws keeping the optical unit and PCB together, this is done by applying glue on the screws and hardening it by UV-light.

When the components are secured, they are assembled in the rear casing. In this working moment, a moist pad is also added in the rear casing to absorb any possible moist. When the whole piece is assembled together, the rear and front casing are sealed together. To check if the sealing is proper, a leak test is performed automatically. When the leak test is performed, the product is ready for final testing. The operator then loads the product in a fixture and a series of test are performed automatically. If the piece passes the test, a label is printed out, put on the product and then placed in a box for packing.

In the process map below, information regarding cycle times, value adding time, setup times, batch sizes, scrap rate, shifts, operators and machine investments is censured due to confidential agreement with the supplier.

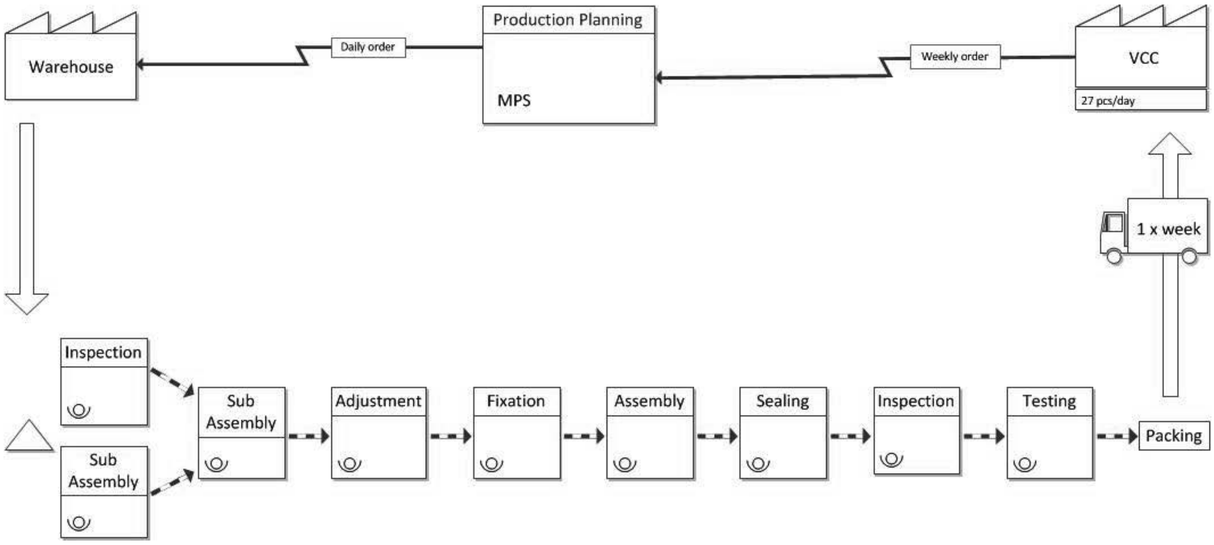


Figure 16 - Process mapping of FSVC's final assembly

4.3.2 Process map of CADS3

This section is divided into two subsections. The first subsection consists of a general process map of the CADS3 final assembly. By combining the information from this subsection and the section above, the last sub section presents a specific assembly process for CADS3 with sufficient data needed to perform a cost calculation.

4.3.2.1 General process map

The process map in Fig. 17 below was created by analysing a document sent from the supplier about the assembly process. The document contained most of the process steps however further information regarding the process was not available.

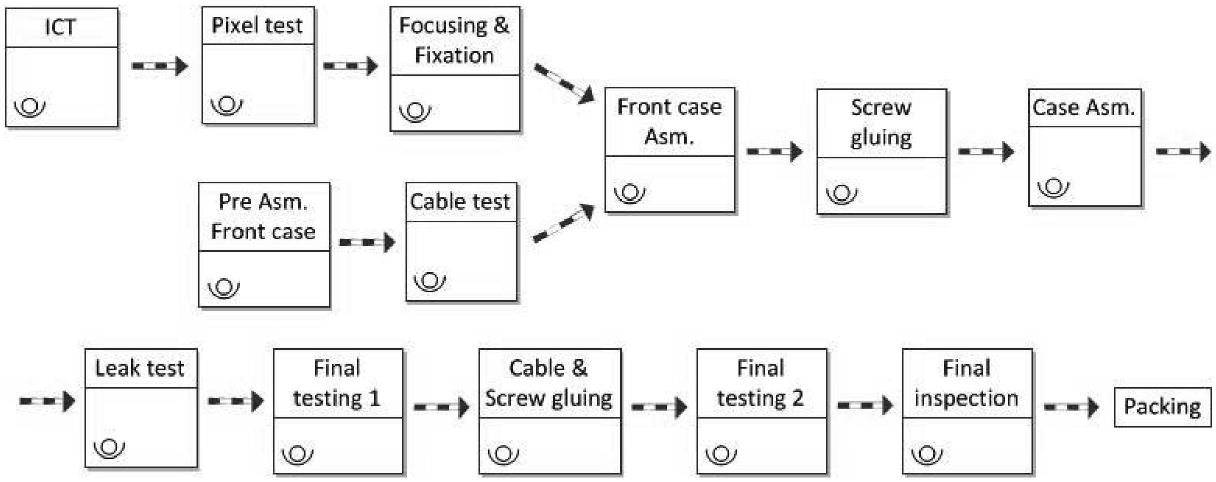


Figure 17 - General CADS3's final assembly process map from supplier

The first process step in the assembly line is an ICT of the PCB. The ICT includes a flash program and an electrical function test. Since the PCB also includes a lens barrel that is mounted on top of an image sensor, the flow continues by having the image sensor tested for dead pixels and spots. When this step is completed, the optics is focused by adjusting the distance between the lenses and the image sensor. When the optics has been focused, the conditions are permanently fixed by dispensing adhesive material and curing this with UV-light.

Whilst PCB and its components are being processed as described above, the assembly of the casing is started in parallel. The first operation is to assemble a ventilation pad and a metal block on to the front casing. After that, the cable is inserted and the casings are temporarily assembled for the next step. When the cable is in position, adhesive material is dispensed for tightening and heat solidification. After this operation, the rear casing is disassembled again. The previous operations are then secured by doing a continuity test and a semi-finished product inspection.

The assembly is then continued by putting an O-ring on to the lens holder and placing the PCB in to the front casing. Finally, the front and rear casing are assembled together by screws. To make sure that the product is tightly assembled, a leak test is performed testing the air-tightness of the product.

When the product is fully assembled, a number of tests are performed to secure the product quality. The first part includes amongst others tests for light brightness, image accuracy, distortion and light source balance. After the first series of tests, adhesive material is dispensed to fix the cable to the casing by UV-light. The second part of tests, which includes testing of the resolution, is then continued. At last, the final product is inspected and labelled.

4.3.2.2 Specific process map

The process map in Fig. 18 below was generated by using the process steps from Chapter 4.3.2.1 and adding the censured process information gathered from Chapter 4.3.1.

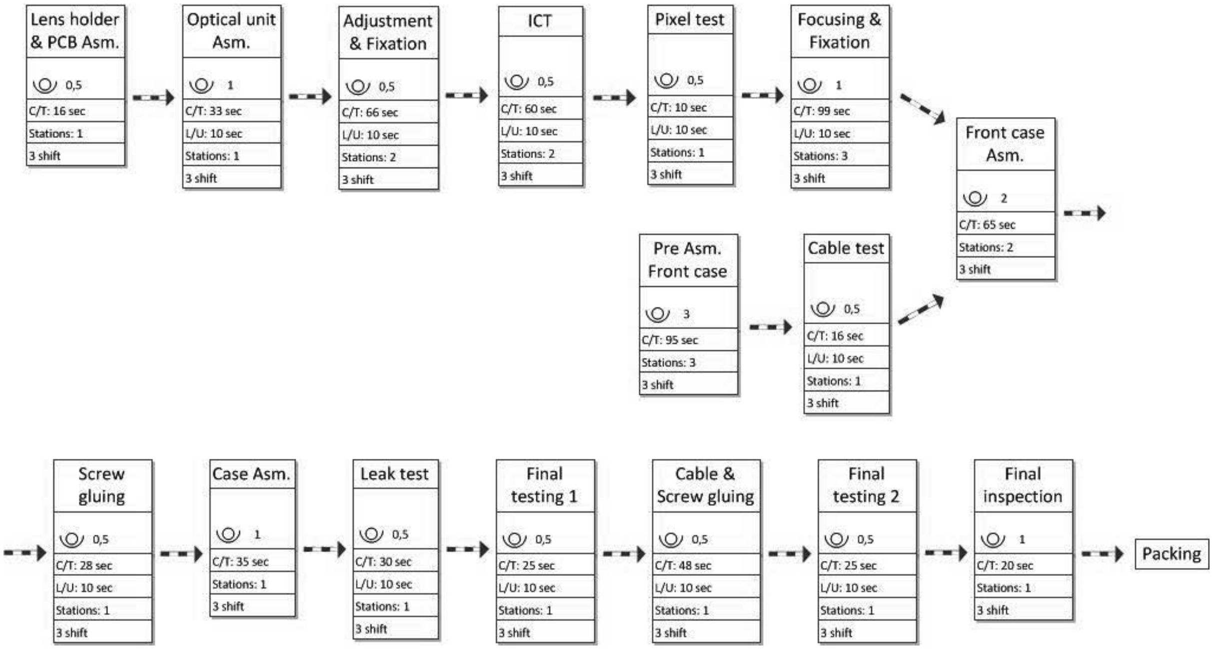


Figure 18 - Specific process map of CADS3's final assembly with data

In Fig. 17 from the previous subchapter, the PCB contains a lens holder when running the ICT. When generating the specific process map for the CADS3 assembly, the process steps to mount the optical unit on to the PCB where included. The first step contains of mounting the lens holder on to the PCB by two thread screws, the lens barrel is then assembled into the lens holder, which makes it an optical unit. Since the lens holder is just screwed on to the PCB, the optical unit is adjusted to the image sensor to improve the image quality. When quality to the specifications has been achieved, the optical unit is fixed to the position on the PCB by gluing the screws and hardening them by UV-light. The process steps after the optical unit has been mounted on to the PCB are the same as described in Chapter 4.3.2.1.

Furthermore, information considering the process like cycle time, load/unload time, setup time and shifts were added to complete the map. The cycle time mentioned in Fig. 18 is the machining time, the load/unload time is the labour time required to operate the machine. Some of the cycle times were obtained by using the censured information from Chapter 4.3.1., this was when the process steps of the assembly of CADS3 and FSVC were similar, most of these steps where performed automatically. Regarding cycle times of manual assembly steps that were not similar to the FSVC, the camera was disassembled and assembled again to specification whilst the steps were being clocked. Information about the load/unload time and setup times were obtained from the censured information in Chapter 4.3.1. When considering the batch size of each station and calculating the cycle times, the cycle times were found to vary a lot. To provide useful information as input for the cost calculation, the cycle times were somewhat evened by adding stations to some steps in the flow thus lowering the cycle times where needed. The information about cycle times and number of stations at each step can be found in Fig 14. Since the assembly line was dedicated to one customer, there were no needs to do changeover hence there was no setup time included in the process map.

When obtaining more evened cycle times, load/unload times and number of stations at each step, the number of operators at each step were estimated. This was done by considering all three factors and assuming that the operator could handle several machines i.e. load/unload one machine whilst the other is running automatically. By estimating the labour needed at each station, the total number of operators In the assembly line were found to be 14.

4.4 Manufacturing process of lens barrel

The manufacturing process of the lens barrel contains of the manufacturing process of lenses and the assembly process of the lens barrel. These activities are described in the sections below.

4.4.1 Lens manufacturing process

The process map with necessary data needed to perform a cost calculation of the lenses is created by using the model in Fig. 2. According to the model, the first subsection presents the schematic model created from the theoretical framework. The second subsection presents the results from a process mapping of a metal lens manufacturer, this was performed in order get more reliable sources of information. This is followed by the third subsection where a document from the supplier regarding general lens manufacturing is described. At last, the specific lens manufacturing process with necessary data needed to perform a cost calculation is presented. Since the manufacturing process differs between the lenses, the process of each individual lens is presented.

4.4.1.1 Process from schematic model

The process map of lens manufacturing in general can be found in Fig.6, it is covered in Chapter 3.2. As mentioned, different paths can be taken regarding processing and treatments to get a final lens; this schematic process map covers all of them. Depending on the purpose of use, lens design and production volumes the lenses are either moulded in forms or trepanned to cylinder shaped in the first stages. After curve generation, the lenses are either mounted on to blocks or processed one by one. When mounting lenses on to a block, material handling increases as the lenses have to be mounted again when processing the other side. However, several lenses are processed at once which gives a lower total cycle time per piece. When polished and smoothed, the lenses are cleaned and inspected. The lenses are then centred and cut to the specified diameter. After that, the treatments of the lenses are performed according to customer specification.

4.4.1.2 Process from metal lens manufacturer

Fig. 19 below describes the result from the process mapping performed at a metal lens manufacturer. The information was collected by observations and interviews with production manager[7].

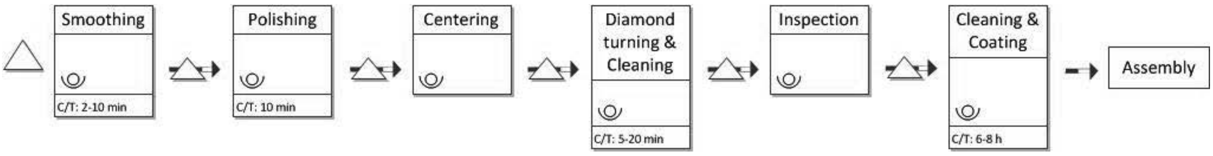


Figure 19 - Process map of metal lens manufacturing

The first inventory in the manufacturing process of silicon and germanium lenses contains of blanks. The blanks are roughly in the same size as the lens specification, to reach the same size; the lenses need to be processed.

In the first process step, which is smoothing, the lenses are grinded finely to specific spherical radius. The coarseness of the tools diamond grains affects the fineness of the lens surface. The process is automatic, however one person is needed to operate the machine, load and unload the lenses. The lenses are processed one by one when both smoothing and polishing.

---

[7] Interview with a production manager at metal lens manufacturing plant

The polishing machines give the lenses a finer surface with polish, this is done automatically but as in the previous step, a worker is needed to operate the machine. After the lenses have been polished, they are cleaned batch wise automatically. When the lens surface is processed, it is centred and excess material is cut if needed.

To reach the specifications of high surface fineness, a diamond tool is used to turn the lens surface. The turning is performed automatically in a machine where lenses are loaded and unloaded one by one. After the diamond turning, the surface of each lens is inspected.

Before the coating procedure, the lenses are cleaned to make the coating attach properly. The coating is performed in a vacuum chamber; the number of lenses loaded into the chamber is dependent on the size of the lenses and the type of fixture that is used. The coated lenses then go through an acid wash and possibly another cleaning procedure. The finished lenses are then stored before continuing to the assembly line.

4.4.1.3 Process map from supplier

Fig. 20 below presents the general process map of lens manufacturing received in a document by personnel communication from a supplier[8].

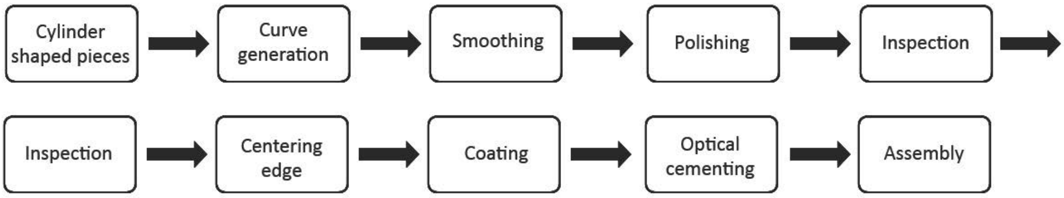


Figure 20 - General process map of lens manufacturing from supplier

The raw material comes in small cylinder shape according to supplier dimensions requirements, from the sub-supplier. At the sub-supplier the melted glass is formed in blocks in sizes of 0.5 m^3. The block is thereafter processed by rolling and cutting to the final small cylinder shape. The small cylinder shape is roughly shaped into the right geometric form of the lens in a curve generating process. The fine grinding operation provides the work piece more accurate geometrics before the polishing process.

The polishing process removes grinding layers and gives the surface a smooth finish. Thereafter inspection is performed so that above operations has fulfilled the specifications regarding transparent and surface regularity. The centring and edging operation centres the work piece and removes the deviation from the centre of the lens.

The optical cementing is done to reduce the loss of reflective lights and to improve the quality of image. It does furthermore simplify the process of complicated parts. In the assembly process, the lenses are mounted in a barrel and fixed to keep the geometric centre line.

4.4.1.4 Specific lens manufacturing process

The information shown in the process boxes of the process maps in Fig. 21, Fig. 22, Fig. 23 and Fig. 24 is gathered from different sources. The machines used in the process have been found by literature studies and by correspondence with lens machine suppliers.

---

[8] Correspondence with lens supplier

Information needed to estimate the cycle times was also retrieved from a correspondence with the lens machine supplier. The data was then compared to data obtained from literature studies to ensure that the information was reliable. The load/unload time of 40 sec was estimated by using literature (Horne, 1972). It considered load/unloading in a grinding operation. However, the handling of the lenses when loading/unloading was similar in many automatic processes since the lenses were assumed to be held by vacuum chucks. This made it possible to generalize the load/unload time to all process steps. The setup times have been estimated in correspondence with a lens machine supplier, they were set to be 5 minutes to configure the computers, additionally 5 min have been added to cover manual changeover steps. Since most of the automatic machines were similar, this information was generalized to cover all process steps. This gave a total setup time of 10 min for each station (Stach, 2011).

The four lenses and the outer lens in the lens barrel are processed in similar ways. The work pieces to be processed to lenses arrive to the supplier in cylinder shapes. The cylinder shapes make up for the first inventory before the curve generating process.

The first process towards shaping the piece into a lens is curve generating machine where the cylinder shapes are milled in order to get a rough shape; the cycle time for this step is 4 min. The curve generation, smoothing and polishing machines are estimated to contain one working spindle, this means that the lenses are processed one by one. Since both sides need to be processed, the cycle times in these stations were doubled, so were the load/unload times since two handling operations are required for each lens.

The smoothing operation refines the surface furthermore. The smoothing operation has a cycle time of 12 minutes for processing both sides. After the polishing operation, the work piece has the shape required by the customer. The cycle time for the polishing operation was estimated to 20 min for processing both sides. The cleaning process right after polishing is needed to remove slurry and other unwanted leftover abrasives from the previous operations. The pieces are cleaned automatically in a machine that has the capacity of processing 72 pcs at the time; this gives a cycle time of 45 sec per piece.

The cleaning is followed by an inspection to ensure that the piece does not contain any residue. The total inspection time during the whole process is estimated to 10 per cent of the total manufacturing time (Horne, 1972).

The centring- and edging operation are similar for all the lenses. The centring operation has a cycle time of 1 min per piece and the edging operation a cycle time of 2 min per piece (Stach, 2011). The following cleaning operation is more thorough than the previous cleaning step. The machines and the cycle time differ giving this cleaning process a cycle time of 50 sec per piece.

All the lenses are treated with anti-reflection coatings; this operation takes 3h per side. However, the chamber can process 80 lenses in the same cycle giving a cycle time of 4.5 min for both sides.

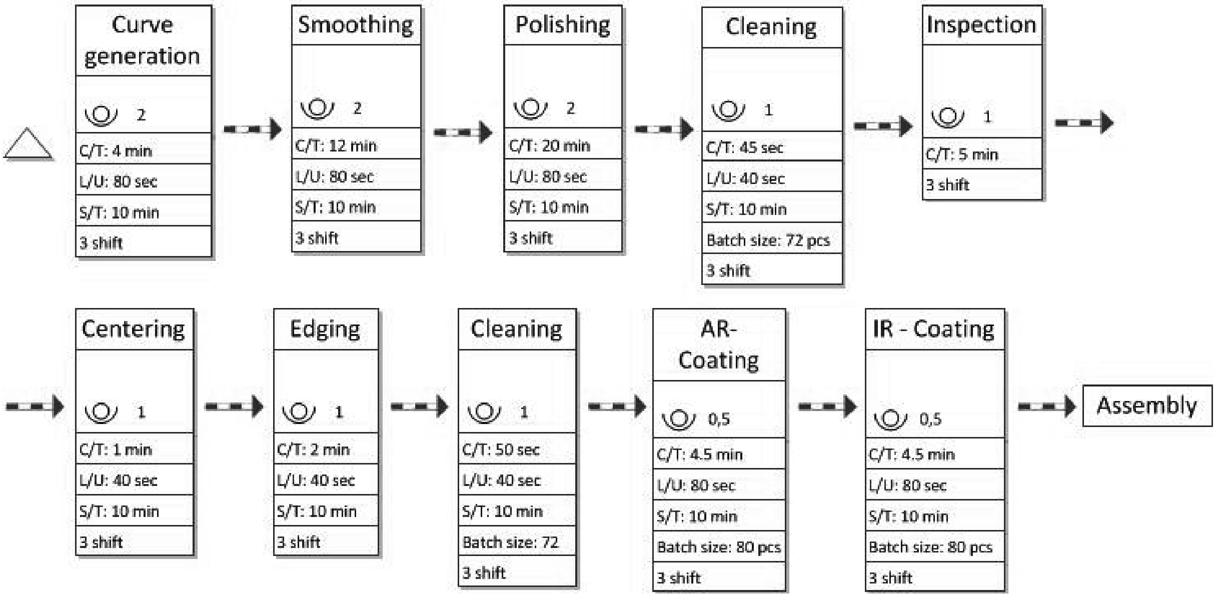


Figure 21 - Specific process map for manufacturing of lens 1 with data

The process map of Lens 1 is presented in Fig. 21 above. It is processed by all the general steps described above, but since this lens is the closest to the imager, it has an additional treatment. The treatment is an IR-reflective coating to improve the image quality. The IR-reflective coating is performed in the same type of chamber as the AR-coating and has the same cycle time as the AR-coating.

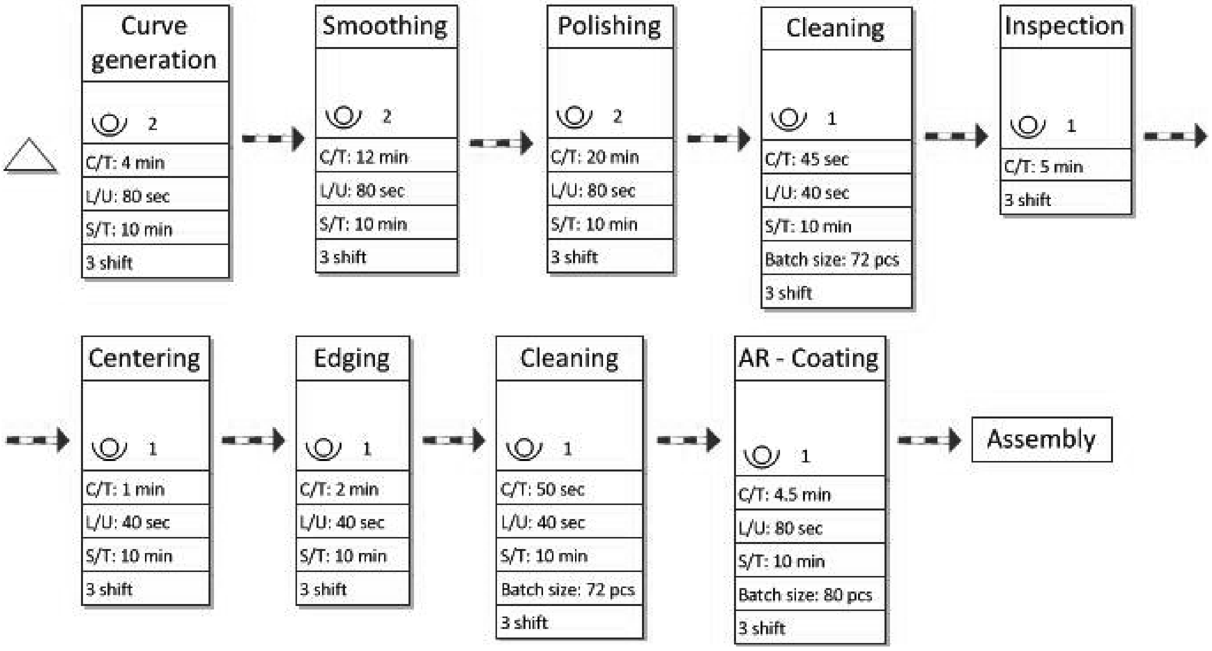


Figure 22 - Specific process map for manufacturing of lens 2 and 4 with data

Lens 2 and lens 4 have identical manufacturing processes; the steps in Fig. 22 are described above where the general steps for all lenses are described. This process map includes fewer steps than rest of the lenses giving these two lenses the shortest processing time.

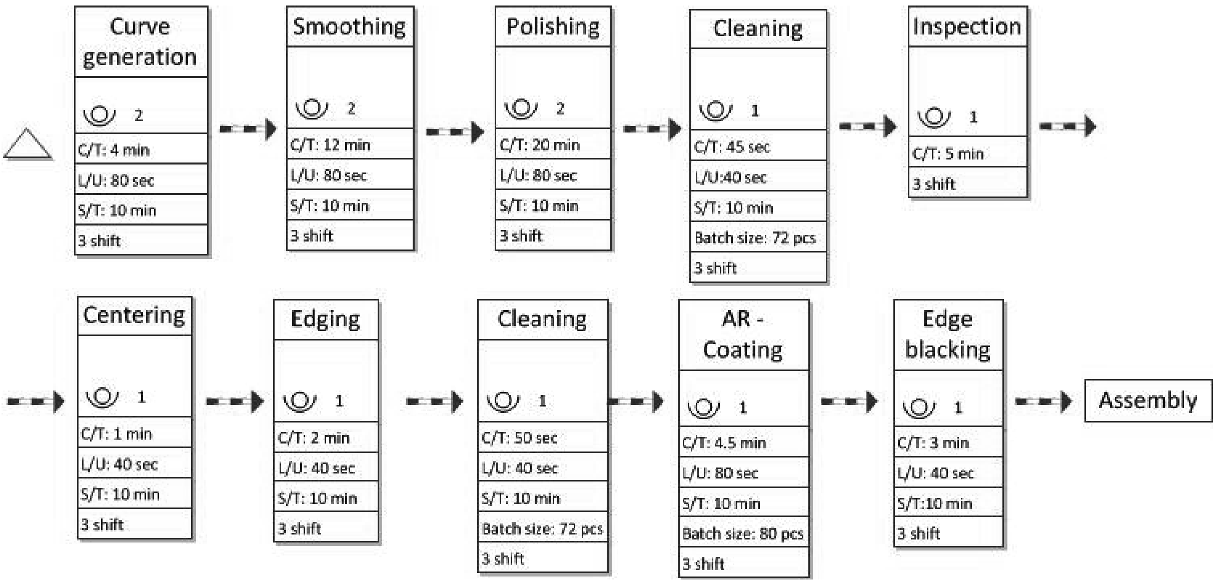


Figure 23 - Specific process map for manufacturing of lens 3 with data

The process map of lens 3 is showed in Fig. 23. Lens 3 includes all the general steps but has an additional edge blackening treatment. This operation is the last one performed and is estimated to have a cycle time of 3 min where dry time for the paint is included.

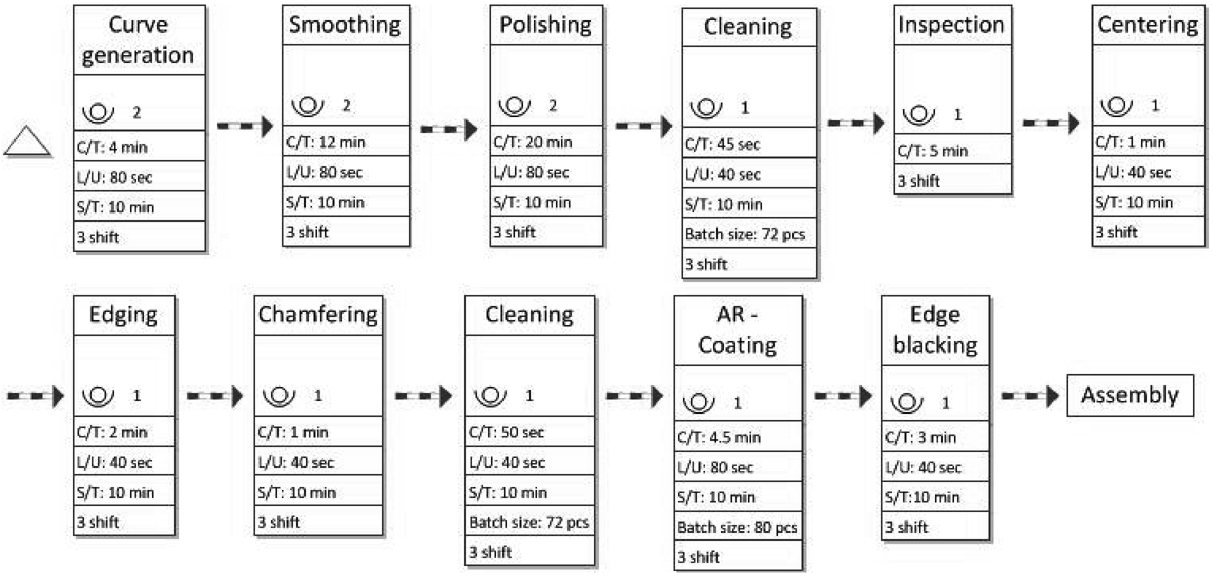


Figure 24 - Specific process map for manufacturing of outer lens with data

The outer lens has a different geometric compared to the other lenses; the process map of this lens is presented in Fig. 24 above. The lens is a convex-concave lens and has a larger diameter. This lens is processed by the general steps but includes a chamfering operation to make tracks where the O-ring is held in the latter assembly process. The cycle time for the chamfering operation is estimated to 1 min. The outer lens is also given an edge blackening as the last process before being finished.

4.4.2 Lens barrel assembly process

Fig. 25 below presents the process map of the lens barrel assembly. This was created by using mainly the literature studies as a source (Chapter 3.2.12) in combination with disassembling the lens barrel. (Chapter 4.2.3)

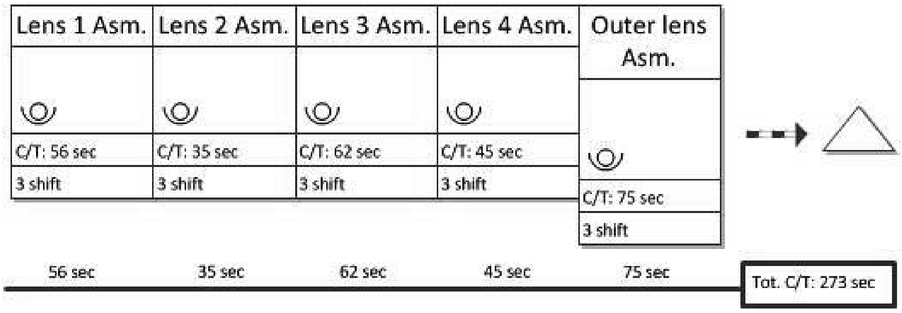


Figure 25 - Specific process map of the lens barrel assembly

The process of lens house assembly has to be performed in an environment where dust and other particles are at a minimum. The reason for this is to have as clear lenses as possible. Before each lens is mounted into the lens barrel, it is inspected manually and possible dust and residue is wiped off. The lenses are then inspected again to see if the lens surface is clean, if not, dust particles could be trapped between the lenses which will affect the image quality .The lenses and the separators are handled by using tweezers to pick them up and hold them whilst inspecting and cleaning. Between all stages in the assembly process, the top of the lens barrel is covered in order to further minimize the risk of trapping dust particles in the between the lenses. One operator at one station performs the whole assembly.

The first lens mounted into the barrel is lens 1 followed by separator 1. The separator's function is to set a pre-calculated distance between the lenses according to the specifications of the optical design.

The next step is to mount lens 2 into the barrel followed by lens 3. After lens 3, separator 2 is placed in the barrel with lens 4 placed over it. Separator 3 is placed on top of lens 4 to get the right spacing to the outer lens.

Before mounting the outer lens into the barrel, an O-ring is put around it. When the outer lens is mounted in the barrel, the unit is secured with a barrel-locking ring with threads that is screwed onto the barrel. Finally, the finished barrel is used in the final assembly of the camera to be assembled with the lens holder. The cycle times in the process map above were obtained by disassembling the lens barrel and then mounting each lens into the barrel again. Whilst the steps were being performed, they were clocked to obtain precise cycle times.

4.5 Cost calculation

The cost calculation was carried out by using VCC's cost model, more information about the cost model can be read in Chapter 4.1.The mark-up percentages are unique for different companies and different within different branches, these percentage are classified with respect to competitors and company strategies. The mark-up percentages for VCC's cost model are censured in this thesis due to confidentiality agreement. The cost to be calculated is a combination of the actual product cost and the expected product cost. This is due to the fact that VCC's cost model uses fixed mark-up percentages that are expected to be maintained by suppliers. However, the input in the cost model e.g. cycle times, machine investment and labour are estimated to be as close to the suppliers present situation as possible. This gives a product cost that could be achieved by the supplier if the process is according to VCC's guidelines. The annual production volume is estimated to 250 000 final products for all the cost calculations.

This chapter is divided into two subchapters, first the cost calculation of all components will be presented and second the assembly activities. This structure follows the method for cost calculation presented in Fig. 3.

4.5.1 Components

In the following subchapters, the cost calculations for all the individual components are to be presented. Each subchapter follows a structure of first presenting their components, which is the Bill Of Material (BOM), and then presenting the activities used to manufacture and assemble the part. Finally, a small description of how the cost model was applied is presented. The description of the components can be found in Chapter 4.2.

4.5.1.1 Casing

Components (BOM)

The casing contains of a front casing, rear casing, a metal block and two screws. The raw material for the casing is aluminium and brass for the metal block. The paint used in the treatment of powder coating of the front and rear case is also included in the calculation as an ingoing component.

Activities (manufacturing)

For the front and rear casing, aluminium is melted and poured into a die, which forms the aluminium to shape in a moulding operation. However, there are differences in the geometrics of the both cases, which makes two different dies necessary. Since the casing is rather small, the material loss is quite high.

Regarding the front case, there is a hole in one of the walls on the side. The hole is for the ingoing cable and is created in the moulding operation.

Both the front case and the back case have undergone a powder coating operation in order to give the cases a protective surface. Additionally there are five holes in both the front- and the rear case used in the final assembly. These tapped holes have been made through drilling.

Cost calculation

The cost model considers the raw materials, ingoing components, the operations needed to manufacture the casing and packing activities.

4.5.1.2 Cable with connector

Components (BOM)

At first, all the components included in the cabling are estimated. These were found to be one contact plug, terminals in each end of the cable and the actual cable. The cost of these components is then estimated by browsing an internal database of standard components. When summing up the cost, a total material cost is acquired.

Activities (manufacturing and assembly)

When material cost is estimated, the cost of the assembly process is estimated in order to get the total product cost. Since some activities are more labour intensive than others, all the activities included in the assembly process are listed regarding their level of automation. This is also how they are categorized in the VCC’s cost model.

The activities included in this process where cutting of cable, cable termination, handling of cables, insertion of terminals into contact plug, handling of contact plug casings, cable shrinking, soldering, testing and finally putting the cable in a box.

Cost calculation

When inserting the activities above needed in the assembly process, standard times for each activity are calculated automatically. It should be mentioned that the activities are categorized regarding level of automation so depending on the activity; either standard machine times and/or standard manual times are calculated. As the cost of all included components are calculated, the total material cost is added to the cost of the assembly process to get the total product cost.

4.5.1.3 Lens holder and lens barrel

Components (BOM)

The ingoing components consist of raw materials used to produce the holder and the barrel. The materials are aluminium and materials for the surface treatment of the pieces. The surface treatment is of either painting or black anodisation.

Activities (manufacturing)

The lens barrel and the holder are both manufactured in the same way. The process starts with an aluminium piece being processed in an automatic turning machine to specification. When the piece has acquired the right geometrics, the pieces are exposed to surface treatment as a finish.

Cost calculation

The input for the cost model is the ingoing components, material cost and processing times. Since the process is mainly automatic, this is considered when applying the input in the cost model.

4.5.1.4 PCB with image sensor

Components (BOM)

The PCB contains of both standard and custom components. The standard components are:

- Image sensor with a resolution of 6 mega pixels
- Crystal (used to generate precise frequencies)
- Tantalum capacitors (used to store and release electrical charge)
- Passive components (capacitors and resistors)
- 6 layer board

The components that are specified according to customer requirements are;

- Field Programmable Gate Array (FPGA)
- Discrete semi-conductors (Transistors and diodes)
- Semi-conductors

Activities (manufacturing and assembly)

The mounting of the PCB is completely automated and performed in a Surface-mount Technology (SMT) line. The different components to be mounted on the board are loaded on to the machine, the board then goes through different chambers where different components are mounted and soldered on according to specification. Additionally an Automated Optical Inspection (AOI) is performed in-line finishing off with an ICT.

Cost calculation

The cost is calculated for the PCB only and not for the optical unit assembled on to it. Since the FPGA is a customer specific component, an estimated development cost is added to the component cost. All the ingoing components are added to the cost of the board, the activities to mount the board and the tests are considered to get the total cost of the PCB.

4.5.1.5 Protective caps

Components (BOM)

The ingoing material for the protective cap is Polyvinyl chloride (PVC) and a release agent.

Activities (manufacturing)

The manufacturing of the caps starts by putting release agent on a thin sheet of plastic. The sheet is then mounted to a cold die where the plastic will form around the die when sunk into liquid for final forming and fixation.

Cost calculation

The cost model is applied by considering the raw material and the specially designed dies and machining costs.

4.5.1.6 Small components

- Screws – made from steel with standardized size
- Separators – made from aluminium with a surface treatment
- Barrel-locking ring – made from aluminium with a surface treatment
- O-rings – made from silicon

These components are either standard components or manufactured with a minimum of operations. However, they are made in large quantities with a production volume of from a quarter of a million or more. The costs for these components have not been calculated using the cost model but estimated by experts at the TVM/CE unit.

4.5.1.7 Lenses

Components (BOM)

The ingoing materials for the processing of lenses are cylinder shapes delivered from a sub supplier. The cost of the ingoing material made of glass is estimated with the assumption of one cutting operation where 16 cylinder shapes are cut out from 1 dm^2 plate of glass. The abrasives used in the polishing and smoothing operations are automatically included in the cost model, however materials for coating and edge blackening have been neglected due to its relatively low cost compared to the total cost.

Activities (manufacturing)

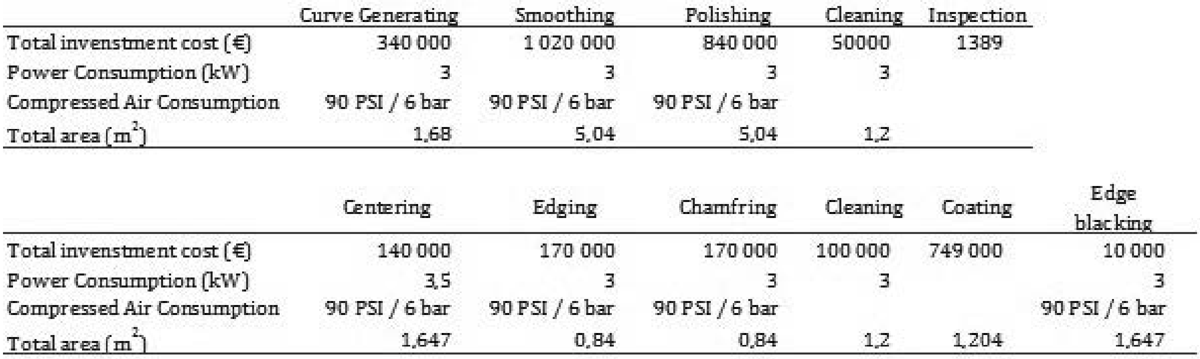
Most lenses in the optical unit have unique specifications and manufacturing processes. The process steps for each lens are described more in detail in Chapter 4.4.1. Process information like cycle times, load/unload times, number of operators and setup times are estimated in the process maps that are presented in the same chapter. The number of operators needed at each step is also presented in these process maps. It was estimated by taking the load/unload time and the number of machines at each step in consideration. The principle that one operator could operate several machines was considered when creating the process map.

Cost calculation

The input in the cost model was amongst others raw material and processing times for all the activities in the manufacturing process. Investment cost for machinery was also included; these were estimated from retrieved information in correspondence with a lens machine supplier. By looking at the process steps, the lens diameter and the annual production volume, appropriate machines were chosen and cost estimated from all the retrieved data.

Since the whole manufacturing is highly automated, information about power consumption, compressed air consumption and the total area for each process step were needed to complement the cost model. In correspondence with a lens machine supplier[9], these factors were estimated when the machines had been estimated. The total area needed for each process step was estimated considering number of machines needed at each step. Table 7 below summarizes the input in the cost model.

Table 7 - Information for the machinery of lens manufacturing retrieved from lens machine supplier[8]



	Curve Generating	Smoothing	Polishing	Cleaning	Inspection
Total investment cost (€)	340 000	1 020 000	840 000	50000	1389
Power Consumption (kW)	3	3	3	3	
Compressed Air Consumption	90 PSI / 6 bar	90 PSI / 6 bar	90 PSI / 6 bar		
Total area (m^2)	1,68	5,04	5,04	1,2	

	Centering	Edging	Chamfring	Cleaning	Coating	Edge blacking
Total investment cost (€)	140 000	170 000	170 000	100 000	749 000	10 000
Power Consumption (kW)	3,5	3	3	3		3
Compressed Air Consumption	90 PSI / 6 bar	90 PSI / 6 bar	90 PSI / 6 bar			90 PSI / 6 bar
Total area (m^2)	1,647	0,84	0,84	1,2	1,204	1,647

4.5.2 Assembly processes

According to the method for cost calculation presented in Fig. 3, there were two assemblies needed to calculate the cost for in order to retrieve a total cost for the product. The cost calculations of these two assemblies are described in the subchapter below.

4.5.2.1 Lens barrel assembly

Components (BOM)

The ingoing components for the lens barrel assembly were calculated beforehand. The components were a barrel, four lenses, one outer lens, three separators, one O-ring and a barrel-locking ring. The description of the cost calculation of these components can be found in Chapter 4.4.2.

Activities (assembly)

The process steps to assemble a lens barrel are described in Chapter 4.4.2. As mentioned, the process steps are manual and performed by one operator per station. The assembly is rather time consuming since there is a high level of cleanliness and inspection of each lens before mounting it into the barrel. In the estimated cycle times, it is assumed that the material needed for the assembly is present at each station.

Cost calculation

The inputs for the cost model were the ingoing components and the labour needed to assemble the barrel. The labour needed was calculated by using the cycle times. The cost was calculated for each individual step in the assembly, the total cost was then retrieved by summing up all the steps. The investment for this line was 50 000 SEK per station, with five stations this gave a total of 28 000 €. This amount includes assembly stations with necessary equipment such as water and electricity. The total area needed for the lens barrel assembly was estimated to 100 m^2; this was done by considering the size of the assembly stations.

---

[9] Correspondence with a sales manager at a lens machine supplier

4.5.2.2 Final assembly of product

Components (BOM)

The components included in the CADS3 can be seen in Fig. 13. The cost of these components had been calculated before the cost of the final assembly was calculated. The description of the cost calculation of these components can be read in Chapter 4.5.1.

Activities (assembly)

The process map for the whole CADS3 assembly with including description can be seen in Chapter 4.3.2.2. Since this is an assembly line and not considered as a batch production, the cycle times in the assembly line were evened by adding extra station where needed to lower the cycle time. After obtaining evened cycle times in the line, there were 14 operators in total estimated to run the final assembly. This was estimated by assuming that operators could work in parallel and only needed for load/unload when machines were running automatically.

Cost calculation

When calculating the cost of the final assembly, the whole assembly line was considered as one station since the cycle times were somewhat even. This was carried out by using an average cycle time of 36 sec, a total of 14 operators and the total machine investment in the line. The investment for each step can be seen in Table 8 below. Further information about the machines was not needed as the assembly process has a low degree of automation. The summed up information about the investment and number of operators was then used as input to the cost model instead of calculating the cost for each process step.

Table 8 - Investment cost for CADS3's final assembly

	Lens holder & PCB Asm.	Optical unit asm.	Adjustment & Fixation	ICT	Pixel Testing	Focusing & Fixation	Pre Asm. Front case	Cable test
Investment cost (€)	5 556	10 000	150 000	200 000	15 000	150 000	5 556	15 000

	Front case Asm.	Screw gluing	Case Asm.	Leak test	Final testing 1	Cable & screw gluing	Final testing 2	Final Inspection
Investment cost (€)	5 556	10 000	5 556	10 000	200 000	10 000	200 000	5 556

.

5 Results

The results from the cost calculations in the previous chapter is presented in Table 9 below. It can be seen that the cost of lenses cover about three quarters of the total cost. The second highest cost item is the PCB with image senor, it covers about one fifth of the total cost. These two cost items cover roughly 90 per cent of the total cost.

Table 9 - Cost items for CADS3

Description	Quantity	Unit cost	Cost	Distribution
Camera asm.	1	1,357 €	1,357 €	1,89%
Front casing	1	0,483 €	0,483 €	0,67%
Back casing	1	0,325 €	0,325 €	0,45%
Cable with connector	1	2,215 €	2,215 €	3,08%
Lens holder	1	0,820 €	0,820 €	1,14%
PCB with image sensor	1	13,246 €	13,246 €	18,44%
Casing O-ring	1	0,010 €	0,010 €	0,01%
Screws	7	0,010 €	0,073 €	0,10%
Protective caps	2	0,016 €	0,031 €	0,04%
Lens barrel asm.	1	0,369 €	0,369 €	0,51%
Lenses	1	51,913 €	51,913 €	72,25%
Separators	3	0,052 €	0,157 €	0,22%
Lens barrel O-ring	1	0,005 €	0,005 €	0,01%
Lens Barrel	1	0,793 €	0,793 €	1,10%
Barrel-locking ring	1	0,052 €	0,052 €	0,07%
		Total	71,851 €	100,00%

The components included in the CADS3 are:

- Front casing – Cost calculation found in Chapter 4.5.1.1
- Back casing - Cost calculation found in Chapter 4.5.1.1
- Cable with connector- Cost calculation found in Chapter 4.5.1.2
- Lens holder - Cost calculation found in Chapter 4.5.1.3
- PCB with image sensor - Cost calculation found in Chapter 4.5.1.4
- O-rings - Cost calculation found in Chapter 4.5.1.6
- Screws - Cost calculation found in Chapter 4.5.1.6
- Protective caps - Cost calculation found in Chapter 4.5.1.5
- Lenses - Cost calculation found in Chapter 4.5.1.7
- Separators - Cost calculation found in Chapter 4.5.1.6
- Lens barrel - Cost calculation found in Chapter 4.5.1.3
- Barrel-locking ring - Cost calculation found in Chapter 4.5.1.6

The activities are:

- Camera assembly - Cost calculation found in Chapter 4.5.2.2
- Lens barrel assembly - Cost calculation found in Chapter 4.5.2.1

The two subchapters below describe the cost items in more detail.

5.1 Lens barrel assembly

The activity of lens barrel assembly consists of mounting the lenses and separators into a lens barrel and securing it with a barrel-locking ring. The item of highest cost of all the components were the lenses, the cost of each individual lens is presented in Table 10 below.

Table 10 - Cost items for lenses in CADS3

Item	Cost
Lens 1	10,39 €
Lens 2	10,15 €
Lens 3	10,39 €
Lens 4	10,15 €
Outer Lens	10,84 €
Total	51,91 €

As described in Chapter 4.4.1.4, lens 2 and lens 4 are manufactured with the least number of operations; this is reflected on the cost of these lenses, which is the lowest of all five. The outer lens is the one manufactured with most process steps, it has an additional edge blackening and chamfering operation compared to lens 2 and 4, this is also reflected in the cost which is the highest of all the lenses.

When comparing lens 1 with lens 2, it can be seen that the cost of one extra coating for lens 1 was 0,236 €. It should be noted that even though coating materials are very expensive, e.g. 3 €/g for magnesium fluoride (MgF_2) (Goodfellow Cambridge Ltd., 2011) they do not have a great impact on the overall cost since the thickness of coating is around 7-10 nm according to the production manager at a metal lens manufacturing plant[10]. The machinery cost however have greater impacts on the total cost since the process time is rather long compared to the other machines in the lens manufacturing process.

In Fig. 26 below, the distribution per process of the total cost for manufacturing lens 1 is presented. The figure below also describes the accumulated percentage of the total cost distribution between the processes. Since lens 1 contains of an additional coating, the total cost of coating makes up for 34 % of the total manufacturing cost for this lens. This is due to the longer process time when two coatings are applied.

It can also be seen that the polishing process is the most costly individual operation of them all; it makes up for 26% of the total cost. Referring to Fig. 21 it can be seen that the process time for the polishing is 8 min longer than smoothing, this is directly reflected in the distribution of the total cost since the machinery for both processes is very similar. The investment cost for the machinery is presented in Table 7.

The cumulated graph in Fig. 26 shows that the costs of cleaning, inspection, centring, edging and chemical cleaning are rather low compared to how the cost increases for the other processes. In Fig. 21 it can be seen that the process times for these operations are lower compared to the other operations, this is the reason for why the costs are a lower part of the total cost.

There is an uncertainty of the calculated lens cost since the input data was estimated in discussion with experts at the TVM/CE unit. Depending on choice of machines and relevant process information, the calculated cost could differ for each lens. However, the calculated costs are not completely unacceptable since the sources from which data was gathered are reliable.

---

[10] Interview with the production manager at a metal lens manufacturing plant

Operation	Distribution Lens 1
Curve generating	9%
Smoothing	18%
Polishing	26%
Cleaning	1%
Inspection	3%
Centring	3%
Edging	4%
Chemical cleaning	2%
AR coating	17%
IR coating	17%
Sum	100%

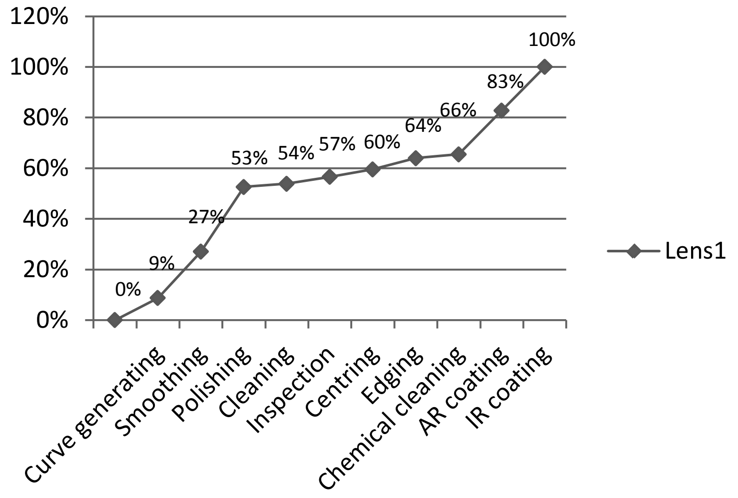


Figure 26 - Distribution of cost per operation step for lens 1

Fig. 27 below describes the distribution of the total cost of manufacturing the outer lens, this is the lens with the most process steps of them all. The same figure shows the cumulated distribution of cost between the operations. Like the case with lens 1, the polishing is the most costly operation for the outer lens as well, followed by the smoothing operation. These are the processes with the highest investment costs referring to Table 7 and the highest process times referring to Fig. 24.

The AR-coating is the third most costly operation, even though the process times are rather similar to the curve generating process, the distribution of cost differ greatly between these two operations. The reason is the large difference between investment cost of the machinery where the coating operation has nearly the double the cost compared to the curve generating machinery. More details about the investment can be read in Table 7.

Operation	Distribution Outer lens
Curve generating	10%
Smoothing	21%
Polishing	29%
Cleaning	1%
Inspection	3%
Centring	3%
Edging	5%
Chamfring	4%
Chemical cleaning	2%
AR coating	20%
Edge blacking	2%
Sum	100%

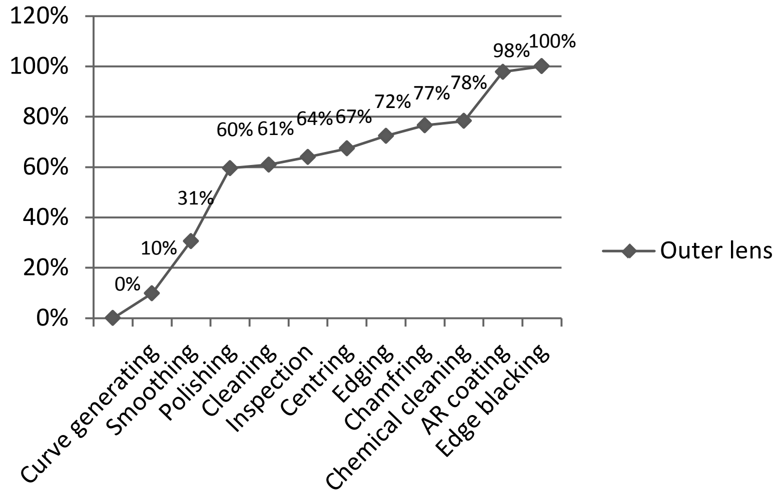


Figure 27 - Distribution of cost per operation step for outer lens

The cost of the assembly of the barrel is very low compared to the costs of ingoing components. This is because the assembly is mainly manual which is beneficial in low labour cost countries. Since the barrel assembly is dedicated to the customer, there are no setup times where the assembly line stops.

5.2 CADS3 Assembly

When building up the costs according to Chapter 4.3.2.2, the greatest costs add up early in the assembly process. This is visualized in Fig. 28 below; it shows both the individual distribution and the cumulative build up distribution.

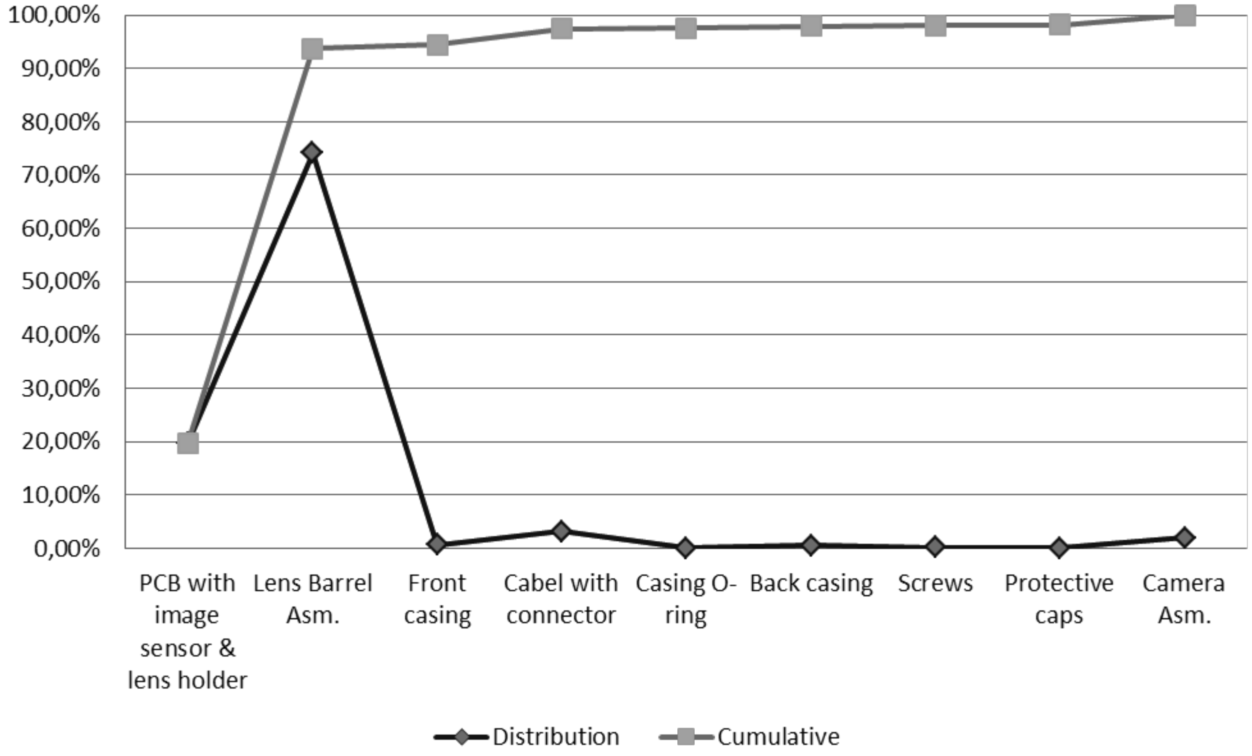


Figure 28 - Distribution of cost items for CADS3's final assembly

The cost of the final assembly makes up for approximately 2% of the total cost, which is very low. This is because the process steps in the final assembly are mostly manual which is beneficial in a country with low labour cost. By having many manual process steps, the total cost can be kept low which gives fewer reasons to increase the degree of automation.

The PCB with image sensor constitute for the second highest cost of all the components. The reason for this are several, one is that other components are made with a simpler manufacturing process compared to the PCB and the image sensor. Another reason is that the PCB and image sensor contain of many ingoing components of which some are custom made, the image sensor is of a fairly high resolution compared to similar camera applications, this also contributes to the higher cost.

The cable with connector has a cost of 2,22 €, when comparing this cost to the other components it should be noted that the connector contains many ingoing components. This in combination with both manual and automatic assembly of the cable and connector constitutes for the cost.

Other components like the casing, O-rings, separators, and the lens holder are of lower cost due to the fact that they involve less process steps and ingoing components. One must also keep in mind that the total assembly only weights 90 grams so the material need for one component is quite small. Most of these components are standard and not custom made; this means that the production volume is rather high enabling to use appropriate machines for this type of production.

6 Discussion

The working procedure for the thesis was well formulated and helpful when executing the work. There was a natural transfer between the different phases where the information was sufficient enough to continue the next phase. The models for how to execute the work within each phase helped avoiding deviation from the purpose and communicate the working procedure to concerned parties. By having models for each phase, the writing of the report was eased since the chapters and subchapter could be defined by the help of the models. The different methods of collecting data was helpful when creating the process maps, all the methods described in Chapter 2 were used in this phase. By including many sources in the models of the different phases, the data gathered became more useful and reliable since there was a possibility of comparing the different sources to each other.

The theoretical framework was started by introducing some general facts about motion cameras. This information was gained when trying to understand the product and the functions of the different components in the product. This was necessary in order to further understand the importance and manufacturing process of each component.

The main part of the theoretical framework was to provide a knowledge base for the whole analysis of lens manufacturing. This was successfully achieved since the schematic model presented in the theoretical framework for lens manufacturing was very well applicable for the lenses that were to be analysed in this thesis. It was used as a base when comparing the data gathered from different sources when creating process maps.

Since the report included many visual process maps that followed the same structure, it was necessary to provide some basic information about process mapping. This knowledge was used when doing process maps by observation and then visualizing the process by presented only necessary facts.

A big part of the thesis was to calculate the cost of the product. Since some parts of VCC's cost model were censured, the general information about cost calculation from theoretical framework was useful as a support when understanding how VCC's cost model works.

By following the structure of the working procedure, the chapter where analysis was presented was started with a presentation of the different components. Since the FSVC was chosen as a substitute for mapping the assembly process, its components were also presented to provide the reader with a clearer picture of why this product was chosen to be mapped. By using the information gained from the process mapping, a detailed map of the CADS3 assembly could be created. The process steps were very similar between the different camera applications and where information was missing from the document received from the CADS3 supplier regarding its final assembly, assumptions was made by experience from the observations.

When receiving the document with a general lens manufacturing description from the supplier, it was verified by comparing it to the schematic model presented in Fig. 6 and complemented by using the information from the theoretical framework. The document was also questioned by inspecting the lenses to see what process steps were involved in each lens. Since observations had been made at a metal lens manufacturer, all the different sources combined made the final lens manufacturing process with data more reliable. The information was complemented by correspondence with lens machine suppliers; this made the data regarding machine types, cycle times and investment costs more reliable. To be able to present interesting results, the cost of each individual operation in the lens manufacturing process was calculated. This gave the opportunity to provide the cost for each individual lens.

When presenting the total cost of the product, graphs were plotted in order to motivate the cost of each item in a relevant way. By referring to the analysis chapter, each cost could be motivated by the input data. The distribution of the total cost between the components was found to be interesting since the lenses made up for a larger percentage of the total cost than expected. This brings the importance of further work in research in lens manufacturing for more data that are accurate and process improvements in order to reduce the cost for the product.

7 Conclusion

This thesis states that camera applications with optics and integrated electronics can be cost calculated as any other product. Moreover, the way to do this is to separate all individual components and perform a research in how they are manufactured as well as how they all are connected to each other. When doing so, the total product cost was found to be 71,85 €.

The contribution that this thesis will have is first and foremost to visualise the process map of lens manufacturing with each individual step and provide detailed information about each operation. Furthermore, a presentation of how the cost items build up for the camera application also contributes with valuable information regarding the cost of the product.

In this thesis, cost calculations for the lens manufacturing have been based on lens manufacturing machines from two suppliers. A good idea would be to further investigate other types of lens machines to get a range of variety. Furthermore, machines for high/low production and of different level of automation should be investigated to get more understanding of the manufacturing process.

The result showed how the costs build up in the final assembly line; the value of a Work In Progress (WIP) was found to be very high from the beginning. This should be taken in consideration by keeping the buffer sizes to a minimum throughout the whole assembly process in order to reduce costs.

The distribution of costs showed that the lenses constituted for approximately 72 % of the total product cost. This shows the importance of further research within optical manufacturing and the need to review product requirements and specifications concerning the optical system. By doing so, other materials and manufacturing methods could be considered to keep the total product cost low.

8 Bibliography

Canon Inc., 2011. [Online] Available at: http://www.canon.com/camera-museum/tech/l_plant/ [Accessed 26 january 2011].

Christiansson, F. & Rondell, M., 2006. *DV - ett revolutionerande format*. C-uppsats. Stockholm: KTH CSC Kungliga Tekniska Högskolan.

Corning Incorporated, 2003. *Magnesium Flouride MgF2 Physical and Chemical Properties*. [Online] Corning Incorporated Available at: http://www.corning.com/docs/specialtymaterials/pisheets/H0607_MgF2_Product_Sheet.pdf [Accessed 4 March 2011].

Damelio, R., 1996. *THe Basics of Process Mapping*. Chicago: Productivity Press.

Encyclopedia Britannica, 2011. *Refractive Index*. [Online] Ecyclopedia Britannica Available at: http://www.britannica.com/EBchecked/topic/495677/refractive-index [Accessed 4 March 2011].

Fynn, G.W. & Powell, W.J.A., 1988. *Cutting and Polishing Optical and Electronic Materials*. Second ed. IOP Publishing Ltd.

Goodfellow Cambridge Ltd., 2011. *GoodFellow*. [Online] Available at: http://www.goodfellow.com/E/Magnesium-Fluoride-Lump.html [Accessed 20 May 2011].

Hicks, R. & Schultz, F., 1994. *The Lens Book*. Newton Abbot, Devon: David & Charles.

Horne, D.F., 1972. *Optical production technology*. London: Adam Hilger Ltd.

HowStuffWorks Inc., 2011. *HowStuffWorks Inc.* [Online] Available at: http://electronics.howstuffworks.com/cameras-photography/digital/question362.htm [Accessed 3 may 2011].

Ikumo, T., 2003. *The Basics of Camera Technology*. Sony Corporation.

Jones, D. & Womack, J., 2002. *Seeing the Whole - Mapping the Extended Value Stream*. Brookline, Massachusetts, USA: The Lean Entreprise Institute.

Karow, H.H., 2004. *Fabrication methods for precision optics*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Kullvén, H., Ax, C. & Johansson, C., 2005. *Den nya ekonomistyrningen*. 3rd ed. Sverige: Liber.

Lin, B., Collins, J. & Su, R.K., 2001. Supply chain costing: an activity-based perspective. *International Journal of Physical Distribution & Logistics Management*, 31(10), pp.702-13.

MAJ MEDIA SEC, 2011. *How It's made*. [Online] Available at: http://www.metacafe.com/watch/1059892/how_its_made_camera_lens/ [Accessed 11 January 2011].

Nationalencyklopedin, 2011. *www.ne.se*. [Online] Available at: http://www.ne.se.proxy.lib.chalmers.se/enkel/kamera [Accessed 28 February 2011].

Nationalencyklopedin, 2011. *www.ne.se*. [Online] Available at: http://www.ne.se.proxy.lib.chalmers.se/avbildningsfel/kromatisk-aberration [Accessed 28 February 2011].

Optic, S., 2010. *Swiss Optic*. [Online] Available at: http://www.swissoptic.com/htdocs_en/company/spherical_optics.html [Accessed 28 March 2011].

Phillips, P.P. & Stawarski, C.A., 2008. *Data Collection: Planning for and Collecting All Types of Data*. Chicago, USA: Pfeiffer.

Poling, S.R. & Nash, M.A., 2008. *Value Stream Mapping - A Comprehensive Guide to Production and Transactional Processes*. Oregon, USA: Taylor & Francis Inc.

Ren, D., 2003. *Encyclopedia of Optical Engineering*. Macel Dekker, Inc.

Rother, M. & Shook, J., 2001. *Learning to See - Value Stream Mapping to Add Value and Eliminate Muda*. Brookline, MA 02446 USA: The Lean Enterprise Institute, Inc.

Skärvad, P.-H. & Olsson, J., 2011. *Företagsekonomi 100 Faktabok*. 15th ed. Liber.

Stach, G., 2011. *regarding glass lens manufacturing*. [Online] ([email] (Personal communication, 27 April, 15 May 2011)).

Svenska Optiksällskapet, 2008. *Svenska Optiksällskapet*. [Online] Available at: http://www.svenskaoptiksallskapet.com [Accessed 6 June 2011].

Twyman, F., 1988. *Prism and Lens Making*. 2nd ed. Taylor & Francis Group.

Wildi, E., 1996. *The Hasselblad Manual*. 4th ed. Focal Press.

Volvo Car Corporation, 2008. *Cost Estimating*. [folder].

Volvo Car Corporation, 2010. *2010 POCKET GUIDE*. Gothenburg, Sweden: Volvo Car Corporation.

Volvo Personvagnar AB, 2009. *Årsredovisning*.

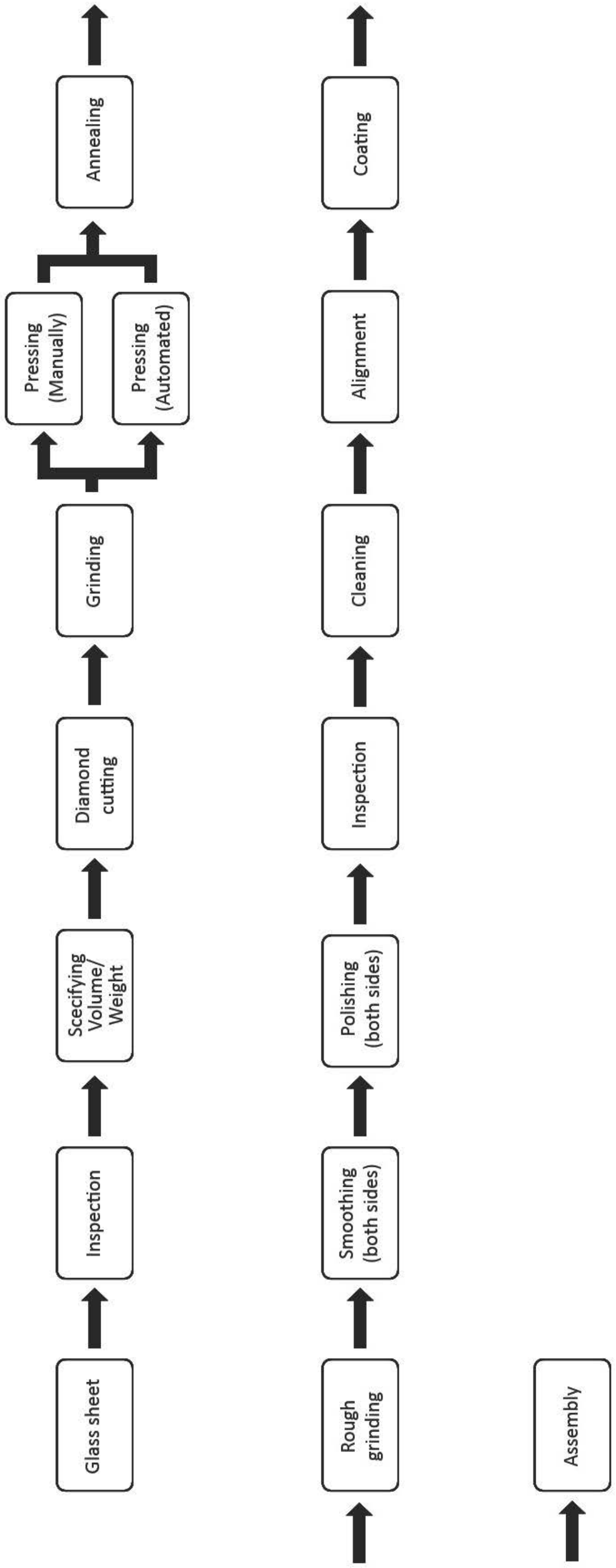
Volvo Personvagnar AB, 2010. *FÖRETAGSRAPPORT MED HÅLLBARHET*. Göteborg: Publish Affairs, Sustainability.

Zemetrics, Inc., 2011. *Zemetrics*. [Online] Available at: http://www.zemetrics.com [Accessed 01 June 2011].

9 Appendix

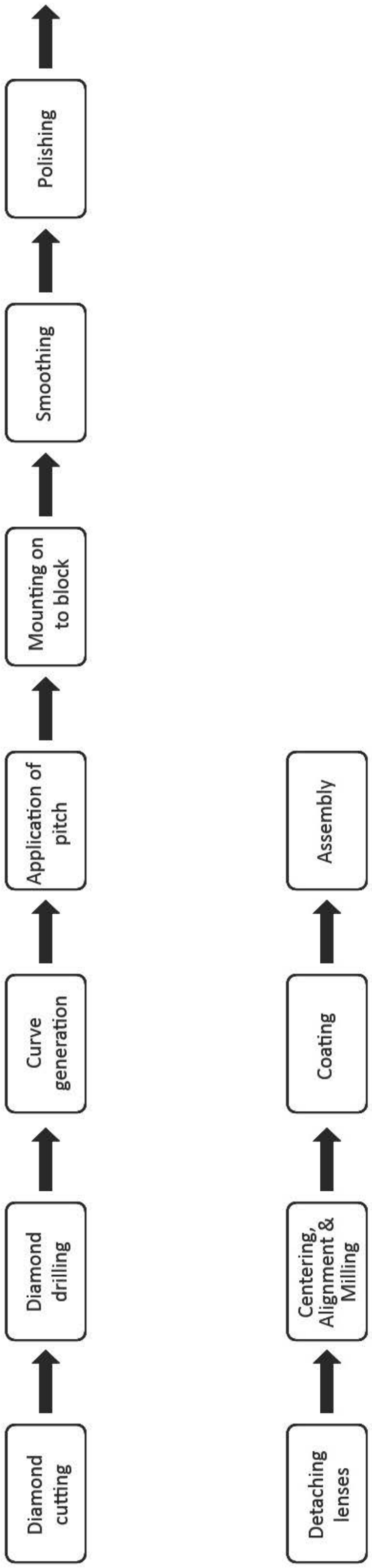
9.1 Appendix I – Lens manufacturing process 1

The process map was created by analysis information from its source (Canon Inc., 2011).



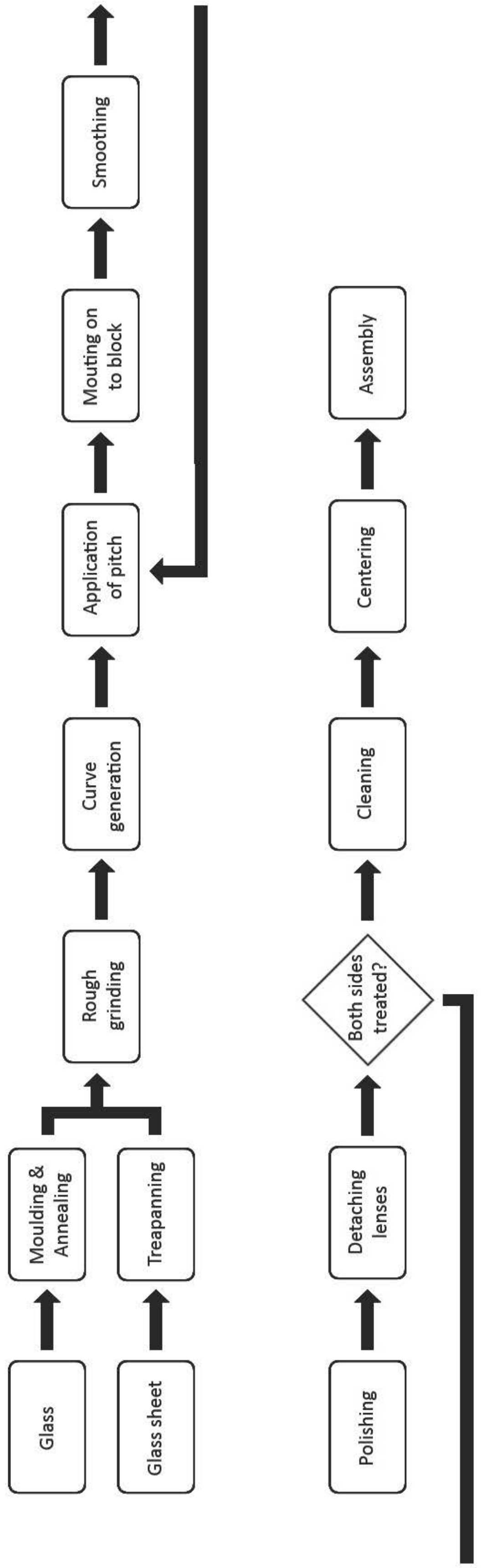
9.2 Appendix II – Lens manufacturing process 2

The process map was created by analysis information from its source (MAJ MEDIA SEC, 2011).



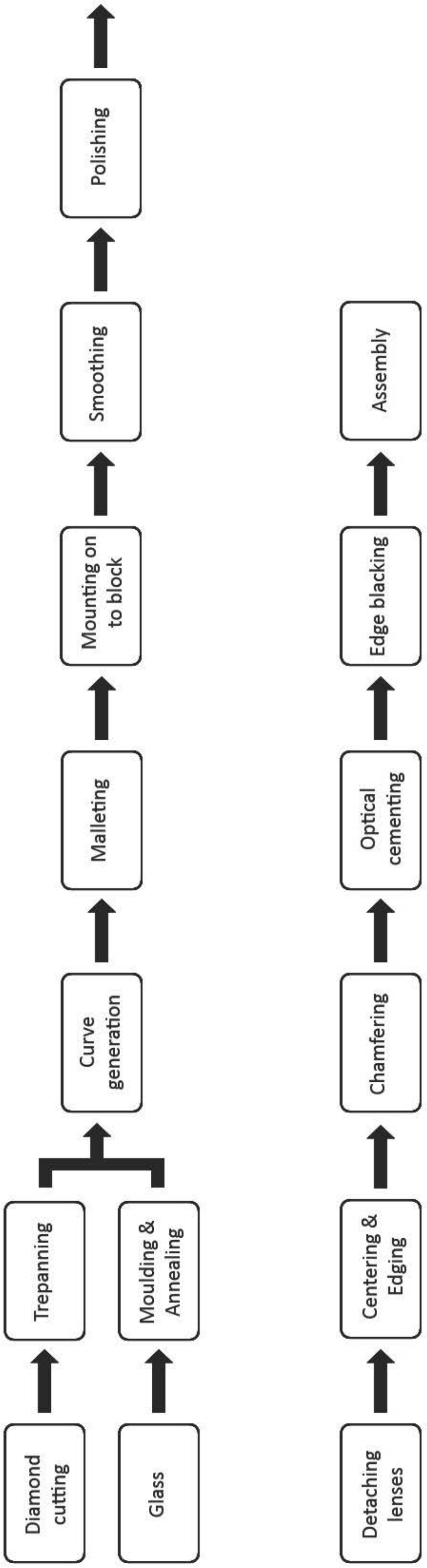
9.3 Appendix III – Lens manufacturing process 3

The process map was created by analysis information from its source (Twyman, 1988).



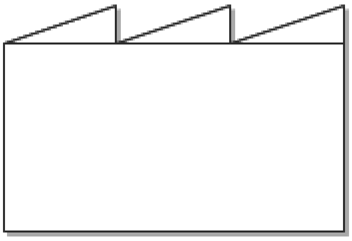
9.4 Appendix IV – Lens manufacturing process 4

The process map was created by analysis information from its source (Horne, 1972).

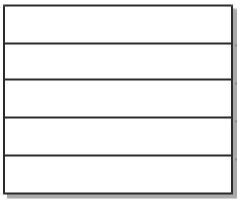


9.5 Appendix V – VSM symbols

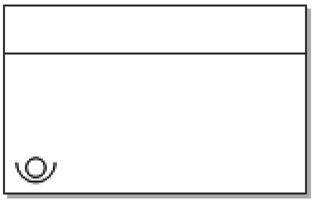
The symbols were created by using information from Rother & Shook (2001).



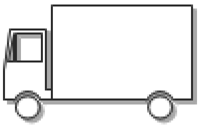
Outside Sources



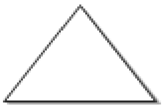
Data Box



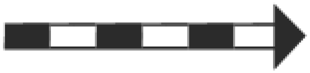
Process Box



Shipment

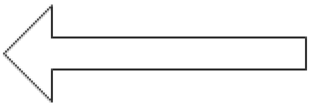


Inventory

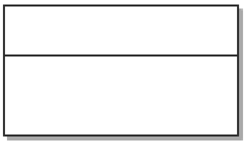


PUSH Arrow

Withdrawal



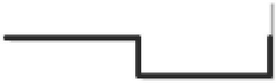
Finished Goods Delivery



Production Control

Manual Information Flow

Electrionic Information Flow



Timeline